Gowhar Hamid Dar
Rouf Ahmad Bhat
Mohammad Aneesul Mehmood
Khalid Rehman Hakeem *Editors*

Microbiota and Biofertilizers, Vol 2

Ecofriendly Tools for Reclamation of Degraded Soil Environs

Springer

Microbiota and Biofertilizers, Vol 2

Gowhar Hamid Dar • Rouf Ahmad Bhat
Mohammad Aneesul Mehmood
Khalid Rehman Hakeem
Editors

Microbiota and Biofertilizers, Vol 2

Ecofriendly Tools for Reclamation of Degraded Soil Environs

Springer

Editors
Gowhar Hamid Dar
Department of Environmental Science
Sri Pratap College, Cluster University
Srinagar, Higher Education Department
Jammu and Kashmir, India

Rouf Ahmad Bhat
Division of Environmental Science
Sher-e-Kashmir University of Agricultural
Sciences and Technology of Kashmir
Jammu and Kashmir, India

Mohammad Aneesul Mehmood
Government Degree College
Pulwama, Jammu and Kashmir, India

Khalid Rehman Hakeem
Department of Biological Sciences
King Abdulaziz University
Jeddah, Saudi Arabia

ISBN 978-3-030-61009-8 ISBN 978-3-030-61010-4 (eBook)
https://doi.org/10.1007/978-3-030-61010-4

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2021
This work is subject to copyright. All rights are reserved 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

Dedicated to COVID-19 frontline workers.

Foreword

The huge enslavement of modern farming and the additional artificial input of "chemical fertilizers" have caused numerous ecological tribulations associated with global warming and soil contamination. As a result, there is an essential requirement for doable agricultural practices on a comprehensive level. Accordingly, biofertilizers, including microbes, have been recommended as feasible, environmentally sound solutions for agricultural practices, which not only are natural and cost-effective but also preserve soil environs and important biota of agricultural land. Moreover, it enhances and sustains the nutrient status and quantity in soils in an ecofriendly manner. Microbial biofertilizers promote plant growth by escalating the proficient absorption of nutrients for the plants and by triggering an excellent disease-fighting mechanism.

The book is a coherent assembly of speckled topics relatable to ecofriendly tools for the reclamation of degraded soil environs. It contains 16 chapters from diverse geographic regions of the world. Chapter 1 deals with the subject of "Chemical Fertilizer Use and Their Impact on Soil Health". The authors from India in this chapter have discussed the importance of soil as it carries out vital ecological functions that are imperative for the existence of life on earth, upkeep of biodiversity, and the continuation of sustainable agronomic practices. The chapter elaborates well how continuous chemical fertilizer usage can change the soil physicochemical characteristics, giving rise to issues as reduction of organic matter and humus content, distressed microbial communities, and inhibition of plant development.

Chapter 2 presents the valuable statistics about the "Microbial Bioremediation of Pesticides/Herbicides in Soil" by making use of microorganisms. Microbial remediation has been the most exceptional biotechnological tool for the revitalization of impaired environments. This chapter provides details about the categories of pesticides, their resources, environmental apprehensions, and the numerous microbes used for their bioremediation.

In Chap. 3, the latest techniques for cleaning polluted environments have been discussed in detail by the group of authors from India. They have emphasized that technological advancement, in addition to the growing population and over-exploitation of natural resources, has resulted in an upsurge in environmental pollution, and there is an immediate need to rectify the poor practices of humans by using cost-effective and ecofriendly techniques to regulate and terminate these pollutants. Techniques such as phytoremediation, rhizofiltration, and phytovolatilization have been stressed upon in this chapter.

Chapter 4 focuses on the "Role of Mushrooms in the Bioremediation of Soil". It is a well-known fact that one of the prominent environmental issues the world is facing nowadays is soil pollution. Therefore, mycoremediation can be an appropriate, cost-efficacious, and environmentally friendly technique to clean up the contaminated soil. The authors have discussed how this technique makes use of fungi to degrade toxic pollutants proficiently and concretely.

The authors of Chap. 5 have presented how "Microbial Degradation of Organic Constituents for Sustainable Development". Environmental contamination by organic compounds has resulted in a multitude of ecological threats, especially to agriculture. The problems are further escalating due to the recalcitrant nature of these organic constituents like hydrocarbons, pesticides, dyes, and heavy metals. The extermination of these toxic pollutants from the environment is vital for achieving sustainable development. This chapter has presented an overview of the role of microorganisms in the degradation of organic components to accomplish sustainable development.

In Chap. 6, titled "Traditional Farming Practices and Its Consequences", the authors have discussed the traditional farming practices, based on the indigenous knowledge and experience developed over the centuries and has remained popular even now. They have mentioned various categories of traditional farming, which include agroforestry, intercropping, crop rotation, cover cropping, conventional organic composting, integrated crop-animal agriculture, shifting cultivation, and slash-and-burn farming. Furthermore, the authors conclude that there are many benefits involved in these practices such as improved soil fertility, carbon sequestration, resource utilization, biodiversity maintenance and sustainability, and environmental protection. Still, there are also specific negative implications associated with some practices, for example, slash-and-burn activities, in shifting agriculture.

The significance of "Soil Organic Matter and Its Impact on Soil Properties and Nutrient Status" has been discussed in Chap. 7. The authors have stressed the impacts of population explosion and an upsurge in food demand on the agriculture land depletion and how it is risking our future advancement. Moreover, the authors have discussed that to overcome this problematic situation, the soil organic matter plays a vibrant and pivotal role in the maintenance and recuperation of soil properties as it has incredible ecological benefits such as regulating ecosystem productivity, soil health, and climate quality. This chapter reviews the influence of organic matter on the physical, chemical, and biological properties of soil.

The vital topic of “Sustainable Agricultural Practices” has been discussed in Chap. 8. The authors have emphasized that the rising need for non-toxic and nourishing food has caused organic agriculture to achieve great significance internationally and how food demand has moved from the chemically dependent farming to intensive organic agriculture. The role of organic agriculture is highlighted due to its capacity of sustaining soil health, increasing crop output, and providing disease-free crops.

Another group of authors from Pakistan have presented their views on the “Values of Composting” as an excellent tool for sustainable agriculture practice in Chap. 9. Composting is an ecofriendly technique, and it provides nourishment to plants on a long-term basis. The authors have discussed the various types of composts and their many benefits. This chapter also covers the role of composting on soil properties and its influence on soil and environmental pollution.

Chapter 10 has provided an introduction to “Microbiota and Biofertilizers”. The section discusses the repercussions of the extensive use of synthetic fertilizers on the environmental, plant, soil, and animal health. The chapter explores the use of microbes as fertilizers and their substantial role in nutrient cycling and nitrogen fixation as well as in enhancing and maintaining the content of soil nutrients. These microbes, as biofertilizers, are ecologically friendly, non-toxic, and best replacements for chemical fertilizers.

Chapter 11, titled “Fungi and Their Potential as Biofertilizers”, provides information on the use of fungi as an environmentally friendly alternative to man-made harmful chemical fertilizers. It has also been perceived in this chapter that fungi play a very central role in stimulating plant growth and output and for the improvement of soil fertility. How fungal biofertilizers influence plant growth and development has been discussed in detail by the authors. The chapter mainly focuses on the fungi that have the potential to be used as biofertilizers.

The title “*Bacillus thuringiensis* as a Biofertilizer and Plant Growth Promoter” is the topic of Chap. 12. According to the authors of this chapter, the utilization of beneficial microorganisms like *Bacillus thuringiensis* as biofertilizers is of paramount significance in agriculture. Its ability to check insect and pest populations and contribute to controlling plant diseases has been comprehensively elaborated. In addition, its plant growth-promoting abilities as biofertilizers are discussed in this chapter. The authors have stated that its use in agriculture can be a chance for curtailing the practice of using chemical fertilizers. This chapter further evaluates the role of phosphate-solubilizing *B. thuringiensis* as a biofertilizer and biostimulator.

The authors of Chap. 13 have presented valuable information on “Cyanobacteria as Sustainable Microbiome for Agricultural Industries” as an ecofriendly, effective, and economical alternative for synthetic fertilizers. They have discussed the importance of cyanobacteria as a potential stimulant of nitrogen fixation and plant growth-promoting hormones. Furthermore, the role of cyanobacteria for the remediation of pesticides, herbicides, and heavy metals has been studied significantly.

This chapter also emphasizes the utilization of these microbes as biofertilizers in the farming sector to improve crop production and increase crop output.

Chapter 14, “Intercropping: A Substitute but Identical of Biofertilizers”, has been presented by scientists from China and Pakistan. The authors have revealed that conventional cropping and the use of inorganic chemical-based pesticides and fertilizers are the main obstructions to sustainable agriculture. They have explored the practice of intercropping as an old but efficient and ecofriendly way to improve soil health and increase crop production. This chapter elucidates the mechanisms behind intercropping, which assist in nitrogen and phosphorus acquisition and prevent insect pest and disease frequency, and discusses how intercropping can be employed to reclaim degraded agricultural lands.

“Application of Phyllosphere Microbiota as Biofertilizers” is the theme of Chap. 15. The authors have discussed the influence of phyllosphere microbiota on the fitness and functions of the host plant, plant biogeography, and ecosystem working. This chapter focuses on the advantages of plant-microbe phyllosphere interactions that have a significant role in plant health and productivity as well as their contribution to achieving environmental sustainability.

The authors from Pakistan have presented their views on “Biofertilizers: A Viable Tool for Future Organic Agriculture” in Chap. 16. They have discussed the use of organic farming as a substitute nutrient management practice. Organic agriculture, as an ecofriendly, fiscally lucrative approach with pronounced market potential as well as a sustainable agricultural practice, has been particularized by the authors. They have also mentioned the significant obstacles in the implementation of organic farming.

I am convinced that the book titled *Microbiota and Biofertilizers, Vol. 2 – Ecofriendly Tools for Reclamation of Degraded Soil Environs* will serve as a milestone in conserving the soil health which is crucial in sustaining hundreds of the well-knit ecosystems of nature. Besides this book will serve as an inspiring force for teachers to make students and other stakeholders aware of the cutting-edge technologies that can be efficiently used for transforming agriculture under changing climatic scenario. Human population is increasing at an alarming pace, which gets aggravated with the shrinking of water and land resources. Human population is expected to increase from 7.6 billion (2020) to 9.4 billion in 2050. It is the need of the hour to sustain the crop production to feed the ever-increasing populace, for which technological interventions in the form of organic farming and biofertilizers are essentially required to improve and conserve “Mother Soil”. This book is a way forward in this direction. The editors must be highly praised and appreciated for their creditable hard work in bringing this book.

MABhat

M. Ashraf Bhat

Chief Scientist, Division of Genetics and Plant
Breeding, SKUAST Kashmir, FoA and RRS,
Wadura, Sopore, Jammu and Kashmir, India

Preface

Agriculture, the backbone of human sustenance, has been put under tremendous pressure by the ever-increasing human population. Although various modern agro-techniques boosted agricultural production, the excessive use of synthetic fertilizers, pesticides, and herbicides has proven to be extremely detrimental to agriculture as well as to the environmental quality. Besides this, some faulty agricultural practices like monoculture and poor irrigation further complicated the scenario of problems by eliminating the critical biota. The influx of nutrients into the waterbodies (eutrophication) and the formation of algal blooms further damage the water quality and reduce the fish stocks. Therefore, it becomes imperative to involve specific scientific approaches like the development of biofertilizers, which could be beneficial for sustainable agriculture practices.

The application of biofertilizers helps increase mineral and water uptake and root development in plants and also in nitrogen fixation. It liberates growth-promoting substances and minerals, which helps in the maintenance of soil fertility. Furthermore, biofertilizers act as antagonists and play a pivotal role in neutralizing the soil-borne plant pathogens, thus helping in the bio-control of diseases. The application of biofertilizers instead of synthetic fertilizers could be a promising technique to raise agricultural productivity without degrading the environmental quality.

The book is an articulate assemblage of assorted topics in the shape of chapters, pertinent to the reliability of "microbiota and biofertilizers" as ecofriendly tools for reclamation of degraded soil environs. The starting chapters provide an outline of the sources and detrimental impacts of synthetic chemical substances on soil and human health. A precious space has been given to the latest techniques for cleaning polluted environs, as well as for the bioremediation technologies involving various biota of the environment. Traditional and organic farming has been considered the backbone of this book. Furthermore, a valuable consigned space related to microbiota as biofertilizers is given at the end of the chapters. In general, the opening chapters of this book deal with the contamination and its impacts, followed by the ecofriendly strategies towards sustainable developments.

The book is an accurate, broad description of the involvement of biota and biofertilizers for pollution remediation and the sustainable strategies for healthy environs. Academicians, researchers, and students will find it a perfect bind about “microbiota and biofertilizers” as intrusion in agricultural practices for the reclamation of degraded soil environs and should sufficiently suffice the requirements of training, teaching, and research purposes.

Srinagar, Jammu and Kashmir, India	Gowhar Hamid Dar
Srinagar, Jammu and Kashmir, India	Rouf Ahmad Bhat
Pulwama, Jammu and Kashmir, India	Mohammad Aneesul Mehmood
Jeddah, Saudi Arabia	Khalid Rehman Hakeem

Acknowledgements

The editors would like to thank and appreciate the efforts of all the authors who contributed to this volume. Acknowledgement is also extended to the Principal of Sri Pratap College, Higher Education Department (J&K), and Cluster University Srinagar for the encouragement and support in bringing this volume to fruition. The editors would also like to take this opportunity to thank the faculty and non-teaching staff of PG Department of Environmental Science and Department of Environment and Water Management, Sri Pratap College, Cluster University Srinagar, for their kind guidance and support. The help from all friends and colleagues who encouraged us to edit this volume is greatly acknowledged. Special thanks go to Mr. Asif Ahmad Bhat and Mr. Shahid Bashir for their lovable support while drafting this book.

About the Book

This volume of the book series Microbiota and Biofertilisers provides clear information on the indiscriminate use of synthetic agrochemicals in conventional agriculture and their drastic impacts on the ecological balance aggravated by some critical environmental challenges like global warming, climate change, and environmental pollution. It focuses on the sustainable agriculture demands and alternatives to deal with both agricultural production and environmental pollution. Moreover, the book highlights the involvement of microbiota and organic amendments as emerging options which are cost-effective and provide overwhelming results at field level and at the same time maintain soil health without degrading the environmental quality, particularly on soil biota and biochemistry. In general, the introductory chapters of this volume focus on the environmental degradation and issues raised due to unplanned agriculturale practices, followed by the ecofriendly approaches and alternatives replacing synthetic substances. The closing chapters provide an insight into the bioremediation with the help of the latest agricultural tools and techniques and research findings to keep a balance between the various components of the agricultural environment. Furthermore, the book is a detailed comprehensive interpretation of doable approaches from quiver to sustainable. Academicians, researchers, and students should find it as an absolute bind about microbial intrusion as biofertilizer for ecofriendly reclamation of degraded soil environs.

Contents

Contributors

Tawseef Ahmad Department of Biotechnology, Punjabi University, Patiala, Punjab, India

Aarif Ali Faculty of Veterinary Sciences and Animal Husbandry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shuhama, Jammu and Kashmir, India

Irfan Ali Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

Tahir Ali Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Waqas Ashraf Department of Plant Pathology, University College of Agriculture and Environmental Sciences, Islamia University of Bahawalpur, Bahawalpur, Pakistan

Rezwana Assad Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

Zahoor Ahmad Baba Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

S. A. Bangroo Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Iqra Bashir Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

Owais Bashir Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Madiha Batool Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Varsha Bharati Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Rouf Ahmad Bhat Division of Environmental Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Jammu and Kashmir, India

S. J. A. Bhat Faculty of Forestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Benhama, Ganderbal, Jammu and Kashmir, India

Gowhar Hamid Dar Department of Environmental Science, Sri Pratap College, Cluster University Srinagar, Higher Education Department, Jammu and Kashmir, India

K. A. Dar Mountain Livestock Research Institute, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Manasbal, Jammu and Kashmir, India

Mohammad Irfan Dar Department of Biotechnology, Jamia Millia Islamia, New Delhi, India

R. A. Dar Mountain Livestock Research Institute, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Manasbal, Jammu and Kashmir, India

Jorge Delfim Instituto de Investigação Agronômica, Huambo, Angola

Programa de Pós-Graduação em Agronomia, Centro de Ciências Agrárias, Universidade Estadual de Londrina, Londrina, PR, Brazil

Zulaykha Khurshid Dijoo Department of Environmental Sciences/Centre of Research for Development, University of Kashmir, Srinagar, Jammu and Kashmir, India

Shahla Faizan Environmental Physiology Laboratory, Department of Botany, Aligarh Muslim University, Aligarh, India

A. A. Ganie Faculty of Veterinary Sciences and Animal Husbandry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shuhama, Jammu and Kashmir, India

A. Gazal Plant Breeding and Genetics, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Syed Maqbool Geelani Division of Environmental Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Jeelani Gousia Centre of Research for Development, University of Kashmir, Srinagar, Jammu and Kashmir, India

Charu Gupta School of Studies in Microbiology, Jiwaji University, Gwalior, Madhya Pradesh, India

Mahendra K. Gupta Microbiology Research Lab., School of Studies in Botany, Jiwaji University, Gwalior, Madhya Pradesh, India

Aukib Habib Microbiology Research Lab., School of Studies in Botany, Jiwaji University, Gwalior, Madhya Pradesh, India

H. Hamadani Mountain Livestock Research Institute, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Manasbal, Jammu and Kashmir, India

Zahoor Hussain Department of Horticulture, University College of Agriculture, University of Sargodha, Sargodha, Pakistan

Shazia Iqbal Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Shah Ishfaq Department of Environmental Science, University of Kashmir, Srinagar, Jammu and Kashmir, India

Shahid Javid Provincial Reference Fertilizer Testing Laboratory, Raiwind, Lahore, Punjab, Pakistan

Azra N. Kamili Centre of Research for Development, University of Kashmir, Srinagar, Jammu and Kashmir, India

A. A. Khan Faculty of Veterinary Sciences and Animal Husbandry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shuhama, Jammu and Kashmir, India

Mehraj ud din Khanday Division of Soil Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Muhammad Khashi u Rahman Key Laboratory of Biology and Genetic Improvement of Horticultural Crops (Northeast Region), Ministry of Agriculture and Rural Development, Northeast Agricultural University, Harbin, China

College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, China

Jitender Kumar Department of Botany, Lal Bahadur Shastri Govt. PG College, Saraswati Nagar, Jubbal, Himachal Pradesh, India

Nazir Ahmad Malik Department of Botany, Dolphin PG College of Science & Agriculture, Chunni Kalan, Punjab, India

Lone Rafiya Majeed Vivekananda Global University, Jaipur, India

Nadia Manzoor Department of Soil Chemistry, Regional Agricultural Research Institute, Bahawalpur, Pakistan

Rehana Mohiuddin Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Syeed Mudasir Abdul Ahad Azad Memorial Degree College Bemina, Srinagar, Jammu and Kashmir, India

Sofi Danish Mukhtar Department of Chemistry, Jamia Millia Islamia, New Delhi, India

Ghulam Murtaza Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Punjab, Pakistan

Humira Mushtaq Research and Training Center on Pollinators and Pollination Management Section, Division of Entomology, SKAUST Kashmir, Srinagar, Jammu and Kashmir, India

Zeenat Mushtaq Environmental Physiology Laboratory, Department of Botany, Aligarh Muslim University, Aligarh, India

Nasir Naik Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Bisma Nisar Department of Environmental Sciences, University of Kashmir, Srinagar, Jammu and Kashmir, India

Heena Nisar Pahalvi Department of Environmental Sciences, University of Kashmir, Srinagar, Jammu and Kashmir, India

J. D. Parrah Mountain Livestock Research Institute, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Manasbal, Jammu and Kashmir, India

Manzoor Ahmad Parray Research and Training Center on Pollinators and Pollination Management Section, Division of Entomology, SKAUST Kashmir, Srinagar, Jammu and Kashmir, India

Anjali Pathak Microbiology Research Lab., School of Studies in Botany, Jiwaji University, Gwalior, Madhya Pradesh, India

Ayesha Abdul Qadir Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Punjab, Pakistan

Muhammad Akram Qazi Rapid Soil Fertility Survey and Soil Testing Institute, Lahore, Punjab, Pakistan

Mir Sajad Rabani Microbiology Research Lab., School of Studies in Botany, Jiwaji University, Gwalior, Madhya Pradesh, India

Faizan Rafi Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

Iflah Rafiq Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

Lone Rafiya Vivekananda Global University, Jaipur, India

Irfan Rashid Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

S. Mudasir Rashid Faculty of Veterinary Sciences and Animal Husbandry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Division of Veterinary Biochemistry, Faculty of Veterinary Sciences (SKUAST-K) Shuhama, Alusteng, Srinagar, Jammu and Kashmir, India

Sumaira Rashid Department of Environmental Sciences, University of Kashmir, Srinagar, Jammu and Kashmir, India

G. H. Rather Division of Fruit Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Zafar Ahmad Reshi Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

Umair Riaz Soil and Water Testing Laboratory for Research, Agriculture Department, Government of Punjab, Bahawalpur, Punjab, Pakistan

Muhammad Shakir Rapid Soil Fertility Survey and Soil Testing Institute, Lahore, Punjab, Pakistan

Rachna Singh School of Studies in Microbiology, Jiwaji University, Gwalior, Madhya Pradesh, India

Irshad Ahmad Sofi Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

Irfan-ur-Rauf Tak Department of Zoology, S.P. College, Cluster University Srinagar, Srinagar, Jammu and Kashmir, India

Younas Rasheed Tantray Department of Botany, Punjabi University, Patiala, Punjab, India

Shivani Tripathi Microbiology Research Lab., School of Studies in Botany, Jiwaji University, Gwalior, Madhya Pradesh, India

Muhammad Tuseef National Institute of Food Science and Technology, University of Agriculture, Faisalabad, Punjab, Pakistan

Baba Uqab Sri Pratap College, Srinagar, Jammu and Kashmir, India

Mohammad Saleem Wani Department of Botany, Punjabi University, Patiala, Punjab, India

Aadil Farooq War Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

Fengzhi Wu Key Laboratory of Biology and Genetic Improvement of Horticultural Crops (Northeast Region), Ministry of Agriculture and Rural Development, Northeast Agricultural University, Harbin, China

College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, China

Xingang Zhou Key Laboratory of Biology and Genetic Improvement of Horticultural Crops (Northeast Region), Ministry of Agriculture and Rural Development, Northeast Agricultural University, Harbin, China

College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, China

About the Editors

Gowhar Hamid Dar, (PhD) is currently working as an assistant professor of environmental science at Sri Pratap College, Cluster University Srinagar, Department of Higher Education (J&K). He has a PhD in environmental science with specialization in environmental microbiology (fish microbiology, fish pathology, industrial microbiology, taxonomy, and limnology). He has been teaching postgraduate and graduate students for the past many years in the Post Graduate Department of Environmental Science, Sri Pratap College, Cluster University Srinagar. Dr. Dar has more than 45 papers in international and national journals of repute and a number of books with international publishers to his credit. Moreover, he is supervising a number of students for the completion of their degrees. Dr. Dar has been working on the isolation, identification, and characterization of microbes and their pathogenic behaviour and the impacts of pollution on the development of diseases in the fish fauna for the last several years. He has received many awards and appreciations for his services towards science and development. In addition, he acts as a member of various research and academic committees.

Rouf Ahmad Bhat, (PhD) is working at Cluster University Srinagar (J&K), India, in the capacity of assistant professor and has his specialization in limnology, toxicology, phytochemistry, and phytoremediation. He is an author of more than 50 research papers and 25 book chapters and has published more than 15 books with international publishers. He has presented and participated in numerous state, national, and international conferences, seminars, workshops, and symposiums. Dr. Bhat has worked as an associate environmental expert in the Flood Emergency Recovery Project funded by the World Bank and also as an environmental support staff in development projects funded by the Asian Development Bank (ADB). He has received many awards, appreciations, and recognitions for his services to the science of water testing and air and noise analysis. He has served as an editorial board member and reviewer of reputed international journals (Springer, Elsevier, CRC Press Taylor and Francis, Apple Academic Press, John Wiley, IGI Global). Dr. Bhat is still writing and experimenting with diverse capacities of plants for use in aquatic pollution remediations.

Mohammad Aneesul Mehmood, (PhD) has his specialization in limnology and environmental toxicology. He completed his doctorate from the Division of Environmental Science, SKUAST-K, with a meritorious certificate from the university. He received the Dr. Mumtaz Ahmad Khan Gold Medal and Shri Bhushan Memorial Gold Medal for being a topper during his master's programme. He has qualified various national competitive tests in the discipline of Environmental Science. Dr. Mehmood was also awarded with INSPIRE Merit Fellowship (JRF & SRF) by the Department of Science and Technology, GoI, during his doctoral programme. He has been teaching graduate and postgraduate students for the past 2 years in the Department of Environmental Science, School of Sciences, Sri Pratap College Campus, Cluster University Srinagar, J&K, India. He has been supervising many students for their MSc projects. Furthermore, he has a number of publications in international journals of repute and a number of books with international publishers.

Khalid Rehman Hakeem, (PhD) is a professor at King Abdulaziz University, Jeddah, Saudi Arabia. After completing his doctorate in botany with specialization in plant eco-physiology and molecular biology from Jamia Hamdard, New Delhi, India, in 2011, he worked as a lecturer at the University of Kashmir, Srinagar, for a short period. Later, he joined Universiti Putra Malaysia, Selangor, Malaysia, and worked there as a postdoctorate fellow in 2012 and as a research fellow (associate professor) from 2013 to 2016. Dr. Hakeem has more than 12 years of teaching and research experience in plant eco-physiology, biotechnology and molecular biology, medicinal plant research, and plant-microbe-soil interactions as well as in environmental studies. He is the recipient of several fellowships at both national and international levels and has served as a visiting scientist at Jinan University, Guangzhou, China. Currently, he is involved in a number of international research projects with different government organizations. So far, Dr. Hakeem has authored and edited more than 60 books with international publishers, including Springer Nature, Academic Press (Elsevier), and CRC Press. He also has to his credit more than 120 research publications in peer-reviewed international journals and 60 book chapters in edited volumes with international publishers. At present, Dr. Hakeem serves as an editorial board member and reviewer of several high-impact international scientific journals from Elsevier, Springer Nature, Taylor and Francis, Cambridge, and John Wiley Publishers. He is recently elected as the Fellow, Royal Society of Biology, UK. He is included in the advisory board of Cambridge Scholars Publishing, UK. He is also a fellow of Plantae group of the American Society of Plant Biologists, member of the World Academy of Sciences, member of the International Society for Development and Sustainability (Japan), and member of the Asian Federation of Biotechnology (Korea). Dr. Hakeem has been listed in Marquis Who's Who in the World, since 2014–2019. Currently, he is engaged in studying the plant processes at eco-physiological as well as molecular levels.

Chapter 1
Chemical Fertilizers and Their Impact on Soil Health

Heena Nisar Pahalvi, Lone Rafiya, Sumaira Rashid, Bisma Nisar, and Azra N. Kamili

1.1 Introduction

Agriculture is facing considerable problems such as low soil organic carbon (SOC) stock, low fertilizer use efficiencies, and the imbalance between nutrient removal and addition to the soil. The whole scenario of agriculture is at a confluence where one has to rethink and improve agricultural packages and processes in meeting the dreams of millions of people. Improvement and maintenance of soil fertility and sustaining crop production are of worldwide importance. The management of soil health is necessary for securing sustainable agricultural production and sustenance of biodiversity. Modern agriculture mostly relies on various inputs, such as pesticides, chemical fertilizers, assured irrigation, improved seeds, and herbicides. Their employment in agriculture increases the production, but their improper utilization has unfavorable impact on environment quality and soil productivity which is a matter of concern (Dar and Bhat 2020). Chemical fertilizers are compounds which encompass the large nutrient concentration needed for growth of plant. In other words, these are man-made materials that supply the required nutrients to plants (Khanday et al. 2016; Dar et al. 2013; Bhat et al. 2018a, b; Mushtaq et al. 2018; Singh et al. 2018). Fertilizers and pesticides are unavoidable risks in agriculture. Nevertheless, they continue to be vital means for worldwide food safety, their negative impacts cannot be unnoticed particularly when sustainable agriculture is the

---

H. N. Pahalvi (✉) · S. Rashid · B. Nisar
Department of Environmental Sciences, University of Kashmir,
Srinagar, Jammu and Kashmir, India

L. Rafiya
Vivekananda Global University, Jaipur, India

A. N. Kamili
Centre of Research for Development, University of Kashmir,
Srinagar, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_1

Table 1.1 Chemical fertilizer usage in various countries

Country	Chemical fertilizers (kg/ha)
Netherlands	665.6
Egypt	624.8
Japan	373.2
China	301.5
Britain	287.5
Germany	205.4
France	180.1
USA	160.8
Italy	126.4
India	121.4
Greece	115.4
Indonesia	106.9
Turkey	100.4

global target. Chemical fertilizer has a vital role in increasing soil fertility and crop productivity (Hera 1996; Bhatti et al. 2017). Different countries use different amounts of fertilizers, for example, Turkey uses less chemical fertilizer per hectare than many developing and developed countries. The values for chemical fertilizer usage in different countries are shown in Table 1.1. Chemical fertilizer use in India has increased from 2.65 million tons (mt) of NPK in 1971–1972 to 28.12 mt in 2010–2011. Fertilizer usage in India is highly skewed (Chand and Pavithra 2015).

The fertilizer industry is a source of heavy metals and radionuclides. It consists of most of the metals such as cadmium (Cd), arsenic (As), mercury (Hg), nickel (Ni), lead (Pb), copper (Cu); natural radionuclide, such as U^{238}, Th^{232}, and Po^{210} (FAO 2009; Sönmez et al. 2007). Fertilization can be responsible for the accumulation of heavy metal in soil system. Through the soil, plants absorb fertilizers and these make their entry into the food chain. Large amounts of chemical fertilizers are used in greenhouses, aquacultures during the top season. The prolonged use of chemical fertilizer has declined the agricultural soil quality with the reduction in soil organic matter (SOM) content, and even an increase in environment pollution and soil acidity (Dinesh et al. 2010; Dar et al. 2016), that has become a serious concern (Chaudhry et al. 2009; Bhat et al. 2017a, b; Dervash et al. 2020; Mushtaq et al. 2020; Singh et al. 2020). Chemical fertilizers are detrimental to agriculture as salt is one of its major contents, which is detrimental for plants and soil. Chemical fertilizers lessen vital soil minerals and nutrients. They do not provide benefit in restoring soil fertility and its nutrients.

1.2 Types of Chemical Fertilizers

There are three kinds of chemical fertilizers available. These are nitrogenous fertilizer, phosphorus fertilizer, and potassium fertilizer. Chemical fertilizer consists of elements, such as nitrogen, potassium, and phosphorus. These are used for increasing productivity of land (Fig. 1.1).

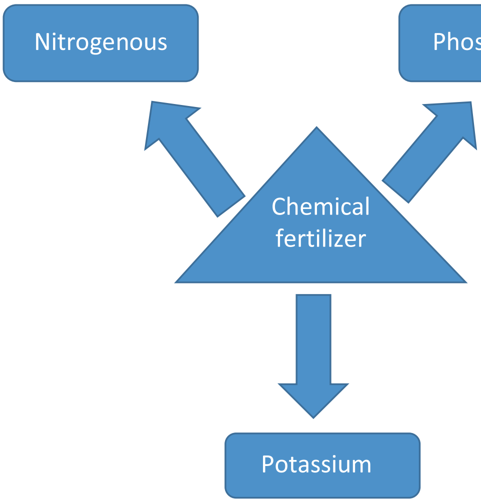


Fig. 1.1 Types of chemical fertilizers

1.3 Nitrogenous Fertilizer

In this type of fertilizer, nitrogen is present in the form of ammoniacal nitrogen, such as ammonium chloride, ammonium sulfate; amide nitrogen, such as urea; nitrate-nitrogen, such as calcium ammonium nitrate in which both ammoniacal and nitrate nitrogen are present. This fertilizer is used for meeting the nitrogen deficiency in the land. This is the most beneficial fertilizer for the plant. It supplies nutrients to both plants and land.

1.3.1 Characteristics

(a) The power of ammonium sulfate is much greater than urea.
(b) Nitric nitrogen is more effective when it is used during the start of a reproductive process of paddy plant.
(c) After the ammonium nitrogen application, the paddy plant may take 30–35% of total nitrogen. But when fertilizers are used at 5–10 cm depth, the nutrient becomes more available.
(d) The continuous use of acid-making fertilizers, such as ammonium sulfate, urea, nitrate, and ammonium chloride ought to be prevented in calcium-deficient soil and acid soil. At least, liming ought to be done 15 days prior to sowing of the crop.
(e) It is water-soluble and flows quickly from the point of its application to all directions. Nitrogenous fertilizer application ought to be as per crop requirement.
(f) Every nitrogenous fertilizer is equitably useful in the rainy season.

1.4 Phosphorus Fertilizer

In phosphorus fertilizers, phosphorus is present as available phosphate. This fertilizer is vital terrestrial fertilizer. Its requirement is less as compared to nitrogen fertilizer.

1.4.1 Characteristics

(a) The combined use of phosphate and nitrogenous fertilizer boosts the uptake efficiency of the plant.
(b) Phosphate fertilizers, such as rock phosphate, basic slag, are the most appropriate for acidic soils.
(c) Phosphate compost such as superphosphate ought to be applied close to the crop root area or in the soil layer.
(d) Super phosphate ought to be applied in the soil ranges from neutral to alkaline.
(e) It ought to be placed deep in fruit trees, such as apple and citrus.

1.5 Potassium Fertilizer

The potassium requirement can be fulfilled with Muriate (potassium chloride) and sulfate of potash. Potassium sulfate is necessary for healthy plant growth. The formation of carbohydrate in the plants is possible with the help of potassium. It is divided into two subtypes, that is, potash in non-chloride and in chloride forms. Sulfate of potash and muriate of potash are the examples of potash in non-chloride nature and potash in chloride form, respectively.

1.5.1 Characteristics of Potassium Fertilizer

(a) It is suitable for all crops.
(b) It can be utilized for a wide range of soils.
(c) It boosts power of resistance of plants.
(d) Potassium sulfate is superior to potassium nitrate for a variety of crops such as fruit trees and potatoes.
(e) It is soluble in water.
(f) It dissociates to K^+ ions and gets consumed in the soil. It is later absorbed by the plant.

1.6 Advantages of Chemical Fertilizer

Chemical fertilizer is utilized to restore lands' fertility. The land loses its fertility because of the enormous number of crops cultivated during the year. Fertilizers are exceptionally fundamental for the development of the crop, quality parameters, yield, in any event, for soil well-being, when utilized appropriately. Fertilizer makes nutrient status better and the nature of the soil, by adding supplements which it needs. Some points of interest are as under:

1. It enhances power of resistance in plants.
2. Growing better crops.
3. Plant growth gets faster.
4. Plants obtain all the nutrients from chemical fertilizer in equal proportion.
5. Soil readily absorbs chemical fertilizer, as it is water-soluble.
6. No unnecessary ingredient is found in chemical fertilizer.
7. Plant growth and development become accurate.

1.7 Drawbacks of Chemical Fertilizer

The health of soil and plants will deteriorate by improper employment of chemical fertilizer. The primary drawbacks are as follows:

1. Some artificial fertilizer elements disturb the soil properties.
2. Artificial fertilizers become costly for small farmers.
3. It enhances the emission of nitrate.
4. Crop growth is not sufficient, so results in the decrease in crop production.
5. Often crops are damaged due to insufficient water supply, particularly in regions with less rainfall.
6. When N-fertilizer is applied in the field, only then bacteria already present can turn the nitrogen into nitrate.
7. It spoils the constitution of the soil due to lack of organic material.
8. Soil dwelling organisms, such as earthworms, which make the soil fertile, also are destroyed due to improper application.
9. The nitrogen fertilizer is toxic to both animals and humans.

1.8 Important Nutrients in Fertilizers

Chemical fertilizers are sources of the main macronutrients for plants, such as nitrogen, potassium, phosphorus, and a number of micronutrients and additives. Plants need sufficient amounts of nutrients in addition to three prime component elements,

Table 1.2 Important nutrients and their chemical forms

Element	Chemical forms of elements absorbed by plants
Primary nutrients	
Nitrogen (N)	NO_3^-, NH_4^+
Phosphorus (P)	$H_2PO_4^-$, HPO_4^{3-}, PO_4^{3-}
Potassium (K)	K^+
Secondary nutrients	
Magnesium (Mg)	Mg^{2+}
Calcium (Ca)	Ca^{2+}
Sulfur (S)	SO_4^{2-}
Micronutrients	
Boron (B)	BO_3^{3-}
Chlorine (Cl)	Cl^-
Copper (Cu)	Cu^+, Cu^{2+}
Iron (Fe)	Fe^{3+}
Manganese (Mn)	Mn^{2+}
Molybdenum (Mo)	MoO_4^{2-}
Nickel (Ni)	Ni^{2+}
Zinc (Zn)	Zn^{2+}

oxygen, carbon, and hydrogen. The nutrients are classified as primary nutrients, secondary nutrients, and micronutrients (Table 1.2).

1.9 Primary Nutrients

Primary nutrients are those nutrients which are demanded by plants in adequate quantities for their development and growth. It comprises three elements, such as nitrogen (N), phosphorus (P) and potassium (K). They play an important role in plants.

- Nitrogen (N) is a basic element for various vital plant substances, such as chlorophyll, and thus help in plant growth.
- Phosphorus (P) is responsible for numerous important plant processes such as energy transfer, root growth, fruiting, and flowering. Plants need it in range of mild to high levels for proper development of fruits and seeds.
- Potassium (K) assists in activating various enzymes involved in different processes, such as respiration and photosynthesis. It also helps in movement of water, promotes fruiting and flowering.

1.10 Secondary Nutrients

The nutrients needed by plants in moderate quantities. It comprises calcium (Ca), magnesium (Mg), and sulfur (S).

- Calcium (Ca) is responsible for activation of certain plant enzymes, governs the transfer of certain nutrients into the plant. It plays an important part in the photosynthesis and structure of plants.
- Magnesium (Mg) is an important member of the chlorophyll molecule. It also plays a role as an efficient activator in various enzyme reactions.
- Sulfur (S) is an important constituent of a few vitamins and amino acids. It is necessary for function and growth of chloroplast and is essential for legumes to fix N_2. It helps in transforming nitrate to amino acids and then to proteins.

1.11 Micronutrients

These are demanded by plants in minute quantities. These nutrients are equally essential as macronutrients. They are also known as trace elements, rare elements which are shown below:

- Copper (Cu) has a primary function in the photosynthesis process and in the developments of crops. It is also vital for the formation of lignin.
- Iron (Fe) acts as a cofactor of enzymes in plants and is important in the photosynthesis process.
- Manganese (Mn) is involved in chloroplast formation.
- Molybdenum (Mo) is an important cofactor in the formation of amino acid and also helps in nitrogen metabolism.
- Zinc (Zn) has an important role in a wide variety of enzymes. It has a vital function in the transcription of DNA.
- Boron (B) carries out various roles in a plant. It includes in cell division, pollen germination, fruiting and flowering, and active absorption of salt.
- Silicon (Si) enhances strength of cell walls, increases strength, productivity, and health of plant.
- Cobalt (Co) is necessary in nitrogen fixation.
- Vanadium (V) is needed, at very low concentration, by some plants. It may also be used as a substitute for molybdenum.

1.12 Soil Health Concept

The primary role of the soil is to produce sufficient food and secure human health. There is, increasingly, an understanding of the relation between human health and soil with respect to health enhancing elements such as nitrogen (N), phosphorus (P), and other elements, such as arsenic (As) and cadmium (Cd), which are detrimental to human health (Brevik and Burgess 2013). The idea of "health" also covers the soil. Soil, in the form of complex ecosystem, promotes an immense variety of life. The idea of soil health is easy to comprehend when the system is regarded as a whole. Soil quality (health) is characterized as a soil's ability to perform within ecosystems and land use boundaries to preserve biological productivity and quality of environment, and to improve animal and plant health (Doran and Parkin 1994; Bhat et al. 2017a, b). While the basic concept is to maintain the soil so that it carries on various necessary functions without the deterioration of the soil itself or adversely impacting the environment. According to Kibblewhite et al. (2008), a healthy soil is able to support fiber and food production to a level, and with a quality, enough to satisfy human needs, and of sustaining certain functions which are vital to protect the human life, and conserve biodiversity. The fundamental idea is to sustain the quality of soil and prevent practices such as nutrient mining and erosion which deteriorate the soil. When the decaying rate of "inferior quality" or high C:N ratio organic materials and SOM increases, the health of soil is affected (Recous et al. 1995; Bhat et al. 2018a, b).

1.13 Positive Effects of Fertilizers

While fertilization does not have any direct useful effect on the activities of microbes in the soil, a gaining in microflora activity in soil, as well as diversity has been revealed as a secondary effect of increased SOC, elevated concentration of nutrients, such as NPK, and improved crop yields affecting rhizo deposition. A favorable stimulation of large number of soil parameters was observed, after the application of inorganic phosphorus fertilizers to paddy soil for 13 years. The number of cultivable microbes, population functional diversity, and microbial biomass increased in the soil without phosphate treatment. The application of N fertilizer, in combination with sufficient quantities of phosphorus, was found to be useful on microbial behavior, diversity, and rice crop production, while, on the other side, K showed no effect (Zhong and Cai 2007). Likewise, a positive effect has been observed in rice field after it is treated with NPK fertilizer for 39 years. This has improved C, N pools, which in turn resulted in positive effect on soil fertility and soil enzyme activities and microbial population (Bhattacharyya et al. 2013). In a few studies, it has been found that continuing application resulted in no significant alteration in the characteristics of soil microbes. In northeast China, black soils showed no significant difference in functional diversity and microbial biomass when exposed to varied combinations of NPK fertilizers for prolonged periods (Kong et al. 2008). The functional variability is likely to increase with the increase in fertilization dose, that is, double or triple fertilizer therapy. Inorganic fertilizers can generate different consequences when applied alone or in association with organic inputs. For instance, no improvement in abundance of bacteria after incessant use of inorganic fertilizers in the rice field alone. Nevertheless, use of rice straw, coupled with chemical fertilizers, significantly increased abundance of bacteria with alteration in the composition of the bacterial population. Moreover, the bacterial phylogenetic classes also varied in their reaction to soil fertilization. Inorganic fertilizer primarily influenced π-proteobacteria and ÿ-proteobacteria, while rice straw incorporation affected β-proteobacteria and verrucomicrobia (Wu et al. 2011). Continuing fertilizer use in production of crops results in the accumulation of SOM (Geiseller and Scow 2014; Ladha et al. 2011) and soil health is enhanced by the addition of a large quantity of root biomass and litter to the soil.

1.14 Impacts of Chemical Fertilizers on Soil Health

1.14.1 Soil Quality

Soil quality has worsened due to increased application of chemical fertilizers, especially urea, muriate of potash, and single super phosphate (SSP), as a means to increase farm output. Since soils serve as the main reservoir of reactive nutrient types, their complete management is crucial to address worldwide food security challenges and reducing environmental nutrient losses that can affect the quality of water and air. There are various risks to soil health (Velthof et al. 2011): soil compaction, acidification, erosion, contamination, salinization, and decline in organic matter, which can affect P and N losses to water and air.

1.14.2 Physicochemical Properties of Soil

The management of soil nutrient is essential to preserve the quality of good soil and the constant productivity of nursery systems. Fertilization influences N and C quantity in soil by alteration of soil structure, organic N and C component of soil (Hai et al. 2010), and soil aggregation (Su 2007). Continuous utilization of chemical fertilizers has a distinct impact on the soil's biochemical properties, which results in the shift of microbial populations. Alteration in nitrogen (N) content, SOC, moisture, pH, and the availability of nutrients to microbes has been observed as a result of incessant use of fertilizer in different crops such as corn, wheat, and others (Bohme et al. 2005). Fertilizer application declined bulk density of soil, which may be due to increase in organic C of soil (Selvi et al. 2005). The higher SOC level can be attributed to increased growth of root, resulting in more residues in soil, which may have enhanced SOC amount after decomposition (Kumpawat and Jat 2005). Sradnick et al. (2013) reported the difference in SOC amount and pH of soil, as a result of fertilization, which is a reason of variation in the profile of microorganisms of sandy soil.

1.14.3 Soil Enzyme Activity

The activities of various soil enzymes, such as alkaline phosphatases, dehydrogenase, proteases, and ß-glucosidases, are essential indicators of soil fertility as well as microbial activity (Nannipieri et al. 1990). The long-term application of chemical fertilizer has no positive impact on microbial biomass and dehydrogenase activity, while organic fertilizers have positive influence on this. In addition, copper, a commonly found contaminant in soil because of excessive use of pesticides and fertilizers or irrigation, unfavorably affects the activity of soil dehydrogenase (Xie et al. 2009). Likewise, the organic nitrogen application stimulated different soil enzyme activities, such as saccharase and urease, in contrast to chemical fertilization. The significant decrease in enzyme activity, in inorganically treated soils than organic-treated soils continually cultivated with spring cereals, wheat, and clover, was observed (Balezentiene and Klimas 2009). The activities of various enzymes of soil, such as catalase, urease, invertase, arylsulfatase, and caseine protease and soil pH showed positive effect in organic-treated soils, but there is no considerable variation in functional activity of microorganisms of soils treated with organic and inorganic fertilizers (Lopes et al. 2011).

1.14.4 Soil Compaction

Soil compaction deals with the formation of thick, well-filled layers that occurs on cultivated ground; even more, the compressive forces are applied to compressible soil from wheels (Hamza and Anderson 2005). Soil compaction occurs by the lower use of organic fertilizer, heavy machinery use, constant use of chemical fertilizer and continual plowing at a consistent depth (Mari et al. 2008). In addition, compaction of soil causes problems, such as inadequate aeration, extreme soil strength, poor drainage, erosion, runoff, and soil degradations (Batey 2009). These changes lead to the decrease in permeability, hydraulic conductivity, and groundwater recharge (Blanco-Canqui et al. 2002; Mehmood et al. 2019). Soil compaction forms an essential part of land deterioration syndrome. It is a considerable threat facing agriculture which negatively impacts nearly all soil properties (Weisskopf et al. 2010). It alters soil structure by breaking aggregate units, decreasing the pore space size between the soil particles, lessening in soil volume and porosity resulting in an increase in the bulk density of soil.

1.14.5 Soil Acidification

Soil acidity is the concentration of H^+ in the solution. Acid soils are soils with pH levels below 7. The effect of constant and enormous application of N fertilizers, particularly as reduced N (NH_3, NH_4^+), on the health of soil depends on the degree of its action on acidification (Table 1.3).

Nitrogen molecules which alter pH of the soil are ammonium ion, nitrate ion, and the urea molecule. The transformation of N from one form to the other and their uptake by plants influence the soil acidity. Acidification of soil, as a result of nitrogen fertilizer, relies on the kind of N added, soil buffering capacity, the net balance between proton-generating and consuming processes. Nitrogenous fertilizer, such as ammonium sulfate, binds to sulfuric acid in the soil with water. Due to the hydrogen ions emitted from the acid, it results in loss of soil nutrients replacing alkaline elements on the exchange sites. The free oxygen produced in the reaction oxidizes the organic matter, causing it to combust at low levels in the soil (Casiday and Frey 1998).

Ammonium-dependent fertilizers cause soil acidification as they produce two H^+ ions for each molecule of ammonia nitrified to nitrate. The degree of acidification relies on whether the nitrate is consumed by plant or is leached. When nitrate is absorbed by plant, the acidification is halved per molecule of ammonium compared to the nitrate leaching. It is because of the intake of one H^+ ion for each nitrate molecule taken up (Smiley and Cook 1973). Excess application of N fertilizers results in an increase in nitrate leaching and cations (Ca, Mg) to water bodies. The leached nitrate in the subsoil can lead to pyrite oxidation, which releases sulfate and other elements, such as arsenic (As), nickel (Ni), Copper (Cu), cobalt (Co), lead (Pb), manganese (Mn), and zinc (Zn).

Urea and anhydrous ammonia have a lesser acidification potential in comparison to ammonium-dependent products, as one H^+ ion is used in the transformation to ammonium. Nitrate-based fertilizers can raise pH of soil because one H^+ ion is absorbed by plant in the nitrate uptake.

Nitrogen-fixing bacteria and free-living fungi are very responsive to high levels of nitrogen and microbial community changes which influence various soil processes, such as nutrient cycling and mineralization of organic matter (Velthof et al. 2011). The nitrogen fixation process, that is, nitrification and denitrification, encourages nitrous oxide (N_2O) production, a greenhouse gas, in soil with less pH. Chemical

Table 1.3 pH and the degree of soil acidity

S. no.	Soil acidity	pH range
1.	Extremely acidic	<4.5
2.	Very strongly acidic	4.5–5.0
3.	Strongly acidic	5.1–5.5
4.	Moderately acidic	5.6–6.0
5.	Slightly acidic	6.1–6.5
6.	Neutral	6.6–7.3

fertilizer application causes an accumulation of acids, such as sulfuric acid and hydrochloric acid, to create a harmful impact on soil called soil friability. Such acids break down the soil crumbs that assist in holding the particles of rock together. The mixing of decomposed material such as dead leaves and humus with clay results in the formation of soil crumbs which help in improving air circulation in the soil and are important to soil drainage. Chemical fertilizers dissolve soil crumbs, which leads to a high compacted soil with decreased circulation of air and drainage (Tien and Chen 2012; Venkateshwarlu 1993).

Soil releases base cations, such as magnesium (Mg) and calcium (Ca), in the course of acidification process; the base cations may be decreased over time through continued addition of nitrogen and aluminum (Al^{3+}) released from minerals often reaching harmful stage, which cause nutrient deficiencies in plants. Indirectly, soil acidification results in decreased microbial N immobilization (Venterea et al. 2004). The acidification of soil can also influence the mineralization and decomposition of SOM, so that affects quality of SOM.

Soil acidity is influenced by phosphorus fertilizers through the gain or release of H^+ ions, depending on the type of P fertilizer used as well as soil pH. When phosphoric acid is added to the soil with pH less than 6.2, it releases one H^+ ion, and two H^+ ions will be released when the pH of soil is greater than 8.2. SSP, MAP, and TSP all can acidify the soil if the soil pH is above 7.2. They add phosphorus in the $H_2PO_4^-$ ion form. DAP, in the form of HPO_4^{2-}, is responsible for making acidic soils more alkaline. When the soil pH is greater than 7.2, it will not show any effect. In APP, phosphorus present in $P_2O_7^{4-}$ form undergoes hydrolysis and transforms to HPO_4^{2-} which is pH neutral. Thus, acidification as a result of APP is considered same as DAP.

1.14.6 Effect on Soil Biota

Soil microbial activity is a vital part of soil health. Bacteria, fungi, protozoa, algae, and viruses constitute soil microflora which form an important part of the agriculture ecosystem. These have many essential and basic roles in soil, such as soil fertility, nutrient cycling, enhancing productivity by increasing limited nutrient availability, and degradation of inorganic as well as organic matter (Fig. 1.2). Soil biodiversity is the cornerstone of global food security along with more aspects of agro-biodiversity, that is, plant and animal resources. The impact of fertilizer on microorganisms in the soil may be beneficial or harmful, and vary in duration relying on time-period considered, the amount, quality, and the way of application of fertilizer. More recently, it has been pointed out that diversity in microbial culture collection (MCC) is crucial in maintaining the health of soil (Mele and Crowley 2008; Shen et al. 2008) because of their role in the formation of soil structure, soil organic matter (SOM) decomposition, and the biogeochemical cycling of nutrients (Paul 2007).

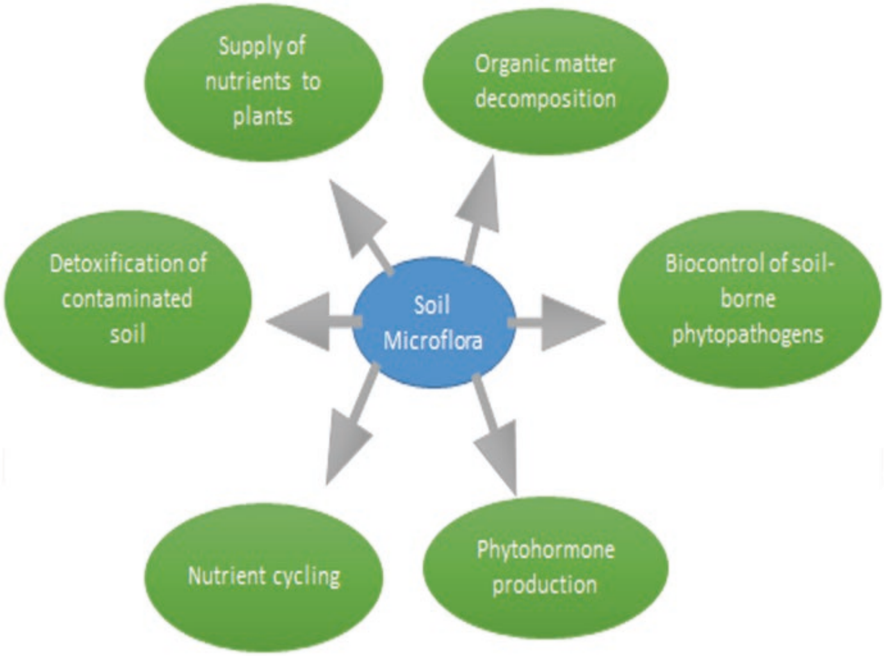


Fig. 1.2 Different functions of soil microorganisms

Agricultural activities, such as pesticide use, surplus inorganic fertilizer use, and tillage, influence soil microorganism by disturbing their habitats and functions (Kibblewhite et al. 2008). Fertilizers continue to remain in the soil for longer duration, so that they are confined to change soil microflora and thus affect soil health. The functional diversity of the soil microbial population is mainly controlled by the resource availability such as N, P, and C (Lupwayi et al. 2012). Therefore, there is an important co-relation between microbial communities and SOC and activities of microorganisms (Bohme et al. 2005). It clearly implies that the type as well as constituent of fertilizer used undoubtedly disrupt the structure of microbial community of the lands. Modification of soil with fertilizer greatly affects function and properties of soil, such as soil organic carbon (SOC), rhizodeposition, pH, soil nutrient content, enzyme activities of soil, moisture, and many others. All of these factors potentially result in an alteration in the soil microflora population dynamics. The constant use of pesticides and chemical fertilizers disturbs the functional as well as structural properties of soil microbial populations (Yang et al. 2000) and simultaneously forms a nutrient-imbalance in soils. Mycorrhizal fungi regularly reduced as a result of P fertilizer application, but the intensity of effect depends on the fungus species included and the amount of plant-available P.

The unlimited use of N fertilizers affects soil biota directly as well as indirectly and are caused by alteration in productivity, pH, SOM levels (Fig. 1.3). The disturbance of microorganisms of soil by application of the high ammonia fertilizer

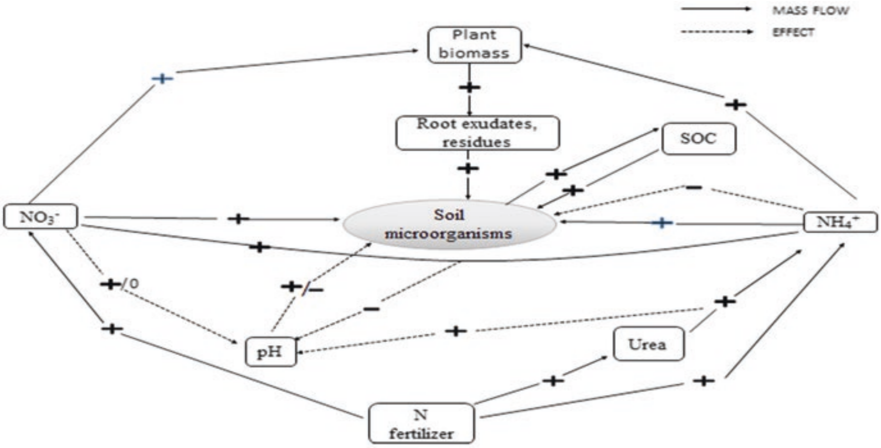


Fig. 1.3 A model showing direct and indirect effects of N fertilizer on microorganisms

concentration in bands is generally temporary, and only in the zone of application. Nitrogen fertilizer, such as urea, is transformed to anhydrous ammonia and carbon dioxide when it is consumed by bacteria. Ammonia is poisonous and is responsible for destroying life in the soil. The reaction takes place between urea and ammonia gas when urea is mixed with soil to form ammonium hydroxide with pH 11.6 (Anderson 2004). It is very caustic and creates serious burns. It forms an unsafe environment that destroys seedlings, seeds, plants, and soil dwelling organisms.

Potassium chloride associates with nitrates in the soil to form chlorine gas which destroys soil microorganisms. Excess potassium results in the deficiency of calcium in plants; some plants consume Ca, Mg, and K mostly in the percentage they are present in the soil. Excess potassium in the soil is responsible for the loss of soil structure (Anderson 2004). The decrease in soil air results in declined root respiration, and the generation of harmful compounds in plants. The reduction in soil air and inadequate calcium leads to reduction in the number of soil microbe and a subsequent reduction in the supply of organic matter/nutrients to plants (Pevear 1999).

Although total microbial counts are greater in fertilized soils relative to untreated soils, the impact is more definite in organic fertilizer treated soils than inorganic fertilizer treated soils, in the long run (Islam et al. 2009). In a few studies, an increase in organic C amount, microbial species and activities is observed in organic fertilizer-treated soils than inorganic ones in various crops, such as wheat, mustard, tobacco, and maize-wheat rotation (Chauhan et al. 2011; Yang et al. 2011). The structure of the bacterial population of inorganic fertilizer-treated soil is different from that of the untreated one (Sun et al. 2004). Furthermore, the population of bacteria, such as pseudomonas, a gram-negative bacteria, is affected by the constant use of chemical fertilizer, while the bacterial population in organic-treated soils remains similar in soils as that of untreated soil in crops, such as rice and wheat (Islam et al. 2009). In inorganic fertilizer-treated soils, the exposure of soil microflora to pesticides and heavy metals, such as cadmium and cypermethrin, is higher.

Additionally, lower cypermethrin dissipation rate is reported in soils. This indicates that, compared to organically treated soils, inorganic ones show more distinct effects of pollutants such as heavy metals (Xie et al. 2009). In agricultural environments treated with organic inputs, greater and more functionally diversified microbial communities were found as compared to inorganic ones in a wide range of crops (Tan et al. 2012). Fertilization has distinct effects on the composition of total agricultural soil bacteria. Chemical fertilization results in nutrient patches being produced, thus forming nutrient gradient in the soil that change the population of microbes (Wu et al. 2012). Li et al. (2013) investigated the effect of the N-gradient on nitrogen transition, microbial functional diversity, and soil microbial biomass due to chemical fertilizers such as ammonium sulfate or urea. The change with the N-gradient was observed in soil microbial biomass and microbial functional diversity. The magnitude of improvement, however, was governed by the type of inorganic fertilizer and concentration of nitrogen. Although functional diversity indices and microbial communities' average well color production (AWCD) decreased after ammonium sulfate treatment, the urea application resulted in the higher AWCD and Shannon indices. These have been found to differ with the soil layer depth. The impact of practices of soil management, can also differ with crop, especially in the form of fertilization.

1.15 Soil Organic Matter (SOM)

Different studies have reported that SOM alters with nitrogenous fertilizer inputs and cultivation; this is a problem which has become progressively contentious. SOM declines with cultivation where nitrogen fertilization is not performed, but may enhance with N fertilizer application. The use of nitrogen fertilizer influences SOM by way of two mechanisms:

1. It may help in increasing SOM by promoting growth of plant so that it increases the quantity of litter and root biomass added to the soil against the soil without nitrogen fertilization.
2. It can increase the loss of SOM by decay or microbial litter transformation (straw, leaves, etc.) and native types of organic carbon already present (Recous et al. 1995). Ammonium sulfate binds to sulfuric acid in the soil with water. Due to hydrogen ions emitted from the acid, it results in the loss of soil nutrients replacing alkaline elements on the cation exchange sites. The free oxygen produced in the reaction, causes the organic matter to combust at low levels, by oxidation of organic matter (Cassiday 1988).

1.16 Soil Salinity

Salts are a major content in chemical fertilizers and are believed to be destructive to agriculture, as salts are damaging to soil and plants. The dissolution of chemical fertilizer applied to the soil affects many soil properties, in particular the salinity. The salinity induced by N can adversely influence the nitrification process in soil, resulting in accumulation of NO_2 in the soil (Akhtar and Alam 2001). Upon applying phosphorus fertilizer, such as DAP, the concentration of soluble salts gets increased which causes salinity. Increased salinity causes inhibition of nitrification process, resulting in lesser transformation of ammonia (NH_4) to nitrate-nitrogen, therefore, an enormous amount of N was present in the form of NH_4 at the highest level of salinity (Irshad et al. 2018). K fertilizers usually have significant effects on salinity. The application of potassium fertilizer, typically based on sulfate or chloride salts, may lead to salinization of soil because of their large salt index (Pirhadi et al. 2018).

1.17 Effect on Plants

Soil fertility and vegetation are highly dependent upon a sufficient supply of essential minerals and nutrients. The excessive use of nutrients causes a soil nutrient supply imbalance, which lead, to deterioration of stable soil. Chemical fertilizers, however, help plants to grow quickly; but plants growing this way have little time to develop proper root growth. Plants are incapable of making their stems strong, or nutritious vegetables and fruits. In these circumstances, chances of survival are likely to be lower as they tend to be more susceptible to diseases and pests. Moreover, chemical fertilizers impede sufficient water intake for the plants, resulting in root burning or fertilizer burning.

1.18 Conclusion

The use of fertilizers today is viewed as a technology needed for agriculture. The long-term application of chemical fertilizers has a negative impact on the physicochemical properties and soil biological properties. Chemical fertilizers disrupt the microorganisms in respect of their dominant soil species and structural and functional diversity. Soil reaction and electrical conductivity were influenced by inorganic fertilizer addition. NPK fertilizer application appears mainly to reduce the functions of various soil enzymes.

Chemical fertilizers should be applied in due time and in appropriate quantities. First, examination of the soil should be carried out carefully. Fertilizer should be given to the soil after that. The chemical content and structure of the soil should be understood, and the most effective fertilizer should be picked. There should be processing of the most appropriate method. Otherwise, it will lead to loss of both finance and energy. Fertilizing ought to be performed in time, should not be at inappropriate times.

References

Akhtar M, Alam SM (2001) Effect of incubation period on phosphate sorption from two P sources. J Biol Sci 1:124–125

Anderson AB (2004) The anatomy of life and energy in agriculture. Acres U.S.A, Metairie, p 114

Balezentiene L, Klimas E (2009) Effect of organic and mineral fertilizers and land management on soil enzyme activities. Agron Res 7(Special issue I):191–197

Batey T (2009) Soil compaction and soil management -a review. Soil Use Manag 25(4):335–345

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytother 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 189–209

Bhattacharyya P, Nayak AK, Mohanty S, Tripathi R, Shahid M, Kumar A, Raja R, Panda BB, Roy KS, Neogi S, Dash PK, Shukla AK, Rao KS (2013) Greenhouse gas emission in relation to labile soil C, N pools and functional microbial diversity as influenced by 39 years' long-term fertilizer management in tropical rice. Soil Tillage Res 129:93–105

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Blanco-Canqui H, Gantzer CJ, Anderson SH, Alberts EE, Ghidey F (2002) Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Sci Soc Am J 66:1596–1602

Bohme L, Langer U, Bohme F (2005) Microbial biomass, enzyme activities and microbial community structure in two European long-term field experiments. Agric Ecosyst Environ 109:141–152

Brevik EC, Burgess LC (2013) Soils and human health. CRC Press, Boca Raton

Casiday R, Frey R (1998) Natural acidity of rainwater. Washington University, St. Louis Missouri. http://www.chemistry.wustl.edu/~edudev/LabTutorials/Water/FreshWater/acidrain.html

Chand R, Pavithra S (2015) Fertilizer use and imbalance in India: Analysis of States. Economic Political Weekly 50:44

Chaudhry AN, Jilani G, Khan MA, Iqbal T (2009) Improved processing of poultry litter to reduce nitrate leaching and enhance its fertilizer quality. Asian J Chem 21:4997–5003

Chauhan PK, Singh V, Dhatwalia VK, Abhishek B (2011) Physico-chemical and microbial activity of soil under conventional and organic agricultural systems. J Chem Pharm Res 3:799–804

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir Valley India. Ecol Balk 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (Labeo rohita) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Dinesh R, Srinivasan V, Hamza S, Manjusha A (2010) Short term incorporation of organic manures and biofertilizers influences biochemical and microbial characteristics of soils under an annual crop [Turmeric (*Curcuma longa* L.)]. Biores Technol 101:4697–4702

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA (eds) Defining soil quality for a sustainable environment. Soil Science Society of America, Inc., Madison, pp 3–21

Geisseler D, Scow KM (2014) Long-term effects of mineral fertilizers on soil microorganisms – A review. Soil Biology and Biochemistry 75:54–63

FAO (2009) ResourceSTAT-Fertilizer. Food and Agriculture Organization of the United Nations. http://faostat.fao.org/site/575/DesktopDefault.aspx?PageID=575#ancor. 12.03.2009

Hai L, Li X G, Li F M, Suo D R, Guggenberger G (2010) Long-term fertilization and manuring effects on physicallyseparated soil organic matter pools under a wheat-wheatmaize cropping system in an arid region of China. Soil Biology and Biochemistry 42, 253–259

Hamza MA, Anderson WK (2005) Soil compaction in cropping systems: a review of the nature, causes, and possible solutions. Soil Tillage Res 82:121–145

Hera C (1996) The role of inorganic fertilizers and their management practices. Fertil Res 43:63–81

Irshad M, Hafeez F, Naseem M, Rizwan M, Al-Wabel MI (2018) Effect of coal and wood ash on phosphorus immobilization in different textured soils. Arab J Geosci 11(18):536

Islam MR, Trivedi P, Palaniappan P, Reddy MS, Sa T (2009) Evaluating the effect of fertilizer application on soil microbial community structure in rice based cropping system using fatty acid methyl esters (FAME) analysis. World J Microbiol Biotechnol 25:1115–1117

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kibblewhite MG, Ritz K, Swift MJ (2008) Soil health in agricultural systems. Philos Trans Royal Soc B 363:685–701

Kong WD, Zhu YG, Fu B, Han X, Zhang L, He J (2008) Effect of long-term application of chemical fertilizers on microbial biomass and functional diversity of a black soil. Pedosphere 18:801–808

Kumpawat BS, Jat ML (2005) Profitable and energy efficient integrated nutrient management practices for maize-mustard cropping system in Southern Rajasthan. Curr Agric 29:97–102

Ladha JK, Kesava Reddy C, Padre AT, Kessel CV (2011) Role of Nitrogen Fertilization in Sustaining Organic Matter in Cultivated Soils. Journal of Environmental Quality 40(6):1756–1766

Li F, Liu M, Li Z, Jiang C, Han F, Che Y (2013) Changes in soil microbial biomass and functional diversity with a nitrogen gradient in soil columns. Appl Soil Ecol 64:1–6

Lopes AR, Faria C, Prieto-Fernandez A, Trasar-Cepeda C, Manaia CM, Nunes OC (2011) Comparative study of the microbial diversity of bulk paddy soil of two rice fields subjected to organic and conventional farming. Soil Biol Biochem 43:115–125

Lupwayi NZ, Lafond GP, Ziadi N, Grant CA (2012) Soil microbial response to nitrogen fertilizer and tillage in barley and corn. Soil Tillage Res 118:139–146

Mari GR, Changying J, Zhou J (2008) Effects of soil compaction on soil physical properties and nitrogen, phosphorus, potassium uptake in wheat plants. J Trans CSAE 24(1):74–79

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mele PM, Crowley DE (2008) Application of self-organizing maps for assessing soil biological quality. Agric Ecosyst Environ 126:139–152

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 152–178

Mushtaq N, Singh DV, Bhat RA, Dervash MA, Hameed UB (2020) Freshwater contamination: sources and hazards to aquatic biota. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 27–50

Nannipieri P, Grego S, Ceccanti B (1990) Ecological significance of the biological activity in soil. In: Bollag JM, Stotzky G (eds) Soil biochemistry, vol 6. Marcel Dekker, New York, pp 293–355

Paul E (2007) Soil microbiology, ecology, and biochemistry. Academic, Oxford

Pevear DR (1999) Illite and hydrocarbon exploration. Proc Natl Acad Sci U S A 96:3440–3446

Pirhadi M, Enayatizamir N, Motamedi H, Sorkheh K (2018) Impact of soil salinity on diversity and community of sugarcane endophytic plant growth promoting bacteria (*Saccharumofficinarum*l. var. CP48). Appl Ecol Environ Res 16(1):725–739

Recous S, Robin D, Darwis D, Mary B (1995) Soil inorganic nitrogen availability: effect on maize residue decomposition. Soil Biol Biochem 27:1529–1538

Selvi D, Santhy P, Dhakshinamoorthy M (2005) Effect of inorganics alone and in combination with farmyard manure on physical properties and productivity of Vertic Haplustepts under long-term fertilization. J Indian Soc Soil Sci 53:302–307

Shen W et al (2008) Land use intensification affects soil microbial populations, functional diversity and related suppressiveness of cucumber Fusarium wilt in China's Yangtze River Delta. Plant Soil 306:117–127

Singh DV, Bhat JIA, Bhat RA, Dervash MA, Ganei SA (2018) Vehicular stress a cause for heavy metal accumulation and change in physico-chemical characteristics of road side soils in Pahalgam. Environ Monit Assess 190:353. https://doi.org/10.1007/s10661-018-6731-2

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Smiley RW, Cook RJ (1973) Relationship between take-all of wheat and rhizosphere pH in soils fertilized with ammonium vs nitrate-nitrogen. Phylopathology 63:882–890

Sönmez I, Kaplan M, Sönmez S (2007) An investigation of seasonal changes in nitrate contents of soils and irrigation waters in greenhouses located in Antalya-Demre region. Asian J Chem 19(7):5639–5646

Sradnick A, Murugan R, Oltmanns M, Raupp J, Joergensen RG (2013) Changes in functional diversity of the soil microbial community in a heterogeneous sandy soil after long-term fertilization with cattle manure and mineral fertilizer. Appl Soil Ecol 63:23–28

Sun HY, Deng SP, Raun WR (2004) Bacterial community structure and diversity in a century- old manure-treated agroecosystem. Appl Environ Microbiol 70:5868–5874

Su YZ (2007) Soil carbon and nitrogen sequestration following the conversion of cropland to alfalfa forage land in northwest China. Soil and Tillage Research 92, 181–189

Tan H, Barret M, Rice O, Dowling DN, Burke J, Morrissey JP, O'Gara F (2012) Long-term agrichemical use leads to alterations in bacterial community diversity. Plant Soil Environ 58:452–458

Tien CJ, Chen CS (2012) Assessing the toxicity of organophoshorus pesticides to indigenous algae with implication for their ecotoxicological impact to aquatic life. J Environ Sci Health B 47:901–912

Velthof GL, Barot S, Bloem J, Butterbach-Bahl K, de Vries W, Kros J, Lavelle P, Olesen JE, Oenema O (2011) Nitrogen as a threat to European soil quality. In: Sutton MA, Howard CM, Erisman JW, Billen G, Bleeker A, Grennfelt P, van Grinsven H, Grizzetti B (eds) The European nitrogen assessment. Cambridge University Press, Cambridge, UK, pp 494–509

Venkateshwarlu K (1993) Pesticide interaction with cyanobacteria in soil and pure culture. Soil Biochem 8:137–139

Venterea RT, Groffman PM, Verchot LV, Magill AH, Aber JD (2004) Gross nitrogen process rates in temperate forest soils exhibiting symptoms of nitrogen saturation. For Ecol Manage 196:129–142

Weisskopf P, Reiser R, Rek J, Oberholzer HR (2010) Effect of different compaction impacts and varying subsequent management practices on soil structure, air regime and microbiological parameters. Soil Tillage Res 111(1):65–74

Wu M, Qin H, Chen Z, Wu J, Wei W (2011) Effect of long-term fertilization on bacterial composition in rice paddy soil. Biol Fertil Soils 47:397–405

Wu F, Gai Y, Jiao Z, Liu Y, Ma X, An L, Wang W, Feng H (2012) The community structure of microbial in arable soil under different long-term fertilization regimes in the Loess Plateau of China. Afr J Microbiol Res 6:6152–6164

Xie W, Zhou J, Wangb H, Chen X, Lu Z, Yu J, Chen X (2009) Short-term effects of copper, cadmium and cypermethrin on dehydrogenase activity and microbial functional diversity in soils after long-term mineral or organic fertilization. Agric Ecosyst Environ 129:450–456

Yang YH, Yao J, Hu S, Qi Y (2000) Effects of agricultural chemicals on DNA sequence diversity of soil microbial community: a study with RAPD marker. Microb Ecol 39:72–79

Yang YH, Chen DM, Jin Y, Wang HB, Duan YQ, Guo XK, He HB, Lin WX (2011) Effect of different fertilizers on functional diversity of microbial flora in rhizospheric soil under tobacco monoculture. Acta Agron Sin 37:105–111

Zhong WH, Cai ZC (2007) Long-term effects of inorganic fertilizers on microbial biomass and community functional diversity in a paddy soil derived from quaternary red clay. Appl Ecol 36:84–89

Chapter 2
Microbial Bioremediation of Pesticides/Herbicides in Soil

Mohammad Saleem Wani, Younas Rasheed Tantray, Nazir Ahmad Malik, Mohammad Irfan Dar, and Tawseef Ahmad

2.1 Introduction

The term "pesticide" is characterized as a material or a combination of materials proposed to repel, devastate, or control several pests together with carriers of human or other faunal diseases, undesirable faunal/floral species, leading to destruction regardless meddling with the preparing, handling, stockpiling, or promoting of foodstuff, horticultural possessions, timber and timber items, or foodstuffs of animal, or might be directed to animals, for the management of bugs or other pests in or on their bodies (FAO and US EPA 2014). Pesticides are sorted primarily dependent on their combat targets or similarities in their chemical structure. Examples of the earlier are insecticides, acaricides, nematicides, fungicides, herbicides, or more rarely rodenticides, molluscicides, or plant growth regulators (Table 2.1), while the case of the latter is given in Tables 2.2–2.13. Herbicides are a class of pesticides that are utilized to execute weeds and other undesirable life forms, including insects, while fungicides are utilized to confine the development of molds and mildew. The use of disinfectants forbid the outbreak of bacteria and is also used to control mice and rodents (Fig. 2.1).

M. S. Wani · Y. R. Tantray
Department of Botany, Punjabi University, Patiala, Punjab, India

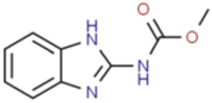
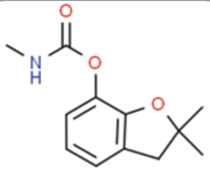
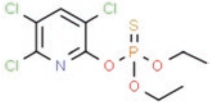
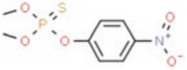
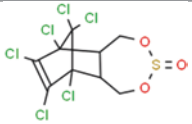
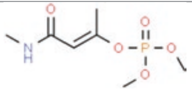
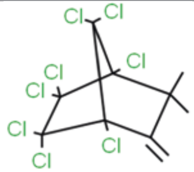
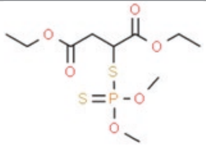
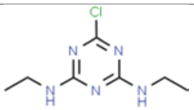
N. A. Malik
Department of Botany, Dolphin PG College of Science & Agriculture, Chunni Kalan, Punjab, India

M. I. Dar
Department of Biotechnology, Jamia Millia Islamia, New Delhi, India

T. Ahmad (✉)
Department of Biotechnology, Punjabi University, Patiala, Punjab, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_2

Table 2.1 Characterization of pesticides based on their target

S. No	Pesticides	Chemical nature	Target hosts	Chemical structure
1.	Carbendazim	Fungicides	*Pericularia oryzae*	
2	Carbofuran	Nematodes	*Hershieminella oryzae*	
3	Chloropyrifos	Insecticide	Yellow stem borer	
4	Methyl parathion	Insecticide	Stem and leaf borer	
5	Endosulfan	Insecticide	Fruit and leaf borer	
6	Monocrotophos	Insecticide	Brown plant hopper	
7	Toxaphene	Insecticide	Fruit borer	
8	Malathion	Insecticides	Leaf hoppers	
9	Simazine	Herbicides	Grass plants	

(continued)

Table 2.1 (continued)

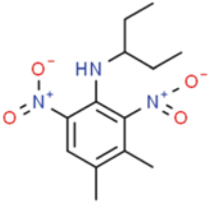
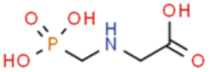
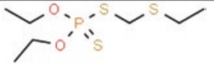
S. No	Pesticides	Chemical nature	Target hosts	Chemical structure
10	Pendimethalin	Herbicides	Broad leaves, Grass	
11	Glyphosate	Herbicides	Cyanodondoctylon	
12	Phorate	Nematodes	*Hershieminella oryzae*	

Table 2.2 Characterization of pesticides based on their chemical nature

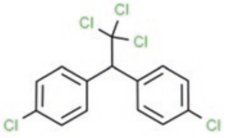
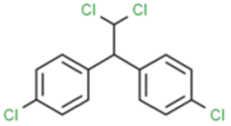
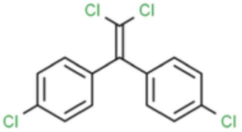
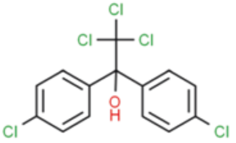
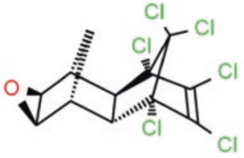
S. no	Chemical group	Chemical names
1	Organochlorines	BHC, Chlordane, Chloro propylate, Chlorobenziate, DDT, DDD, Dicofol, Dieldrin, Eldrin, Endosulfan,, Heptachlor, Isobenzan, Isodrin, Lindane, Methoxychloro Aldrin, Toxaphene
2	Organophosphates	Abate, Caumphos, Dimefox, Dicrotophos, Dimethoate, Dichlorovas, Demethon-S-methyl, Dipterex, Fenitrothion, Fenthion, Malathion, Mipafox, Methyl Parathion, Oxydemeton-methyl, Phorate, Phosphamidon, Ronnel, Trichlorofan
3	Carbamates	*Methyl* Aminocarb, Aldicarb, Carbaryl, Carbanolate, Carbofuran, Dimetilan, Isolan, Propoxur, Pyrolan
		Thio Butylate, Cycloate, Diallate, Pebulate, Trillate, Thiourea, Vernolate
		Dithio Dithane M-45, Thiram, Ferbam, Amoban, Naban, Zineb, Maneb, Ziram Polyran
4	Pyrethroids	Allethrin, Alphamethrin, Bifenthrin, Cypermethrin, Cyclethrin, Dimethrin, Decamethrin, Furethrin, Fenvalerate, Pyrethrin, Tetramethrin
5	Phenyl amides	*Carbanilates* Barban, Bromuron, Carbetamide, Chlororprofan, Prophan, Phenyl Urea, Fenuron, Monuron, Diuron, Flumeturon, Chloroxuron, Neburon
		Acylanalide Propanil, Solan, Dicryl, Karsil, Propachlor, Alachlor, Butachlor
		Toluidines Trifluralin, Dipropanil, Benefin, Oryzalin, Isopropanil, Nitralin
		Acetamide Diphenamid

(continued)

Table 2.2 (continued)

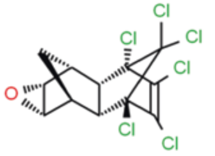
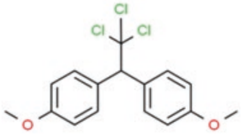
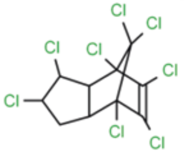
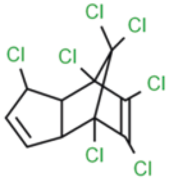
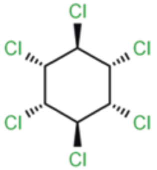
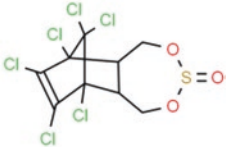
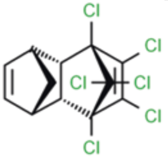
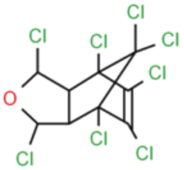
S. no	Chemical group	Chemical names
6	Phenoxy alkonates	2,4-D(2,4 Dichloro phenoxy acetic acid) 2,4 5 T(2,4 5 Trichloro Phenoxy acetic acid) Dichloroprop, Mecoprop, Erbin, Sesone
7	Trazines	Atrazine, Simazine, Ametryn, Atratone, Chlorazine, Cynazine, Cyprazine, Metribuzin, Propazine, Turbutryn, Simetryn
8	Benzoic acid	Dicamba, Dichlorobenil, Chloroambin, Tricamba, Neptalan, Bromoxynil
9	Phthalimide	Captan, Diflotan, Folpet
10	Dipyrids	Paraquat, Diaquat
11	Others	Pentachlorophenol, Floroacetate, Phenyl mercuric acetate, Ethyl mercuric Phosphate, Methyl mercuric chloride, Sodium arsenate, Calcium arsenate, Lead arsenate, Cacodylic acid, Aluminium phosphide, Zinc phosphide

Table 2.3 Organochlorine pesticides, their chemical structures, and use

S. no	Chemical name	Chemical structures	Use
1	Dichlorodiphenyltrichloroethane (DDT) ($C_{14}H_9Cl_5$)		Acaricide andinsecticide
2	1,1-dichloro-2,2-bis(p-chlorophenyl)ethane (DDD) ($C_{14}H_{10}Cl_4$)		Insecticide
3	Dichloro diphenyl dichloroethane (DDE) ($C_{14}H_8Cl_4$)		Insecticide
4	Dicofol ($C_{14}H_9C_{15}O$)		Acaricide
5	Endrin ($C_{12}H_8Cl_6O$)		Insecticide

(continued)

Table 2.3 (continued)

S. no	Chemical name	Chemical structures	Use
6	Dieldrin ($C_{12}H_8Cl_6O$)		Insecticide
7	Methoxychlor ($C_{16}H_{15}Cl_3O_2$)		Insecticide
8	Chlordane ($C_{10}H_6Cl_8$)		Insecticide
9	Heptachlor ($C_{10}H_5Cl_7$)		Insecticide
10	Lindane ($C_6H_6Cl_6$)		Acaricide, insecticide, and rodenticide
11	Endosulfan ($C_9H_6Cl_6O_3S$)		Insecticide
12	Isodrin ($C_{12}H_8Cl_6$)		Insecticide
13	Isobenzan ($C_9H_4Cl_8O$)		Insecticide

(continued)

Table 2.3 (continued)

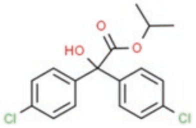
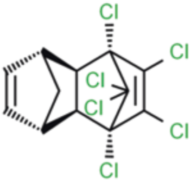
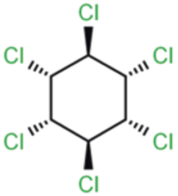
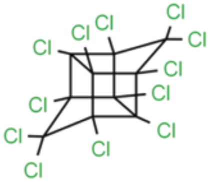
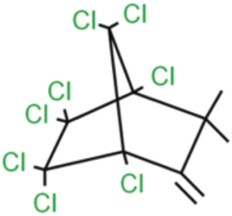
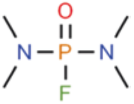
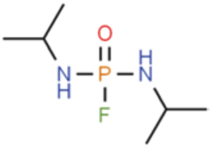
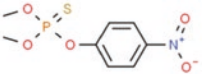
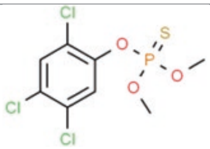
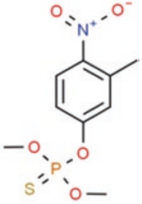
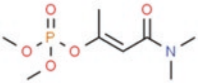
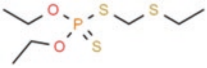
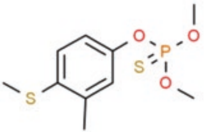
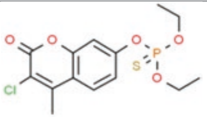
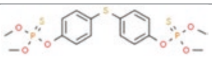
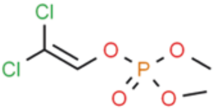
S. no	Chemical name	Chemical structures	Use
14	Chloropropylate ($C_{17}H_{16}Cl_2O_3$)		Insecticide and acaricide
15	Aldrin ($C_{12}H_8Cl_6$)		Insecticide
16	1,4- dichlorobenzene ($C_6H_4Cl_2$)		Insecticide
17	Benzene hexachloride (BHC) ($C_6H_6Cl_6$)		Acaricide, insecticide, and rodenticide
18	Mirex ($C_{10}Cl_{12}$)		Insecticide
19	Pentachlorophenol (C_6HCl_5O)		Fungicide, herbicide, and insecticide
20	Toxaphene (Camphechlor) ($C_{10}H_{10}Cl_8$)		Acaricide and insecticide

Table 2.4 Organophosphates pesticides, their chemical structures, and use

S. no	Chemical name	Chemical structures	Use
1	Dimefox ($C_4H_{12}FN_2OP$)		Insecticide
2	Mipafox ($C_6H_{16}FN_2OP$)		Insecticide
3	Methyl Parathion ($C_8H_{10}NO_5PS$)		Insecticide
4	Ronnel ($C_8H_8Cl_3O_3PS$)		Insecticide
5	Fenitrothion ($C_9H_{12}NO_5PS$)		Insecticide
6	Dicrotophos ($C_8H_{16}NO_5P$)		Insecticide
7	Phorate ($C_7H_{17}O_2PS_3$)		Insecticide and acaricide
8	Fenthion ($C_{10}H_{15}O_3PS_2$)		Insecticide
9	Caumaphos ($C_{14}H_{16}ClO_5PS$)		Insecticide
10	Abate ($C_{16}H_{20}O_6P_2S_3$)		Larvicide
11	Dichlorvos ($C_4H_7Cl_2O_4P$)		Insecticide

(continued)

Table 2.4 (continued)

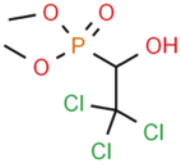
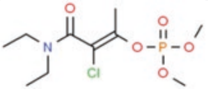
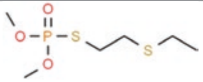
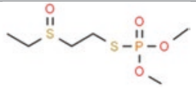
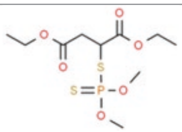
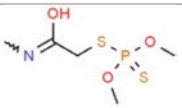
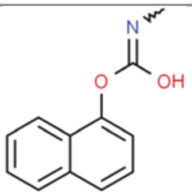
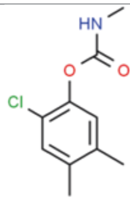
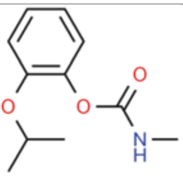
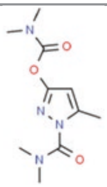
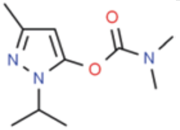
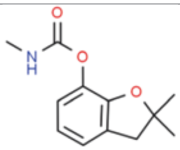
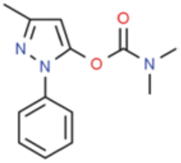
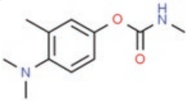
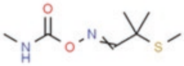
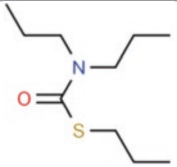
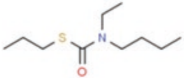
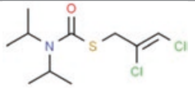
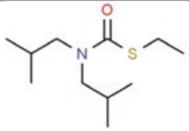
S. no	Chemical name	Chemical structures	Use
12	Dipterex ($C_4H_8Cl_3O_4P$)		Insecticide
13	Phosphamidon ($C_{10}H_{19}ClNO_5P$)		Insecticide
14	Demethon-S-methyl ($C_6H_{15}O_3PS_2$)		Insecticide and acaricide
15	Oxydemeton-methyl ($C_6H_{15}O_4PS_2$)		Insecticide
16	Malathion ($C_{10}H_{19}O_6PS_2$)		Insecticide
17	Dimethoate ($C_5H_{12}NO_3PS_2$)		Insecticide and acaricide

Table 2.5 Carbamate pesticides, their chemical structures, and use

	S. no	Chemical name	Chemical structures	Use
Methyl	1	Carbaryl $C_{12}H_{11}NO_2$		Insecticide
	2	Carbanolate ($C_{10}H_{12}ClNO_2$)		Insecticide
	3	Propoxur ($C_{11}H_{15}NO_3$)		Insecticide

(continued)

Table 2.5 (continued)

	S. no	Chemical name	Chemical structures	Use
	5	Dimetilan ($C_{10}H_{16}N_4O_3$)		Insecticide
	6	Isolan ($C_{10}H_{17}N_3O_2$)		Aphicides and insecticides
	7	Carbofuran ($C_{12}H_{15}NO_3$)		Insecticide
	8	Pyrolan ($C_{13}H_{15}N_3O_2$)		Insecticide
	9	Aminocarb ($C_{11}H_{16}N_2O_2$)		Insecticide
	10	Aldicarb ($C_7H_{14}N_2O_2S$)		Insecticide
Thio	1	Vernolate ($C_{10}H_{21}NOS$)		Herbicides
	2	Pebulate ($C_{10}H_{21}NOS$)		Herbicides
	3	Diallate ($C_{10}H_{17}C_{12}NOS$)		Herbicide
	4	Butylate ($C_{11}H_{23}NOS$)		Herbicide

(continued)

Table 2.5 (continued)

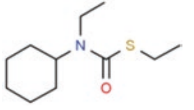
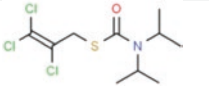
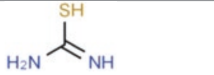
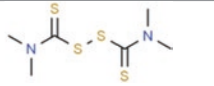
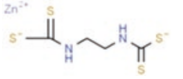
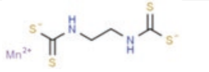
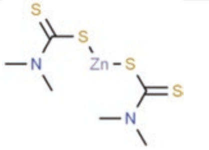
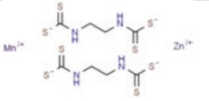
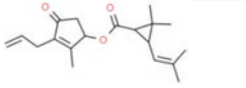
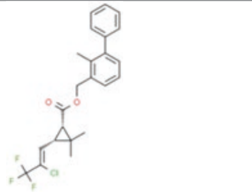
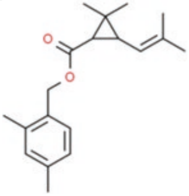
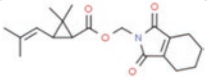
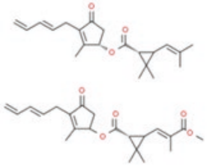
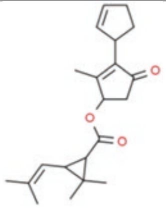
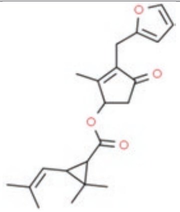
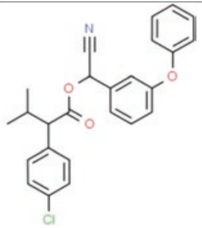
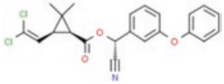
	S. no	Chemical name	Chemical structures	Use
	5	Cycloate ($C_{11}H_{21}NOS$)		Herbicide
	6	Triallate ($C_{10}H_{16}C_{13}NOS$)		Herbicide
	7	Thiourea (CH_4N_2S)		Herbicide
Dithio	1	Thiram ($C_6H_{12}N_2S_4$)		Fungicide
	2	Ferbam ($C_9H_{18}FeN_3S_6$)		Fungicide
	3	Zineb ($C_4H_6N_2S_4Zn$)		Fungicide
	4	Maneb ($C_4H_6MnN_2S_4$)		Fungicide
	5	Ziram ($C_6H_{12}N_2S_4Zn$)		Fungicide
	6	Dithane M- 45 ($C_8H_{12}MnN_4S_8Zn$)		Fungicide

Table 2.6 Pyrethroid pesticides, their chemical structures, and use

S. no	Chemical name	Chemical structures	Use
1	Allethrin ($C_{19}H_{26}O_3$)		Insecticide
2	Bifenthrin ($C_{23}H_{22}ClF_3O_2$)		Insecticide

(continued)

Table 2.6 (continued)

S. no	Chemical name	Chemical structures	Use
3	Dimethrin ($C_{19}H_{26}O_2$)		Insecticide
4	Tetramethrin ($C_{19}H_{25}NO_4$)		Insecticide
5	Pyrethrin ($C_{43}H_{56}O_8$)		Insecticide
6	Cyclethrin ($C_{21}H_{28}O_3$)		Insecticide
7	Furethrin ($C_{21}H_{26}O_4$)		Insecticide
8	Fenvalerate ($C_{25}H_{22}ClNO_3$)		Insecticide
9	Alphamethrin ($C_{22}H_{19}Cl_2NO_3$)		Insecticide and acaricide

(continued)

Table 2.6 (continued)

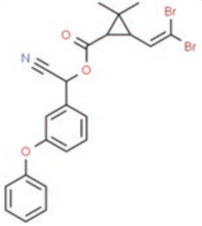
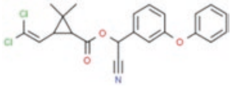
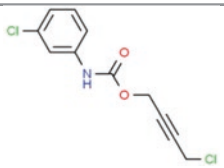
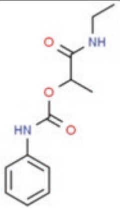
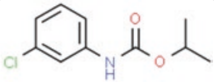
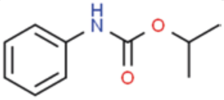
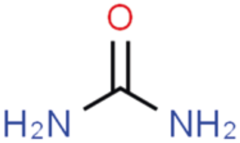
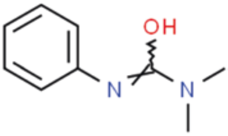
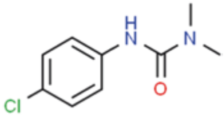
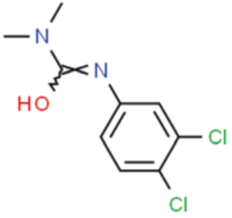
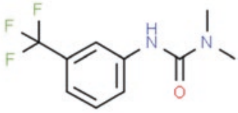
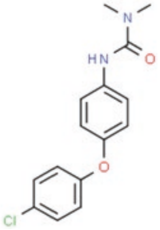
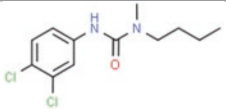
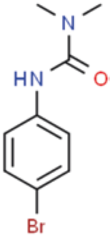
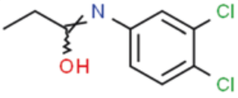
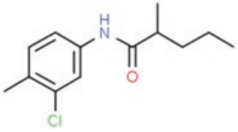
S. no	Chemical name	Chemical structures	Use
10	Decamethrin ($C_{22}H_{19}Br_2NO_3$)		Insecticide
11	Cypermethrin ($C_{22}H_{19}Cl_2NO_3$)		Insecticide and acaricide

Table 2.7 Phenyl amide pesticides, their chemical structures, and use

	S. no	Chemical name	Chemical structures	Use
Carbanilates	1	Barban ($C_{11}H_9Cl_2NO_2$)		Herbicide
	2	Carbetamide ($C_{12}H_{16}N_2O_3$)		Herbicide
	3	Chlorpropham ($C_{10}H_{12}ClNO_2$)		Herbicide
	4	Propham		Herbicide
	6	Urea CH_4N_2O		Fungicide and herbicide
	7	Fenuron ($C_9H_{12}N_2O$)		Herbicide

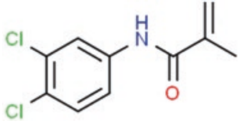
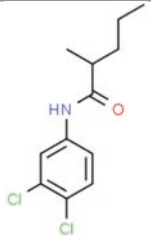
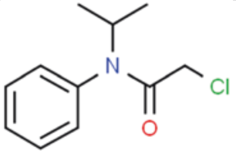
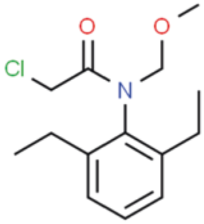
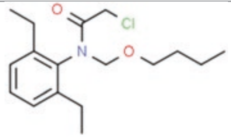
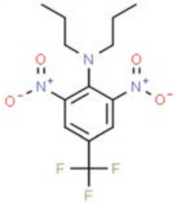
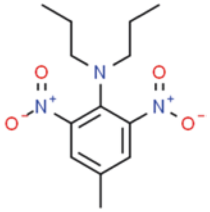
(continued)

Table 2.7 (continued)

	S. no	Chemical name	Chemical structures	Use
	8	Monuron ($C_9H_{11}ClN_2O$)		Herbicide
	9	Diuron ($C_9H_{10}Cl_2N_2O$)		Herbicide
	10	Flumeturon ($C_{10}H_{11}F_3N_2O$)		Herbicide
	11	Chloroxuron ($C_{15}H_{15}ClN_2O_2$)		Herbicide
	12	Neburon $C_{12}H_{16}Cl_2N_2O$		Herbicide
	13	Bromuron ($C_9H_{11}BrN_2O$)		Herbicide
Acylanalide	1	Propanil ($C_9H_9Cl_2NO$)		Herbicide
	2	Solan ($C_{13}H_{18}ClNO$)		Herbicide

(continued)

Table 2.7 (continued)

	S. no	Chemical name	Chemical structures	Use
	3	Dicryl ($C_{10}H_9Cl_2NO$)		Herbicide
	4	Karsil ($C_{12}H_{15}Cl_2NO$)		Herbicide
	5	Propachlor ($C_{11}H_{14}ClNO$)		Herbicide
	6	Alachlor ($C_{14}H_{20}ClNO_2$)		Herbicide
	7	Butachlor ($C_{17}H_{26}ClNO_2$)		Herbicide
Toluidines	1	Trifluralin ($C_{13}H_{16}F_3N_3O_4$)		Herbicide
	2	Dipropalin ($C_{13}H_{19}N_3O_4$)		Herbicide

(continued)

Table 2.7 (continued)

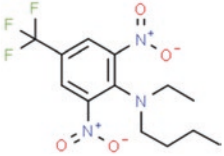
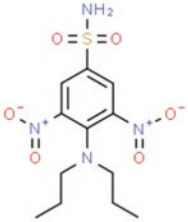
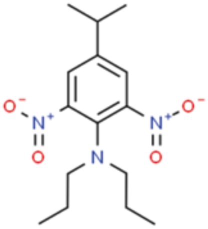
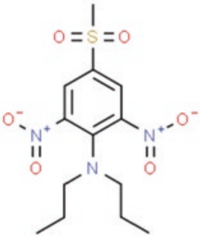
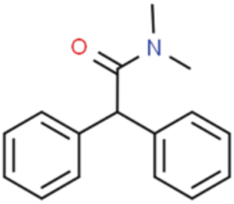
	S. no	Chemical name	Chemical structures	Use
	3	Benefin ($C_{13}H_{16}F_3N_3O_4$)		Herbicide
	4	Oryzalin ($C_{12}H_{18}N_4O_6S$)		Herbicide
	5	Isopropalin ($C_{15}H_{23}N_3O_4$)		Herbicide
	6	Nitralin ($C_{13}H_{19}N_3O_6S$)		Herbicide
Acetamide	1	Diphenamid ($C_{16}H_{17}NO$)		Herbicide

Table 2.8 Phenoxy alkonate pesticides, their chemical structures, and use

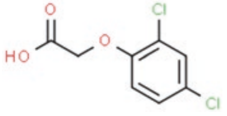
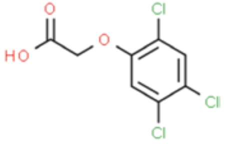
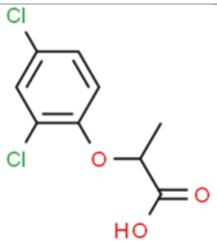
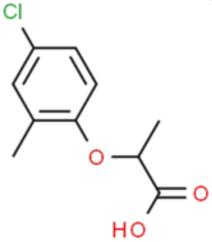
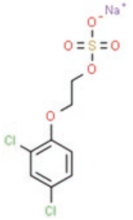
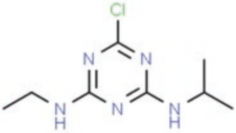
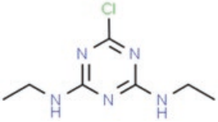
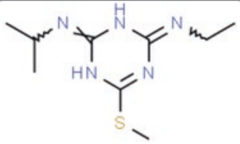
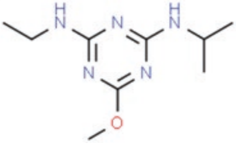
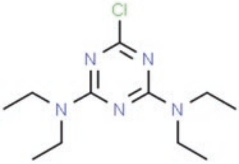
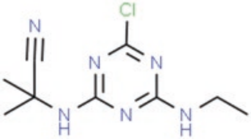
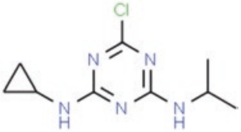
S. no	Chemical name	Chemical structures	Use
1	2,4-Dichloro phenoxy acetic acid ($C_8H_6Cl_2O_3$)		Herbicides
2	2,4, 5-Trichloro Phenoxy acetic acid ($C_8H_5C_{13}O_3$)		Herbicides
3	Dichloroprop ($C_9H_8C_{12}O_3$)		Herbicides
4.	Mecoprop ($C_{10}H_{11}ClO_3$)		Herbicides
5.	Sesone ($C_8H_7Cl_2NaO_5S$)		Herbicides

Table 2.9 Trazine pesticides, their chemical structures, and use

S. no	Chemical name	Chemical structures	Use
1	Atrazine ($C_8H_{14}ClN_5$)		Herbicide
2	Simazine ($C_7H_{12}ClN_5$)		Herbicide
3	Ametryn ($C_9H_{17}N_5S$)		Herbicide
4	Atratone ($C_9H_{17}N_5O$)		Herbicide
5	Chlorazine ($C_{11}H_{20}ClN_5$)		Pesticide
6	Cynazine ($C_9H_{13}ClN_6$)		Herbicide
7	Cyprazine ($C_9H_{14}ClN_5$)		Pesticide

(continued)

Table 2.9 (continued)

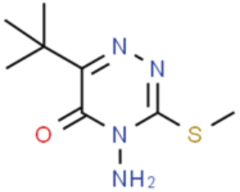
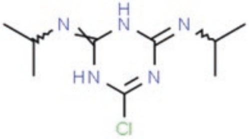
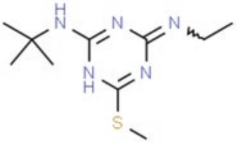
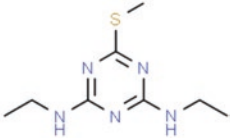
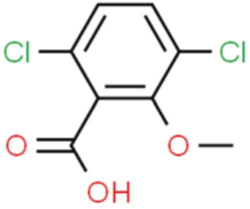
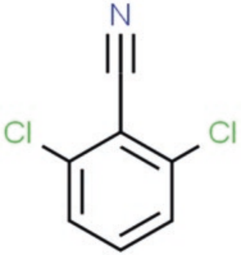
S. no	Chemical name	Chemical structures	Use
8	Metribuzin ($C_8H_{14}N_4OS$)		Herbicide
9	Propazine ($C_9H_{16}ClN_5$)		Herbicide
10	Terbutryn ($C_{10}H_{19}N_5S$)		Herbicide
11	Simetryn ($C_8H_{15}N_5S$)		Herbicide

Table 2.10 Benzoic acid pesticides, their chemical structures, and use

S. no	Chemical name	Chemical structures	Use
1	Dicamba ($C_8H_6Cl_2O_3$)		Herbicide
2	Dichlobenil ($C_7H_3Cl_2N$)		Herbicide

(continued)

Table 2.10 (continued)

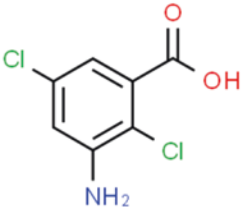
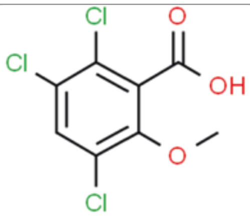
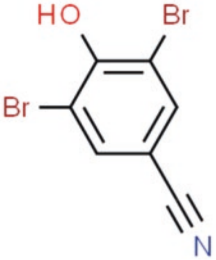
S. no	Chemical name	Chemical structures	Use
3	Chloramben ($C_7H_5Cl_2NO_2$)		Herbicide
4	Tricamba ($C_8H_5Cl_3O_3$)		Herbicide
6	Bromoxynil ($C_7H_3Br_2NO$)		Herbicide

Table 2.11 Phthalimide pesticides, their chemical structures, and use

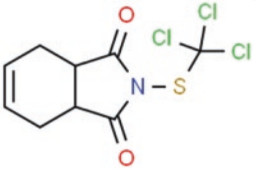
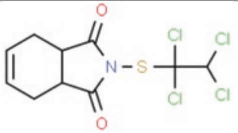
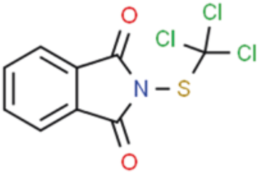
S. no	Chemical name	Chemical structures	Use
1	Captan ($C_9H_8Cl_3NO_2S$)		Fungicide
2	Diflotan ($C_{10}H_9Cl_4NO_2S$)		Fungicide
3	Folpet ($C_9H_4Cl_3NO_2S$)		Fungicide

Table 2.12 Dipyrids pesticides, their chemical structures, and use

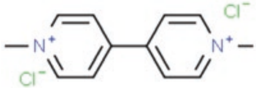
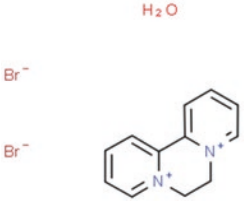
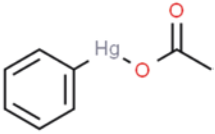
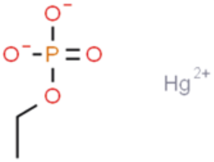
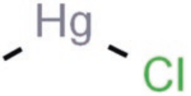
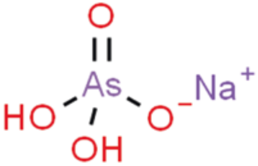
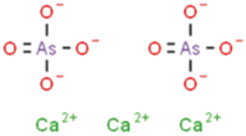
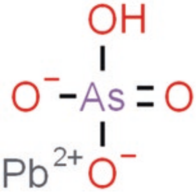
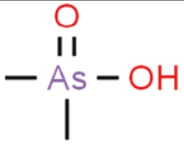
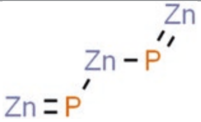
S. no	Chemical name	Chemical structures	Use
1	Paraquat ($C_{12}H_{14}Cl_2N_2$)		Herbicide
2	Diaquat ($C_{12}H_{14}Br_2N_2O$)		Herbicide

Table 2.13 Other pesticides, their chemical structures, and use

S. sno	Chemical name	Chemical structures	Use
1	Pentachlorophenol (C_6HCl_5O)		Pesticide
3	Phenyl mercuric acetate ($C_8H_8HgO_2$)		Herbicide and fungicide
4	Ethyl mercuric Phosphate ($C_2H_5HgO_4P$)		Pesticide
5	Methyl mercuric chloride (CH_3ClHg)		Pesticide

(continued)

Table 2.13 (continued)

S. sno	Chemical name	Chemical structures	Use
6	Sodium arsenate (H_2AsNaO_4)		Insecticides and herbicides
7	Calcium arsenate ($As_2Ca_3O_8$)		Germicide
8	Lead arsenate ($HAsO_4Pb$)		Insecticides
9	Cacodylic acid ($C_2H_7AsO_2$)		Herbicides
10	Aluminium phosphide (AlP)		Rodenticide and insecticide
11	Zinc phosphide (P_2Zn_3)		Rodenticide

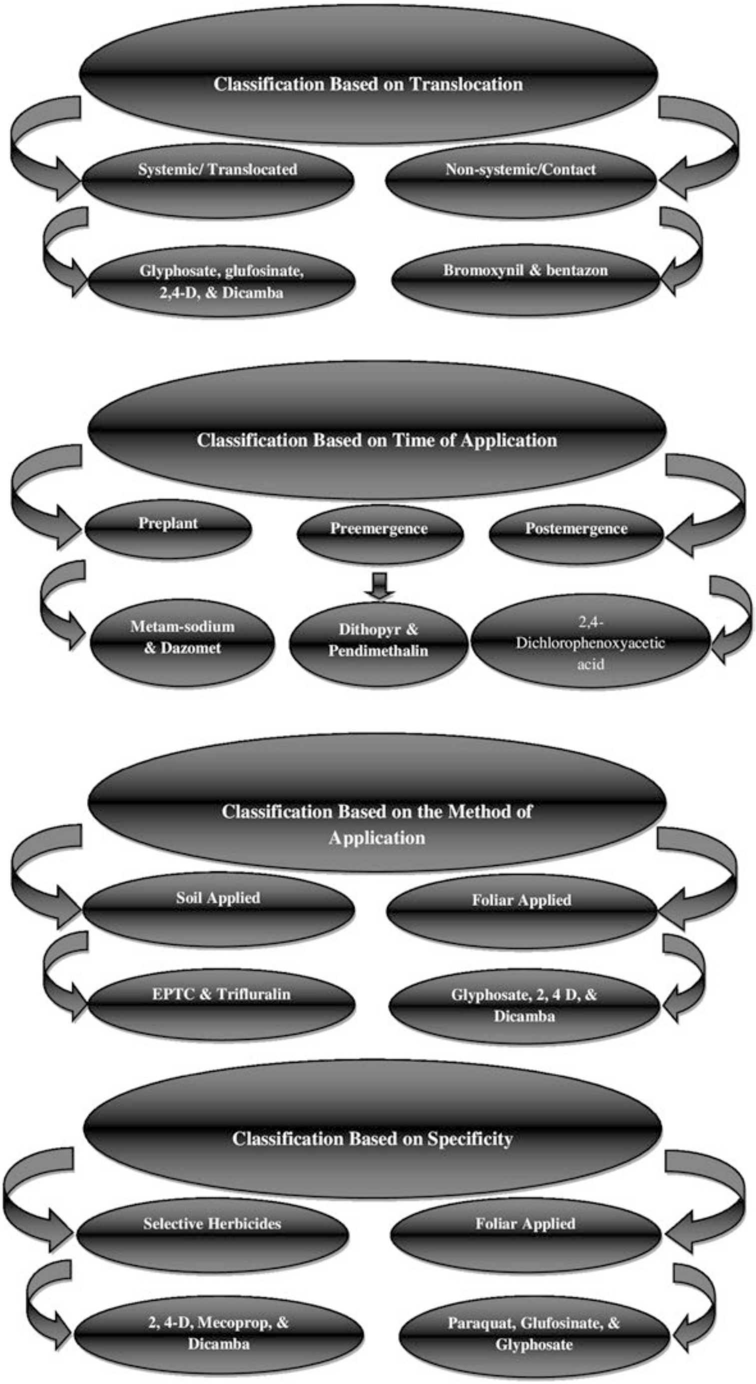


Fig. 2.1 Classification of herbicides

2.2 Merits of Pesticide Use

The primary, as well as secondary, assets are being provided by pesticides, the primary asset is evident by their direct usage, for example, the effect of killing caterpillars feeding on the harvest brings the prime advantage of increasing yields and improved quality of cabbage. The secondary assets are the consequence of the primary benefits and they are for longer periods. It follows that for secondary gain, it is consequently more complicated to set up cause and effect, however, in any case, they provide strong justifications for pesticide use. For instance, the increased yield of cabbage may provide supplementary income that possibly will be utilized towards education of children as well as their health care, which ultimately leads towards an improved, healthier, and better-educated community. In Table 2.14, we have provided the detailed results including primary and secondary advantages, and their connections. Around the world, 40% of the agronomical manufacture has vanished because of diseases occurring in plants, unwanted plants and pests on the whole. On the other hands, crops would have been in more loss if there would have been no pesticides. Additionally, these crop-sparing resources do not just shield the harvests from diseases inflicted by pests, they likewise improve the crop yields impressively. In their investigation, Webster et al. (1999) confirmed that "widespread economic losses" might be tolerated with no use of pesticides and quantified the considerable boost in yield and financial margin that result from pesticide use. Warren (1998) likewise drew awareness to the notable boost in yield of crops in the USA in the twentieth century. Furthermore, in presence of light, majority of the pesticides undergo chemical transformation to deliver metabolites that are rather non-toxic to both humans and the habitat (Kole et al. 1999; Bhat et al. 2017a, b; Bhat et al. 2018a, b; Mushtaq et al. 2018).

The handling of a broad array of human and flock disease vectors thus diminishing the quantity of contaminated persons and deaths, followed by the avoidance of global sickness spread is among critical obvious rewards of wide pesticide use. The killing of vectors is the best technique to battle them. Many insect-borne ailments, such as encephalitis, Rocky Mountain, typhoid fever, yellow fever, typhus, bubonic plague, ticks, and rodents, have been managed by the successful utilization of pesticides. As per the WHO, without the use of chemical control techniques, existence of life will be unsafe for an enormous extent of humanity (Anon 2004).

In the annihilation of various living beings that adversely affect human behavior, communications, and the tools of daily life, pesticides assume an important role. In various specified sectors of human operation, pesticides are used to handle undesirable species, such as preventing accelerated corrosion of metallic constructions, maintaining the turf on game pitches, golf courses and cricket grounds, serving an immensely common activity that provides hygienic air and exercise for a huge number of people around the globe (Maksymiv 2015; Bhat et al. 2017a, b).

Table 2.14 The primary and secondary benefits of pesticides

Primary advantages	Secondary advantages
1. Plant disease vectors and Controlling pests	Community advantages
(a) Improved crop/ flock quality (b) Reduced energy use for weeding (c) Reduced soil interruption (d) Invasive species prohibited	(a) Nutrition and fitness improved (b) Food security (c) Life likelihood increased (d) Reduced protection costs
2. Nuisances and organisms Controlling disease vectors	National benefits
(a) Human lives rescued (b) Human disorder reduced (c) Animal distress reduced (d) Increased stock quality	(a) National agricultural wealth (b) Increased export interest (c) Reduced soil erosion/ moisture loss
3. Prevent or manage of organisms that damage other human actions and structures	Global benefits
(a) Tree/bush/leaf hazards stopped (b) Recreational sod protected (c) Frame structures protected	(a) Less demands on uncropped land (b) Scanty pest introductions outside (c) Global tourism revenue

2.3 Risks Associated with Pesticide Use

Certainly, the broad utilization of pesticides and chemical fertilizers boost agricultural productivity. Nonetheless, from the last 20 years, the pesticide utilization throughout the globe has been growing and their occurrence grew to be inescapable in freshwater and marine environments. As indicated by United States Environmental Protection Agency (2012), the pesticide utilization had been lifted from two billion kg to two and half billion kg between year 2000 and 2007 all over (Staley et al. 2015). In systems of croplands throughout the globe, utilization of pesticides was up to 328,854.2 tonnes in 2007, in which commitments of herbicides was used to be most (200,487.66 tonnes), trailed by insecticides (78,471.42 tonnes), fungicides (19,958.05 tonnes), pesticides (18,597.27 tonnes), rodenticides (11,339.8 tonnes) and other pesticides (18,597.27 tonnes), respectively. In the Indian context, the utilization of herbicides, fungicides, and insecticides was 20,618.83, 13,055.44, and 6334.98 tonnes, respectively in 2010 (Roser and Ritchie 2017). The normal application of pesticides (kg ha^{-1}) per zone of cropland has been expanded much since the 1990s in many countries, such as Columbia (1990–3.64, 2014–20.79) chased by China, (1990-0 but in 2014 accomplished to 14.82), while in India the utilization rate was 0.44 in 1990 which reduced to 0.24 (kg ha^{-1}) further in 2010 (Roser and Ritchie 2017).

Pesticides have dire effects on non-target species and have an effect on plant and animal biodiversity, including both terrestrial and aquatic communities. Over 95% of herbicides and 98% of splashed insecticides arrive at a goal besides their objective species, together with non-target species, atmosphere, H_2O and soil (Miller 2004). Unscientific and unseemly use may likewise decrease the populace of useful organisms existing within the soil. The chemical fertilizers and pesticides entering the soil in critical amounts pose an immediate threat to the biological aspects of soil biota, health hazards, and environmental contamination (Martin et al. 2011; Dar et al. 2013; Dar and Bhat 2020). They cause abiding alterations to the flora present within the soil (Aleem et al. 2003; Bhat et al. 2018a; Bhat et al. 2018b; Singh et al. 2020a, b), hazardous impact on fertility of soil and yield of crops, having strong negative impact on nitrogen-fixing microorganisms (Sachin 2009), intervene with process of ammonification, negative impact on fungal existence associated with plant roots and nodulation in legumes (Reinhardt et al. 2008). The detailed study proved that target pests get hold of only about 0.1% of the tested pesticides, whereas remaining 99.9% is targeted into the soils, therefore manipulating the biota inside the soil and soil health parameters, such as enzyme activities, diversity of microbes (Singh et al. 2018). Hill reaction or attack against the PS-II is found in herbicides such as acylanilides, cyclic urea, phenyl carbamates, triazinones, triazines and urea, while others such as paraquat and diquat, are negative in PS-I. The mode of action of pesticides may vary among species of microorganisms and are known to inhabit cellular processes such as photosynthesis, respiration, and chemical reactions concerned with biosynthetic pathways, cell division, process of growth, molecular composition, etc. (DeLorenzo et al. 2001).

Pesticides can produce grave troubles for individual well-being; for example, genomic mutations, and may additionally cause fatality (Morillo and Villaverde 2017). Generally, there are four main ways through which pesticides can go into the individual body: oral, dermal, respiratory pathways, and through the eyes. The main path of human contact to pesticides is through water, food chain, soil, air, plants, and animals (Anderson and Meade 2014; Mehmood et al. 2019). Among the several groups of pesticides, insecticides are treated as the most lethal, followed by fungicides and herbicides, as far as their toxicity is concerned.

Water-soluble pesticides get easily dissolved in H_2O and come into groundwater, lakes, and rivers thus causing harm to non-targeted species. Conversely, the pesticides which are soluble in fats invade the animal bodies by a procedure recognized as “bioamplification” and get retained in the oily tissues of animals, consequently resulting in the perseverance of pesticides for prolonged durations in food chains (Daley et al. 2009; Dar et al. 2020).

2.4 Microbial Bioremediation

The remediation techniques which are used to overcome the polluted H_2O and soil by these pesticide sprays can be biological, physical, and chemical, or a grouping of a few or all of these processes (Pascal-Lorber and Laurent 2011). By tradition, the pollution caused by the pesticides has been reduced utilizing various physical and chemical methods whereby soils are later shifted to specific landfills, where the substances may likewise be burned or neutralized nearby (McGuinness and Dowling 2009). The frequently utilized chemical and physical strategies are not only costly but their side-products are also dangerous to the surroundings (Gaur et al. 2014). Moreover, when evaluation of soils is done by this mode, the disturbance caused in ecosystems is serious and restoration possibly will take generations (Dijkgraaf and Vollebergh 2004). As these strategies are so expensive and comprehensive, they found advantage in only small areas with high pollution; however, their use on extensive areas with limited pollution is unpracticable (Jin et al. 2006; Dar et al. 2016).

Data has indicated that there are new convenient remediation strategies for the end of these ecological pollutants and, among them, bioremediation is the most convenient and naturally accepted management that utilizes life forms or their outputs to diminish or kill the unfavorable impacts of toxic waste in the surroundings (Quintella et al. 2019; Mushtaq et al. 2020). The procedure is improved either during bioaugmentation, which includes the addition of extrinsic micro-biota into polluted soil or during biostimulation, where the inventory of supplements administered into the soil is changed, which ultimately quickens the breakdown ability of native microorganisms (Imam et al. 2019). A huge variety of micro-biota, for example, fungi, bacteria, algae, and genetically modified organisms have been examined in detail for terrestrial and aquatic habitat bioremediation (Alegbeleye et al. 2017; Khanday et al. 2016).

A few ecological parameters, for example, amount of moisture, degree of heat or coolness, and pH, alter the development of micro-biota. Control and maintenance of these frameworks can extend the pace of breakdown process significantly (Guarino et al. 2017). There are several fungal species (*Lecanicillium muscarium*, *Pestalotiopsis palmarum*, *Pleurotus eryngii*, *Phanerochacte chryososporium*, *Tramates versicolor*, etc.), algal species (*Anabaena*, *Chlorella*, *Chlamydomonas reinhardtii*, *Cladophora*, *Monoraphidium braunii*, *Oscillatoria, Phaeodactylum tricornutum*, *Spirulina* sp., *Scenedesmus*, etc.) and bacterial species (*Acinetobacter radioresistens*, *Enterobacter hormaechei*, *Pseudomonas aeruginosa*, *Rhodococcus erythropolis*, etc.), which are having a distinct catabolic route for the breakdown of pollutants at the site of contamination. There are also examples of some species of microorganisms which degrade contaminants solely under in vitro conditions (Abtahi et al. 2020; Singh et al. 2020a, b; Bwapwa et al. 2017). Microbial bioremediation of various pesticides and herbicides is summarized in Table 2.15.

Table 2.15 Microbial bioremediation of various Pesticides and herbicides

Phenoxyacetic acid ($C_8H_8O_3$) herbicide	Degrading strain	References
2,4-D ($C_8H_6Cl_2O_3$)	*Bacterium globiforme*	Audus (1951)
	Flavobacterium aquatile	Jensen and Petersen (1952)
	Clavibacter michiganese ATZ1	Johnson et al. (1967)
	Pseudomonas sp. N.C.I.B.9340	Gaunt and Evans (1971)
	Aspergillus niger	Loos et al. (1967a)
	Arthrobacter sp.	Loos et al. (1967b)
	Pseudomonas sp. HV3	Kilpi et al. (1983)
	Cupriavidus necator JMP 134	Don et al. (1985)
	Flavobacterium sp. 50001	Chaudhry and Huang (1988)
	Sphingomonas herbicidovorans MH	Zipper et al. (1998)
	Xanthobacter sp. CP	Ditzelmüller et al. (1989)
	Pseudomonas sp. EST4002	Ausmees and Kheĭnaru (1990)
	Azotobacter chroococcum	Balajee and Mahadevan (1990), Chinalia et al. (2007)
	Alcaligenes eutrophus JMP134	Haugland et al. (1990)
	Alcaligenes eltrophui, *A. faecali*, *A. paradoxus* 2811P, *Sphingomnonas paucimobil*, *Pseudomnonas picketti*, *P. solanacearurn*,	Ka et al. (1994)
	Comamonas testosteroni JH5	Arensdorf and Focht (1995)
	Pseudomonas aeruginosa PAOlc	Filer and Harker (1997)
	Pseudomonas cepacia P166	Noh et al. (2000)
	Halomonas sp. EF43	Kleinsteuber et al. (2001)
	Bradyrhizobium sp. HW13	Kitagawa et al. (2002)
	Pseudomonas putida	Khalil (2003)
	Aeromonas hydrophila IBRB-36 4CPA	Markusheva et al. (2004)

(continued)

Table 2.15 (continued)

Phenoxyacetic acid ($C_8H_8O_3$) herbicide	Degrading strain	References
	Achromobacter xylosoxidans subsp. *denitrificans* EST4002	Vedler et al. (2004)
	Sphingomonas sp. TFD44	Thiel et al. (2005)
	Corynebacterium sp. SOGU16	Igbinosa et al. (2007a, b)
	Achromobacter sp. SOGU11	Igbinosa et al. (2007a, b)
	Penicillium sp.	Silva et al. (2007)
	Sphingomonas agrestis	Shimojo et al. (2009)
	Delftia acidovorans	González et al. (2012)
	Burkholderia, Dyella, Mycobacterium, Microbacterium	González-Cuna et al. (2016)
	Achromobacter sp. QXH	Quan et al. (2015)
	Burkholderia cepacia (DS-1), *Pseudomonas* sp. (DS-2) and *Sphingomonas paucimobilis* (DS-3)	Cycoń et al. (2011)
	Cupriavidus campinensis BJ71	Han et al. (2015)
	Cupriavidus necator strain N-1	Zabaloy and Gómez (2014)
	Pseudomonas sp.; *Stenotrophomonas species*, *Alphaproteobacteria*, *Betaproteobacteria*, *Gammaproteobacteria*	Han et al. (2014)
	Achromobacter anxifer LZ35	Xia et al. (2017)
	Corynebacterium humireducens MFC-5	Wu et al. (2013)
	Cupriavidus sp. CY-1	Chang et al. (2015)
	Novosphingobium strain DY4	Dai et al. (2015)
	Delftia acidovorans	
MCPA ($C_9H_9ClO_3$)	*Pseudomonas* sp. HV3	Kilpi et al. (1983)
	Flavobacterium sp. 50001	Chaudhry and Huang (1988)
	Alcaligenes eutrophus JMP134	Pieper et al. (1988)
	Flavobacterium sp. MH	Horvath et al. (1990)
	Sphingomonas herbicidovorans MH	Kohler (1999)
	Alcaligenes denitrificans Strain	Marriott et al. (2000)

(continued)

Table 2.15 (continued)

Phenoxyacetic acid ($C_8H_8O_3$) herbicide	Degrading strain	References
	Enterobacter sp. SE08	Tan et al. (2013)
	Sphingomonas sp. ERG5	Nielsen et al. (2013)
Quinclorac ($C_{10}H_5Cl_2NO_2$)	*Burkholderia cepacia* WZ1	Lü et al. (2003)
	Bordetella sp. HN36	Xu et al. (2012)
	Alcaligenes sp. J3	Dong et al. (2013)
	Pantoea sp. QC06	Fan et al. (2013)
	Bacillus megaterium Q3	Liu et al. (2014)
Endosulfan ($C_9H_6Cl_6O_3S$)	*Bacillus, Staphylococcus*	Abatenh et al. (2017)
Chlorpyrifos ($C_9H_{11}Cl_3NO_3PS$)	*Enterobacter* strain B-14, *Providencia stuartii* strain MS09, *Enterobacter*, *Aeromonas* sp.,	Singh et al. (2004), Rani et al. (2008), Abatenh et al. (2017), Chen et al. (2012)
Ridomil MZ 68 ($C_{23}H_{33}MnN_5O_4S_8Zn$), Malation ($C_{10}H_{19}O_6PS_2$)	*Pseudomonas putida, Acinetobacter* sp., *Arthrobacter* sp.	Abatenh et al. (2017)
Chlorpyrifos ($C_9H_{11}Cl_3NO_3PS$) & methyl parathion ($C_8H_{10}NO_5PS$)	*Acenetobactor* sp., *Pseudomonas* sp., *Enterobacter* sp. and *Photobacterium* sp.	Abatenh et al. (2017)
s-Triazine ($C_3H_3N_3$)	*Pseudomonas* sp. strain MHP41, *Pseudomonas* sp. strain YAYA6, *Pseudomonas* sp. strain ADP, *Arthrobacter* sp. strain AD1, β-proteobacterium strain CDB21, *Nocardioides* sp, *Chelatobacter heintzii*, *Aminobacter aminovorans*, *Stenotrophomonas maltophilia* (Gram-negative species), *Arthrobacter crystallopoietes* (Gram-positive genus), *Rhodococcus* strain TE1, *Pseudomonas putida*, *P. fluorescens*, and *P. stutzeri*, *Streptomyces* sp. PS1/5,	Hernández et al. (2008), Yanze-Kontchou and Gschwind (1994), Mandelbaum et al. (1993), Cai et al. (2003), Iwasaki et al. (2007), Topp et al. (2000), Rousseaux et al. (2001), Behki et al. (1993), Behki and Khan (1986), Fadullon et al. (1998)
Pentachlorophenol (C_6HCl_5O)	*Arthrobacter* strains KC-3 and ATCC 33790	Chu and Kirsch (1972), Reiner et al. (1978)
Metamitron (3-methyl-4-amino-6--phenyl-1,2,4-triazin-5-one) ($C_{10}H_9N_3O$)	*Arthrobacter* sp. DSM 20389	Engelhardt et al. (1982)
N-phenyl carbamate (IPC) ($C_7H_6NO_2^-$)	*Arthrobacter oxydans* P52	Pohlenz et al. (1992)

(continued)

Table 2.15 (continued)

Phenoxyacetic acid ($C_8H_8O_3$) herbicide	Degrading strain	References
Isopropyl *N*-(3-chlorophenyl) carbamate (CIPC) ($C_{10}H_{12}ClNO_2$)	*Pseudomonas striata* Chester, *Flavobacterium* sp., *Agrobacterium* sp., and *Achromobacter* sp.	Kaufman (1967)
Dalapon ($C_3H_4Cl_2O_2$)	*Arthrobacter* sp.	Burge (1969)
Carbofuran (2,3-dihydro-2, 2-dimethyl-7-benzofuranyl N-methylcarbamate) ($C_{10}H_{12}O_2$)	*Arthrobacter* sp.	Ramanand et al. (1991)
Tetrachlorvinphos (TCV) ($C_{10}H_9Cl_4O_4P$)	*Stenotrophomonas malthophilia*, *Proteus vulgaris*, *Vibrio metschinkouii*, *Serratia ficaria, Serratia* spp. & *Yersinia enterocolitica*	Ortiz-Hernández and Sánchez-Salinas (2010)
Atrazine ($C_8H_{14}ClN_5$)	*Pseudomonas* strain YAYA6	Yanze-Kontchou and Gschwind (1994)
2,4,5-Trichlorophenoxyacetic acid ($C_8H_5Cl_3O_3$)	*Brevibacterium* sp	Horvath (1970)
Thiobencarb ($C_{12}H_{16}ClNOS$)	*Corynebacterium* sp.	Miwa et al. (1988)
Pentachlorophenol (C_6HCl_5O)	*Mycobacterium chlorophenolicum* PCP-1	Briglia et al.(1994)
Fluoranthene ($C_{16}H_{10}$)	*Alcaligenes denitrificans*	Tewari et al. (2012)
Carbofuran ($C_{12}H_{15}NO_3$), Parathion ($C_{10}H_{14}NO_5PS$), S-ethyl dipropylthiocarbamate ($C_9H_{19}NOS$), Pentachlorophenol (C_6HCl_5O), Glyphosate ($C_3H_8NO_5P$)	*Arthrobacter sp.*	Tewari et al. (2012)
Urea herbicides, Parathion ($C_{10}H_{14}NO_5PS$)	*Bacillus sphaericus*	Tewari et al. (2012)
Cyclohexylamine ($C_6H_{13}N$)	*Brevibacterium oxydans* DH35A	Tewari et al. (2012)
1,2,4,5-TeCB ($C_6H_2Cl_4$)	*Burkholderia* sp. P514	Tewari et al. (2012)
Quinoline (C_9H_7N), Glyphosate ($C_3H_8NO_5P$)	*Clostridium*	Tewari et al. (2012)
Acetonitril (C_2H_3N)	*Corynebacterium nitrophilus*	Tewari et al. (2012)
Trichloroethylene (TCE) (C_2HCl_3)	*Dehalococcoides ethanogenes*	Tewari et al. (2012)
Pentachlorophenol (C_6HCl_5O), Parathion ($C_{10}H_{14}NO_5PS$)	*Flavobacterium* sp.	Tewari et al. (2012)
Aromatic compounds	*Geobacter sp.*	Tewari et al. (2012)
3 Hydrobenzoate ($C_7H_5O_3^-$) &4 Hydrobenzoate ($C_7H_6O_3$)	*Klebsiella pneumoniae*	Tewari et al. (2012)
Trichloroethylene (C_2HCl_3)	*Methylococcus capsulatus*	Tewari et al. (2012)
1,1,1-Trichloroethane	*Nitrosomonas europaea*	Tewari et al. (2012)
Quinoline (C_9H_7N)	*Nocardia*	Tewari et al. (2012)

(continued)

Table 2.15 (continued)

Phenoxyacetic acid ($C_8H_8O_3$) herbicide	Degrading strain	References
Parathion ($C_{10}H_{14}NO_5PS$), Methyl parathion ($C_8H_{10}NO_5PS$)	*Pseudomonas stutzeri*	Tewari et al. (2012)
2,4,5-T ($C_8H_5Cl_3O_3$), Diazinon ($C_{12}H_{21}N_2O_3PS$)	*Pseudomonas capaciea*, *Pseudomonas* sp.	Tewari et al. (2012)
Pentachlorophenol (PCP) (C_6HCl_5O)	*Rhodococcus chlorophenolicus*	Tewari et al. (2012)
Carbaryl ($C_{12}H_{11}NO_2$)	*Agrobacterium* sp., *Bacillus* sp.	Zhao et al. (2005), Hamada et al. (2015)
Butachlor ($C_{17}H_{26}ClNO_2$)	*Anabaena* sp.	Agrawal et al. (2015)
Cyhalothrin ($C_{23}H_{19}ClF_3NO_3$), cypermethrin ($C_{22}H_{19}Cl_2NO_3$), HCH ($C_6H_6Cl_6$)	*Arthrobacter* sp., *Bacillus* sp.	Wang et al. (2015), Pankaj et al. (2016)
Ethion ($C_9H_{22}O_4P_2S_4$), cyanophos ($C_9H_{10}NO_3PS$)	*Azospirillum* sp.	Foster et al. (2004), Romeh (2014)
Acibenzolar-S-methyl ($C_8H_6N_2OS_2$), Metribuzin ($C_8H_{14}N_4OS$), napropamide ($C_{17}H_{21}NO_2$), propamocarb hydrochloride ($C_9H_{21}ClN_2O_2$), thiamethoxam ($C_8H_{10}ClN_5O_3S$)	*Bacillus* sp.	Myresiotis et al. (2012)
Bifenthrin ($C_{23}H_{22}ClF_3O_2$)	*Bacillus* sp.	Chen et al. (2012)
Allethrin ($C_{19}H_{26}O_3$), beta-cyfluthrin ($C_{22}H_{18}Cl_2FNO_3$), cyper- methrin ($C_{22}H_{19}Cl_2NO_3$), flumethrin ($C_{28}H_{22}Cl_2FNO_3$), permethrin ($C_{21}H_{20}Cl_2O_3$)	*Acidomonas* sp., *Aspergillus niger*, *Pseudomonas* sp., *Pseudomonas stutzeri*, *Serratia* sp.	Grant and Betts (2004), Liang et al. (2005), Paingankar et al. (2005), Saikia et al. (2005)
Gramoxone ($C_{12}H_{14}Cl_2N_2$)	*Pseudomonas putida*	Kopytko et al. (2002)
Trifluralin ($C_{13}H_{16}F_3N_3O_4$)	*Bacillus* sp., *Herbaspirillum* sp., *Klebsiella* sp., *Pseudomonas* sp	Bellinaso et al. (2003)
Linuron ($C_9H_{10}Cl_2N_2O_2$)	*Variovorax* sp	Horemans et al. (2013)
Azoxystrobin ($C_{22}H_{17}N_3O_5$)	*Rhodanobacter* sp.	Howell et al. (2014)

2.5 Factors Affecting Microorganism Bioremediation of Pesticide

Degradation of pesticide residues by microbes is limited by numerous components which are separated into internal and external ecological components, in which the impact of internal components commenced from the pesticide structure and the microbes. As reported by Hugo et al. (2014), transformation and deterioration of pesticides were influenced by microorganism species, adaptability, and metabolic activity. Numerous trials have indicated that the responses of various species of microorganisms or similar types of various strains to the toxic metal or similar organic substrate had been diverse, and the micro biota in the soil is having a solid capability to acclimatize to the surroundings and to be cultivated. With the aid of modified procedure, the novel blends enable these organisms to provide the related enzyme machinery or create a fresh enzyme machinery to degenerate them. Utilitarian distinctiveness and variations in degradation had been the most critical factors (Hussain et al. 2009; Baxter and Cummings 2006).

The intrinsic factors of pesticides, for example, their molecular mass, configuration, the quantity and nature of constituents, constituent distinctiveness, and position influenced the speed and effectivity of microbic breakdown of pesticides (Chaw and Stoklas 2013; Mahro et al. 2001). Luan et al. (2006) noted that the large-sized molecules were least biodegradable as compared to low mass molecules. The large sized molecules have been found to be resistant to biodegradation in comparison to the simpler ones, which were efficiently broken down.

Humidity, temperature, pH, salinity, oxygen, carbon dioxide, substrate concentration, surfactant, redox conditions, wetness, content of organic residues, content of nutrients, and nature and quantity of clay influence the microorganism action and chemical dissemination in soils (Sartoros et al. 2015). Soil water influences the dampness accessible to microorganisms as well as the reduction oxidation state in soil that prompt diverse biochemical responses. Schroll et al. (2006) assessed the impact of soil water oxygen consuming microbial mineralization of preferred pesticides (isoproturon, glyphosphate, and benzoin-ethyl) in various types of soils. The workers examined a direct relationship ($p < 0.0001$) between growing moisture in the soil and accelerated relative mineralization of pesticides. The most ideal mineralization by pesticides was achieved in a soil having Ψ value of -0.015 MPa. Additional increase in water diminished the pesticide mineralization as excess water limits oxygen diffusion and accessibility and can make the surroundings anoxic. Further rise in H_2O reduced the pesticide mineralization because surplus H_2O restricts O_2 dispersion, and availability causes the environment to become anoxic.

The temperature and pH are the main elements influencing the microbial assisted breakdown of pesticides in soil (Arshad et al. 2007; Bhatti et al. 2017; Dervash et al. 2020). The proper temperature not just influences the degree of chemical reactions, but it directly affects the proteins involved in various physiological process and permeability of plasma membranes (Alberty 2006; Guillot et al. 2000; Mastronicolis et al. 1998). A temperature scale between 15 to 40 °C is viewed as agreeable for the deterioration of pesticides by microorganisms meant for their breakdown (Hong et al. 2007). It has been revealed by Singh et al. (2006) that the bacterial population had been capable of deteriorating fenamiphos and chlorpyrifos between 15 and 35 °C; however, their breakdown capacity was forcefully diminished at 5 or 50 °C. Siddique et al. (2002) examined that an incubation temperature of 30 °C was best for the successful breakdown of alpha and gamma -HCH isomers.

2.6 Conclusion

Pesticide contamination creates a widespread risk to the surroundings and general well-being. In soil, different species of microorganisms exist with enormous actions equipped for deteriorating various groups of pesticides. This inherent potential of microbial organisms could be used for both on-site and off-site bioremediation purposes. Stimulation and expression of microbial genes preferred pesticide-deteriorating enzymes in original microflora have magnified the viable utilization of bioremediation in the detoxification of polluted environments. Conditions at every polluted location fluctuate, thus all location-specific variables need to be studied, and on the basis of the most appropriate accessible skill, a choice needs to be made. The organization of pilot-scale remediation investigation by various research teams vows to extend our insight into the application and limitation of this novel strategy. In order to widen the utilization and effective use of remediation, in-depth study is required for better and clear understanding of the effectiveness of microbial biota under various natural environments. This would probably assist in effective planning of the designed frameworks for remediation of polluted locations. In order to accomplish this objective, attempts need to be directed to extend the study concerning the interaction of soil and microbial organisms to interpret successfully the bench- and pilot-scale results to field scale.

References

Abatenh E, Gizaw B, Tsegaye Z, Wassie M (2017) Application of microorganisms in bioremediation-review. J Environ Microbiol 1:2–9

Abtahi H, Parhamfar M, Saeedi R, Villaseñor J, Sartaj M, Kumar V, Coulon F, Parhamfar M, Didehdar M, Koolivand A (2020) Effect of competition between petroleum-degrading bacteria and indigenous compost microorganisms on the efficiency of petroleum sludge bioremediation: field application of mineral-based culture in the composting process. J Environ 258:110–013

Agrawal C, Sen S, Yadav S, Rai S, Rai LC (2015) A novel aldo-keto reductase (AKR17A1) of *Anabaena* sp PCC 7120 degrades the rice field herbicide butachlor and confers tolerance to abiotic stresses in *E. coli*. PLoS One 10(9):e0137744

Alberty RA (2006) Biochemical reactions at specified temperature and various pHs. Biochemical thermodynamics. Wiley, Cambridge, pp 43–70

Aleem A, Isar J, Malik A (2003) Impact of long term application of industrial wastewater on the emergence of resistance traits of *Azotobacter vinelandii* isolated from rhizosphere soil. Bioresour Technol 86:7–13

Alegbeleye OO, Opeolu BO, Jackson VA (2017) Polycyclic aromatic hydrocarbons: a critical review of environmental occurrence and bioremediation. Environ Manag 60:758–783

Anderson SE, Meade BJ (2014) Potential health effects associated with dermal exposure to occupational chemicals. Environ. Health Insights 8:51–62

Anon (2004) The World Health Organization. WHO, Geneva. Available at: http://www.who.int/mediacentre/news/releases/ 2006/pr50/en/index.htmlS

Arensdorf JJ, Focht DD (1995) A meta cleavage pathway for 4-chlorobenzoate, an intermediate in the metabolism of 4-chlorobiphenyl by Pseudomonas cepacia P166. Appl Environ Microbiol 61:443–447

Arshad M, Hussain S, Saleem M (2007) Optimization of environmental parameters for biodegradation of alpha and beta endosulfan in soil slurry by *Pseudomonas aeruginosa*. Appl Microbiol 104:364–370

Audus LJ (1951) The biological detoxication of hormone herbicides in soil. Plant Soil Environ 3:170–192

Ausmees NR, Kheĭnaru AL (1990) New plasmids of herbicide 2, 4-dichlorophenoxyacetic acid biodegradation. Genetika 26:770–772

Balajee S, Mahadevan A (1990) Dissimilation of 2, 4-dichlorophenoxyacetic acid by *Azotobacter chroococcum*. Xenobiotica 20:607–617

Baxter J, Cummings SP (2006) The application of the herbicide Bromoxynil to a model soil-derived bacterial community: impact on degradation and community structure. Lett Appl Microbiol 43:659–665

Behki RM, Khan SU (1986) Degradation of atrazine by *Pseudomonas*: N-dealkylation and dehalogenation of atrazine and its metabolites. J Agric Food Chem 34:746–749

Behki R, Topp E, Dick W, Germon P (1993) Metabolism of the herbicide atrazine by Rhodococcus strains. Appl Environ Microbiol 59:1955–1959

Bellinaso MD, Greer CW, Peralba MD, Henriques JAP, Gaylarde CC (2003) Biodegradation of the herbicide trifluralin by bacteria isolated from soil. FEMS Microbiol Ecol 43:191–194

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of Toxic Heavy Metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, U.K, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Briglia M, Eggen RIL, van Elsas DJ, de Vos WM (1994) Phylogenetic evidence for transfer of pentachlorophenol-mineralizing *Rhodococcus chlorophenolicus* PCPI to the genus *Mycobacterium*. Int J Sys Bacteriol 44:494–498

Burge WD (1969) Populations of dalapon-decomposing bacteria in soil as influenced by additions of dalapon or other carbon sources. Appl Microbiol 17:545–550

Bwapwa JK, Jaiyeola AT, Chetty R (2017) Bioremediation of acid mine drainage using algae strains: a review. S Afr J Chem Eng 24:62–70

Cai B, Han Y, Liu B, Ren Y, Jiang S (2003) Isolation and characterization of an atrazine-degrading bacterium from industrial wastewater in China. Lett Appl Microbiol 36:272–276

Chang YC, Reddy MV, Umemoto H, Sato Y, Kang MH, Yajima Y, Kikuchi S (2015) Bio-augmentation of Cupriavidus sp. CY-1 into 2,4-D contaminated soil: microbial community analysis by culture dependent and independent techniques. PLoS One 10:e0145057

Chaudhry GR, Huang GH (1988) Isolation and characterization of a new plasmid from a Flavobacterium sp. which carries the genes for degradation of 2, 4-dichlorophenoxyacetate. J Bacteriol 170:3897–3902

Chaw D, Stoklas U (2013) Cocomposting of cattle manure and hydrocarbon contaminated flare pit soil. Compost Sci Util 9:322–335

Chen WM, Tang YQ, Mori K, Wu XL (2012) Distribution of culturable endophytic bacteria in aquatic plants and their potential for bioremediation in polluted waters. Aquat Biol 15:99–110

Chinalia FA, Regali-Seleghin MH, Corre EM (2007) 2,4-D toxicity: cause, effect and control. Terr Aquat Environ Toxicol 1:24–33

Chu JP, Kirsch EJ (1972) Metabolism of pentachlorophenol by an axenic bacterial culture. Appl Microbiol 23:1033

Cycoń M, Żmijowska A, Piotrowska-Seget Z (2011) Biodegradation kinetics of 2,4-D by bacterial strains isolated from soil. Open Life Sci 6:188–198

Dai Y, Li N, Zhao Q, Xie S (2015) Bioremediation using *Novosphingobium* strain DY4 for 2, 4-dichlorophenoxyacetic acid-contaminated soil and impact on microbial community structure. Biodegradation 26:61–170

Daley JM, Leadley TA, Drouillard KG (2009) Evidence for bioamplification of nine polychlorinated biphenyl (PCB) congeners in yellow perch (*Perca flavascens*) eggs during incubation. Chemosphere 75:1500–1505

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecologia Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish Fuana. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 51–68

DeLorenzo ME, Scott GI, Ross PE (2001) Toxicity of pesticides to aquatic microorganisms: a review. Environ Toxicol Chem 20:84–98

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Dar GH. Springer Nature, Singapore, pp 183–196

Dijkgraaf E, Vollebergh HRJ (2004) Burn or bury? A social cost comparison of final waste disposal methods. Ecol Econ 50:233–247

Ditzelmüller G, Loidl M, Streichsbier F (1989) Isolation and characterization of a 2, 4-dichlorophenoxyacetic acid-degrading soil bacterium. Appl Microbiol Biotechnol 31:93–96

Don RH, Weightman AJ, Knackmuss HJ, Timmis KN (1985) Transposon mutagenesis and cloning analysis of the pathways for degradation of 2, 4-dichlorophenoxyacetic acid and 3-chlorobenzoate in *Alcaligenes eutrophus* JMP134 (pJP4). J Bacteriol 161:85–90

Dong J, Luo K, Bai L, Zhou X, Zeng A (2013) Isolation, identification and characterization of an *Alcaligenes* strain capable of degrading quinclorac. Chin J Pesticide Sci 15:316–322

Engelhardt G, Ziegler W, Wallnöfer PR, Jarczyk HJ, Oehlmann L (1982) Degradation of the triazinone herbicide metamitron by *Arthrobacter* sp. DSM 20389. J Agric Food Chem 30:278–282

Fadullon FS, Karns JS, Torrents A (1998) Degradation of atrazine in soil by Streptomyces. J Environ Sci Health B 33:37–49

Fan J, Bo L, Liu M, Zhou X, Ren Z, Dong J, Sun L, Liu E (2013) Isolation, identification and degradation characteristics of quinclorac-degrading strain QC06. Chin J Biol Control 29:431–436

Filer K, Harker AR (1997) Identification of the inducing agent of the 2,4-Dichlorophenoxyacetic acid pathway encoded by plasmid pJP4. Appl Environ Microbiol 63:317–320

Food and Agriculture Organization and US Environmental Protection Agency (FAO and US EPA) (2014) The International Code of Conduct on Pesticide Management. WHO and US EPA, pp 8–10.

Foster LJR, Kwan BH, Vancov T (2004) Microbial degradation of the organophosphate pesticide, Ethion. FEMS Microbiol Lett 240:49–53

Gaunt JK, Evans WC (1971) Metabolism of 4-chloro-2-methylphenoxyacetate by a soil pseudomonad. Preliminary evidence for the metabolic pathway. Biochem J 122:51–526

Gaur N, Flora G, Yadav M, Tiwari A (2014) A review with recent advancements on bioremediation-based abolition of heavy metals. Environ Sci Process Impacts 16:180–193

González AJ, Gallego A, Gemini VL, Papalia M, Radice M, Gutkind G, Planes E, Korol SE (2012) Degradation and detoxification of the herbicide 2, 4-dichlorophenoxyacetic acid (2, 4-D) by an indigenous *Delftia* sp. strain in batch and continuous systems. Int Biodeterior Biodegradation 66:8–13

González-Cuna S, Galíndez-Mayer J, Ruiz-Ordaz N, Murugesan S, Piña-Escobedo A, García-Mena J, Lima-Martínez E, Santoyo-Tepole F (2016) Aerobic biofilm reactor for treating a commercial formulation of the herbicides 2,4-D and dicamba, biodegradation kinetics and biofilm bacterial diversity. Int Biodeterior Biodegrad 107:123–131

Grant RJ, Betts WB (2004) Mineral and carbon usage of two synthetic pyrethroid degrading bacterial isolates. J Appl Microbiol 97:656–662

Guarino C, Spada V, Sciarrillo R (2017) Assessment of three approaches of bioremediation (natural attenuation, landfarming and bioagumentation–assistited landfarming) for a petroleum hydrocarbons contaminated soil. Chemosphere 170:10–16

Guillot A, Obis D, Mistou MY (2000) Fatty acid membrane composition and activation of glycine-betaine transport in *Lactococcus lactis* subjected to osmotic stress. Int J Food Microbiol 55:47–51

Hamada M, Matar A, Bashir A (2015) Carbaryl degradation by bacterial isolates from a soil ecosystem of the Gaza Strip. Braz J Microbiol 46:1087–1091

Han L, Liu Y, He A, Zhao D (2014) 16S rRNA gene phylogeny and tfdA gene analysis of 2, 4-D-degrading bacteria isolated in China. World J Microbiol Biotechnol 30:2567–2576

Han L, Zhao D, Li C (2015) Isolation and 2, 4-D-degrading characteristics of *Cupriavidus campinensis* BJ71. Braz J Microbiol 46:433–441

Haugland RA, Schlemm DJ, Lyons RP, Sferra PR, Chakrabarty AM (1990) Degradation of the chlorinated phenoxyacetate herbicides 2, 4-dichlorophenoxyacetic acid and 2, 4, 5-trichlorophenoxyacetic acid by pure and mixed bacterial cultures. Appl Environ Microbiol 56:1357–1362

Hernández M, Villalobos P, Morgante V, González M, Reiff C, Moore E, Seeger M (2008) Isolation and characterization of a novel simazine-degrading bacterium from agricultural soil of Central Chile, *Pseudomonas* sp. MHP41. FEMS Microbiol Lett 206:184–190

Hong Q, Zhang ZH, Hong YF, Li SP (2007) A microcosm study on bioremediation of fenitrothion-contaminated soil using Burkholderia sp. FDS-1. Int Biodeterior Biodegrad 59:55–61

Horemans B, Vandermaesen J, Vanhaecke L, Smolders E, Springael D (2013) *Variovorax* sp. mediated biodegradation of the phenyl urea herbicide linuron at micropollutant concentrations and effects of natural dissolved organic matter as supplementary carbon source. Appl Microbiol Biotechnol 97:9837–9846

Horvath RS (1970) Microbial cometabolism of 2, 4, 5-trichlorophenoxyacetic acid. B Environ Contam Tox 5:537–541

Horvath M, Ditzelmüller G, Loidl M, Streichsbier F (1990) Isolation and characterization of a 2-(2,4-dichlorophenoxy) propionic acid-degrading soil bacterium. Appl Microbiol Biotechnol 33:213–216

Howell CC, Semple KT, Bending GD (2014) Isolation and characterization of azoxystrobin degrading bacteria from soil. Chemosphere 95:370–378

Hugo HJ, Mouton C, Malan AP (2014) Accelerated microbial degradation of nematicides in vineyard and orchard soils. S Afr J Enol Vitic 35:157–167

Hussain S, Siddique T, Saleem M, Arshad M, Khalid A (2009) Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. Adv Agron 102:159–200

Igbinosa O, Ajisebutu OS, Okoh IA (2007a) Aerobic dehalogenation activities of two petroleum degrading bacteria. Afr J Biotechnol 6(7):897

Igbinosa OE, Ajisebutu OS, Okoh IA (2007b) Studies on aerobic biodegradation activities of 2, 4-dichlorophenoxyacetic acid by bacteria species isolated from petroleum polluted site. Afr J Biotechnol 6(12):1426

Imam A, Suman SK, Ghosh D, Kanaujia PK (2019) Analytical approaches used in monitoring the bioremediation of hydrocarbons in petroleum-contaminated soil and sludge. Trac-Trend Anal Chem 118:50–64

Iwasaki A, Takagi K, Yoshioka Y, Fujii K, Kojima Y, Harada N (2007) Isolation and characterization of a novel simazine-degrading β- proteobacterium and detection of genes encodings-triazine-degrading enzymes. Pest Manag Sci 63:261–268

Jensen HL, Petersen HI (1952) Decomposition of hormone herbicides by bacteria. Acta Agric Scand 2:215–231

Jin JJ, Wang ZS, Ran SH (2006) Solid waste management in Macao practices and challenges. J Waste Manag 26:1045–1051

Johnson BT, Goodman RN, Goldberg HS (1967) Conversion of DDT to DDD by pathogenic and saprophytic bacteria associated with plants. Science 157:560–561

Ka JO, Holben WE, Tiedje JM (1994) Genetic and phenotypic diversity of 2, 4-dichlorophenoxyacetic acid (2, 4-D)-degrading bacteria isolated from 2, 4-D-treated field soils. Appl Environ Microbiol 60:1106–1115

Kaufman DD (1967) Degradation of carbamate herbicides in soil. J Agric Food Chem 15:582–591

Khalil AB (2003) Isolation and characterization of 2, 4-dichlorophenoxyacetic acid degrading organisms from soil in Jordan Valley. Biotechnology 2:73–85

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kilpi S, Backström V, Korhola M (1983) Degradation of catechol, methylcatechols and chlorocatechols by *Pseudomonas* sp. HV3. FEMS Microbiol Lett 18:1–5

Kitagawa W, Takami S, Miyauchi K, Masai E, Kamagata Y, Tiedje JM, Fukuda M (2002) Novel 2, 4-dichlorophenoxyacetic acid degradation genes from oligotrophic *Bradyrhizobium* sp. strain HW13 isolated from a pristine environment. J Bacteriol 184:509–518

Kleinsteuber S, Müller RH, Babel W (2001) Expression of the 2, 4-D degradative pathway of pJP4 in an alkaliphilic, moderately halophilic soda lake isolate, Halomonas sp. EF43. Extremophiles 5:375–384

Kohler EHP (1999) *Sphingomonas herbicidovorans* MH: a versatile phenoxyalkanoic acid herbicide degrader. J Ind Microbiol Biotechnol 23:336–340

Kole RK, Banerjee H, Bhattacharyya A, Chowdhury A, Aditya Chaudhury N (1999) Photo transformation of some pesticides. J Indian Chem Soc 76:595–600

Kopytko M, Chalela G, Zauscher F (2002) Biodegradation of two commercial herbicides (Gramoxone and Matancha) by the bacteria *Pseudomonas putida*. Electron J Biotechnol 5:182–195

Liang WQ, Wang ZY, Li H, Wu PC, Hu JM, Luo N, Cao LX, Liu YH (2005) Purification and characterization of a novel pyrethroid hydrolas from *Aspergillus niger* ZD11. J Agric Food Chem 53:7415–7420

Liu M, Luo K, Wang YS, Zeng AP, Zhou XM, Luo F, Bai LY (2014) Isolation, identification and characteristics of an endophytic quinclorac degrading bacterium *Bacillus megaterium* Q3. PLoS One 9:e108012

Loos MA, Bollag JM, Alexander M (1967a) Phenoxyacetate herbicide detoxication by bacterial enzymes. J Agric Food Chem 15:858–860

Loos MA, Roberts RN, Alexander M (1967b) Phenols as intermediates in the decomposition of phenoxyacetates by an *Arthrobacter* species. Can J Microbiol 13:679–690

Lü Z, Min H, Wu S, Ruan A (2003) Phylogenetic and degradation characterization of *Burkholderia cepacia* WZ1 degrading herbicide quinclorac. J Environ Sci Health B 38:771–782

Luan TG, Keith SH, Zhong Y, Zhou HW, Lan CY, Tam NF (2006) Study of metabolites from the degradation of polycyclic aromatic hydrocarbons pahs by bacterial consortium enriched from mangrove sediments. Chemosphere 65:2289–2296

Mahro B, Müller R, Kasche V (2001) Bioavailability-the key factor of soil bioremediation. Treat Contam Soil 01:181–195

Maksymiv I (2015) Pesticides: benefits and hazards. J Vasyl Stefanyk Precarpathian National Univ 2:70–76

Mandelbaum RT, Wackett LP, Allan DL (1993) Mineralization of the s-triazine by stable bacterial mixed cultures. Appl Environ Microbiol 59:1695–1701

Markusheva TV, Zhurenko EY, Galkin EG, Korobov VV, Zharikova NV, Gafiyatova LR (2004) Identification and characterization of a plasmid in strain *Aeronomas hydrophila* IBRB-36 4CPA carrying genes for catabolism of chlorophenoxyacetic acids. Russ J Genet 40:1210–1214

Marriott MW, Smejkal CW, Lappin-Scott HM (2000) Biodegradation of mixtures of chlorophenoxyalkanoic acid herbicides by *Alcaligenes denitrificans*. J Ind Microbiol 25:255–259

Martin XM, Sumathi CS, Kannan VR (2011) Influence of agrochemical and *Azotobacter* spp. application on soil fertility in relation to maize growth under nursery conditions. Eurasian. J Biosci 5:19–28

Mastronicolis SK, German JB, Megoulas N, Petrou E, Foka P, Smith GM (1998) Influence of cold shock on the fatty-acid composition of different lipid classes of the food-borne pathogen *Listeria monocytogenes*. Food Microbiol 15:299–306

McGuinness M, Dowling D (2009) Plant-associated bacterial degradation of toxic organic compounds in soil. Int J Environ Res Public Health 6:2226–2247

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess Environ 191:104. https://doi.org/10.1007/s10661-019-7245-2

Miller GT (2004) Sustaining the earth, chapter 9. Thompson Learning, Inc, Pacific Grove, pp 211–216

Miwa N, Takeda Y, Kuwatsuka S (1988) Plasmid in the degrader of the herbicide thiobencarb (Benthiocarb) isolated from soil. A possible mechanism for enrichment of pesticide degraders in soil. J Pestic Sci 13:291–293

Morillo E, Villaverde J (2017) Advanced technologies for the remediation of pesticide contaminated soils. Sci Total Environ 586:576–597

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge,UK, pp 152–178

Mushtaq N, Singh DV, Bhat RA, Dervash MA, Hameed UB (2020) Freshwater contamination: sources and hazards to aquatic biota. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 27–50

Myresiotis CK, Vryzas Z, Papadopoulou-Mourkidou E (2012) Biodegradation of soil-applied pesticides by selected strains of plant growth-promoting rhizobacteria (PGPR) and their effects on bacterial growth. Biodegradation 23:297–310

Nielsen TK, Xu ZF, Gözdereliler E, Aamand J, Hansen L, Sørensen SR (2013) Novel insight into the genetic context of the cadAB genes from a 4-chloro-2 methylphenoxyacetic acid-degrading *Sphingomonas*. PLoS One 8:e83346

Noh SJ, Kim Y, Min KH, Karegoudar TB, Kim CK (2000) Cloning and nucleotide sequence analysis of xylE gene responsible for meta-cleavage of 4-chlorocatechol from Pseudomonas sp. S-47. Mol Cell 10:475–479

Ortiz-Hernández ML, Sánchez-Salinas E (2010) Biodegradation of the organophosphate pesticide tetrachlorvinphos by bacteria isolated from agricultural soils in México. Rev Int Contam Ambie 26:27–38

Paingankar M, Jain M, Deobagkar D (2005) Biodegradation of allethrin, a pyrethroid insecticide, by an *Acidomonas* sp. Biotechnol Lett 27:1909–1913

Pankaj P, Sharma A, Gangola S, Khati P, Kumar G, Srivastava A (2016) Novel pathway of cypermethrin biodegradation in a *Bacillus* sp. strain SG2 isolated from cypermethrin-contaminated agriculture field. Biotech 6:45

Pascal-Lorber S, Laurent F (2011) Phytoremediation techniques for pesticide contaminations. In: Lichtfouse E (ed) Alternative farming systems, biotechnology, drought stress and ecological fertilisation. Sustainable agriculture reviews, vol 6. Springer, Dordrecht

Pieper DH, Reineke W, Engesser KH, Knackmuss HJ (1988) Metabolism of 2,4-dichlorophenoxyacetic acid, 4-chloro-2-methylphenoxyacetic acid and 2-methylphenoxyacetic acid by *Alcaligenes eutrophus* JMP 134. Arch Microbiol 150:95–102

Pohlenz HD, Boidol W, Schüttke I, Streber WR (1992) Purification and properties of an *Arthrobacter oxydans* P52 carbamate hydrolase specific for the herbicide phenmedipham and nucleotide sequence of the corresponding gene. J Bacteriol 174:6600–6607

Quan X, Ma J, Xiong W, Wang X (2015) Bioaugmentation of half-matured granular sludge with special microbial culture promoted establishment of 2 dichlorophenoxyacetic acid degrading aerobic granules. Bioprocess Biosyst Eng 38:1081–1090

Quintella CM, Mata AM, Lima LC (2019) Overview of bioremediation with technology assessment and emphasis on fungal bioremediation of oil contaminated soils. J Environ Manag 241:156–166

Ramanand K, Sharmila M, Singh N, Sethunathan N (1991) Metabolism of carbamate insecticides by resting cells and cell-free preparations of a soil bacterium, *Arthrobacter* sp. B Environ Contam Tox 46:380–386

Rani MS, Lakshmi KV, Devi PS, Madhuri RJ, Aruna S, Jyothi K, Narasimha G, Venkateswarlu K (2008) Isolation and characterization of a chlorpyrifos degrading bacterium from agricultural soil and its growth response. Afr J Microbiol Res 2:26–31

Reiner EA, Chu J, Kirsch EJ (1978) Microbial metabolism of pentachlorophenol. In: Rao KR (ed) Environmental science research, vol 12. Pentachlorophenol: chemistry, pharmacology and environmental toxicology. Plenum Press, New York, p 67

Reinhardt EL, Ramos PL, Manfio GP, Barbosa HR, Pavan C, Filho CAM (2008) Molecular characterization of nitrogen fixing bacteria isolated from Brazilian agricultural plants at also Paulo state. Brazilian J Microb 39:414–422

Romeh AA (2014) Phytoremediation of cyanophos insecticide by *Plantago major* L. in water. J Environ Health Sci 12:38

Roser M, Ritchie H (2017) Yields and land use in agriculture. Our World in Data

Rousseaux S, Hartmann A, Soulas G (2001) Isolation and characterization of new Gram-negative and Gram-positive atrazine degrading bacteria from different French soils. FEMS Microbiol Ecol 36:211–222

Sachin DN (2009) Effect of *Azotobacter chroococcum* (PGPR) on the growth of bamboo (*Bambusa bamboo*) and maize (Zea mays) plants. Biofrontiers 1:24–31

Saikia N, Das SK, Patel BKC, Niwas R, Singh A, Gopal M (2005) Biodegradation of beta-cyfluthrin by *Pseudomonas stutzeri* strain S1. Biodegradation 16:581–589

Sartoros C, Yerushalmi L, Béron P, Guiot SR (2015) Effects of surfactant and temperature on biotransformation kinetics of Anthracene and Pyrene. Chemosphere 61:1042–1050

Schroll R, Becher HH, Dorfler U, Gayler S, Grundmann S, Hartmann HP, Ruoss J (2006) Quantifying the effect of soil moisture on the aerobic microbial mineralization of selected pesticides in different soils. Environ Sci Technol 40:3305–3312

Shimojo M, Kawakami M, Amada K (2009) Analysis of genes encoding the 2, 4-dichlorophenoxyacetic acid-degrading enzyme from *Sphingomonas agrestis* 58-1. J Biosci Bioeng 108:56–59

Siddique T, Okeke BC, Arshad M, Frankenberger WT (2002) Temperature and pH effects on biodegradation of hexachlorocyclohexane isomers in water and soil slurry. J Agric Food Chem 50:5070–5076

Silva TM, Stets MI, Mazzetto AM, Andrade FD, Pileggi SA, Fávero PR, Cantú MD, Carrilho E, Carneiro PI, Pileggi M (2007) Degradation of 2, 4-D herbicide by microorganisms isolated from Brazilian contaminated soil. Braz J Microbiol 38:522–525

Singh BK, Walker A (2006) Microbial degradation of organophosphorus compounds. FEMS Microbiol Rev 30:428–471

Singh BK, Walker A, Morgan JAW, Wright DJ (2004) Biodegradation of chlorpyrifos by *Enterobacter* strain B-14 and its use in bioremediation of contaminated soils. Appl Environ Microbiol 70:4855–4863

Singh AK, Singh PP, Tripathi V, Verma H, Singh SK, Srivastava AK, Kumar A (2018) Distribution of cyanobacteria and their interactions with pesticides in paddy field: a comprehensive review. J Environ Manag 224:361–375

Singh RK, Tripathi R, Ranjan A, Srivastava AK (2020a) Fungi as potential candidates for bioremediation. In: Abatement of environmental pollutants. Elsevier, Amsterdam/Oxford/Cambridge, pp 177–191

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020b) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Staley ZR, Harwood VJ, Rohr JR (2015) A synthesis of the effects of pesticides on microbial persistence in aquatic ecosystems. Crit Rev Toxicol 45:813–836

Tan L, Hu QL, Xiong XY, Su XJ, Huang YN, Jiang ZW, Zhou QM, Zhao SY, Zeng WA (2013) Isolation and characterization of a novel 2-methyl-4-chlorophenoxyacetic acid-degrading *Enterobacter* sp. strain SE08. Ecotoxicol Environ Saf 96:198–204

Tewari L, Saini J, Arti (2012) Bioremediation of pollutants. I.K. International Publishing House Pvt. Ltd, New Delhi

Thiel M, Kaschabek SR, Gröning J, Mau M, Schlömann M (2005) Two unusual chlorocatechol catabolic gene clusters in *Sphingomonas* sp. TFD44. Arch Microbiol 183:80–94

Topp E, Mulbry WM, Zhu H, Nour SM, Cuppels D (2000) Characterization of striazine herbicide metabolism by a *Nocardioides* sp. isolated from agricultural soils. Appl Environ Microbiol 66:3134–3141

U.S. Environmental Protection Agency (2012) (http://www.epa.gov/)

Vedler E, Vahter M, Heinaru A (2004) The completely sequenced plasmid pEST4011 contains a novel IncP1 backbone and a catabolic transposon harboring tfd genes for 2, 4-dichlorophenoxyacetic acid degradation. J Bacteriol 186:7161–7174

Wang Y, Wang C, Li A, Gao J (2015) Biodegradation of pentachloronitrobenzene by *Arthrobacter nicotianae* DH19. Lett Appl Microbiol 61:403–410

Warren GF (1998) Spectacular increases in crop yields in the United States in the twentieth century. Weed Technol 12:752–760

Webster JPG, Bowles RG, Williams NT (1999) Estimating the economic benefits of alternative pesticide usage scenarios: wheat production in the United Kingdom. J Crop Prod 18:83–89

Wu TM, Lin WR, Kao YT, Hsu YT, Yeh CH, Hong CY, Kao CH (2013) Identification and characterization of a novel chloroplast/mitochondria co-localized glutathione reductase 3 involved in salt stress response in rice. Plant Mol Biol 83:379–390

Xia ZY, Zhang L, Zhao Y, Yan X, Li SP, Gu T, Jiang JD (2017) Biodegradation of the herbicide 2, 4-dichlorophenoxyacetic acid by a new isolated strain of *Achromobacter* sp. LZ35. Curr Microbiol 74:193–202

Xu Sx, Zhou J, Huang N, Hs LIU, Hb FENG, Jf HAN (2012) On the way of isolating, identifying and characterization of quinclorac-degrading bacterium HN36. J Safety Environ 2:45–49.

Yanze-Kontchou C, Gschwind N (1994) Mineralization of the herbicide atrazine as a carbon source by a *Pseudomonas* strain. Appl Environ Microbiol 60:4297–4302

Zabaloy MC, Gómez MA (2014) Isolation and characterization of indigenous 2, 4-D herbicide degrading bacteria from an agricultural soil in proximity of Sauce Grande River, Argentina. Ann Microbiol 64:969–974

Zhao S, Arthur EL, Moorman TB, Coats JR (2005) Evaluation of microbial inoculation and vegetation to enhance the dissipation of atrazine and metolachlor in soil. Environ Toxicol Chem 24(10):2428–2434

Zipper C, Bunk M, Zehnder AJ, Kohler HPE (1998) Enantioselective uptake and degradation of the chiral herbicide dichlorprop [(RS)-2-(2, 4-dichlorophenoxy) propanoic acid] by *Sphingomonas herbicidovorans* MH. J Bacteriol 180:3368–3374

Chapter 3
Pollution Cleaning Up Techniques

Baba Uqab, Jeelani Gousia, Syeed Mudasir, and Shah Ishfaq

3.1 Introduction

The relentless and inexorable extraction of natural resources, mostly from the nineteenth century, is doing irrevocable harm to the Earth's ecological balance. The intense and unsustainable development work gave rise to an unstoppable beast "Environmental Pollution". The word pollution became much familiar with the industrial revolution (Wu et al. 2018). Development of scientific and industrial technology has benefited the society in numerous ways, but has also produced many undesirable and toxic pollutants. A number of contaminants, such as heavy metals, pesticides, aerosols, sulfur oxides, and nitrogen oxides (SOX and NOX), now abundantly present in the atmosphere, are directly correlated with the industries. The whole world bears the brunt of the rapid and unplanned build-up. Pollution of all kinds has serious consequences for all spheres of life (Dar et al. 2016; Wu et al. 2018; Mushtaq et al. 2018). The haphazard use of chemicals to solve any agricultural or industrial problem contributes to the nasty aftermath of the existence in virtually all environments of widespread and unnecessary harmful pollutants (Lajayer et al. 2019; Bhatti et al. 2017; Bhat et al. 2018a, b). This poses a serious threat to the biosphere either in the form of diversity loss or degradation.

B. Uqab
Sri Pratap College, Srinagar, Jammu and Kashmir, India

J. Gousia
Centre of Research for Development, University of Kashmir,
Srinagar, Jammu and Kashmir, India

S. Mudasir
Abdul Ahad Azad Memorial Degree College Bemina, Srinagar, Jammu and Kashmir, India

S. Ishfaq (✉)
Department of Environmental Science, University of Kashmir,
Srinagar, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_3

Various pollutants have direct impact on human life, which is a serious concern and calls for immediate attention (Wu et al. 2018; Bhat et al. 2017a, b; Dar and Bhat 2020).

Heavy metal pollution is one of the worst issues that seriously affect the world's environment (Wong et al. 2006). Heavy metals are the metals or metalloids with densities greater than 5 g/cm^3. At present, the increased concentration of heavy metals in an environment can be due to the unnecessary use of pesticides (Zhang et al. 2011; Bhat et al. 2017a, b, 2018a, b; Mushtaq et al. 2020). Because of its unfavorable effects, soil containing heavy metal above the permissible limits is one of the major concerns. Even at a very low concentration, heavy metals are known to be one of the major pollutants in the soil.

Heavy metals act as major soil contaminants due to their widespread occurrence, their toxicity (acute and chronic), and their nature (persistence, non-biodegradability, and non-thermo-degradability). The reason for accumulation of heavy metals to toxic levels in soils is mostly due to their non-biodegradable and persistent nature (Dar et al. 2013; Uqab et al. 2016; Zojaji et al. 2014; Rezaei et al. 2014; Khanday et al. 2016; Singh et al. 2018).

Pesticides are the substances used for pest control. Pesticides are the xenobiotics that accumulate in the environment and require the adoption of new techniques in order to eliminate them from the environment. Techniques such as pyrolysis, landfilling, and recycling are some of the earlier techniques used for remediation of xenobiotics, but these also affect the environment adversely due to formation of intermediate toxic products (Debarati et al. 2005; Dervash et al. 2020) and proved difficult to execute due to their expensiveness (Jain et al. 2005).

Biotechnology provides an appropriate solution for the management of these deteriorated ecosystems. Environmental biotechnology investigators have extensively studied and managed many contaminations, including chlorinated solvents, hydrocarbons, PAHs, heavy metals, among others. Bioremediation is one such technology associated with reclamation of sites polluted with contaminants through bacteria, fungi, and plants which immobilize and detoxify toxic chemicals from the environment (Kvesitadze et al. 2006; Morel et al. 2002; Gadd 2001; Baker and Herson 1994). Alternative to incineration and catalytic destruction, bioremediation is a cost-effective technique and natural process. Bioremediation involves the combination of areas such as microbiology, biochemistry, molecular biology, chemical and environmental engineering, and analytical chemistry (Uqab et al. 2016; Tang et al. 2007). Microbes that are native to the degraded site are allowed to grow and perform the restoration activities (Agarwal 1998). Sometimes nutrients are added to promote the growth of microbes or the ways, such as terminal electron receptor and temperature and moisture control are applied to enhance the microbial growth (Hess et al. 1997). For the body metabolism, microbes are in need of nutrients or the energy source and the same is present in the contaminants in degraded environment (Uqab et al. 2016; Tang et al. 2007; Singh et al. 2020).

3.2 Agricultural Pollution

Agricultural practices in the world are considered incomplete without the use of fertilizers, pesticides, insecticides, and other chemicals as these are directly related to agriculture production (Aelion et al. 2008). The excessive and indispensable use of such chemicals has resulted in heavy metal accumulation in the soils above permissible limits (Table 3.1). Majority of the pesticides are mostly organic compounds and not many are inorganic compounds that contain metals such as As, Hg, Cu, and Zn, among others (Arao et al. 2010) and therefore, contribute largely toward the heavy metal contamination of soil.

Besides these sources, farmyard manures and coal ash metal processing units are also sources of heavy metal contamination in the soils around the globe (Bhat et al. 2019).

3.3 Bioremediation Via Microbes

Microorganisms that are used for bioremediation are known as Bio-remediators. Microbial tendency to inhabit and adapt to the extreme conditions have made these tiny creatures ideal for the remediation of xenobiotics as they can survive in aerobic as well as anaerobic conditions. The basic requirement for their survival is energy and carbon (Vidali 2001). The key needs for the bioremediation process are microorganisms that are either indigenous or foreign in nature (Prescott et al. 2002). The process of bioremediation depends upon the chemical composition of the polluting agent and the type of microbe used. The selection of microorganism should be performed carefully as they have a limited range of chemical pollution in which they live (Dubey 2004; Prescott et al. 2002). There is diversity of pollutants present in the degraded environment and to deal with these pollutants diverse microorganisms are needed (Watanabe et al. 2001). Microbes that have shown promising results in dealing with the xenobiotics and have degrading potential includes variety of species from *Pseudomonas, Alcaligens, Arthrobacter, Bacillus, Azotobacter, Rhodococcus, Mycobacterium,* and *Xanthomonas.* These microorganisms have potential to deal with toxic chemicals such as PCBs, benzene, anthracene, aromatics, polycyclic aromatic, long chain alkanes, phenols, halogenated hydrocarbons, cycloparaffins, formaldehyde, and biphenyls (Uqab et al. 2016).

About 70 microbial agents were reported to have the capability to degrade the petroleum compounds (US Congress, 1991) and, subsequently, an equal number was added to the list in the recent decades (Gjorgieva 2018). The contact between bacteria and the chemical is a prior requirement for degradation of contaminants, which is not easily achievable due to nonuniform distribution of microbes in soil. However, certain bacteria show chemo-tactic response, that is, sensing the contaminant and move toward it.

Table 3.1 Heavy metal concentration around globe in soil (1000 tonnes/annum) along with their few sources

Source	Arsenic	Cadmium	Chromium	Copper	Mercury	Nickel	Lead	Zinc	References
Agriculture and food waste	0 ~ 0.6	0 ~ 0.3	4.5 ~ 90	3 ~ 38	0 ~ 1.5	6 ~ 45	1.5 ~ 27	12 ~ 150	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Municipal wastes	0.09 ~ 0.7	0.88 ~ 7.5	6.6 ~ 33	13 ~ 40	0 ~ 0.26	2.2 ~ 10	18 ~ 62	22 ~ 97	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Commodity impurities	36 ~ 41	0.78 ~ 1.6	305 ~ 610	395 ~ 790	0.55 ~ 0.82	6.5 ~ 32	195 ~ 390	310 ~ 620	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Logging and timber industry wastes	0 ~ 3.3	0 ~ 2.2	2.2 ~ 18	3.3 ~ 52	0 ~ 2.2	2.2 ~ 23	6.6 ~ 8.2	13 ~ 65	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Organic wastes	0 ~ 0.25	0 ~ 0.01	0.1 ~ 0.48	0.04 ~ 0.61	–	0.17 ~ 3.2	0.02 ~ 1.6	0.13 ~ 2.1	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Municipal sludge	0.01 ~ 0.24	0.02 ~ 0.34	1.4 ~ 11	4.9 ~ 21	0.01 ~ 0.8	5.0 ~ 22	2.8 ~ 9.7	18 ~ 57	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Marl	0.04 ~ 0.5	0 ~ 0.11	0.04 ~ 0.19	0.15 ~ 2.0	0 ~ 0.02	0.22 ~ 3.5	0.45 ~ 2.6	0.15 ~ 3.5	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Atmospheric deposition	8.4 ~ 18	2.2 ~ 8.4	5.1 ~ 38	14 ~ 36	0.63 ~ 4.3	11 ~ 37	202 ~ 263	49 ~ 135	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)
Fertilizer	0 ~ 0.02	0.03 ~ 0.25	0.03 ~ 0.38	0.05 ~ 0.58	–	0.20 ~ 3.5	0.42 ~ 2.3	0.25 ~ 1.1	Bhat et al. (2019); Uqab et al. (2016); Chao et al. (2014)

3.4 Microbial Processes Concerned with Bioremediation

Biological or microbial processes for elimination and remediation of toxic metals is considered to be economical due to certain features such as selective metal binding, high capacity to bind metal, and effective absorption methods. Microbial transformation of heavy metals mostly affects solubility, bioavailability, and mobility (Francis 1997) and the mechanisms associated with these processes include chelation of these elements by metabolites, oxidation – reduction in metals, that affects the solubility, change in pH, biosorption, biotransformation, immobilization, biomethylation, and biodegradation.

A number of microorganisms have shown promising results in association and subsequent transformation of metals (Poole and Gadd 1989). Metal resistance is an inherent property of most microorganisms but these microorganisms have evolved/enhanced this property of metal resistance due to constant exposure to the heavy metal-contaminated environments (Banjerdkij et al. 2003). Different microbially mediated heavy metal transformations have been identified (Roane and Pepper 2000), many of which can immobilize metals in the environment. The processes of metal resistance include complexation, precipitation, and solubilization, leading to microbial metal transformation (Table 3.2).

Table 3.2 Mechanisms of resistance shown by microbes utilizing the heavy metals

Mechanisms of resistance	Microorganisms	Heavy metals	References
1. Intracellular and extracellular sequestration 2. Efflux reduction	1. *Gloeothece magna* 2. *Staphylococcus aureus* 3. *Fusarium oxysporum* 4. *Pseudomonas sp.* 5. *Azotoformans sp.*	Cd	1. Ahmad et al. (2002) 2. Nair et al. (2007) 3. Uqab et al. (2016) 4. Hesse et al. (2018)
1. Intra and extracellular sequestration	1. *Saccharomyces cerevisiae*	Cu	1. Culotta et al. (1994) 2. Kacholi and Sahu (2018)
1. Extracellular sequestration and reduction	1. *Streptomyces sp.*	Cr	1. Amoroso et al. (2001) 2. Lioyd (2003)
1. Efflux	1. *Ralstonia metallidurans*	Zn	1. Nies (2003) 2. Uqab et al. (2016)
1. Volatilization	1. *Clostridium glycolicum*	Hg	1. Meyer et al. (2007) 2. Stanković et al. (2018)
1. Biosurfactant 2. Extracellular sequestration	1. *Pseudomonas aeruginosa*	Pb	1. Nair et al. (2007) 2. Uqab et al. (2016)
1. Reduction 2. Efflux 3. Intracellular sequestration	1. *Lactobacillus sp.*	Ar	1. Nair and Pradeep (2002) 2. Stanković et al. (2018)

3.4.1 Metal Microbe Mechanism of Interaction

The approach implemented to bioremediate polluted lands depends entirely on the association of metals with microbes (Tabak et al. 2005). Forces such as electrostatic force, Van-der Waals force, redox reactions, covalent bonding, and extracellular precipitation promote the metal binding to the cell surface in ionic form. In fact, contact may be a mixture of all these mechanisms as well. Bacterial cell wall tends to maintain metal cations through mineral nucleation after adsorption by groups that are negatively charged, such as carboxyl, hydroxyl, and phosphoryl (Wase and Forster 1997). Material biosorption, such as U, Zn, Pb, Cd, Ni, Cu, Hg, Cs, Th, Au, Ag, Sn, and Mn, varies significantly with both the material and microorganism. In nature, microbes immobilize heavy metals through the process of cell accumulation or extra-cellular precipitation (Maier et al. 2009). Through generating surfactants, such as rhamnolipids, Pseudomonas aeruginosa shows a high sensitivity for some metals such as Pb and Cd. Similarly, other bacteria, including Thiobacillus ferroxidans and Leptospirillum ferroxidans, can oxidize iron and sulfur (Sand et al. 1992). Eubacteria and archaebacteria also conserve energy by reducing metals such as, Mn, Fe, Co, As, and Se. A strain of *Alcaligenes faecalis* oxides AsO^{2-} to $AsO4^{3-}$ and *Pseudomonas fluorescens* LB 300 and *Enterobacter cloacae* reduces $CrO4^{2-}$ to Cr(OH)3 enzymatically. The non-enzymatic detoxification involves the secretion of inorganic metabolic products, such as carbonate, sulfide, and phosphate ions precipitating toxic metals (Maier et al. 2009).

Factors such as humidity, pH, and temperature influence microbial development. Although microbes have been isolated from extreme environments, but maximum growth for most of them is obtained over a narrow range as optimal conditions are rarely achieved. For example, additives such as lime can be added to elevate pH if soil is acidic; similarly temperature maintenance is done using plastic covers in late spring, winter, and autumn to boost solar warming. The other imperative requirements for most favorable microbial growth are availability of water supply and oxygen, which are obtained by irrigation and tillage or sparge air, respectively. Sometimes hydrogen peroxide can also be used as an aerator of soil. However, soil structures control the delivery of air, water, and nutrients; these can be improved by using gypsum or organic matter. It is necessary to maintain the soil structures as low permeability can affect the movement of nutrients, water, and oxygen and hence are rendered not appropriate for in situ clean up (Tabak et al. 2005; Mehmood et al. 2019; Dar et al. 2020).

3.5 Bioremediation Strategies

Stimulation of the indigenous microbes for their activity is the primary and most important requisite for the bioremediation process and activation of the indigenous microbes is carried out by nutrient addition and regulation of redox condition and pH control (Table 3.3).

Table 3.3 Developmental methods applied in bioremediation

Technique	Examples	Applications
Microfiltration	Microfiltration membranes are used at a constant pressure	Mostly used for waste water treatment
Electrodialysis	Uses cation-anion exchange membrane pairs	Efficiently removes dissolved solids
Precipitation	Non-directed physicochemical complex action reaction between contaminant and charged particles	Heavy metal removal
Ex situ	Land forming Composting Bio-piles	Surface application Application of organic material to natural soils Agriculture to municipal wastes
In situ	Bio-sparging Bioventing Bioaugmentation	Biodegradative capacities of indigenous microorganisms Distribution of pollutants
Bioreactors	Slurry reactors Aqueous reactor	Decreases toxic concentration of contaminants

3.6 Phytoremediation

Phyto-remediation is an environmental clean-up treatment of plants and their associated microbes (Salt et al. 1998; Raskin et al. 1994). It involves detoxification organic and inorganic contaminants using plants and their rhizospherical microbiota. Chemical pollutants found in the environment are of xenobiotic origin, emitted primarily from leaks, combat operations, forestry, mining, and wood processing, etc. Such organic pollutants are remedied by sequestration, degradation, or volatilization according to their plant properties. Some of the successfully phytoremediated organic pollutants are most common groundwater pollutant-TCE (Newman et al. 1997), herbicides such as atrazine (Burke 2003), explosives such as TNT (Hughes et al. 1997), PCBs, PAHs, and MTBE (Davis et al. 2003). Phytoremediation is a modern method used by plants to remove toxins from water and soils (Bhadra et al. 1999).

The biotechnological interventions, such as genetically modified plants along with the rhizospheric microbiota, have proved promising in decontamination of soil and water (Uqab et al. 2016). Pollutants such as metals, hydrocarbon products, fungicides, pesticides, antibiotics are removed by phytoremediation. These pollutants are sequestered in the cell walls and chelated to inactive forms in the soil or complex and store them in vacuoles and produce small proteins such as metallothioneins and phytochelatins unavailable to the metabolically responsive cytoplasm. The volatilization of highly toxic chemicals, such as mercury and methyl mercury, can be acquired by the process of remediation through plants. In addition, plants have acquired the tendency to extract micronutrients from the atmosphere even at lower concentrations. The remediation techniques through plants involve; phytoextraction, phytostabiliazation, rhizofiltration, and phytovolatilization.

3.7 Phytoextraction

Phytoextraction involves the uptake of pollutants by the roots of the plants and sequestering them in their biological system, which are later available at the harvesting of associated plant. This method is most effective for soil, sediment, and sludge treatment of contaminants (Raskin et al. 1994). Plants are capable of absorbing huge amounts of heavy metals through roots and store it into the upper ground parts of the plant, resulting in formation of large biomass (Macek et al. 2000). Plants used for phytoextraction are called "hyperaccumulators". These are the plants which achieve greater than one shoot-to-root metal-concentration ratio. A plant can grow in hazardous conditions to be an effective hyperaccumulator, need minimal maintenance and yield high biomass, but few plants fulfill such criteria completely (Meenambigai et al. 2016). Hyperaccumulator plant species have tendency to bind metals such as Cd, Zn, Co, Mn, Ni, and Pb upto concentrations 100–1000 times more than the nonaccumulator plants (Endo et al. 2002). About 400 plant species, belonging to 45 plant families, are known to be hyperaccumulators. Among them, most of the plants bioaccumulate Ni, about 30 are capable of binding Co, Cu, and Zn, and few are efficient in Mn and Cd accumulation (Baker 1999).

3.8 Phytostabilization

This is the approach used for sediment, soil, and sludge remediation. The primary process of this approach requires the processing of certain chemicals by plants that immobilize the pollutants rather than degrade them and thus avoid their transfer to groundwater or their exposure to the food chain (Verma et al. 2006). The phytostabilization method is straightforward as it happens by the removal of precipitation, sorption, complexation, or metal valence, and because of these properties, this technique is commonly used to handle metals, such as arsenic, cadmium, chromium, copper, and zinc contaminants (Raskin et al. 1994).

3.9 Rhizofiltration

Rhizofiltration is the deliberate use of plants belonging to both terrestrial and aquatic ecosystems to consume, collect, and store pollutants in their roots from contaminated aqueous sources (Verma et al. 2006). The terrestrial plants are much preferred in order of preference over aquatic plants, since their root system, which is long and fibrous, increases the area of roots and removes potentially toxic metals effectively (Newman and Reynolds 2004). This is also called as Hydroponic

Systems for Treating Water Streams. Rhizofiltration is used primarily for remediating soil, groundwater, and low-contaminant wastewater. It can also be used for the metals which are primarily held in the roots, such as Cd, Cu, Pb, Zn, Ni, and Cr.

3.10 Phytovolatilization

The approach mainly uses plants to absorb pollutants from waste water as well as soil and convert them into volatilized compounds and finally transpire them into the atmosphere, the process known as phytovolatilization (Vazquez et al. 2006). It is used primarily for soils contaminated with mercury. In this process, growing trees and other plants will take up the pollutants with water and transfer them to the leaves through the xylem vessels, turn them into non-toxic forms and eventually volatilize them into the atmosphere (Newman and Reynolds 2004).

3.11 Aquatic Plant Species Studied for Phytoremediation

Various aquatic plants have been reported to remediate pollutants, *namely, Azolla pinnata*, *Lemna minor* accumulate Cu and Cr (Jain et al. 1990), *Pistia stratiotes* accumulates Ag, Cd, Cr, Cu, Hg, Pb and Zn (Odjegba and Fasidi 2004), *Lemna gibba* biosorbs As (Mkandvire and Dude 2005), and *Myriophyllum heterophyllum* and *Potamogeton crispus* accumulate Cd (Sivaci et al. 2008). Table 3.4 provides a list of some aquatic plants investigated for their phytoremediation potential (hydroponics) in water media.

3.12 Pesticide Degradation by Bacteria

Bacteria that remediate the pesticides belong to generas such as pseudomonas, Burkholderia, Aztobacter, Flavobacterium, Arthobacter, and Bacteruim raoultella sp. (Glazer and Nikaido 2007). The complete biological degradation of pesticides involves the oxidation resulting carbon dioxide and water as products that provide energy to microbes. In case the native bacterial diversity is incapable of bioremediation of pesticides, external addition of capable microbiota is added to the soil. Bacterial degradation of pesticides depends on the enzyme systems as well as conditions such as pH, temperature, and nutrients. Certain pesticides are easily degraded, where some are recalcitrant due to presence of anions in the compound. The pesticides such as organophosphorus compounds, the Neonicotinoids are degraded by the Pseudomonas species.

Table 3.4 Plants investigated for phytoremediation potential on water medium (hydroponics)

S. No.	Plant species	Researcher	Heavy metals	Result
1.	1. *Ceratophyllum demersum* 2. *Myriophyllum spicatum*	El-Khatib et al. (2014)	(Lead)	Plants accumulated large concentrations of Pb and thus demonstrated promise for usage in aquatic bodies with low Pb contamination as phytoremediator organisms
2.	1. *Ceratophyllum demersum*	AlUbaidy and Rasheed (2015)	(Cadmium)	*C. Demersum* has a high potential in ecosystem eradication of cadmium
3.	1. *Utricularia gibba*	Augustynowicz et al. (2015)	(Chromium)	*U. Gibba* may be successful for chromate removal on a short time scale
4.	*Ceratophyllum demersum*, *Myriophyllum spicatum*, *Eicchornia crassipes*, *Lemna gibba*, *Phragmites australis*, and *Typha domingensis*	Kamel (2013)	(Cadmium, copper, cobalt, nickel, lead, and zinc)	The surveyed native aquatic plant species displayed higher rates of aggregation of heavy metals which have the ability to be used in phytoremediation

3.12.1 Role of Fungi

The fungi render the pesticides into non-toxic substances by incurring minor structural changes in pesticides and later release them into the surrounding soil, where it is further degraded (Gavrilescu 2005).

3.12.2 Role of Enzymes

Enzymes play a vital role in the degradation of any xenobiotics and possess the capability of regenerating toxins at a significant pace and are likely to regenerate the degraded atmosphere (Rao et al. 2010). Enzymes also lead to the destruction of pesticide compounds in the target organism by intrinsic detoxification pathways and established metabolic tolerance, as well as in broader environments. *P. putida* theoretical oxygen necessity (TOD) enzyme is a subset of a much broader enzyme family of application of biologically-related reactions in biocatalysis (Watanabe and others 2001). In particular, fungal enzymes, oxidoreductases, lacquers, and peroxidases have a popular role in the removal of pollutants of polyaromatic hydrocarbons (PAHs) in natural, marine, or terrestrial water (Balaji et al. 2014). The enzymes play an important role in the biodegradation of any compounds in xenobiotics. The compounds of organophosphorus have been analyzed in depth and so much of the literature is available that explains the enzymes that kill the OP. The first bacterium to kill OP compounds was extracted from a Philippine soil sample in 1973 and has been known as Flavobacterium sp. ATCC 27551-ATCC (Suthersan 1999). Several bacteria have since been isolated, including a few fungi and cyanobacteria, which can use OP compounds as a source of carbon, nitrogen, or phosphorus.

3.13 Conclusion

Pollution has no doubt caused severe impact on every part of the earth. Pesticide and heavy metal-polluted fields have gained significant concern because it affects human health and the natural environment. Bioremediation has enormous potential for soil remediation which is affected by pesticides. Microorganisms present in soils are capable of removing pesticides from the environment. Biopesticides and enzymatic-contaminated environment degradation represent the most important strategy for the removal of contaminants and the degradation of persistent chemical substances by metabolic enzymes. Bioremediation is therefore a very positive approach that can definitely solve the problem of soil contamination. This technique has consistently demonstrated the ability for destroying not only pesticides but also other organic compounds. Knowing the microbial populations and their reaction to the natural environment and contamination, improving the awareness of microbial genetics to enhance their capacity to degrade the contaminants, and performing field trials of new bioremediation techniques are the need of the hour. Bioremediation paves the way for greener pastures. Its technique provides a reliable and cost-effective way to treat contaminated groundwater and land, irrespective of which type of bioremediation is being used. The positives of this tool have out-classified the weaknesses and the obvious example of this is that this methodology is in increasing demand. This thereby demonstrates that bioremediation is a form of management. So the time has come to use this environmentally friendly technology for a better and safer world.

References

Aelion CM, Davis HT, McDermott S (2008) Metal concentrations in rural topsoil in South Carolina: potential for human health impact. Sci Total Environ 402:149–156

Agarwal SK (1998) Environmental biotechnology, 1st edn. APH Publishing Corporation, New Delhi, pp 267–289

Ahmad A, Mukherjee P, Mandal D, Senapati S, Khan MI, Kumar R, Sastry M (2002) Enzyme mediated extracellular synthesis of CdS nanoparticles by the fungus, *Fusarium oxysporum*. J Am Chem Soc 124:12108–12109

Amoroso MJ, Castro GR, Durain A, Peroud O, Oliver G, Hill RT (2001) Chromium accumulation by two Streptomyces spp. isolated from riverine sediments. J Ind Microbiol Biotechnol 26:210–215

Arao T, Ishikawa S, Murakami M, Abe K, Maejima Y, Makino T (2010) Heavy metal contamination of agricultural soil and countermeasures in Japan. Paddy Water Environ 8(3):247–257

Augustynowicz J, Łukowicz K, Tokarz K, Płachno BJ (2015) Potential for chromium (VI) bioremediation by the aquatic carnivorous plant Utricularia gibba L. (Lentibulariaceae). Environmental Science and Pollution Research, 22(13):9742–9748

Baker KH, Herson DS (1994) Introduction and overview of bioremediation. In: Baker KH, Herson DS (eds) Bioremediation. McGraw-Hill, New York

Balaji V, Arulazhagan P, Ebenezer P (2014) Enzymatic bioremediation of polyaromatic hydrocarbons by fungal consortia enriched from petroleum contaminated soil and oil seeds. J Environ Biol 35:521–529

Banjerdkij P, Vattanaviboon P, Mongkolsuk S (2003) Cadmium-induced adaptive resistance and cross-resistance to zinc in *Xanthomonas campestris*. Curr Microbiol 47:260–262

Bhadra R, Wayment DG, Hughes JB, Shanks JV (1999) Confirmation of conjugation processes during TNT metabolism by axenic plant roots. Environ Sci Technol 33:446–452

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Burke IC, Thomas WE, Spears JF, Wilcut JW (2003) Influence of environmental factors on broadleaf signalgrass (Brachiaria platyphylla) germination. Weed science 51(5):683–689

Chao S, LiQin J, WenJun Z (2014) A review on heavy metal contamination in the soil worldwide: situation, impact and remediation techniques. Environ Skeptics Critics 3(2):24–38

Culotta VC, Howard WR, Liu XF (1994) CRS5 encodes a metallothionein-like protein in *Saccharomyces cerevisiae*. J Biol Chem 269:25295–25302

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from Fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish fuana. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 51–68

Davis LC, Erickson LE, Narayanan N, Zhang Q (2003) Modeling and design of phytoremediation. In: McCutcheon SC, Schnoor JL (eds) Phytoremediation: transformation and control of contaminants. Wiley, New York, pp 663–694

Debarati P, Gunjan P, Janmejay P, Rakesh VJK (2005) Accessing microbial diversity for bioremediation and environmental restoration. Trends Biotechnol 23(3):135–142. ISSN 0167-9430

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 183–196

Dubey RC (2004) A text book of biotechnology, 3rd edn. S. Chand and Company Ltd., New Delhi, pp 365–375

El-Khatib AA, Hegazy AK, Abo-El-Kassem AM (2014) Bioaccumulation potential and physiological responses of aquatic macrophytes to Pb pollution. International Journal of Phytoremediation, 16(1):29–45

Endo G, Narita M, Huang C, Silver S (2002) Microbial heavy metal resistance. J Environ Biotechnol 2(2):71–82

Francis JA (1997) Biotechnology of radioactive wastes: a general overview. In: Ronneau C, Bitchaeva O (eds) Biotechnology for waste management and site restoration, NATO ASI Series, 2/34. Klüwer Academic Publisher, Dordrecht/Boston/London, pp 18–28

Gadd GM (2001) Fungi in bioremediation. Cambridge University Press, Cambridge

Gavrilescu M (2005) Fate of pesticides in the environment and its bioremediation. Engineering in life sciences, 5(6):497–526

Gjorgieva AD (2018) Heavy metals and their general toxicity on plants. Plant Sci Today 5(1):15–19

Glazer AN, Nikaido H (2007) Microbial biotechnology: fundamentals of applied microbiology, 2nd edn. Cambridge University Press, Cambridge/New York, pp 510–528

Hess A, Zarda B, Hahn D, Hanner A, Stax D (1997) In situ analysis of denitrifying toluene and m-xylene degrading bacteria in a diesel fuel contaminated laboratory aquifer column. J Appl Environ Microbiol 63:213–214

Hesse E, O'Brien S, Tromas N, Bayer F, Luján AM, van Veen EM, Hodgson DJ, Buckling A (2018) Ecological selection of siderophore-producing microbial taxa in response to heavy metal contamination. Ecol Lett 21(1):117–127

Hughes JB, Shanks J, Vanderford M, Lauritzen J, Bhadra R (1997) Transformation of TNT by aquatic plants and plant tissue cultures. Environ Sci Technol 31:266–271

Jain RK, Kapur M, Labana S, Lal B, Sarma PM, Bhattacharya D, Thakur IS (2005) Microbial diversity: application of microorganisms for the biodegradation of xenobiotics. Curr Sci 89:101–112. ISSN 0011-3891

Kacholi DS, Sahu M (2018) Levels and health risk assessment of heavy metals in soil, water, and vegetables of Dar es Salaam, Tanzania. J Chem 2018:1–9

Kamel AK (2013) Phytoremediation potentiality of aquatic macrophytes in heavy metal contaminated water of El-Temsah Lake, Ismailia, Egypt. Middle–East Journal of Scientific Research, 14(12):1555–1568

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kvesitadze G, Khatisashvili G, Sadunishvili T, Ramsden JJ (2006) Biochemical mechanisms of detoxification in higher plants. Springer, Berlin

Lajayer B A, Najafi N, Moghiseh E, MosaferiM, & Hadian J (2019) Micronutrient and heavy metal concentrations in basil plant cultivated on irradiated and non-irradiated sewage sludge-treated soil and evaluation of human health risk. Regulatory Toxicology and Pharmacology, 104:141–150

Lioyd JR (2003) Microbial reduction of metals and radionuclides. FEMS Microbiol Rev 27:411–425

Macek T, Mackova M, Káš J (2000) Exploitation of plants for the removal of organics in environmental remediation. Biotechnol Adv 18(1):23–34

Maier RM, Pepper IL, Gerba CP (2009) Environmental microbiology. Academic Press, San Diego

Meenambigai P, Vijayaraghavan R, Shyamala Gowri R, Rajarajeswari P, Prabhavathi P (2016) Biodegradation of heavy metals – a review. Int J Curr Microbiol App Sci 5(4):375–383. https://doi.org/10.20546/ijcmas.2016.504.045

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Meyer J, Schmidt A, Michalke K, Hensel R (2007) Volatilization of metals and metalloids by the microbial population of an alluvial soil. Syst Appl Microbiol 31:81–87

Mkandawire M, Taubert B, Dude EG (2005) Resource manipulation in uranium and arsenic attenuation by Lemna gibba L. (duckweed) in tailing water of a former uranium mine. Water, Air, & Soil Pollution. 166:83–101

Morel JL, Echevarria G, Goncharova N (2002) Phytoremediation of metal-contaminated soils. IOS Press, Amsterdam, and Springer in conjunction with the NATO Public Diplomacy Division – Springer

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–178

Mushtaq N, Singh DV, Bhat RA, Dervash MA, Hameed UB (2020) Freshwater contamination: sources and hazards to aquatic biota. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 27–50

Nair B, Pradeep T (2002) Coalescence of nanoclusters and formation of submicron crystallites assisted by Lactobacillus strains. Cryst Growth Des 2:293–298

Nair VD, Haile SG, Michel GA, Nair PK (2007) Environmental quality improvement of agricultural lands through silvopasture in southeastern United States. Scientia Agricola, 64(5):513–519

Newman LA, Strand S, Choe N, Duffy J, Ekuan G, Ruszaj M, Shurtleff BB, Wilmoth J, Heilman P, Gordon MP (1997) Uptake and biotransformation of trichloroethylene by hybrid poplars. Environmental Science and Technology 31:1062–1067

Newman LA, Reynolds CM (2004) Phytodegradation of organic compounds. Curr Opin Biotechnol 15:225–230

Nies DH (2003) Efflux mediated heavy metal resistance in prokaryotes. FEMS Microbiol Rev 27:313–339

Odjegba VJ, Fasidi IO (2004) Accumulation of trace elements by Pistia stratiotes: implications for phytoremediation. Ecotoxicology, 13(7):637–646

Poole RK, Gadd GM (1989) Metal-microbe interaction. IRL Press, Oxford

Prescott LM, Harley JP, Klein DA (2002) Microbiology, 5th edn. McGraw Hill, New York, p 1014

Rao MA, Scelza R, Scotti R, Gianfreda L (2010) Role of enzymes in the remediation of polluted environments. J Soil Sci Plant Nutr 10(3):333–353

Raskin I, Kumar PBAN, Dushenkov S, Salt DE (1994) Bioconcentration of heavy metals by plants. Curr Opin Biotechnol 5:285–290

Rezaei MN, Dornez E, Jacobs P, Parsi A, Verstrepen KJ, Courtin CM (2014) Harvesting yeast (*Saccharomyces cerevisiae*) at different physiological phases significantly affects its functionality in bread dough fermentation. Food Microbiol 39:108–115

Roane TM, Pepper IL (2000) Microorganisms and metal pollution. In: Maier RM, Pepper IL, Gerba CB (eds) Environmental microbiology, vol 55. Academic Press, London, pp 403–423

Salt DE, Smith RD, Raskin I (1998) Phytoremediation. Annu Rev Plant Physiol Plant Mol Biol 49:643–668

Sand W, Gerke T, Hallmann R, Schippers A (1995) Sulfur chemistry, biofilm, and the (in) direct attack mechanism—a critical evaluation of bacterial leaching. Applied microbiology and biotechnology, 43(6):961–969

Singh DV, Bhat JIA, Bhat RA, Dervash MA, Ganei SA (2018) Vehicular stress a cause for heavy metal accumulation and change in physico-chemical characteristics of road side soils in Pahalgam. Environ Monit Assess 190:353. https://doi.org/10.1007/s10661-018-6731-2

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Sivaci A, Elmas E, Gümüş F, Sivaci ER (2008) Removal of cadmium by Myriophyllum heterophyllum Michx. and Potamogeton crispus L. and its effect on pigments and total phenolic compounds. Archives of environmental contamination and toxicology, 54(4):612–618

Stanković JD, Sabovljević AD, Sabovljević MS (2018) Bryophytes and heavy metals: review. Acta Bot Croat 77(2):109–118

Suthersan SS (1999) Remediation engineering design concepts. CRC Press Lewis Publishers, Boca Raton

Tabak HH, Lens P, van Hullebusch ED, Dejonghe W (2005) Developments inbioremediation of soils and sediments polluted with metals andradionuclides—microbial processes and mechanisms affecting bioremediation of metalcontamination and influencing metal toxicity and transport. Rev Environ Sci Biotechnol 4:115–156

Tang CY, Criddle QS, Fu CS, Leckie JO (2007) Effect of flux (transmembrane pressure) and membranes properties on fouling and rejection of reverse osmosis and nanofiltration membranes treating perfluorooctane sulfonate containing waste water. J Environ Sci Technol 41:2008–2014

Uqab B, Mudasir S, Sheikh AQ, Nazir R (2016) Bioremediation: a management tool. J Bioremed Biodegr 7:331. https://doi.org/10.4172/2155-6199.1000331

Vazquez S, Agha A, Granado A, Sarro M, Esteban E, Penlosa J, Carpena R (2006) Use of white lupin plant for phytostabilization of Cd and As polluted acid soil. Water Air Soil Pollut 177:349–365

Verma P, George K, Singh S, Juwarkar A, Singh R (2006) Modeling rhizofiltration: heavy metal uptake by plant roots. Environ Model Assess 11:387–394

Vidali M (2001) Bioremediation. An overview. Pure Appl Chem 73(7):1163–1172

Wase J, Forster CF (1997) Biosorbents for metal ions. Taylor & Francis, London

Watanabe K, Kodoma Y, Stutsubo K, Harayama S (2001) Molecular characterization of bacterial populations in petroleum contaminated groundwater discharge from undergoing crude oil storage cavities. Appl Environ Microbiol 66:4803–4809

Wong CS, Li X, Thornton I (2006) Urban environmental geochemistry of trace metals. Environ Pollut 142(1):1–16

Wu X, Chen S, Guo J (2018) Effect of air pollution on the stock yield of heavy pollution enterprises in China's key control cities. J Clean Prod 170:399–406

Zhang W, Jiang F, Ou J (2011) Global pesticide consumption and pollution: with China as a focus. Proc Int Acad Ecol Environ Sci 1(2):125–132

Zojaji F, Hassani AH, Sayadi MH (2014) Bioaccumulation of chromium by *Zea mays* in wastewater-irrigated soil: an experimental study. Proc Int Acad Ecol Environ Sci 4(2):62–67

Chapter 4
Role of Mushrooms in the Bioremediation of Soil

Nazir Ahmad Malik, Jitender Kumar, Mohammad Saleem Wani, Younas Rasheed Tantray, and Tawseef Ahmad

4.1 Introduction

The soil has much importance for human health and the environment. Presently, the world is facing a global soil crisis (Zhu and Meharg 2015; Bhatti et al. 2017). The whole biodiversity depends on this resource as it is a fundamental part of our planet due to water resources going through it and this soil becomes a substrate for flora and fauna (Montanarella and Vargas 2012). The turnover of organic matter in soil and the transformation of nutrients are an essential part of soil quality. The soil has potential to improve or hinder the success of revegetation on retired agricultural land, but the enrichment of soil by decomposition of nitrogen requires longer years since they were revegetated (Bourne et al. 2008). There are many shreds of evidence supporting that the productivity of terrestrial ecosystems and their multifunctionality are determined by the biodiversity of soil and composition of a biological community (Wagg et al. 2014; van der Heijden et al. 2008). Industrial development continues to increase and release chemicals into the soil with the consequent accumulation of heavy metals in agricultural soils causing growing public concern about food security worldwide (Wong et al. 2002). These heavy metals are non-biodegradable and persistent, which can pose long-term environmental and health

---

N. A. Malik
Department of Botany, Dolphin PG College of Science & Agriculture,
Chunni Kalan, Punjab, India

J. Kumar
Department of Botany, Lal Bahadur Shastri Govt PG College,
Sarswati Nagar, Jubbal, Himachal Pradesh, India

M. S. Wani · Y. R. Tantray
Department of Botany, Punjabi University, Patiala, Punjab, India

T. Ahmad (✉)
Department of Biotechnology, Punjabi University, Patiala, Punjab, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_4

implications (Zhao et al. 2011; Dar and Bhat 2020). Heavy metals such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), silver (Ag), and copper (Cu) are non-essential for growth and development of plant, but unnecessarily absorbed by them and accumulated in toxic forms, and consumption of these plants represents a possible risk to human health and wildlife. Various researchers showed that the use of contaminated water with heavy metals for irrigation increases these contents in the soil above the permissible limit. The uptake of heavy metals by plants depends upon the soil type, plant growth stages, and plant species (Abbas et al. 2011; Dar et al. 2013; Bhat et al. 2017a, b). Major sources of pollutants are industrial effluents, sewage sludge, inadequate use of fertilizers, pesticides, and insecticides, etc. (Varjani 2017; Bagul et al. 2015; Bhat et al. 2018a, b). All these pollutants can be divided into two major groups: (i) organic and (ii) inorganic, which can cause an adverse effect on flora, fauna, and human health (Varjani et al. 2015; Dervash et al. 2020; Mushtaq et al. 2020; Singh et al. 2020). Soil pollution has harmful consequences for the ecosystem. It is a necessary and challenging job to remediate the polluted soil. Biological approaches, mainly mycoremediation, are used as a cleanup technology, which has value on the conversion of pollutants into a usable form.

Mycoremediation is derived from the ancient Greek term "mukes" meaning fungus and "medium" meaning restoring balance. It is the use of fungi to degrade or remediate pollutants (Esterhuizen-Londt et al. 2016; Bhat et al. 2017a, b; Singh et al. 2018). It is the usage of fungi-based technology to decontaminate the environment from pollution. It is an eco-friendly method for decontamination of soil by the fungi present in aquatic sediments, terrestrial habitats, and water surfaces and plays a significant role in natural remediation of heavy metals (Dugal and Gangawane 2012; Dar et al. 2016; Mehmood et al. 2019).

It is a cheaper remediation process that does not require any expensive equipment. For these reasons, its use is in small-scale applications, namely, mycofiltration of domestic wastewater (Molla and Fakhru'l-Razi 2012) and to help with the decomposition process of a compost toilet. This process is a very cheap, effective, and environmentally beneficial way for the removal of toxins from the polluted environment. The organic pollutants include heavy metals, dyes, chemicals and wastewater, petroleum fuels, polycyclic aromatic hydrocarbon, pharmaceuticals, pesticides and herbicides, inland, freshwater, and marine environments (Deshmukh et al. 2016; Mushtaq et al. 2018). The by-products of the remediation are valuable enzymes such as laccase (Strong and Burgess 2007). This enzymatic machinery for the degradation of pollutants can be applied to a wide variety of pollutants (Kulshreshtha et al. 2013; Purnomo et al. 2013). It is described that edible or medicinal mushrooms make the remediation process even more profitable (Kulshreshtha et al. 2014). Mushrooms are not only used for bioremediation but can grow its sporocarp as a source of protein. They can degrade waste by the secretion of hydrolyzing and oxidizing enzymes (Zhu et al. 2013; Bhat et al. 2018a, b). The extracellular enzymes produced by mushrooms are cellulases, pectinases, peroxidases, ligninases (lignin peroxidase, manganese dependent peroxidase, and laccase), oxidases, and xylanases (Kulshreshtha et al. 2014; Khanday et al. 2016). These enzymes can oxidize recalcitrant pollutants in vitro. These enzymes also degrade non-polymeric, recalcitrant pollutants, namely, nitrotoluenes (Kulshreshtha et al. 2014), PAHs (Kulshreshtha et al. 2014), organic and synthetic dyes, and pentachlorophenol, under in vitro conditions (Kulshreshtha et al. 2014). These macrofungi are also able to degrade plastics (Kulshreshtha et al. 2014). It is a complex process as the influence of other biochemical systems and interactions of ligninolytic enzymes with cytochrome P450 monooxygenase system, hydroxyl radicals and the level of H_2O_2, which are produced by the mushroom. Mushrooms are future vegetables, so the researchers have a keen interest in the cultivation of mushrooms and waste remediation. Various workers have studied and examined the enzymatic role in the waste degradation process (Zhu et al. 2013; Akinyele et al. 2011; Novotný et al. 2004). Mycoremediation degrades hazardous materials into nonpoisonous substances. It is a biological tool to degrade, transform or immobilize environmental contaminants.

Bioremediation is the process of living organisms, such as fungi, bacteria, and green plants, to breakdown hydrocarbon and organic contaminants from soil (Atlas and Bartha 1992). Bioremediation is the use of plants to degrade environmental pollutants or to prevent pollution (Varjani 2017). Among these, the fungi are important in the decomposition, transformation, and nutrient cycling (Archana and Jaitly 2015). These organisms enhance biodegradation of contaminated soil. The synthetic organic compounds called xenobiotics do not occur naturally in the biosphere and some of them are not easily degraded by microbes (Sullia 2004). Several classes of chemicals are targeted by the United States Environmental Agency (USEPA) as priority toxic pollutants, namely, polycyclic aromatic hydrocarbons (PAHs), pentachlorophenols, polychlorinated biphenyls, 1,1,1- trichloro – 2,2- bis (4-chlorophenyl) ethane, benzene, toluene, ethylbenzene xylene, and trinitrotoluene. Loske et al. (1990) reported that the main contaminants in polluted soils are polycyclic aromatic hydrocarbons (PAHs), i.e., residues from the processing of oil, tar, coal, and comparable substances, polychlorinated biphenyls (PCBs), used as cooling agents in transformers, and dioxins, which are by-products of chemical manufacturing and are found in fly-ashes from combustion processes. These chemicals are a significant threat to the earth system. So it is an absolute requirement to promote sustainable development for low environmental impact. Due to the magnitude of this problem and the lack of a reasonable solution, a rapid, cost-effective, ecologically responsible method of clean up is greatly needed (Hamman 2004). Mycoremediation has a versatile role in environmental protection. It is an eco-friendly, cheaper, and easy way that can overcome the pollution of environment and convert the same into harmless forms (Perelo 2010). Mushrooms are disintegrators and the degradation is dependent upon the occurrence of nutrients present in the soil (Rhodes 2012). Some mushroom species, such as *Pleurotus ostreatus, P. tuber-regium, P. pulmonarius, P. eryngii, Lentinula edodes, Lentinus squarrosulus, L.tigrinus, Agaricus bisporus, Nematolana prowardii, Irex lacteus*, and *Stropharia coronilla*, are suitable for interacting with intractable substrates (fats, chitin, and keratin, and degrade their starches, hemicellulases, celluloses, pectins) and other sugar polymers. Flack (1902) developed a method for improving the digestibility of lignocellulosic material by white-rot fungi, such as *Pleurotus* sp. It has the ability to show rapid growth on cotton stacks (Kerem et al. 1992). This activity can also be applied to bioremediation of various pollutants having structural similarities to lignin.

4.2 Mushroom as a Significant Tool for Mycoremediation

The extensive research on mycoremediation shows that this method is to treat soil without the formation of dangerous metabolites. They were recognized to degrade various compounds (Abdel-Shafy and Mansour 2016). Various published reports emphasize the role of mushroom in the remediation of pollutants by the process of biodegradation, biosorption, and bioconversion (Kulshreshtha et al. 2013; Kumhomkul and Panich-Pat 2013; Lamrood and Ralegankar 2013; Akinyele et al. 2012), as given in Table 4.1. Mushrooms are major decomposers of cellulose, hemicelluloses, and lignin (Pletsch et al. 1999; Christian et al. 2005). They can store and release different elements and ions and also accumulate toxic elements (Annible et al. 2006). Edible and medicinal mushrooms are natural environment remediators

Table 4.1 List of mushrooms/fungi with their roles in the biodegradation of pollutants/waste

Mushroom species	Waste pollutants	References
Pleurotus ostreatus	Green polyethylene (GP) starch based plastic polymer degradation and oxodegradable plastic degradation; convert passion fruit waste into βglucoside	Da Luz et al. (2013, 2015) and Zilly et al. (2012)
Pleurotus platypus	Copper, zinc, iron, cadmium, nickel, lead	Lamrood and Ralengenker (2014)
Pleurotus pulmonarius, *Pleurotus* sp., *Polyporus* sp.	Crude oil/petroleum hydrocarbons	Njoku et al. (2017) and Kristanti et al. (2011)
Pleurotus sajor	Heavy metals	Jibran and Milsee Mol (2011)
P. ostreatus var. *florida*	Grow on solid sludges and effluent of cardboard and handmade paper industries	Kulshreshtha et al. (2013)
Lentinula edodes	Degradation of Eucalyptus waste	Tsujiyama et al (2013)
Lentinula tigrinus	Characterization of the production of ligninolytic enzymes and wheat straw into fruiting body	Lechner and Papinutti (2006)
Coriolus versicolor	Mushroom species possess the ability to degrade PAH with enzymes MnP and LiP	Jang et al. (2009)
Trametes versicolor	Act as biocatalysts for decolorization of different industrial dyes and waste	Amaral et al. (2004)

(continued)

Table 4.1 (continued)

Mushroom species	Waste pollutants	References
Auricularia sp. *Schizophyllum, Polyporus* sp.	Green dye, namely, malachite was degraded	Rajput et al. (2011)
Ganoderma lucidum, Volvariella volvacea, Coriolopsis strumosa, Daedalea tenuis, Lenzites malacanis, Phellinus xeranticus, Trametes lactenia, Agaricus bisporus, Lactarius piperatus	CU, CD, PB, CO, CU II	Nagy et al. (2013) and Das (2005)
Agaricus macrosporus, Beauveria bassiana	Cd, Hg, Cu, Zn, Pb, Cr, Cd	Gola et al. (2018) and García et al. (2005)
Flammulina velutipes	Copper ions from aqueous waste	Luo et al. (2013)
Fomes fasciatus	Copper ions	Sutherland and Venkobachar (2013)
Agaricus bisporus, Calocybe indica	Copper, zinc, iron, cadmium, nickel, lead	Lamrood and Ralengenker (2014)
L. edodes	Grow on agricultural waste such as oakwood sawdust, wheat straw corn cobs	Israilides and Philippoussis (2003)
Macrocybe titans, Grifola frondosa, G. lucidum	Convert passion fruit waste into βglucoside	Zilly et al. (2012)
Pleurotus sp., *Lentinus connatus*	Convert sorghum stalk, paddy straw, and banana pseudostem waste into mushroom	Rani et al. (2008)
V. volvacea	Enzymatic activities were measured during fermentation of agroindustrial wastes, such as cassava, sugar beet pulp, wheat bran, and apple pomance	Akinyele et al. (2012)

(Pletsch et al. 1999). These remediators stimulate organisms with nutrients and other chemicals for decontamination. It is a biotechnological method to clean up the contaminated sites (Thomas et al. 2009). This method has broader potential to perform and clean the polluted soil. Native mushrooms and their inoculum are applied to the contaminated soils to remove and degrade contaminants (Thomas et al. 2009). Mushroom taxa, such as *Agaricus, Amanita, Cortinarius, Boletus, Leccinum, Suillus,* and *Phellinus* are applicable for the mobilization of various toxic metals in the soil (Ali et al. 2017). The fungal hyphae have the ability to degrade heavy metals as well as xenobiotic compounds. This property makes them more advantageous and beneficial than bacteria. The moulds, yeasts, and filamentous fungi are removing the wastes (Thakur et al. 2015). Fungal spores and their hyphae can be used for their regeneration.

4.3 Remediation Through Mushrooms

Mushrooms use three effective methods to reclaim and ameliorate polluted lands. These methods are (a) biodegradation, (b) bioconversion, and (c) biosorption.

4.3.1 Biodegradation

The breakdown of organic matter by organisms, such as bacteria and fungi, is called biodegradation (Vert et al. 2012). This biodegradation includes biodeterioration, fragmentation, and assimilation. Biodeterioration is a surface-level degradation that modifies the mechanical, physical, and chemical properties of the material (Lucas et al. 2008). It is influenced by abiotic factors which allow degrading by weakening the material's structure. These factors are light, temperature, and chemicals in the environment. This process is the first stage of biodegradation. Biodeterioration is the undesirable action of living organisms on materials, such as the breakdown of stone, corrosion of metals by organisms (Hueck 1966). Mushrooms accumulate toxic metals with the hyphal network. They have the ability to absorb these metals from the soil (Mejstrik and Lepsova 1992). Mushrooms are being utilized as myco-remediation agents due to their characters concerning the uptake potential of heavy metal. Mushrooms degrade the polycyclic aromatic hydrocarbons (Hammel et al. (1991). It converts compounds to simple and inorganic forms. They can produce extracellular enzymes that degrade PAHs, Plastic, organic and synthetic dyes, 2, 4-dichlorophenol, crude oil, malachite green, radioactive cellulosic-based waste (Nyanhongo et al. 2007; Da Luz et al. 2013).

4.3.2 Bioconversion

It is biotransformation that is the conversion of organic materials, namely, plant or animal waste, into usable products by biological agents, such as mushrooms. This process is based on utilizing sugar from cellulose and hemicellulose to form their metabolites that are very essential for the growth and survival of mushrooms. The sources of lignocellulosic wastes are pulp and paper, agriculture, and food industries. Ligninolytic enzymes catalyze lignin compounds and fall into peroxidases and oxidases. Peroxidases use hydrogen peroxide (H_2O_2) or organic hydroperoxides (R-OOH) as co-substrates. Some peroxidases contain heme proteins with substrate spectrum, including organic and inorganic compounds (Dunford 1999). They form free radicals, such as phenoxyl and aryl cation radicals, reactive cations (e.g., Mn^{3+}), or anions (e.g., OCl–), which destroy the lignin and humic substances (Hofrichter and Ullrich 2010). Phenol oxidases are biocatalysts and the representatives are laccase and tyrosinase, that consist of copper in their active sites, which are produced by various mushrooms, such as Agaricus, and *Pleurotus* (Mikolasch and Schauer 2009). According to Reddy and Mathew (2001), white-rot fungi consists of peroxidases, laccases, etc., that are involved in the formation of free radicals that cleave the carbon-carbon and carbon-oxygen bonds of the lignin xenobiotic by a free radical mechanism. Cellulolytic enzymes are responsible for cellulolytic and xylanolytic activities. Fungal cellulolytic enzymes include cellulases, hemicellulases, pectinases, chitinases, amylases, proteases, phytases, mannoses, and xylanases. By using agricultural wastes as substrate, fungi produce cellulases, mannanases, and pectinases which can degrade cellulosic materials.

Wild mushrooms are a source of enzymes and secondary metabolites. Mushrooms use enzymes to biodegrade and biotransform the lignin of wood. The enzymes degrade lignocellulosic material for the production of ethanol using yeast, (Conceição et al. 2018). The waste, consisting of lignocellulose, can be used for mushroom cultivation and helps in solving pollution problems. The cultivation of *Pleurotus citrinopileatus, Lentinula edodes, Pleurotus eous*, *Lentinus connatus*, etc., can be carried out on various agro wastes. These grown mushrooms biotransform the agro biomass into valuable commercial substances, such as enzymes, carbohydrates, proteins, and various secondary metabolites (Brienzo et al. 2007; Rani et al. 2008; Kulshreshtha et al. 2014). Wild mushrooms, such as Lactarius sp., *Lentinula boryana*, and *Pycnoporus* sp., produce enzymes such as laccase (Khaund and Joshi 2014; Gavrilescu 2004). *Tricholoma saponaceum* can hydrolyze fibrinogen and fibrin by an enzyme Metaloendo-peptidases (Kim and Kim 2001).

4.3.3 Biosorption

It is the removal of metals or contaminants by mushrooms from aqueous solution. Various species of mushrooms remove pollutants by biosorption. *Lentinus tuberregium* biosorbs heavy metals from contaminated soil (Oyetayo et al. 2012). *Pleurotus platypus, Agaricus bisporus, Calocybe indica*, etc., are biosorbent agents for the removal of Cu, Zn, Fe, Cd, Pb, and Ni from aqueous solution (Lamrood and Ralegankar 2013). Accumulation of metal contents in fruiting bodies is affected by factors, namely, mycelium age, substrate composition, and the life span of fructification. It was observed by Thomet et al. (1999) that maximum metal concentrations in the pileus, but not in basidiospores, lower contents in cap and the very low in the stipe.

4.4 White-Rot Fungi Degradation System

Approximately 30% of the literature on fungal bioremediation is concerned with white-rot fungi (Rhodes 2014; Singh 2006). Four groups of white-rot fungi include *Phanerochaete, Trametes, Bjerkandera*, and *Pleurotus* that has the potential for bioremediation (Hestbjerg et al. 2003). This group of fungi can degrade naturally occurring polymer, lignin, a component of wood that is similar in molecular structure to petroleum hydrocarbons (Varjani 2017; Kshirsagar 2013; Hattaka 1994; Shah et al. 1992). These white-rot fungi can degrade toxic or insoluble compounds more efficiently than another group of fungi. Several white-rot fungi, such as *Lentinula edodes, Pleuritic ostreatus, Bjerkandera adusta, Trametes versicolor,* and *Irpex lacteus*, are well-known fungi that are able to degrade insoluble compounds (Siddiquee et al. 2015; Adenipekun and Lawal 2012; Hamman 2004; Shah et al. 1992; Bumpus et al. 1985). These have lignin degradation systems, such as manganese peroxidase (MnP), lignin peroxidase (LiP), H_2O_2 producing enzymes (Kirk and Farrell 1987) and laccase. All these enzymes are stimulated by nutrient limitation (Aust et al. 2004). These extracellular lignin modifying enzymes (LMEs) have very low substrate specificity, therefore mineralize highly recalcitrant organ pollutants which are similar to lignin (Veignie 2004; Pointing 2001; Cajthaml et al. 2002). Lignin peroxidase is a glycosylated heme protein that has a higher redox potential as compared to most peroxidases and oxidizes chemicals, which include some non-phenolic aromatic compounds (Reddy and Mathew 2001). Manganese peroxidase (MnP) also requires hydrogen peroxide for oxidation. The Mn^{3+} state of the enzyme mediates the oxidation of phenolic substrates (Mester and Tien 2000). Laccase is a multicopper oxidase enzyme that can catalyze the oxidation of dihydroxy and diamino aromatic compounds (Aust et al. 2004). The main reactions that are catalyzed by enzymes are demethoxylation, depolymerization, hydroxylation, decarboxylation, and aromatic ring opening resulting in oxygen activation, creating radicals that perpetuate oxidation of the organ pollutants (Reddy and Mathew 2001). The details of enzymes producing fungal taxa and mechanism of action are given in Table 4.2. White-rot fungi decontaminate the polluted sites by removing coal tar, creosote, and crude oil (Loske et al. 1990). Isikhuemhen et al. (2000) showed in his experiment that Lentinus squarrosulus has maximum lignocellulolytic enzyme activities and are a good producer of exopolysaccharides. *Lentinus squarrosulus* is ideal for application in industrial pretreatment and biodelignification of lignocellulosic biomass. *Elfvingia applanata* successfully applies for the bioconversion of bisphenol. The sophisticated symbiotic system of white-rot fungi of the genera Termitomyces with fungus-growing termites is also an attractive example which is a cooperation between termites and fungi that accomplishes the efficient decomposition of lignin and complete bio recycling of plant litter.

Brown rot fungi produce compounds which are able to penetrate the cell wall and help in degradation reactions. Their compounds depolymerize polysaccharides of wood and also break the glycosidic bonds of polysaccharides by penetration spores (Koenigs 1972). They have the ability to produce hydrogen peroxide (Koenigs 1974). The hydrogen peroxide produced by this group of fungi oxidizes the two valance transition metals (Fe^{2+}, Mn^{2+}, Co^{2+}).

Another group of fungi, called soft rot fungi, also helps in the degradation of cell walls of wood by forming chains that follow the orientation of the S2 elementary fibrils causing soft rot. They also produce cellulolytic enzymes. Their lignin-degrading ability is variable as there is a limitation in the functioning of peroxidases and oxidases (Cragg et al. 2015).

Table 4.2 Fungal taxa, their enzymes, along with their mechanism of action

Fungal taxa	Enzymes	Action of enzymes	References
Ascomycota	Caldariomyces fumago haeme thiolate chloroperoxidase	H_2O_2-dependent halogenation of organic compounds in the presence of halides; H_2O_2-dependent one-electron oxidations of phenols and anilines in the absence of halides, and H_2O_2-dependent peroxygenation	Hofrichter et al. (2010)
Basidiomycota	Lignn peroxdaes	H_2O_2-dependent one-electron oxidation of aromatic compounds	Hofrichter et al. (2010)
	Versatile peroxidases	H_2O_2-dependent one-electron oxidation of Mn^{2+} to Mn^{3+} and oxidizes organic compounds.	Hofrichter et al. (2010) and Ruiz-Dueñas et al. (2009)
	Coprinopsis cinerea peroxidase	H_2O_2-dependent one-electron oxidation of aromatic compounds	Hofrichter et al. (2010) and Ikehata et al. (2005)
	Dye decolonizing peroxidases	H_2O_2-dependent one-electron oxidation of organic compounds, additional hydrolyzing activity	Hofrichter et al. (2010)
	Reductive dehalogenases	Two-component system with membrane-bound glutathione S-transferase and a soluble glutathione conjugate reductase that releases reductively dechlorinated compounds	Nakamiya et al. (2005) and Jensen et al. (2001)
	Haemethiolate peroxygenases	H_2O_2-dependent peroxygenation of aromatic aliphatic, and heterocyclic compounds, leading to aromatic and alkylic carbon hydroxylation, double-bond epoxidation, ether cleavage, sulfoxidation or N-oxidation reactions (depending on the substrate), H_2O_2-dependent one-electron abstractions from phenols, and H_2O_2-dependent bromination of organic substrate	Hofrichter et al. (2010)

(continued)

Table 4.2 (continued)

Fungal taxa	Enzymes	Action of enzymes	References
Ascomycota, Basidiomycota, Mucoromycotina and *Chytridiomycota*	Cytochrome P450 monooxygenases	Incorporation of a single atom from O_2 into a substrate molecule, with concomitant reduction of the other atom to H_2O	Kasai et al. (2010), Subramanian and Yadav (2009), Ullrich and Hofrichter (2007), and Yadav et al. (2006)
Ascomycota and *Basidiomycota*	Phenol 2- monooxygenases	Incorporation of a single atom from O_2 into a substrate molecule, with concomitant reduction of the other atom to H_2O	Hofrichter et al. (2010) and Ullrich and Hofrichter (2007)
	Laccases	O2-dependent one-electron oxidation of organic compounds	Baldrian (2010) and Majeau et al. (2010)
Ascomycota, Basidiomycota, and *Mucoromycotina*	Nitroreductases	NADPH-dependent reduction of nitroaromatics to hydroxylamino and amino(nitro) compounds and of nitro functional groups of N-containing heterocycles	Crocker et al. (2006), Bhushan et al. (2002), Fournier et al. (2004), Esteve-Núñez et al. (2001), and Scheibner et al. (1997)
	Tyrosinases	O2-dependent hydroxylation of monophenols to o-diphenols (cresolase activity) oxidation of o-diphenols to catechols	Ullrich and Hofrichter (2007) and Halaouli et al. (2006)
	Miscellaneous transferases	Formation of glucoside, glucuronide, xyloside, sulfate, or methyl conjugates from hydroxylated compounds	Kasai et al. (2010)

4.5 Mycoremediation of Solid Wastes

The process of construction and demolition result in the spread of waste debris into the environment. The agricultural solid wastes from agricultural industry are used for mushroom cultivation. In agricultural, paper-pulp industries contaminate the environment with lignocellulosic waste. Mushrooms use agricultural wastes as a substrate for growing and production of enzymes. Therefore, it is a good idea to solve environmental problems. These wastes can be dealt with efficiently by employing lignocellulolytic microorganisms for composting the wastes, such as *Pleurotus ostreatus, Polyporus ostriformis*, and *Phanerochaete chrysosporium*. Crop residues such as straw, leaves, and trash can also be degraded by these fungi. Cellulases are hydrolytic enzymes that hydrolyze these agricultural wastes. Several filamentous fungi, also produce cellulases. The cellulases are endo1,4β-glucanase, cellobiohydrolase, and β-glucosidase. These enzymes enhance the potential for hydrolysis and saccharification of biomasses of willow, rice straw, etc., by application of two fungi *Armilleria gemina* and *Pholiota adipose. P. pulmonarius* engenders pectinase and laccase utilizing orange waste as substrate (Inácio et al. 2015). Orange wastes contain pectin which is one of the most abundant carbohydrates. *P. pulmonarius* can be induced to produce pectinase and laccase by the orange waste. Utilizing orange waste as a solid substratee system, hydrolytic and oxidative enzymes are being engendered by *Pleurotus pulmonarius* and *Pleurotus ostreatus* (Alexandrino et al. 2007).

In recent years, scientists have paid keen attention towards the decomposition of leather wastes. It comprises collagen, keratin, elastin, albumins, and globulins. Their degradation can be possible only due to the action of fungi that are very rich in enzymes. To make the treatment of leather wastes cost-effective and appropriate, fungal mycelia, mycelia pellets, immobilized fungi, or their enzymes are being used (Christopher et al. 2016). Industrial development is the main cause of toxic pollution. Paper and pulp production resulted in contamination of soil. Solid wastes from pulp and paper industries are lime mud, lime slaker grits, green liquor dregs, boiler and furnace ash, scrubber sludges, and wood processing residuals.

Thus essential steps are needed to be taken to completely degrade resultant pollutants which cannot be completely degraded by conventional wastewater treatment methods. Mycoremediation of industrial wastes has gained interest among scientists in recent years. This technology is treating the environmental and health problems associated with these wastes and pollutants (Kulshreshtha et al. 2012). Pulp and paper industry effluents contain lignin, tannic acid, resin, cellulose, and hemicellulose, which are difficult to degrade (Kumar et al. 2012).

Unfortunately, electronic waste has become the fastest-growing segment of Indian waste pour out. Several fungi such as *Penicillium simplicissimum, P. bilaiae, Saccharomyces cerevisiae*, and *Yarrowia lipolytica* have been found to grow in the presence of electronic scrap (Dave et al. 2016). These fungi act as complexing agents and help in the extraction of Cu, Cd, Sn, Al, Ni, Pb, Zn, etc. Arbuscular mycorrhizal fungi can revegetate degraded lands, namely, coal mines or waste sites (Gaur and Adholeya 2004). These mycorrhizal fungi assist plants to grow and degrade unfertile soil of coal mine areas.

4.6 Xenobiotic Organic Compounds (XOCs) and Mycoremediation

Intensive agriculture has resulted in increased release of xenobiotic compounds to the environment. Xenobiotics is derived from the Greek words “Xenos” means foreigner and “bios” means life. XOCs are the unnatural synthetic organic compounds which are not easily biodegradable (Sullia 2004), such as petroleum hydrocarbons, halogenated organic compounds, dyes, polycyclic aromatic hydrocarbons (PAHs), pesticides, and heavy metals. Contamination of soil by XOCs is a worldwide problem. Mycoremediation includes the process, such as myco-enzymes, myco-degradation, and myco-sorption, and is the application of enzymes, namely, manganese peroxidase (MnP), lignin peroxidase (LiP), and laccase is a common and preferred technology for the removal of XOCs (Noman et al. 2019). The main contaminants of polluted soils are petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and halogenated organic compounds (Loske et al. 1990).

4.6.1 Petroleum Hydrocarbons

These are complex compounds which are differentiating into saturates, aromatics, asphaltenes, and resins. Various hydrocarbon compounds based on petroleum sources, namely, diesel, kerosene, petrol, and lubricating oils, are described as total petroleum hydrocarbons. There are several ways that lead petroleum hydrocarbon to contaminate soil. The presence of these components is toxic (Scott 2003) and cause mutations and deaths (Alvarez and Vogel 1991). The prime reason for their toxicity is a low boiling point, with carbon ranging from C10 to C19. Bioremediation is an effective way to treat petroleum-contaminated soils and their applications (Gerhardt et al. 2009; Phillips et al. 2008, 2009; Euliss et al. 2008; Newman and Reynolds 2004).

4.6.2 Polycyclic Aromatic Hydrocarbons (PAHs)

These are the released varieties of environmental activities, namely, incomplete combustion of fossil fuels, accidental disposal of petroleum products, coal gasification, and liquefaction. Incomplete combustion of carbon materials forms PAHs. The man-made sources of PAHs include residential heating, coal-tar pitch and asphalt production, coke and aluminum production, and many more activities related to petroleum refineries and motor vehicle exhaust (Abdel-Shafy and Mansour 2016; Peng et al. 2008). PAHs are hydrophobic and so can be easily accumulated in fatty tissue (Varjani 2017). The harmful PAHs are with more than four rings which are mutagenic and carcinogenic (Varjani et al. 2015; Steffen et al. 2007). According to Fernandez-Luqueño et al. (2011) more than 50 fungal groups can degrade various PAHs. Moreover, they have a mechanism to attack specific PAHs (Abdel-Shafy and Mansour 2016). Oyster mushroom, *Pleurotus ostreatus* can degrade 80–95% of PAHs present in soil (Steffen et al. 2007). *Stropharia rugosoannulata* is the most efficient species of mushroom for the removal of PAHs (anthracene, pyrene, and benzo (a) pyrene).

4.6.3 Halogenated Organic Compounds

These include pentachlorophenol (PCP), trichloroethene (TCE), 2, 4-dichlorophenoxyacetic acid (2, 4-D), polychlorinated biphenyl (PCB), and dioxins. These halogen substituents contribute harmful effects of the compounds, increasing their toxicity, mutagenicity, and other detrimental capacities. These halogen substituents increase the hydrophobicity of the compounds, increasing their tendency to bioaccumulate in food chains and to sorb to the soil.

4.6.4 Synthetic Dyes

These are increasingly employed in various industries, namely, textile, paper, cosmetic, pharmaceutical, and food industries. These are commonly used in printing industries, color photography, and petroleum products. The dyes with azo, anthraquinone, tri- phenylmethane, and heterocyclic polymeric structures, the largest and most versatile class of dyes, the azo dyes, constitute more than half of the yearly manufactured synthetic dyes (Bonugli-Santos et al. 2015; Diwaniyan et al. 2010). The release of such dye-containing effluent results in impaired primary production and interferes dilution of gasses and affects human health (Baughman and Weber 1994; Ciullini et al. 2008; Rodriguez et al. 2015). It is necessary to control dyes for their possible toxicity and carcinogenicity.

4.6.5 Synthetic Pesticides

Mycoremediation is an eco-friendly approach for degradation of pesticides. These were known since DDT was discovered (Tessier 1982). Pesticides contaminate global ecosystems due to their toxicity and persistence in the environment. They can be grouped into insecticides, herbicides, and fungicides. Besides agricultural applications, large amounts of pesticides are used in reducing diseases, namely, malaria, and typhus fever. Large quantities of pesticides are used annually to increase the production through controlling harmful effects caused by the target organisms around the world (Liu and Xiong 2001). Spray of these chemicals also hits no target vegetation and that contaminate the soil. Their misuse results in destruction of soil along with microfauna and flora (Edwards 1986). The influences of pesticides include hormonal disruption, immunosuppression, mutagenicity, reproductive abnormalities, diminished intelligence, and various other health issues (Gupta 2004). The chlorinated insecticides, including DDT, aldrin, dieldrin, heptachlor, endrin, chlordane, and endosulfan, are of major environmental concern. Degradation of DDT by ectomycorrhizal fungal species, namely, *Gomphidius viscidus*, *Boletus edulis, Laccaria bicolor*, and *Leccinum scabrum*, has been reported (Huang et al.

2007). Various fungi, such as *Agrocybe semiorbicularis, Flammulina velupites, Hypholoma fasciculare, Pleurotus ostreatus,* and *Phanerochaete velutina,* degrade herbicides, such as diuron, atrazine, and terbuthylazine (Bending et al. 2001). *Pleurotus pulmonarius* degrades atrazine and produces the N-dealkylated metabolites deethylatrazine, deethyl- deisopropylatrazine, deisopropylatrazine, and 2-chloro-4-ethylamino-6-(1-hydroxyisopropyl) amino- 1,3,5-triazine (Masaphy et al. 1993).

4.6.6 Heavy Metals

These refer to metallic elements having a specific mass >5 gcm^{-3} and are able to form sulfides. The sources of heavy metals are the anthropogenic activities, namely, industrial production, mining, steel and iron industry, agriculture, transportation, chemical industry, as well as domestic activities that release heavy metals into soils, and ultimately to the biosphere (Jantschi et al. 2008; Pantelica et al. 2008; Abbas et al. 2011). The fungi tolerate metals by various mechanisms that help them survive and grow even in metal-contaminated sites (Gadd 2007). To survive under metal-stressed environment, organisms have evolved several mechanisms. Mushrooms are useful to decontaminate soil from heavy metals as they consist of good content of cell wall materials that offer excellent metal-binding features (Mann 1990; Muraleedharan et al. 1991). The mushroom cell walls are cation exchanger because of negative charge (Fomina et al. 2007). Mushrooms, such as *Pleurotus*, have proven to be effective in the removal of lead (Gazem and Nazareth 2013), cadmium, nickel, mercury, arsenic (Joshi et al. 2011), iron (Taştan et al. 2016), and zinc (Vaseem et al. 2017) in marine environment, wastewater, and on land. Mushrooms reduce the toxicity of metallic contaminants through pH change, biosorption, and bioaccumulation. The bioaccumulation of heavy metals and pollutants, such as mercury (Hg), iron (Fe), zinc (Zn), lead (Pb), copper (Cu), nickel (Ni), and cadmium (Cd), by edible mushroom, namely, *Pleurotus squarrosullus, Volvariella volvacea, Schizophyllum commune*, and *Auricularia auricular* (Udochukwu et al. 2014).

4.7 Role of Mycorrhizae in Remediation of Soil

All types of mycorrhizal fungi have paramountcy for planet earth. They perform a vital role in the maintenance of a pristine ecumenical ecosystem. Their mechanism helps sustainable applications in agriculture, conservation, and recuperation, concretely in the exhaustion of natural resources. The state of mycorrhizal fungi in an agroecosystem is not confined to the supply of nutrients to the plant. One consequential concern is the agricultural soil, its health, and structure (Willis 2018). The soils having mycorrhizae decreases the drought conditions (Ortiz et al. 2015; Jayne and Quigley 2014). Agricultural exercises condense and change mycorrhizal diversity (Verbruggen et al. 2013; Verbruggen and Toby Kiers 2010; Williams et al. 2017).

Mycorrhizal fungi growing as symbionts with plant roots can degrade organic pollutants in soil (Robertson et al. 2007). Several types of mycorrhizae, such as ectomycorrhizaa, increase the tolerance against heavy metals. The fungi capture phosphorus (P), nitrogen (N), and other nutrients from the soil and exchanges them with the plant partner derived carbon (C) compounds that feed on fungal metabolism. Various classifications of mycorrhizal fungi are ectomycorrhizas (ECM), arbuscular mycorrhizae (AM), ericoid mycorrhizas (ERM), arbutoid mycorrhizae (ARM), ectendomycorrhizae, orchid mycorrhizae, and monotropoid mycorrhizae. Mycotrophic plants grow on heavily polluted soils due to the accumulation of metals in extrametrical hyphae and extrahyphal slime. Various types of mycorrhiza, such as ECM, ERM, and VAM, increase tolerance to heavy metals. This leads to the immobilization of metals in roots and decreases uptake to shoots. ECM fungi act as useful bioindicators of pollution (Haselwandter et al. 1988). In conclusion, the majority of mycorrhizal fungi appear to be able to degrade a range of contaminants. Mycorrhizal fungi prevent heavy metals from traveling to plant through roots (Rajkumar et al. 2012) and store them in vacuoles. Some mushrooms increase their tolerance against toxicity. They modify the response of the plant against heavy metals at transcription and translation (Ferrol et al. 2016). Mycorrhizae help in the colonization of barren soil. They remain functional under extreme conditions, i.e., after a forest fire. After obtaining minerals and nutrients, released during forest fire before they are leached out of the soil. It increases the ability of regeneration after forest fires (Buchholz and Motto 1981). Mycorrhizal remediation ensures the removal of pollutants from soil and improves the structure of the soil. In addition to that, they detoxify the organic and inorganic toxic substances (Chibuike 2013).

The natural role of mycorrhizosphere organisms declined due to the excessive use of inorganic fertilizers, herbicides, and pesticides (Sturz et al. 1997). Intensive agricultural practices continue stepping up agricultural production regionally and globally along contamination of soil, its fertility, ecosystem balance, and soil biodiversity which can be observed superficially. Nowadays, an appreciation of soil microorganisms has been given in the literature for their role in agricultural sustainability and ecosystem management. The mycorrhizal fungi have beneficial effects on crop production and soil quality (Bethlenfalvay and Schüepp 1994). Artificial mycorrhizae inoculum production should be carefully practiced as soil chemical fertilizer for soil fertility management. An appropriate selection of host/fungus combinations would allow a reduction in the number of inputs without losses in productivity.

4.8 Disadvantages of Mycoremediation

Plenty of research is yet going on in the area of mycoremediation and consequently mycoremediationn can be studied to be in the trial phase. Further explained procedures in the field of biodegradation by fungi are required. The traditional remediation technologies are still conquering the faith of the processing units. They can manage sizably large amplitudes of wastes at a time and are thought as fast processes. Mycoremediation, in this case, would be too slow, and the space required for treatment or storage of materials could be restrictive. The cessation users are always in search of technologies which are 100% efficient, whereas the biological systems cannot promise that caliber of efficiency. The efficiency level of biological systems is never 100% efficient, which is arduous for some end-users to understand. The natural systems always face problems with the competitive natural habitat in a particular area and are withal affected by seasonal variations in extreme habitats. Though we are in the orchestration of commercialization of the technology by fungi, we very strongly ken that the research is still in the experimental phase and, additionally, we are not certain of the time it will take. More work is needed in the field of fungal bioremediation to apply the technology to more astronomically immense-scale projects. We expect to extemporize ways and betokens to eliminate the shortcomings that cause obstructions in the potential of mycoremediation. An immensely large licit issue additionally predominates as many of the fungi and their products and sundry technologies involving them are controlled by one or other scientists. Thus utilization of the mushrooms in bioremediation may pose several licit difficulties.

4.9 Conclusion and Future Aspects

The purpose of this chapter is to provide knowledge about major environmental pollutants and the use of fungi to treat these contaminants present in the environment. Bioremediation is a powerful cleanup technology for hazardous waste pollutants from soil, such as heavy metal. Although there are various sources of bioremediation, only biological treatment is not enough to decontaminate the soil. Only those biological agents should be cultured in the laboratory that require minimal requirement and can be treated pollutants of soil. A detailed study of pollutant region is much needed to finalize the priority area that needs effective removal of the pollutants. Mycoremediation is a necessary bio-tool for the conservation of natural resources and environmental management. Biosorption, a process of bioremediation, is efficient for the remediation of heavy metals from contaminated soil. It could be mediated by both living and dead biomass. Mushrooms are highly preferred biosorbents for heavy metals as they can be grown easily and produce an enormous quantity of biomass. This method has many advantages such as separation of metals over a wide range of pH/temperature and rapid kinetics of adsorption and desorption. Mushrooms play an important function in the renewal of the environment. Toxic metals, synthetic compounds, and chemicals can be transformed/degraded by various mushrooms. Molecular biology studies in future might enhance the biodegradative capabilities of fungi. There is a need for genetic manipulation – different strains of fungi capable of remediating a wide variety of pollutants on multiple heavy metal-contaminated sites under stress conditions. Cumbersomely heavy metal contamination of soil is one of the top ten concerned events cognate to environmental issues throughout the world (Yang and Sun 2009). Besides sundry challenges, mycoremediation is a most preferred method for xenobiotics, trichloroethylene, petroleum, BTEX (benzene, toluene, ethylbenzene, and xylene), explosives, and cumbersomely heavy metal compounds. The use of genetic engineering methods for bioremediation has much importance and interest. Genetically engineered organisms with enzymatic abilities can degrade any environmental pollutant. Many species of mushrooms are biosensors for metal pollution sites. The biodegradation capacity of mushroom is essential to compensate for the depletion of microbial communities due to soil contamination. Even more, the bioremediation potential of different groups of fungi from different ecosystems appears to be interconnected, engendering communities that favor the survival of its members and enhancing the detoxification activities of the different ecosystems. Wunch et al. (1999) for the first time studied that the fungi have the facility to degrade anthropogenic compounds. They reported the degradation of benzo(α]) pyrene by *Marasmiellus troyanus* in liquid culture. Since this time, researchers have been given the task of finding more evidence to solve this quandary (Singh et al. 2015; Rhodes 2014; Anastasi et al. 2013).

The application of this technology is severe; adept and trained personnel with appropriate cognizance of the subject are required to do the work of fungal remedy. Moreover, there is a purpose to research the ability of mushroom and additionally to employ other species of mushrooms for the degradation of pollutants. The main drawback of physicochemical approaches has been mainly owed to the high cost, low wages inhibited multifariousness, and intrusion by other wastewater ingredients and the approach of the excess engendered. The biotic action of the contaminated environment is an economically and ecologically alluring alternative to the present physicochemical methods of practice. This chapter compiles the recent developments, conceptions on the mycoremediation of hydrocarbon, and cumbersomely heavy metal-contaminated environment that is an environmental affair in jeopardous places using fungi.

References

Abbas SAU, Khan MJ, Tariqjan M, Khan NU, Arif M, Parveen S (2011) The effect of using waste water on tomato. Pak J Bot 43:1

Abdel-Shafy HI, Mansour MS (2016) A review on polycyclic aromatic hydrocarbons: source, environmental impact, effect on human health and remediation. Egypt J Pet 25(1):107–123

Adenipekun CO, Lawal R (2012) Uses of mushrooms in bioremediation: a review. Biotechnol Mol Biol Rev 7:62–68

Akinyele BJ, Olaniyi OO, Arotupin DJ (2011) Bioconversion of selected agricultural wastes and associated enzymes by Volvariella volvacea: An edible mushroom. Res J Microbiol. 4:63–70. https://doi.org/10.3923/jm.2011.63.70

Akinyele JB, Fakoya S, Adetuyi CF (2012) Anti-growth factors associated with *Pleurotus ostreatus* in a submerged liquid fermentation. Malays J Microbiol 8:135–140

Alexandrino AM, Faria H, Souza C, Peralta R (2007) Reutilisation of orange waste for production of lignocellulolytic enzymes by *Pleurotus ostreatus* (Jack: Fr). Food Sci Technol (Campinas) 27(2):364–368

Ali A, GuoO D, Mahar A, Wang P, Shen F, Li R et al (2017) Mycoremediation of potentially toxic trace elements—a biological tool for soil cleanup: a review. Pedosphere 27(2):205–222

Alvarez PJJ, Vogel TM (1991) Substrate interactions of benzene, toluene, and p-xylene during microbial-degradation by pure cultures and mixed culture aquifer slurries. Appl Environ Microbiol 57:2981–2985

Amaral PFF, Fernandes LAFD, Tavares APM, Xavier AMR, Cammarota MC, Coutinho JAP, Coelho MAZ (2004) Decolorization of dyes from textile wastewater by *Trametes versicolor*. Environ Technol 25(11):1313–1320

Anastasi A, Tigini V, Varese GC (2013) Fungi as bioremediators. In: The bioremediation potential of different ecophysiological groups of fungi. Springer, Berlin, pp 29–49

Atlas RM, Bartha R (1992) Hydrocarbon biodegradation and oil-spill bioremedition. Adv Microb Ecol 12:287–338

Archana A, Jaitly AK (2015) Mycoremediation: utilization of fungi for reclamation of heavy metals as their optimum remediation conditions. Biolife 3(1):77–106

Aust SD, Swaner PR, Stahl JD (2004) Pesticide decontamination and detoxification. Washington, D.C.: Oxford University Press. Detoxification and metabolism of chemicals by white-rot fungi 3–14

Bagul VR, Shinde DN, Chavan RP, Patil CL (2015) Causes and impacts of water pollution on rivers in Maharashtra: a review. Res J Chem Environ Sci 3:1–4

Baldrian P (2010) Fungal laccases e occurrence and properties. FEMS Microbiol Rev 30:215–242

Bending MP, Anderron A, Ander P, Stenström J, Torstensson L (2001) Establishment of white-rot fungus *Phanerochaete chrysosporium* on unsterile straw in solid substrate fermentation system intended for degradation of pesticides. World J Microbiol Biotechnol 17:627–633

Bethlenfalvay GJ, Schüepp H (1994) Arbuscular mycorrhizas and agrosystem stability. In: Gianinazzi S, Schüepp H (eds) Impact of arbuscular mycorrhizas on sustainable agriculture and natural ecosystems. Birkhäuser Verlag, Basel, pp 117–131

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytother 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Bhushan B, Halasz A, Spain J, Thiboutot S, Ampleman G, Hawari J (2002) Biotransformation of hexahydro- 1,3,5-trinitro-1,3,5-triazine catalyzed by a NAD(P)H: nitrate oxidoreductase from *Aspergillus niger*. Environ Sci Technol 36:3104–3108

Bonugli-Santos RC, dos Santos Vasconcelos MR, Passarini MRZ, Vieira GAL, Lopes VCP, Mainardi PH, dos Santos JA, de Azevedo DL, Otero IVR, da Silva Yoshida AM, Feitosa VA, Pessoa A Jr, Sette LD (2015) Marine-derived fungi: diversity of enzymes and biotechnological applications. Front Microbiol 6:269

Bourne M, Nicotra AB, Colloff MJ, Cunningham SA (2008) Effect of soil biota on growth and allocation by *Eucalyptus microcarpa*. Plant Soil 305:145

Brienzo M, Silva EM, Milagres AM (2007) Degradation of eucalyptus waste components by *Lentinula edodes* strains detected by chemical and near-infrared spectroscopy methods. Appl Biochem Biotechnol 141:37–50

Buchholz K, Motto H (1981) Abundances and vertical distributions of mycorrhizae in Plains and Barrens forest soils from the New Jersey Pine Barrens. Bull Torrey Bot Club 108(2):268–271

Baughman GL, Weber EJ (1994) Transformation of dyes and related compounds in anoxic sediment: kinetics and products. Environ. Sci. Technol. 28:267–276

Bumpus JA, Tien M, Wright D, Aust SD (1985) Oxidation ofpersistent environmental pollutants by a white rot fungus.Science 228:1434–1436

Chibuike GU (2013) Use of mycorrhiza in soil remediation: a review. Sci Res Essays 8:679–1687

Cajthaml TM, Möder P, Kacer V, Šašek P, Popp (2002) Study of fungal degradation products of polycyclic aromatic hydrocarbons using gas chromatography with ion trap mass spectrometry detection. Journal of Chromatography A 974:213–22

Christian V, Shrivastava R, Shukla D, Modi HA, Vyas BRM (2005) Degradation of xenobiotic compounds by lignin-degrading white-rot fungi: enzymology and mechanisms involved. Indian J Exp Biol 43:301–302

Christopher GJ, Kumar G, Tesema A, Thi N, Kobayashi T, Xu K (2016) Bioremediation for tanning industry: a future perspective for zero emission. In: Saleh HE-D (ed) Management of hazardous wastes. InTech. https://doi.org/10.5772/63809

Ciullini I, Tilli S, Scozzafava A, Briganti F (2008) Fungal laccase, cellobiose dehydrogenase, and chemical mediators: combined actions for the decolorization of different classes of textile dyes. Bioresour Technol 99:7003–7010

Conceição AA, Cunha JRB, Vieira VO, Pelaez RDR, Mendonca S, Almeida JRM, Dias ES, de Almeida EG, de Siqueira FG (2018) Bioconversion and biotransformation efficiencies of wild macrofungi [C]. In: Singh B, Lallawmsanga, Passari A (eds) Biology of macrofungi. Fungal biology. Springer, Cham

Cragg SM, Beckham GT, Bruce NC, Bugg TDH, Distel DL, Dupree P, Etxabe AG, Goodell BS, Jellison J, McGeehan JE, McQueen-Mason SJ, Schnorr K, Walton PH, Watts JEM, Zimmer M (2015) Lignocellulose degradation mechanisms across the tree of life. Curr Opin Chem Biol 29:108–119

Crocker FH, Indest KJ, Fredrickson HL (2006) Biodegradation of the cyclic nitramine explosives RDX, HMX, and CL-20. Appl Microbiol Biotechnol 73:274–290

Da Luz JMR, Paes SA, Nunes MD, da Silva MCS, Kasuya MCM (2013) Degradation of oxo-biodegradable plastic by *Pleurotus ostreatus* [J]. PLoS One 8(8):e69386

Da Luz JMR, Paes SA, Ribeiro KVG, Mendes IR, Kasuya MCM (2015) Degradation of green polyethylene by *Pleurotus ostreatus*. PLoS One 10(6):e0126047

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir Valley India. Ecol Balk 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Das N (2005) Heavy metals biosorption by mushrooms. NPR 4:454–459

Dave SR, Shah MB, Tipre DR (2016) E-waste: metal pollution threat or metal resource? SOJ Biotechnol 1(1):14

D"Annibalen A, Rosetto F, Leonardi V, Federici F, Petruccioli M (2006) Role of autochthonous filamentous fungi in bioremediation of a soil historically contaminated with aromatic hydrocarbons. American Soc. Microbiol. 72(1):28–36

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Deshmukh R, Khardenavis AA, Purohit HJ (2016) Diverse metabolic capacities of fungi for bioremediation. Indian J Microbiol 56(3):247–264

Diwaniyan S, Kharb D, Raghukumar C, Kuhad RC (2010) Decolorization of synthetic dyes and textile effluents by basidiomycetous fungi. Water Air Soil Pollut 210:409–419

Dugal S, Gangawane M (2012) Metal tolerance and potential of *Penicillium* species for use in mycoremediation. J Chem Pharm Res 4:2362–2366

Dunford HB (1999) Heme peroxidases. Wiley, New York

Edwards CA (1986) In: Van Hofsten B, Eckstrom G (eds) Agrochemicals as environmental pollutants. In control of pesticide applications and residues in food. A guide and directory. Swedish Science Press, Uppsala

Esterhuizen-Londt M, Schwartz K, Pflugmacher S (2016) Using aquatic fungi for pharmaceutical bioremediation: uptake of acetaminophen by *Mucor hiemalis* does not result in an enzymatic oxidative stress response. Fungal Biol 120:1249–1257

Esteve-Núñez A, Caballero A, Ramos JL (2001) Biological degradation of 2,4,6-trinitrotoluene. Microbiol Mol Biol Rev 65:335–352

Euliss K, Ho C, Schwab AP, Rock S, Banks MK (2008) Greenhouse and field assessment of phytoremediation for petroleum contaminants in a riparian zone. Bioresour Technol 99:1961–1971

Ferrol N, Tamayo E, Vargas P (2016) The heavy metal paradox in arbuscular mycorrhizas: from mechanisms to biotechnological applications. J Exp Bot 67(22):6253–6265

Fernández-Luqueño F, Valenzuela-Encinas C, Marsch R, Martínez-Suárez C, Vázquez-Núñez E, Dendooven L (2011) Microbial communities to mitigate contamination of PAHs in soil—possibilities and challenges: a review. Environmental Science and Pollution Research 18(1):12–30

Fomina M, Charnock J, Bowen AD, Gadd GM (2007) X-ray absorption spectroscopy (XAS) of toxic metal mineral transformations by fungi. Environ Microbiol 9:308–321

Fournier D, Halasz A, Thiboutot S, Ampleman G, Manno D, Hawari J (2004) Biodegradation of octahydro- 1,3,5,7- tetranitro-1,3,5,7-tetrazocine (HMX) by *Phanerochaete chrysosporium*: new insight into the degradation pathway. Environ Sci Technol 38:4130–4133

Flack R (1902) Die cultur der Oidien und ihre Ruckfuhrung in hohere Fruchtformen bei den Basidiomyceten. JU Kerns Verlag Breslau, Prussia

Gadd G (2007) Geomycology: biogeochemical transformation of rocks, minerals, metals and radionuclides by fungi bioweathering and biorerecementation. Mycol Res 111:1–49

García M, Alonso J, Melgar M (2005) Agaricus macrosporus as a potential bioremediation agent for substrates contaminated with heavy metals. J Chem Technol Biotechnol 80(3):325–330

Gaur A, Adholeya A (2004) Prospects of arbuscular mycorrhizal fungi in phytoremediation of heavy metal contaminated soils. Curr Sci 86:528–534

Gavrilescu M (2004) Removal of heavy metals from the environment by biosorption [J]. Eng Life Sci 4:219–232

Gazem MAH, Nazareth S (2013) Sorption of lead and copper from an aqueous phase system by marine-derived Aspergillus species. Ann Microbiol 63(2):503–511

Gerhardt KE, Huang X-D, Glick BR, Greenberg BM (2009) Phytoremediation and rhizoremediation of organic soil contaminants: potential and challenges. Plant Sci 176:20–30

Gola D, Malik A, Namburath M, Ahammad SZ (2018) Removal of industrial dyes and heavy metals by *Beauveria bassiana*: FTIR, SEM, TEM and AFM investigations with Pb(II). Environ Sci Pollut Res 25(21):20486–20496

Gupta P (2004) Pesticide exposure-Indian scene. J Dent Technol 198:118–119

Halaouli S, Asther M, Sigoillot JC, Hamdi M, Lomascolo A (2006) Fungal tyrosinases: new prospects in molecular characteristics, bioengineering and biotechnological applications. J Appl Microbiol 100:219–232

Hammel KE, Green B, Gai WZ (1991) Ring fission of anthracene by a eukaryote [J]. PNAS 88:10605–10608

Hamman S (2004) Bioremediation capabilities of white- rot fungi. Biodegradation 52:1–5

Haselwandter KM, Berreck P, Brunner C (1988) Fungi as bioindicators of radiocaesium contamination: pre- and post-Chernobyl activities. Trans Br Mycol Soc 90:171–174

Hatakka A (1994) Lignin-modifying enzymes from selected white-rot fungi: production and role in lignin degradation. FEMS Microbiol Rev 13:125–135

Hestbjerg H, Willumsen PA, Christensen M, Andersen O, Jacobsen CS (2003) Bioaugmentation of tar-contaminated soils under field conditions using Pleurotus ostreatus refuse from commercial mushroom production. Environ Toxicol Chem 22:692–698

Hofrichter M, Ullrich R (2010) New trends in fungal biooxidation. In: Hofrichter M (ed) The mycota X. Industrial applications. Springer, Berlin/Heidelberg, pp 425–449

Hofrichter M, Ullrich R, Pecyna MJ, Liers C, Lundell T (2010) New and classic families of secreted fungal heme peroxidases. Appl Microbiol Biotechnol 87:871–897

Hueck H (1966) The biodeterioration of materials as part of hylobiology. Mater Org 1(1):5–34

Huang Yi, Zhao Xi, Shengji L (2007) Uptake and biodegradation of DDT by 4 ectomycorrhizal fungi. Science of the Total Environment, 385(1):235–241

Ikehata K, Buchanan ID, Pickard MA, Smith DW (2005) Purification, characterization and evaluation of extra- cellular peroxidase from two *Coprinus* species for aqueous phenol treatment. Bioresour Technol 96:1758–1770

Inácio F, Ferreira R, Araujo C, Peralta R, Souza C (2015) Production of enzymes and biotransformation of orange waste by oyster mushroom, *Pleurotus pulmonarius* (Fr.) Quél. Adv Microbiol 5:1–8

Israilides C, Philippoussis A (2003) Bio-technologies of recycling agro-industrial wastes for the production of commercially important fungal polysaccharides and mushrooms. Biotechnol Genet Eng Rev 20(1):247–260

Isikhuemhen OS, Nerud F, Vilgalys R (2000) Cultivation Studies on Wild and Selected Hybrid Strains of Pleurotus tuberregium. World Journal of Microbiology and Biotechnology, 16:431–435

Jang KY, Cho SM, Seok SJ, Kong WS, Kim GH, Sung JM (2009) Screening of biodegradable function of indigenous ligno-degrading mushroom using dyes. Mycobiology 37:53–61

Jantschi L, Suciu I, Cosma C, Todica M, Bolboaca SD (2008) Analysis of soil heavy metal pollution and pattern in central Transylvania. Int J Mol Sci 9:434

Jayne B, Quigley M (2014) Influence of arbuscular mycorrhiza on growth and reproductive response of plants under water deficit: a meta-analysis. Mycorrhiza 24:109–119

Jensen KA, Houtman CJ, Ryan ZC, Hammel KE (2001) Pathways for extracellular Fenton chemistry in the brown rot basidiomycete *Gloeophyllum trabeum*. Appl Environ Microbiol 67:2705–2711

Jibran AK, Milsee Mol JP (2011) *Pleurotus sajor-caju* protein: a potential biosorptive agent. Adv Biomed Technol 11:25–27

Joshi PK, Swarup A, Maheshwari S, Kumar R, Singh N (2011) Bioremediation of heavy metals in liquid media through fungi isolated from contaminated sources. Indian J Microbiol 51(4):482–487

Kasai N, Ikushiro S, Shinkyo R, Yasuda K, Hirosue S, Arisawa A, Ichinose H, Wariishi H, Sakaki T (2010) Metabolism of mono- and dichloro-dibenzo-p-dioxins by *Phanerochaete chrysosporium* cytochromes P450. Appl Microbiol Biotechnol 86:773–780

Kerem Z, Friesem Db, Hadar Y (1992) Lignocellulose degradation during solid state fermentation: Pleurotus ostreatus versus Phanerochaete chrysosporium. Applied and Environmental Microbiology 58 (4):1121–1127

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Khaund P, Joshi SR (2014) Enzymatic profiling of wild edible mushrooms consumed by the ethnictribes of India. J Korean Soc Appl Biol Chem 550:123–130

Kim JH, Kim YS (2001) Characterization of a metalloenzyme from a wild mushroom, *Tricholoma saponaceum* [J]. Biosci Biotechnol Biochem 65:356–362

Kirk TK, Farrell RL (1987) Enzymatic “combustion”: the microbial degradation of lignin. Annu Rev Microbiol 41:465–505

Koenigs JW (1972) Effect of hydrogen peroxide on cellulose and its susceptibility to cellulase. Mater Org 7:133–147

Koenigs JW (1972) Production of extracellular hydrogen peroxide and peroxidase by wood-rotting fungi. Phytopathology 62:100–110

Koenigs JW (1974) Hydrogen peroxide and iron: a proposed system for decomposition of wood by brown-rot basidiomycetes. Wood and Fiber 6:66–80

Kristanti RA, Hadibarata T, Toyama T, Tanaka Y, Mori K (2011). Bioremediation of crude oil by white rot fungi Polyporus sp. S133. Journal of Microbiology and Biotechnology, 21(9):995–1000

Kshirsagar AD (2013) Application of bioremediation process for wastewater treatment using aquatic fungi. Int J Curr Res 7:1737–1739

Kulshreshtha S, Mathur N, Bhatnagar P (2012) Mycoremediation of paper, pulp and cardboard industrial wastes and pollutants. Fungi Bioremediat 32:77–116

Kulshreshtha S, Mathur N, Bhatnagar P, Kulshreshtha S (2013) Cultivation of *Pleurotus citrinopileatus* on handmade paper and cardboard industrial wastes. Ind Crop Prod 41:340–346

Kulshreshtha S, Mathur N, Bhatnagar P (2014) Mushroom as a product and their role in mycoremediation. AMB Expr 4:29

Kumar V, Dhall P, Kumar R, Prakash Singh Y, Kumar A (2012) Bioremediation of agro-based pulp mill effluent by microbial consortium comprising autochthonous bacteria. Sci World J 2012:127014. https://doi.org/10.1100/2012/127014

Kumhomkul T, Panich-pat T, (2013) Lead Accumulation in the Straw Mushroom, Volvariella volvacea, from Lead Contaminated Rice Straw and Stubble. Bulletin of Environmental Contamination and Toxicology 91(2):231–234

Lamrood PY, Ralegankar SD (2013) Biosorption of Cu, Zn, Fe, Cd, Pb and Ni by non-treated biomass of some edible mushrooms. Asian J Exp Biol Sci 4:190–195

Lamrood P, Ralengenker SD (2014) Biosorption of Cu, Zn, Fe, Cd, Pb and Ni by non-treated biomass of some edible mushrooms. International Journal of Bioassays, 3(9):3318–3323

Lechner BE, Papinutti VL (2006) Production of lignocellulosic enzymes during growth and fruiting of the edible fungus *Lentinus tigrinus* on wheat straw. Process Biochem 41:594–598

Liu YY, Xiong Y (2001) Purification and characterization of a dimethoate-degrading enzyme of Aspergillus niger ZHY256 isolated from sewage. Appl Environ Microbiol 67:3746–3749

Loske D, Huttermann A, Majerczk A, Zadrazil F, Lorsen H, Waldinger P (1990) Use of white rot fungi for the clean-up of contaminated sites. In: Coughlan MP, Collaco (eds.) Advances in biological treatment of lignocellulosic materials. Elsevier, London pp. 311–321

Lucas N, Bienaime C, Belloy C, Queneudec M, Silvestre F, Nava-Saucedo JE (2008) Polymer biodegradation: mechanisms and estimation techniques. Chemosphere 73(4):429–442

Luo D, Yf X, Tan ZL, Li XD (2013) Removal of Cu2+ ions from aqueous solution by the abandoned mushroom compost of *Flammulina velutipes*. J Environ Biol 34:359–365

Majeau JA, Brar SK, Tyagi RD (2010) Laccases for removal of recalcitrant and emerging pollutants. Bioresour Technol 101:2331–2350

Mann H (1990) Removal and recovery of heavy metals by biosorption. In: Volesky B (ed) Biosorption of heavy metals. CRC Press, Raton, pp 93–137

Masaphy S, Levanon D, Vaya J, Henis Y (1993) Isolation and characterization of a novel atrazine metabolite produced by the fungus *Pleurotus pulmonarius*, 2-Chloro-4- Ethylamino-6-(1-Hydroxyisopropyl)Amino-1,3,5-Triazine. Appl Environ Microbiol 59:4342–4346

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mejstrik V, Lepsova A (1992) Applicability of fungi to the monitoring of environmental pollution by heavy metals [C]. In: Market B (ed) Plants as biomonitors. VCH, Weinheim, pp 365–3771

Mester T, Tien M (2000) Oxidation mechanism of ligninolytic enzymes involved in the degradation of environmental pollutants. International Biodeterioration & Biodegradation 46:51–59

Mikolasch A, Schauer F (2009) Fungal laccases as tools for the synthesis of new hybrid molecules and biomaterials. Appl Microbiol Biotechnol 82:605–624

Molla AH, Fakhru'l-Razi A (2012) Mycoremediation-a prospective environmental friendly technique of bioseparation and dewatering of domestic wastewater sludge. Environ Sci Pollut Res 19(5):1612–1619

Montanarella L, Vargas R (2012) Global governance of soil resources as a necessary condition for sustainable development. Curr Opin Environ Sustain 4:559–564

Muraleedharan TR, Iyengar L, Venkobachar C (1991) Biosorption: an attractive alternative for metal removal and recovery. Curr Sci 61:379–385

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 152–178

Mushtaq N, Singh DV, Bhat RA, Dervash MA, Hameed UB (2020) Freshwater contamination: sources and hazards to aquatic biota. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 27–50

Nagy B, Măicăneanu A, Indolean C, Mânzatu C, Silaghi-Dumitrescu MC (2013) Comparative study of Cd(II) biosorption on cultivated *Agaricus bisporus* and wild *Lactarius piperatus* based biocomposites. Linear and nonlinear equilibrium modelling and kinetics. J Taiwan Inst Chem Eng. https://doi.org/10.1016/j.jtice.2013.08.013

Nakamiya K, Hashimoto S, Ito H, Edmonds JS, Yasuhara A, Morita M (2005) Degradation of dioxins by cyclic ether degrading fungus, *Cordyceps sinensis*. FEMS Microbiol Lett 248:17–22

Newman LA, Reynolds CM (2004) Phytodegradation of organic compounds. Curr Opin Biotechnol 15:225–230

Njoku K, Yussuf A, Akinola M, Adesuyi A, Jolaoso A, Adedokun A (2017) Mycoremediation of petroleum hydrocarbon polluted soil by *Pleurotus pulmonarius*. Ethiop J Environ Stud Manag 9(1):865

Noman E, Al-Gheethi A, Mohamed RMSR, Talip BA (2019) Myco-remediation of xenobiotic organic compounds for a sustainable environment: a critical review. Top Curr Chem (Cham) 377(3):17

Novotný C, Svobodová K, Erbanová P, Cajthaml T, Kasinath A, Lang E, Šašeka V (2004) Ligninolytic fungi in bioremediation: extracellular enzyme production and degradation rate. Soil Biol Biochem. 4:1545–1551

Nyanhongo GS, Gübitz G, Sukyai P, Leitner C, Haltrich D, Ludwig R (2007) Oxidoreductases from Trametes spp. in biotechnology: a wealth of catalytic activity. Food Technol Biotechnol 45:250–268

Ortiz N, Armada E, Duque E, Roldan A, Azcon R (2015) Contribution of arbuscular mycorrhizal fungi and/or bacteria to enhancing plant drought toleranceunder natural soil conditions: effectiveness of autochthonous or allochthonous strains. Funct Biotechnol 174:87–96

Oyetayo VO, Adebayo AO, Ibileye A (2012) Assessment of the biosorption potential of heavy metals by *Pleurotus tuber-regium*. Int J Adv Biol 2:293–297

Pantelica A, Cercasov V, Steinnes E, Bode P, Wolterbeek B (2008) Investigation by INAA, XRF, ICPMSnand PIXE of air pollution levels at Galati (Siderurgical Site). In: Ene A (ed) Book of abstracts, 4th National Conference of Applied Physics (NCAP4), September 2008. Galati University Press, Galati

Peng R, Ai-Sheng X, Yong X, Xiao-Yan F, Feng G, Wei Z, Yong-Sheng T, Quan-Hong Y (2008) Microbial biodegradation of polyaromatic hydrocarbons. FEMS Microbiol Rev 32:927–955

Phillips LA, Germida JJ, Farrell RE, Greer CW (2008) Hydrocarbon degradation potential and activity of endophytic bacteria associated with prairie plants. Soil Biol Biochem 40:3054–3064

Phillips LA, Greer CW, Farrell RE, Germida JJ (2009) Field-scale assessment of weathered hydrocarbon degradation by mixed and single plant treatments. Appl Soil Ecol 42:9–17

Pletsch M, de Araujo BS, Charlwood BV (1999) Novel biotechnological approaches in environmental remediation research. Biotechnol Adv 17:679–687

Perelo LW (2010) Review: In situ and bioremediation of organic pollutants in aquatic sediments. Journal of Hazardous Materials 77(1–3):81–89

Pointing SB (2001) Feasibility of bioremediation by white-rot fungi. Applied Microbiology Biotechnology 57:20–33

Purnomo AS, Mori T, Putra SR, Kondo R (2013) Biotransformation of heptachlor and heptachlor epoxide by white-rot fungus Pleurotus ostreatus. International Biodeterioration and Biodegradation 82:40–44. https://doi.org/10.1016/j.ibiod.2013.02.013

Rajkumar M, Sandhya S, Prasad MNV, Freitas H (2012) Perspectives of plant-associated microbes in heavy metal phytoremediation. Biotechnol Adv 30(6):1562–1574

Rajput Y, Shit S, Shukla A, Shukla K (2011) Biodegradation of malachite green by wild mushroom of Chhatisgrah. J Exp Sci 2:69–72

Rani P, Kalyani N, Prathiba K (2008) Evaluation of lignocellulosic wastes for production of edible mushrooms. Appl Biochem Biotechnol 151:151–159

Reddy A, Mathew Z (2001) Bioremediation potential of white rot fungi. In: Gadd GM (ed) Fungi in bioremediation. Cambridge University Press, Cambridge, UK, pp 52–78

Rhodes CJ (2014) Mycoremediation (bioremediation with fungi)–growing mushrooms to clean the earth. Chem Spec Bioavailab 26(3):196–198

Robertson SJ, McGill WB, Massicotte HB, Rutherford M (2007) Petroleum hydrocarbon contamination in boreal forest soils: a mycorrhizal ecosystems perspective. Biol Rev 82:213–240

Rodriguez JPG, Williams DE, Sabater ID, Bonugli-Santos RC, Sette LD, Andersen RJ, Berlinck RGS (2015) The marine-derived fungus *Tinctoporellus* sp. CBMAI 1061 degrades the dye Remazol Brilliant Blue R producing anthraquinones and unique tremulane sesquiterpenes. RSC Adv 5(81):66360–66366

Ruiz-Dueñas FJ, Morales M, García E, Miki Y, Martínez MJ, Martínez AT (2009) Substrate oxidation sites in versatile peroxidase and other basidiomycete peroxidases. J Exp Bot 60:441–452

Scheibner K, Hofrichter M, Herre A, Michels J, Fritsche W (1997) Screening for fungi intensively mineralizing 2,4,6-trinitrotoluene. Appl Microbiol Biotechnol 47:452–457

Scott SL (2003) Biodegradability and toxicity of total petroleum hydrocarbon leachate from land treatment units. M.S. California Polytechnic State University

Shah MM, Barr DP, Chung N, Aust SD (1992) Use of white rot fungi in the degradation of environmental chemicals. Toxicol Lett 64:493–501

Siddiquee S, Rovina K, Al Azad S, Naher L, Suryani S, Chaikaew P (2015) Heavy metal contaminants removal from wastewater using the potential filamentous fungi biomass: a review. J Microb Biochem Technol 7:384–393

Singh H (2006) Mycoremediation: fungal bioremediation. Wiley, London

Singh M, Srivastavar PK, Vermar PC, Kharwar RN, Singhi N, Tripathi RD (2015) Soil fungi Mycoremediation of arsenic pollution in agriculture soils. J Appl Microbiol 119:1278–1290

Singh DV, Bhat JIA, Bhat RA, Dervash MA, Ganei SA (2018) Vehicular stress a cause for heavy metal accumulation and change in physico-chemical characteristics of road side soils in Pahalgam. Environ Monit Assess 190:353. https://doi.org/10.1007/s10661-018-6731-2

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Steffen KT, Schubert S, Tuomela M, Hatakka A, Hofrichter M (2007) Enhancement of bioconversion of high-molecular mass polycyclic aromatic hydrocarbons in contaminated non-sterile soil by litter-decomposing fungi. Biodegradation 18(3):359–369

Strong PJ, Burgess JE (2007) Bioremediation of a wine distillery wastewater using white rot fungi and the subsequent production of laccase. Water Sci Technol 56(2):179–186

Sturz AV, Carter MR, Johnston HW (1997) A review of plant disease, pathogen interactions and microbial antagonism under conservation tillage in temperate humid agriculture. Soil Tillage Res 41:169–189

Subramanian V, Yadav JS (2009) Role of P450 monooxygenases in the degradation of the endocrine-disrupting chemical nonylphenol by the white rot fungus Phanerochaete chrysosporium Applied and Environmental Microbi-ology 75:5570–5580

Sutherland C, Venkobachar C (2013) Equilibrium modeling of Cu (II) biosorption onto untreated and treated forest macro-*fungus Fomes fasciatus*. Int J Plant Anim Environ Sci 3:193–203

Sullia SB (2004) Environmental Applications of Biotechnology. Asian J. Microbiol. Biotechnol. Environ. Sci. 4:65–68

Taştan BE, Çakir DN, Dönmez G (2016) A new and effective approach to boron removal by using novel boron-specific fungi isolated from boron mining wastewater. Water Sci Technol 73(3):543–549

Tessier J (1982) The path to deltamenthrin. In: Deltamenthrin Monograph. Roussel uncarf, Paris 25–36

Thakur Y, Kumar M, Singh S (2015) Microbial biosorption as a green technology for bioremediation of heavy metals. Res J Pharm Biol Chem Sci 6(3):1717–1724

Thomet U, Vogel E, Krahenbuhl U (1999) The uptake of cadmium and zinc by mycelia and their accumulation in mycelia and fruiting bodies of edible mushroom. Eur Food Res Technol 209:317–324

Thomas SA, Aston LM, Woodruff DL, Cullinan VI (2009). Field demonstration of mycoremediation for removal of fecal coliform bacteria and nutrients in the Dungeness Watershed, Washington. Pacific Northwest National Laboratory, Richland, Washington 99352

Tsujiyama S, Muraoka T, Takada N (2013) Biodegradation of 2,4-dichlorophenol by shiitake mushroom (Lentinula edodes) using vanillin as an activator. Biotechnol Lett. 4:1079–1083. https://doi.org/10.1007/s10529-013-1179-5

Udochukwu U, Nekpen BO, Udinyiwe OC, Omeje FI (2014) Bioaccumulation of heavy metals and pollutants by edible mushroom collected from Iselu market Benin-city. Int J Curr Microbiol App Sci 3(10):52–57

Ullrich R, Hofrichter M (2007) Enzymatic hydroxylation of aromatic compounds. Cell Mol Life Sci 64:271–293

Van der Heijden MGA, Bardgett RD, van Straalen NM (2008) The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecol Lett 11:296–310

Varjani SJ (2017) Microbial degradation of petroleum hydrocarbons. Bioresour Technol 223:277–286

Varjani SJ, Rana DP, Jain AK, Bateja S, Upasani VN (2015) Synergistic *exsitu* biodegradation of crude oil by halotolerant bacterial consortium of indigenous strains isolated from on shore sites of Gujarat, India. Int Biodeterior Biodegrad 103:116–124

Vaseem H, Singh VK, Singh MP (2017) Heavy metal pollution due to coal washery effluent and its decontamination using a macrofungus, Pleurotus ostreatus. Ecotoxicology and Environmental Safety 145:42–49

Veignie EC, Rafin P, Woisel F, Cazier (2004) Preliminary evidence of the role of hydrogen peroxide in the degradation of benzo[a]pyrene by a non-white rot fungus Fusarium solani. Environmental Pollution 129:1–4

Verbruggen E, Toby Kiers E (2010) Evolutionary ecology of mycorrhizal functional diversity in agricultural systems. Evol Appl 3(5–6):547–560

Verbruggen E, van der Heijden MG, Rillig MC, Kiers ET (2013) Mycorrhizal fungal establishment in agricultural soils: factors determining inoculation success. New Phytol 197(4):1104–1109

Vert M, Doi Y, Hellwich KH, Hess M, Hodge P, Kubisa P, Rinaudo M, Schué F (2012) Terminology for biorelated polymers and applications (IUPAC recommendations 2012). Pure Appl Chem 84(2):377–410

Wagg C, Bender SF, Widmer F, van der Heijden MGA (2014) Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proc Natl Acad Sci U S A 111:5266–5270

Williams A, Manoharan L, Rosenstock NP, Olsson PA, Hedlund K (2017) Long-term agricultural fertilization alters arbuscular mycorrhizal fungal community composition and barley (Hordeum vulgare) mycorrhizal carbon and phosphorus exchange. New Phytol 213(2):874–885

Willis KJ (ed) (2018) State of the world's fungi 2018. Report. Royal Botanic Gardens, Kew

Wong SC, Li XD, Zhang GQ, Min YS (2002) Heavy metals in agricultural soils of the Pearl River Delta, South China. Environ Pollut 119:33–44

Wunch KG, Alworth WL, Bennett JW (1999) Mineralization of benzo[a]pyrene by *Marasmiellus troyanus*, a mushroom isolated from a toxic waste site. Microbiol Res 154:75–79

Yadav JS, Doddapaneni H, Subramanian V (2006) P450ome of the white rot fungus *Phanerochaete chrysosporium*: structure, evolution and regulation of expression of genomic P450 clusters. Biochem Soc Trans 34:1165–1169

Yang YB, Sun LB (2009) Status and control countermeasures of heavy metal pollution in urban soil. Environ Prot Sci 35:79–81

Zhao KL, Liu XM, Zhang WW, Xu JM, Wang F (2011) Spatial dependence and bioavailability of metal fractions in paddy fields on metal concentrations in rice grain at a regional scale. J Soil Sediments 11:1165–1177

Zhu YG, Meharg AA (2015) Protecting global soil resource for ecosystem services. Ecosyst Health Sustain 1(3):11

Zhu MJ, Du F, Zhang GQ, Wang HX, Ng TB (2013) Purification a laccase exhibiting dye decolorizing ability from an edible mushroom Russula virescens. Int Biodeterior Biodegrad. 4:33–39. https://doi.org/10.1016/j.ibiod.2013.02.010

Zilly A, dos Santos Bazanella G C, Helm CV, Araújo CAV, de Souza CGM, Bracht A, Peralta RM (2012) Solid-state bioconversion of passion fruit waste by white-rot fungi for production of oxidative and hydrolytic enzymes. Food and Bioprocess Technology, 5(5):1573–1580

Chapter 5
Microbial Degradation of Organic Constituents for Sustainable Development

**Zeenat Mushtaq, Humira Mushtaq, Shahla Faizan,
and Manzoor Ahmad Parray**

5.1 Introduction

A dramatic increase in the range of chemically synthesized products such as pesticides, plastics, hydrocarbons, dyes, soaps, detergents, and other useful substances have been found in the last few decades. These pollutants impart an immense effect on the environment and are considered as potential pollutants because most of these compounds are resistant to biodegradation. To clean up these pollutants from the environment is a global problem and that too real. These pollutants directly or indirectly affect all forms of life on the planet (Sajna and Pandey 2015; Souza et al. 2014).

The various compounds, including halogenated organic pollutants such as dichlorodiphenyltrichloroethane (DDT), polychlorinated biphenyls (PCBs), poly brominated diphenyl ethers (PBDEs), decarbromodiphenyl ethane (DBDPE), and dechlorane plus (DP) have been of great concern due to their perseverance, bioaccumulation, and potential toxicity to animals and humans. PCBs were primarily used as dielectric and coolant fluids (Xing et al. 2005). The rest are used as flame retardants in textiles, thermoplastics, electronics, polyurethane, foams, and building materials (Covaci et al. 2011; Alaee et al. 2003; Bhat et al. 2018a; Qadri and Bhat 2020). Petroleum hydrocarbons are the important source of energy and a raw material for numbers of industries. Hydrocarbon contaminants are recalcitrant substances and are therefore considered as priority pollutants. Industrial effluents, municipal runoffs, offshore and onshore petroleum activities, as well as accidental spills, cause (petroleum) hydrocarbon pollution.

Z. Mushtaq (✉) · S. Faizan
Environmental Physiology Laboratory, Department of Botany,
Aligarh Muslim University, Aligarh, India

H. Mushtaq · M. A. Parray
Research and Training Center on Pollinators and Pollination Management Section,
Division of Entomology, SKAUST Kashmir, Srinagar, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_5

In addition to the above, a wide spectrum of hazardous pollutants with different structures originates from human activities and cause global threat to environment continuously. The three main sources of organic pollutants are classified as: industrial wastes, agricultural wastes, and military wastes; as already mentioned, the important organic contaminants include petroleum products, polycyclic aromatic hydrocarbons, dioxins, organophosphates, carbonates, plastics, and related compounds (Connell et al. 2006). Modern agronomy depends on the four main aspects, namely, water, fertilizers, seeds, and pesticides. Pesticides are considered as essential part of modern agronomy. About 35–45% is lost due to weeds, insects, pests and diseases, while during storage, 35% of crop produced is lost. Heavy metals are other potential anthropogenic pollutants.

Urban and industrial wastes are frequently disposed directly into pits dug into the ground, which leads to pollution of the earth and, sometimes, into the nearby ground waters. Organic contaminants can be grouped into following classes, namely, (a) oxygen, nitrogen, and phosphorous compounds, (b) hydrocarbons, and (c) metallic substances. These substances may encompass elements such as carbon, oxygen, and sometimes chlorine as well. Hydrocarbons are lipophilic, least soluble in water, and persistent in the environment. The source of hydrocarbon is already discussed as from industries and motor vehicles, etc. The other group which contains oxygen, nitrogen, and phosphorous compounds is very diverse, but constitutes the components having comparatively higher solubility in water but low fat solubility and rather low perseverance in the environment (Connell et al. 2006). The third group is the organometallic group which is said to be of least importance in view of environmental properties. It may consist of substances that result from the amalgamation of metals such as lead and tin with carbon-based compounds (Connell et al. 2006; Dar et al. 2016; Bhat et al. 2017; Dar and Bhat 2020; Dervash et al. 2020).

5.2 Some Persistent Organic Pollutants (POPs)

A diverse group of chemicals have created a particular havoc to the environment, due to their fat solubility, bio magnification, bioaccumulation, and persistence in the ecosystem. These substances are termed as organic pollutants and are now widely distributed up to the global scale. They have been observed to remain for a longer period of time in the environment and can accumulate, and thereby show biomagnification from one tropic level to another in a food chain (Eskenazi et al. 2009). Persistent organic contaminants include two types of important compounds:

(a) Polycyclic aromatic hydrocarbons (PAHs): These are the class of hydrophobic organic contaminants (HOCs) broadly established in air, soil, and sediments. They are mainly released from industries, are highly toxic, persistent, and can accumulate in fish as well as human beings via consuming aquatic foods (Connell et al. 2006; Dar et al. 2013; Bhat et al. 2017a, b).
(b) Polychlorinated biphenyls (PCBs) or halogenated hydrocarbons. Halogenated ones contain the organochlorines such as DDT and PCBs. The dioxins produced

at large scale are released to the environment. They do not easily undergo microbial degradation. The biphenyls being highly chlorinated tend to accumulate up to higher extent than less chlorinated PCBs. PCBs disrupt the endocrine system and can cause cancer. Thus, PCBs being the highly toxic and mutagenic components, are therefore of increasing concern (Seeger et al. 2010; Bhat et al. 2018a, b).

Pesticides are chemical substances utilized for prevention, destruction, and mitigation of pest in agricultural fields. Long-term application of pesticides can lead to contamination of pesticide residues in the soil and causes a serious problem, as most of the used pesticides cannot undergo degradation easily.

Dyes are chemical compounds used in textile industries, printing, paper, color photography, cosmetics, pharmaceuticals, and various other industries and factories (Raffi et al. 1997). There are large numbers of dyes present with different uses. The most commonly used are basic dyes, acidic dyes, mordant dyes, azoic dyes, vat dyes, reactive dyes, etc. Among all the dyes, azoic dyes are a large class of the synthetic dye and highly important for commercial purposes (Verma and Madamwar 2003; Mushtaq et al. 2018). They have the complex structure due to which they are poorly degradable and contaminate the soil as well as water bodies (Mehmood et al. 2019).

Heavy metals are another class of contaminants which can persist in the soil for extended period and create threat to both flora as well as fauna because of their bioaccumulation and non-biodegradability in nature (Gautam et al. 2014; Wai et al. 2012; Singh et al. 2018). Heavy metals such as lead, aluminium, cadmium, gold, mercury, and silver have no biological role and are very toxic to living beings. These metals cannot be degraded, but can be converted from complex form to simple and stable form with the help of essential soil microbes.

There is an immediate need to remediate these pollutants from the surroundings. However, several physiochemical strategies have been used to detoxify these persistent pollutants, but these methods are costly and also give rise to secondary pollutants (Zhang et al. 2004). Microbes or their by-products are used in degradation and detoxification of contaminants from soil, and can successfully increase plant growth and development (Mushtaq et al. 2020). They can significantly remove, immobilize, and transform into less toxic forms the pollutants from the environment and also reduce their harmful impacts on plants as well animals. This is a cheap, natural, sustainable and eco-friendly approach to clean up the environment (USEPA 2012). This book chapter aims to provide a general overview about the role of microbes in the degradation of organic substances for sustainable development.

5.3 Role of Microbes in the Degradation of Organic Substances

In the past few decades, wide research has resulted in isolation of different microorganisms having the capability of degrading a huge number of organic compounds. They are used for eradicating the various types of pollutants from surroundings and diminishing their hazardous effects on the environment (EPA 2016). Microbes possess the enzyme system with the help of which they can eradicate, degrade, or immobilize the pollutants from the soil either naturally or artificially (Uqab et al. 2016).

5.4 Microbial Degradation of Persistent Organic Pollutants

PAHs are highly carcinogenic organic pollutants with complex structures. They are difficult to degrade and impose a threat on the environment. However, microbes show the property of degrading these organic contaminants and convert them into less toxic forms. Microorganisms, such as bacteria, fungi, and other microbes are involved in the biodegradation of PAHs and are cost-effective and natural processes (Anwar et al. 2016; Khanday et al. 2016). Bacteria which can degrade the hydrocarbons are called as hydrocarbon degrading bacteria. Bacteria degrade these substances both, aerobically (*Pseudomanas* sp., *Brevibacillus* sp.) as well as anaerobically. However, anaerobic biodegradation is of much importance (Wiedemeier et al. 1995). *Streptococcus, Klebsiella, Bacillus, Shigella, Staphylococcus, Alcaligenes, Escherichia, Corynebacterium, Acinetobacter,* and *Enterobacter* are a few well-known bacteria involved in biodegradation of hydrocarbons (Kafilzadeh et al. 2011). Teng et al. (2010) observed that microbes, such as *Sphingomonas, Beijerinckia*, *and Rhodococcus*, can degrade anthracene with the help of dihydriol, a first oxygenated intermediate component. Jin et al. (2016) reported that the Pseudomonas strain can degrade aromatic hydrocarbon, such as pyrene, efficiently. Microbes possess varied genes related to the degradation of PAHs and usually follow different mechanisms for the degradation of these compounds. In some mechanisms, nutrients such as carbon, nitrogen, and phosphorous are added to soil contaminated with hydrocarbons. These nutrients stimulate the microbes that are involved in biodegradation processes. Application of nutrients to hydrocarbon contaminant soils boost the growth of microbes and enhance the degradation process as these sites are usually polluted and did not contain enough nutrient for microbial growth.

A single bacterium is less potent to degrade the large number of organic substances present in polluted soil as it alone does not have all the enzymatic properties of degradation. It was proved that the microbial consortium which contains the number of microbes that live together symbiotically and has the most potent biodegradation capability because, in consortium, different microbes have different functions that enhance the biodegradation process of a mixture of organic compounds (Fritsche and Hofrichter 2005). Few bacteria have the property of co-metabolism, which means that microbes at polluted sites convert or degrade the organic compounds into the simple compounds which are easily degradable without growing and deriving energy in polluted sites. After that, the coexisting bacteria which actually grow these sites utilize these degraded substances as an energy as well as growth substrate. Beam and Perry (1974) reported that *Mycobacterium vaccae* proliferate on propane while cometabolizing cyclohexane and converts it into cyclohexanol via oxidation and the cyclohexanol then generated can be used by different microbes.

Table 5.1 Some examples of microbial strains involved in degradation of polyaromatic hydrocarbons

Microbes	Target substrate	References
Pseudomonas sp. PB2	Degrades pyrene, chrysene, and naphthalene	Nwinyi et al. (2016)
Thalassospira sp. TSL5-1	Pyrene degradation	Zhou et al. (2016)
Pseudomonas oleovorans	Tetrahydrofuran	Zhou et al. (2011)
Acinetobacter sp. WSD	Phenanthrene and fluorine degradation	Shao et al. (2015)
Rhodococcus sp. PI8	Degradation of various high molecular weight poly hydrocarbons	Isaac et al. (2015)
Arhodomonasrozel	Toluene benzene	Dalvi et al. (2012)
Acinetobacter venetianus	n-alkanes	Di Cello et al. (1997)
Burkholderia cepacia F297	Naphthalene degradation	Grifoll et al. (1995)
Stappia aggregate	Phenanthrene and pyrene	Cui et al. (2008)
Oceanobacter kriegii	Petroleum	Teramoto et al. (2009)
Bordetella avium	Naphthalene	Abo-State et al. (2018)

Different microbes degrade the different persistent organic compounds in environments. *Pseudomonas putida* is potent to degrade benzene and toluene, while *Pseudomonas oleovorans* are capable of degrading tetrahydrofuran, xylene, and ethylbenzene (Zhou et al. 2011). An aromatic hydrocarbon, alkylbenzoate, was found to be degraded potentially by *Pseudomonas putida* (Kaldalu et al. 2000). It has been reported that *Virgibacillus salarius* bacteria utilize benzene, toluene, and ethylbenzene as a carbon source, catechol 2, 3-dioxygenase, and chlorocatechol 1,2-dioxygenase enzymes present in this bacterium help in the degradation of HCs (Solanki and Kothari 2012). Examples of microbial stains verified for the degradation of hydrocarbons are listed in Table 5.1.

5.5 Microbial Degradation of Pesticides

Pesticides are broadly consumed to stop the growth of pests in agricultural products. In India, about 11–15% of grains produced annually are lost due to pests. To control such losses of crop productivity, pesticides are widely applied which plays an important role in crop protection. However, the long-term use of pesticides causes a severe threat to soil, water bodies, atmosphere, food stuffs, and threatens human health as well (Fenner et al. 2013; Bhatti et al. 2017; Dar et al. 2020). However, researchers have conducted studies of bacteria that could either degrade the persistent pesticides completely or convert them into degradable form (Akbar and Sultan

2016; Jabeen et al. 2015). From the last few decades, various researches cultured as well as screened numerous microbes from different locations to degrade the microbes. Recent reports regarding pesticide degrading bacteria include Klebsiella, acinetobacter, flavobacterium, alcaligenes, and bacilus are able to degrade endosulfans potentially (Kafilzadeh et al. 2015). Jayabarath et al. (2010) reported that, *Streptoverticillium album, Nocardia vaccine, Nocardia farcinia, Streptomyces alanosinicus, Micromonospora chalcea, Nocardia amarae*, and *Streptomyces atratus candegrade* can also degrade pesticides very well.

Microbes can degrade the pesticides more easily as most of the microbes used the pesticides as their nutrients and converted them into CO_2 and H_2O via enzymatic reactions. Microbes have different enzymatic activities and, when absorbed, these pesticides go through various biochemical and physiological activities and change or degrade these substances into simple molecules with least toxicity (Tang 2018: Chen et al. 2011). Certain microbes have the ability to degrade the pesticides through a series of specific enzymes. For example, Atrazine is said to be the only carbon source of ADP strain of Pseudomonas, and this bacterium degrades the atrazine with the activity of three enzymes, namely, AtzA converts atrazine into hydroxyl atrazine, a non-toxic compound via hydrolysis dechlorination reaction and AtzA is a vital enzyme for atrazine's biological degradation. After that, another enzyme, AtaB, carries the dehydrochlorination reaction of hydroxyl atrazine and generates N-isopropyl cyanuric amide, and then AtzC converts the N-isopropyl cyanuric amide into cyanuric amide and isopropylamine. These two constituents of atrazine i,e cyanuric amide and isopropylamine are then finally converted into NH_3 and CO_2 (Czarnecki et al. 2017; Wackett et al. 2002). Kanade et al. (2012) observed that Bacillus, *Stenotropomonas*, and Staphyloccus, obtained from cultivated as well as non-cultivated soils, are able to decompose DDT efficiently.

5.6 Bacterial Degradations of Azo Dyes

Bacterial strains have been recognized that can capably degrade azo dyes. Bacteria usually degrade azo dyes via biosorption and enzymatic degradation pathways (Wu et al. 2012). Some bacteria degrade azo dyes aerobically and anaerobically (Dos Santos et al. 2007), but microbial degradation or decolorization of azo dyes are more effective under anaerobic environment (Lodato et al. 2007). Microbes degrade azo dyes by producing enzymes, for example, peroxidase, laccase, hydrogenase, and reductase. Wide arrays of microbes are capable of degrading the azo dyes, including bacteria, fungi, yeast, and actinomycetes (Olukanni et al. 2006; Wesenberg et al. 2003). Some examples of bacterial strains which degrade azo dyes either aerobically or anaerobically extensively are *Escherichia coli, Pseudomonas* sp., *Corneybaterium* sp., *Bacilus subtilis, Clostridium* sp., *Enterococcus* sp., *Rhabdobacter* sp., *Acinetobacter* sp., *Lactobacillus, Xenophilus* sp., *Staphylococcus* sp., *Micrococcus dermacoccus* sp., *Geobacillus, Rhizobium, Proteus* sp., *Morganella* sp., *Alcaligenes* sp*., Klebsiellla* sp., and *Aeromonas* sp. (Lin and Leu 2008; Vijaykumar

Table 5.2 Microbial degradation of azo dyes

Microorganism	Target substance	References
Enterobacter agglomerans	Methyl Red decomposition	Keharia and Madamwar (2003)
Bacillus subtilis	Acid Blue 113	Gurulakshmi et al. (2008)
Bacillus fusiformis kmk 5	Acid Orange and Disperse Blue	Kolekar et al. (2008)
Sphingomonas sp. BN6	Acid azo dyes and Direct azo dyes	Russ et al. (2000)
Rhizobium radiobacter	Reactive Red 141	Telke et al. (2008)
Brevibacillus laterosporus	Direct Brown MR, Golden Yellow, and Remazol Red	Gomare et al. (2009)
Proteus mirabilis	Reactive Blue 13	Olukanni et al. (2010)
Sphingobacterium sp.	Orange 3R, Direct Blue GLL	Tamboli et al. (2011)
Bacillus sp. ADR	Methyl Red, Reactive Orange	Telke et al. (2011)
Gloeocapsa pleurocapsoides and *Chroococcus minutus*	Direct Blue-15	Parikh and Madamwar (2005)
Pseudomonas aeruginosa and *Bacillus circulans*	Reactive Black 5	Dafale et al. (2008)
Providencia sp. SDS	Remazol Black, Congo Red, and Methyl Orange Remazol Black	Phugare et al. (2011)

et al. 2007). Coughlin et al. (2002) reported that azo dyes are the only source of carbon and nitrogen to few aerobic bacteria. Various microbes usually degrade azo dyes by secreting different enzymes, such as peroxidases, phenolic oxidases, laccases, and lignin peroxidases.

Besides bacterial degradation, fungi also play an important role in the degradation of dyes (Bumpus 2004). Abundant research exists about the capability of fungi to oxidize the phenolic, soluble, as well non-soluble dyes (Libra et al. 2003; Kapdan and Kargi 2002). Some examples of fungi involved in the degradation of dyes are ligninolytic fungi*, Aspergillus flavus, Penicillium geastrivous, Aspergillus niger, Rhizopus oryzar, Coriolus versicolar, Trametes versicolar, Phanerochaete chrysosporium, Fungalia trogii, Pleurotus ostreatus, Pycnoporus sanguineus*, and *Rigidoporus lignosus* (Bumpus 2004; Wesenberg et al. 2003; Fu and Viraraghavan 2001). It was observed that the White-rot fungi degrade aromatic dyes by secreting different enzymes (Harazono and Nakamura 2005; Madhavi et al. 2007). Degradation of the dyes by different types of microorganisms is listed in Table 5.2.

5.7 Bioremediation of Heavy Metals

Microbes cannot degrade heavy metals completely but can convert them from one oxidation state to another, but are very efficient in bioremediation of heavy metals (Garbisu and Alkorta 2001). Bioremediation is an eco-friendly technique which

Table 5.3 Bacteria used in bioremediation of heavy metals

Microbial strain	Heavy metals	References
B. subtilis BR151 (pTOO24)	Arsenic	Liu et al. (2011)
Pseudomonas sp. (K-62)	Mercury	Kiyono et al. (2009)
Achromobacter sp. (AO22)	Arsenic	Ng et al. (2009)
E. coli	Arsenic	Singh et al. (2008)
Methylococcus capsulatus	Chromium(IV)	Hasin et al. (2010)
Pseudomonas putida (06909)	Cadmium	Wu et al. (2006)
P. fluorescens (4F39)	Nickel	Lopez et al. (2002)
Staphylococcus sp.	Chromium	Sharma and Adholeya (2012)
Cellulosimicrobium sp. (KX710177)	Lead	Bharagava and Mishra (2018)
Bacillus firmus	Lead	Salehizadeh and Shojaosadati (2003)
Enterobacter cloacae	Copper	Jafari et al. (2015)
Vibrio parahaemolyticus (PG02)	Mercury	Jafari et al. (2015)
Bacillus licheniformis	Mercury	Saranya et al. (2017)
Bacillus firmus	Zinc	Salehizadeh and Shojaosadati (2003)
Gemella sp.	Copper	Marzan et al. (2017)

employs microbes, plants, or enzymes for the transformation of heavy metals, as well as other organic contaminants into CO_2, H_2O and other by-products which are less harmful than their parent substances (Chakraborty et al. 2012). Microbes usually detoxify heavy metals by various mechanisms, such as biosorption, extrusion, biotransformation, bioaccumulation, bioleaching, biomineralization, and phytoremediation (Ojuederie and Babalola 2017). Microbes involved in the removal of heavy metals from the soil generally use these heavy metals as an energy source for their growth and development. In a bioaccumulation process, microbes hold and concentrate heavy metals in their body and the microbes having this property are said to be strong agents of decontamination. Akhter et al. (2017) identified and isolated three stains of *Bacillus*, namely, NC7401, AVPI2, and PDPC01 from the root area of *Tagetes minuta* and put forth that these microbial strains have strong potential to solubilize and accumulate nickel, cadmium, and chromium and can biosorb these metals efficiently. Some microbial strains involved in bioremediation of heavy metals are listed in Table 5.3 below.

5.7.1 Biosorption

Biosorption by microbes is simply the sequestration of positively charged heavy metal ions by the ions present on the microbial cell surface (Malik 2004). Microorganisms can accrue HMs either by adsorption or absorption, in which adsorption is a surface phenomenon and absorption takes place all over the microbe's body. Microbes can adsorb a large amount of heavy metals very quickly. He and Tebo (1998) reported that at pH 7.2, *Bacillus* can adsorb up to 60% of Cu ions within 1 minute. While absorption is a slower process and less efficient. Microbial adsorption involves complexation of heavy metals on their cell surfaces from which these metals get absorbed into the cell (Danis et al. 2008). Bacterial cell surface contains ions having nitrogen, phosphorous, sulfur, and oxygen as functional groups which can bind easily with the heavy metal ions and form coordination atoms and permits the metal ions to pass through the cell membranes (Sarret et al. 1998).

5.7.2 Bioleaching

In this process, microbes secrete organic acids that can dissolve the heavy metals present in soil. This process is energy- and nutrient-dependent. Microbes can efficiently leach the metals in presence of nutrients and energy sources. Marchenko et al. (2015) observed that *Citrobacter*, in presence of glucose and nutrients, could generate free inorganic phosphate that can form insoluble metal phosphate coating which can trap abundent quantity of toxic metals. Some microbes took part in redox reactions and can alter the valence of certain heavy metals, thus altering their property, and make them immobile as well as reduce their toxicity. It was reported *Coryne bacterium* can reduce the Cr^{6+} into Cr^{3+}, and *B. licheniformis* R08 can reduce Pb^{2+} Pb^0 (Goyal et al. 2003).

5.7.3 Bioaccumulation

It is a metabolically active process of microbes. In this process, microbes use their importer complexes that act as translocators and uptake heavy metals through lipid bilayer into their intracellular space. When these heavy metals reach inside the cell, they are sequestered by proteins as well protein ligands (Mishra and Malik 2013).

5.8 Conclusion

Increased industrialization has caused harmful effects on soil health due to the generation of polluted as well as non-degradable substances. Microbial degradation is an eco-friendly approach for removing the toxic substances from the environment. Microbes have the capability of detoxifying the contaminants from the soil as well as from water bodies and convert them into easily degradable forms. This chapter briefly overviewed the role of microbes to sustain and decontaminate the environment and demonstrates that microbes are potent agents for the degradation of hydrocarbons, pesticides, dyes, heavy metals, and other industrial effluents. Moreover, imminent information about microbes and their function in degradation processes should be researched.

References

Abo-State MAM, Riad BY, Bakr AA, Abdel Aziz MF (2018) Biodegradation of naphthalene by Bordetella avium isolated from petroleum refinery wastewater in Egypt and its pathway. J Radiat Res Appl Sci 11:1–9

Akbar S, Sultan S (2016) Soil bacteria showing a potential of chlorpyrifos degradation and plant growth enhancement. Braz J Microbiol 47:563–570

Akhter K, Ghous T, Andleeb S, Nasim FH, Ejaz S, Zain-ul-Abdin et al (2017) Bioaccumulation of heavy metals by metalresistant bacteria isolated from tagetes minuta rhizosphere, growing in soil adjoining automobile workshops. Pak J Zool 49:1841–1846

Alaee M, Arias P, Sjodin A, Bergman A (2003) An overview of commercially used brominated flame retardants, their applications, their use patterns in different countries/regions and possible modes of release. Environ Int 29:683–689

Anwar Y, Hanafy AAE, Sabir JS, Al-Garni SM, Ahmed MMM (2016) Microbes using PAHs as energy source: relationship with diseases. Res J Biotechnol 11:94–109

Beam HW, Perry JJ (1974) Microbial degradation of cycloparaffinic hydrocarbons via co-metabolism and commensalism. J Gen Microbiol 82:163–169

Bharagava RN, Mishra S (2018) Hexavalent chromium reduction potential of *Cellulosi microbiome* sp. isolated from common effluent treatment plant of tannery industries. Ecotoxicol Environ Saf 147:102–109

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytother 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Bumpus JA (2004) Biodegradation of azo dyes by fungi. In: Arora D (ed) Fungal biotechnology in agriculture, food and environmental applications. Marcel Dekker Inc, New York, pp 457–469

Chakraborty R, Wu CH, Hazen TC (2012) Systems biology approach to bioremediation. Curr Opin Biotechnol 23:1–8

Chen S, Hu Q, Hu M, Luo J, Weng Q, Lai K (2011) Isolation and characterization of a fungus able to degrade pyrethroids and 3-phenoxybenzaldehyde. Bioresour Technol 102:8110–8116

Connell DW, Rudolf SSW, Richardson BJ, Lam PKS (2006) Chemistry of organic pollutants, including agrochemicals cells. Yonsei Med J 47:688–689

Coughlin MF, Kinkle BK, Bishop PL (2002) Degradation of acid orange 7 in an aerobic biofilm. Chemosphere 46:11–19

Covaci A, Harrad S, Abdallah MAE, Ali N, Law RJ, Herzke D, De Wit CA (2011) Novel brominated flame retardants: a review of their analysis, environmental fate and behaviour. Environ Int 37:532–556

Cui Z, Lai Q, Dong C, Shao Z (2008) Biodiversity of polycyclic aromatic hydrocarbon- degrading bacteria from deep-sea sediments of the middle Atlantic ridge. Environ Microbiol 10(8):2138–2149

Czarnecki J, Dziewit L, Puzyna M, Prochwicz E, Tudek A, Wibberg D, Schlüter A, Pühler A, Bartosik D (2017) Lifestyle-determining extrachromosomal replicon pAMV1 and its contribution to the carbon metabolism of the methylotrophic bacterium Paracoccus aminovorans JCM 7685. Environ Microbiol 19:4536–4550

Dafale N, Rao N, Meshram S, Wate S (2008) Decolorization of azo dyes and simulated dye bath waste water using acclimatized microbial consortium biostimulation and halo tolerance. Bioresour Technol 99:2552–2558

Dalvi S, Azetsu S, Patrauchan MA, Aktas DF, Fathepure BZ (2012) Proteogenomic elucidation of the initial steps in the benzene degradation pathway of a novel halophile, *Arhodomonas* sp. strain Rozel, isolated from a hypersaline environment. Appl Environ Microbiol 78(20):7309–7316

Danis U, Nuhoglu A, Demirbas A (2008) Ferrous ion-oxidizing in *Thiobacillus ferrooxidans* batch cultures: influence of pH, temperature and initial concentration of Fe^{2+}. Fresenius Environ Bull 17:371–377

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balk 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (Labeo rohita) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish Fuana. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 51–68

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Di Cello F, Pepi M, Baldi F, Fani R (1997) Molecular characterization of an n-alkane- degrading bacterial community and identification of a new species, Acinetobacter venetianus. Res Microbiol 148(3):237–249

Dos Santos AB, Cervantes JF, Van Lier BJ (2007) Review paper on current technologies for decolourisation of textile wastewaters: perspectives for anaerobic biotechnology. Bioresour Technol 98:2369–2385

EPA (2016) Greenhouse gas emissions. US Environmental Protection Agency. Available online at: https://www.epa.gov/ghgemissions/overview-greenhousegases/. Accessed 24 Nov 2016

Eskenazi B, Chevrier J, Rosas LG, Anderson HA, Bornman MS, Bouwman H, Chen A, Cohn BA, De Jager C, Henshel DS, Leipzig F, Leipzig JS, Lorenz EC, Snedeker SM, Stapleton D (2009) The Pine River statement: human health consequences of DDT use. Environ Health Perspect 117:1359–1367

Fenner K, Canonica S, Wackett LP, Elsner M (2013) Evaluating pesticide degradation in the environment: blind spots and emerging opportunities. Science 341:752–758

Fritsche W, Hofrichter M (2005) Aerobic degradation of recalcitrant organic compounds by microorganisms. In: Jördening H-J, Winter J (eds) Environmental biotechnology: concepts and applications. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Fu Y, Viraraghavan T (2001) Fungal decolonization of dye waste wasters: a review. Bioresour Technol 793(251):262

Garbisu C, Alkorta I (2001) Phytoextraction: a cost-effective plant based technology for the removal of metals from the environment. Bioresour Technol 77(3):229–236

Gautam RK, Soni S, Chattopadhyaya MC (2014) Functionalized magnetic nanoparticles for environmental remediation. In: Handbook of research on diverse applications of nanotechnology in biomedicine, chemistry and engineering. Engineering Science Reference, Hershey, pp 518–551

Gomare S, Kalme S, Govindwar S (2009) Biodegradation of Navy Blue-3G by Brevibacillus laterosporus MTCC 2298. Acta Chim Slov 56:789–796

Goyal N, Jain SC, Banerjee UC (2003) Comparative studies on the microbial adsorption of heavy metals. Adv Environ Res 7:311–319

Grifoll M, Selifonov SA, Gatlin CV, Chapman PJ (1995) Actions of a versatile fluorine degrading bacterial isolate on polycyclic aromatic compounds. Appl Environ Microbiol 61:3711–3723

Gurulakshmi M, Sudarmani DNP, Venba R (2008) Biodegradation of leather acid dye by Bacillus subtilis. Adv Biotechnol 7:12–18

Harazono K, Nakamura K (2005) Decolorization of mixtures of different reactive textile dyes by the white-rot basidiomycetes *Phanerochaete sordida* and inhibitory effect of polyvinyl alcohol. Chemosphere 59:63–66

Hasin AA, Gurman SJ, Murphy LM, Perry A, Smith TJ, Gardiner PE (2010) Remediation of chromium (VI) by a methane-oxidizing bacterium. Environ Sci Technol 44:400–405

He LM, Tebo BM (1998) Surface charge properties of and Cu (II) adsorption by spores of the marine *Bacillus* sp. strain SG-1. Appl Environ Microbiol 64:1123–1129

Isaac P, Martínez FL, Bourguignon N, Sánchez LA, Ferrero MA (2015) Improved PAHs removal performance by a defined bacterial consortium of indigenous *Pseudomonas* and actinobacteria from Patagonia, Argentina. Int Biodeterior Biodegrad 101:23–31

Jabeen H, Iqbal S, Anwar S, Parales RE (2015) Optimization of profenofos degradation by a novel bacterial consortium PBAC using response surface methodology. Int Biodeterior Biodegrad 100:89–97

Jafari SA, Cheraghi S, Mirbakhsh M, Mirza R, Maryamabadi A (2015) Employing response surface methodology for optimization of mercury bioremediation by *Vibrio parahaemolyticus* PG02 in coastal sediments of Bushehr, Iran. CLEAN-Soil Air Water 43:118–126

Jayabarath J, Musfira SA, Giridhar R, Arulmurugan R (2010) Biodegradation of carbofuran pesticide by saline soil actinomycetes. Int J Biotechnol Biochem 6:187–193

Jin J, Yao J, Zhang Q, Liu J (2016) Biodegradation of pyrene by *Pseudomonas* sp. JPN2 and its initial degrading mechanism study by combining the catabolic *nahAc* gene and structure-based analyses. Chemosphere 164:379–386

Kafilzadeh F, Sahragard P, Jamali H, Tahery Y (2011) Isolation and identification of hydrocarbons degrading bacteria in soil around Shiraz Refinery. Afr J Microbiol Res 4(19):3084–3089

Kafilzadeh F, Ebrahimnezhad M, Tahery Y (2015) Isolation and identification of endosulfan degrading bacteria and evaluation of their bioremediation in Kor River, Iran. Osong Public Health Res Perspect 6:39–46

Kaldalu M, Toots U, De Lorenzo V, Ustav M (2000) Functional domains of the TOL plasmid transcription factor XyIS. J Bacteriol 4:1118–1126

Kanade SN, Ade AB, Khilare VC (2012) Malathion degradation by *Azospirillum lipoferum* Beijerinck. Sci Res Rep 2(1):94–103

Kapdan IK, Kargi F (2002) Biological decolorization of textile dyestuff containing waste water by Coriolus versicolor in a rotating biological reactor. Enzym Microb Technol 30:195–199

Keharia H, Madamwar D (2003) Bioremediation concepts for treatment of dye containing water: a review. Indian J Exp Biol 41:1068

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kiyono M, Sone Y, Nakamura R, Pan-Hou H, Sakabe K (2009) The Mer E protein encoded by transposon Tn21 is a broad mercury transporter in Escherichia coli. FEBS Lett 583:1127–1131

Kolekar YM, Powar SP, Gawai KR, Lokhande PD, Shouche YS, Kodam KM (2008) Bioresour Technol 99:8899–9003

Libra JA, Borchert M, Banit S (2003) Competition strategies for the decolorization of a textile reactive dye with the white-rot fungi *Trametes versicolor* under non-sterile conditions. Biotechnol Bioeng 826:736–744

Lin YH, Leu JY (2008) Kinetics of reactive azo-dye decolorization by *Pseudomonas luteola* in a biological activated carbon process. Biochem Eng J 39:457–467

Liu S, Zhang F, Chen J, Sun GX (2011) Arsenic removal from contaminated soil via biovolatilization by genetically engineered bacteria under laboratory conditions. J Environ Sci 23:544–1550

Lodato A, Alfieri F, Olivieri G, Di Donato A, Marzocchella A, Salatino P (2007) Azo-dye convention by means of *Pseudomonas* sp. OXI. Enzym Microbiol Technol 41:646–652

Lopez A, Lazaro N, Morales S, Margues AM (2002) Nickel biosorption by free and immobilized cells of pseudomonas fluorescens 4F39: a comparative study. Water Air Soil Pollut 135:157–172

Madhavi S, Revankar S, Lele S (2007) Synthetic dye decolorization by white rot fungus, *Ganoderma* sp. WR-1. Bioresour Technol 984:775–780

Malik A (2004) Metal bioremediation through growing cells. Environ Int 30:261–278

Marchenko AM, Pshinko GN, Demchenko VY, Goncharuk VV (2015) Leaching heavy metal from deposits of heavy metals with bacteria oxidizing elemental sulphur. J Water Chem Technol 37:311–316

Marzan LW, Hossain M, Mina SA, Akter Y, Chowdhury AAMM (2017) Isolation and biochemical characterization of heavy-metal resistant bacteria from tannery effluent in Chittagong city, Bangladesh: bioremediation view point. Egypt J Aquat Res 43:65–74

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mishra A, Malik A (2013) Recent advances in microbial metal bioaccumulation. Crit Rev Environ Sci Technol 43:1162–1222

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 152–178

Mushtaq Z, Faizan S, Gulzar B, Hakeem KR (2020) Inoculation of Rhizobium Alleviates Salinity Stress Through Modulation of Growth Characteristics, Physiological and Biochemical Attributes, Stomatal Activities and Antioxidant Defence in Cicer arietinum L. Journal of Plant Growth Regulation. https://doi.org/10.1007/s00344-020-10267-1

Ng SP, Davis B, Polombo EA, Bhave M (2009) Tn 5051 like mercury containing transposon identified in a heavy metal tolerant strain *Achromobacter* sp. AO22. BMC Res Notes 7:2–38

Nwinyi OC, Ajayi OO, Amund OO (2016) Degradation of polynuclear aromatic hydrocarbons by two strains of Pseudomonas. Braz J Microbiol 47:551–562

Ojuederie OB, Babalola OO (2017) Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. Int J Environ Res Public Health 14:1504

Olukanni OD, Osuntoki AA, Gbenle GO (2006) Textile effluent biodegradation potentials of textile effluent adapted and non-adapted bacteria. Afr J Biotechnol 5:1980–1984

Olukanni O, Osuntokia A, Kalyani D, Gbenlea G, Govindwar S (2010) Decolorization and biodegradation of reactive Blue 13 by proteus mirabilis LAG. J Hazard Mater 184:290–298

Parikh A, Madamwar D (2005) Textile dye decolorization using cyanobacteria. Biotechnol Lett 27:323–326

Phugare S, Kalyani D, Patil A, Jadhav J (2011) Textile dye degradation by bacterial consortium and subsequent toxicological analysis of dye and dye metabolites using cytotoxicity, genotoxicity and oxidative stress studies. J Hazard Mater 186:713–723

Qadri H, Bhat RA (2020) The concerns for global sustainability of freshwater ecosystems. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 1–15

Raffi F, Hall JD, Cernigila CE (1997) Mutagenicity of azo dyes used in foods, drugs and cosmetics before and after reduction by Clostridium species from the human intestinal tract. Food Chem Toxicol 35:897–901

Russ R, Rau J, Stolz A (2000) The function of cytoplasmic *flavin reductases* in the reduction of azo dyes by bacteria. Appl Environ Microbiol 66:1429–1434

Sajna KV, Pandey A (2015) Crude oil biodegradation aided by biosurfactants from *Pseudozyma* sp. NII 08165 or its culture broth. Bioresour Technol 191:133–139

Salehizadeh H, Shojaosadati SA (2003) Removal of metal ions from aqueous solution by polysaccharide produced from *Bacillus firmus*. Water Res 37(17):4231–4235

Saranya K, Sundaramanickam A, Shekhar S, Swaminathan S, Balasubramanian T (2017) Bioremediation of mercury by vibrio fluvialis screened from industrial effluents. Biomed Res Int 10:6–12

Sarret G, Manceau A, Spadini L, Roux JC, Hazemann JL, Soldo Y, Eybert-Bérard L, Menthonnex J (1998) Structural determination of Zn and Pb binding sites in *Penicillium chrysogenum* cell walls by EXAFS spectroscopy. Environ Sci Technol 32:1648–1655

Seeger M, Hernández M, Méndez V, Ponce B, Córdova M, González M (2010) Bacterial degradation and bioremediation of chlorinated herbicides and biphenyls. J Soil Sci Plant Nutr 10(3):320–332

Shao Y, Wang Y, Wu X, Xu X, Kong S, Tong L et al (2015) Biodegradation of PAHs by Acinetobacter isolated from karst groundwater in a coal-mining area. Environ Earth Sci 73:7479–7488

Sharma S, Adholeya A (2012) Hexavalentchromium reduction in tannery effluent by bacterial species isolated from tannery effluent contaminated soil. J Environ Sci Technol 5(3):142–154

Singh S, Kang SH, Mulchandani A, Chen W (2008) Bioremediation: environmental cleanup through pathway engineering. Curr Opin Biotechnol 19:437–444

Singh DV, Bhat JIA, Bhat RA, Dervash MA, Ganei SA (2018) Vehicular stress a cause for heavy metal accumulation and change in physico-chemical characteristics of road side soils in Pahalgam. Environ Monit Assess 190:353. https://doi.org/10.1007/s10661-018-6731-2

Solanki P, Kothari V (2012) Metal tolerance in halotolerant bacteria isolated from saline soil of Khambhat. Res Biotechnol 3:1–11

Souza EC, Vessoni-Penna TC, Oliveira RDPS (2014) Biosurfactant enhanced hydrocarbon bioremidation: an overview. Int Biodeterior Biodegrad 89:88–94

Tamboli D, Telke A, Dawkar V, Jadhav S, Govindwar S (2011) Purification and characterization of bacterial aryl alcohol oxidase from *Sphingobacterium* sp. ATM and its uses in textile dye decolorization. Biotechnol Bioprocess Eng 16:661–668

Tang W (2018) Research progress of microbial degradation of organophosphorus pesticides. Prog Appl Microbiol 1:29–35

Telke A, Kalyani D, Jadhav J, Govindwar S (2008) Kinetics and mechanism of reactive red 141 degradations by a bacterial isolate Rhizobium radiobacter MTCC 8161. Acta Chim Slov 55:320–329

Telke A, Ghodake G, Kalyani D, Dhanve R, Govindwar S (2011) Biochemical characteristics of a textile dye degrading extracellular laccase from a *Bacillus* sp. ADR. Bioresour Technol 102:1752–1756

Teng Y, Luo Y, Sun M, Liu Z, Li Z, Christie P (2010) Effect of bioaugmentation by *Paracoccus sp.* strain HPD-2 on the soil microbial community and removal of polycyclic aromatic hydrocarbons from an aged contaminated soil. Bioresour Technol 101:3437–3443

Teramoto M, Suzuki M, Okazaki F, Hatmanti A, Harayama S (2009) Oceanobacter-related bacteria are important for the degradation of petroleum aliphatic hydrocarbons in the tropical marine environment. Microbiology 155(10):3362–3370

United States Environmental Protection Agency (USEPA) (2012) A citizen guide to bioremediation. EPA 542-F-12-003

Uqab B, Mudasir S, Nazir R (2016) Review on bioremediation of pesticides. J Bioremed Biodegr 7:1–5

Verma P, Madamwar D (2003) Decolorization of synthetic dyes by a newly isolated strain of Serratia marcescers. World J Microbiol Biotechnol 19:615–618

Vijaykumar MH, Vaishampayan PA, Shouche YS, Karegoudar TB (2007) Decolorization of naphthalene containing sulfonated azo dyes by *Kerstesia* sp. strain VKY1. Enzym Microbiol Technol 40:204–211

Wackett L, Sadowsky M, Martinez B, Shapir N (2002) Biodegradation of atrazine and related S-triazine compounds: from enzymes to field studies. Appl Microbiol Biotechnol 58:39–45

Wai WL, Kyaw NAK, Nway NHN (2012) Biosorption of Lead (Pb2+) by using *Chlorella vulgaris.* In: Proceedings of the international conference on chemical engineering and its applications (ICCEA), Bangkok

Wesenberg D, Kyriakioles I, Agathos SN (2003) White rot fungi and their enzymes for the treatment of industrial dye effluents. Biotechnol Adv 22:161–187

Wiedemeier TH, Miller RN, Wilson JT (1995) Significance of anaerobic processes for the intrinsic bioremediation of fuel hydrocarbons: In: Proceedings of the petroleum hydrocarbons and organic chemicals in groundwater – prevention, detection, and remediation conference, November 29–December 1, 1995, Houston

Wu CH, Wood TK, Mulchandani A, Chen W (2006) Engineering plant-microbe symbiosis for rhizoremediation of heavy metals. Appl Environ Microbiol 72:1129–1134

Wu Y, Li T, Yang L (2012) Mechanisms of removing pollutants from aqueous solutions by microorganisms and their aggregates: a review. Bioresour Technol 107:10–18

Xing Y, Lu YL, Dawson RW, Shi YJ, Zhang H, Wang TY, Liu WB, Ren HC (2005) A spatial temporal assessment of pollution from PCBs in China. Chemosphere 60:731–739

Zhang F, Yediler A, Liang X, Kettrup A (2004) Effects of dye additives on the ozonation process and oxidation by-products: a comparative study using hydrolyzed CI Reactive Red 120. Dyes Pigments 60:1–7

Zhou YY, Chen DZ, Zhu RY, Chen JM (2011) Substrate interactions during the biodegradation of BTEX and THF mixtures by *Pseudomonas oleovorans* DT4. Bioresour Technol 102(12):6644–6649

Zhou H, Wang H, Huang Y, Fang T (2016) Characterization of pyrene degradation by halophilic *Thalassospira* sp. strain TSL5-1 isolated from the coastal soil of Yellow Sea, China. Int Biodeterior Biodegrad 107:62–69

Chapter 6
Traditional Farming Practices and Its Consequences

H. Hamadani, S. Mudasir Rashid, J. D. Parrah, A. A. Khan, K. A. Dar, A. A. Ganie, A. Gazal, R. A. Dar, and Aarif Ali

6.1 Introduction

Traditional farming is as a primitive method of farming, which is still being used by half of the world's farming population (Shakeel 2018). It involves the application of indigenous knowledge, traditional tools, natural resources, organic fertilizers, and cultural beliefs of the farmers (Shakeel 2018). The production of a variety of household crops and livestock was made possible through this farming (Alam et al. 2014). Traditional farming evolved over foremost thousands of years of agriculture as a sustainable system and in equilibrium with the surrounding ecosystems (Alam et al. 2014). The information has been used over the generations by the producers to produce the materials of their necessities.

With the passing years, the human population increased at a tremendous pace and food security became a major challenge. Although production multiplied several

---

H. Hamadani · J. D. Parrah · K. A. Dar · R. A. Dar
Mountain Livestock Research Institute, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Manasbal, Jammu and Kashmir, India

S. M. Rashid (✉)
Faculty of Veterinary Sciences and Animal Husbandry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shuhama, Jammu and Kashmir, India

Division of Veterinary Biochemistry, Faculty of Veterinary Sciences (SKUAST-K), Shuhama, Alusteng, Srinagar, India
e-mail: mudasir@skuastkashmir.ac.in

A. A. Khan · A. A. Ganie · A. Ali
Faculty of Veterinary Sciences and Animal Husbandry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shuhama, Jammu and Kashmir, India

A. Gazal
Plant Breeding and Genetics, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Shalimar, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_6

folds because of Green Revolution, but it had its own implications. The excessive use of fossil fuels, natural resources, agrochemicals, and machinery exposed the ecological integrity of agroecosystems to a greater risk (Singh and Singh 2017).

Therefore, with the growing environmental issues, such as climate change, population explosion, and natural resource degradation and biodiversity loss, sustainable food production is the need of the hour. Traditional farming is receiving attention worldwide for being a source of sustainable food production in times of global environmental crises (Singh and Singh 2017). The preservation of indigenous knowledge of traditional farming is advantageous in maintaining the biodiversity (Peroni 2017; Alam et al. 2014; Acquaah 2002; Burton 1998), enhancing food-security, and protecting natural resources (Peroni 2017). However, there are certain negative implications as well, which is also a matter of concern.

6.2 Background

Going back to history, the development of agriculture can be classified into three phases, which includes traditional stage, green revolution era, and post-green revolution phase (Kunju 2013). Agriculture transformed gradually through these phases with the passing time, and change in demand and technology. Technology employed for farming operations has been crude in traditional agriculture, which gradually modernized through the modern eras. The period of traditional agriculture can be divided into two phases, which includes the early phase and the pre-modern phase. The time from which the agriculture spread to the beginning of the second half of the nineteenth century marks the early phase of traditional era, after which the pre-modern phase starts (Kunju 2013).

Traditional farming systems gave importance to the agricultural practice which involved sustainable interaction between plants, animals, soil, water, and food, leading to retained soil fertility, pest control, and mixed crop production (Kunju 2013). The inputs used in this system are mainly organic in nature and produced mainly on the farm itself, making it an integrated system of farming (Shiva 1996). Livestock rearing was being combined with agriculture by the farmers at that time and mixed or rotational cropping systems were followed (Shanin 1976). The practice of recycling farm wastes was a common practice, which would help in maintaining the fertility of the soil (Kunju 2013; Dar et al. 2013). Selection of good varieties and maintaining diversity marked the fundamentals of farming. Human and livestock have been used for harvesting and thrashing operations (Barker et al. 1985). The techniques developed have been practiced over the generations and have remained popular in many parts of the Asian subcontinent.

The informal experimentation of judging varieties and making selective choices by the farmers led to the evolution of agriculture (Swaminathan 1993). Knowledge was set by practices and not by scientific factors (Ludden 1996). Traditional farmers passed on the indigenous knowledge about farming practices and related aspects across generations verbally and through practice.

6.3 Traditional Farming Practices

Prominent traditional agricultural practices include agroforestry, intercropping, crop rotation, cover cropping, traditional organic composting, integrated crop-animal farming, shifting cultivation, and slash-and-burn farming (Singh and Singh 2017).

6.3.1 *Agroforestry*

Agroforestry, an age-old practice dating back to the beginning of farming and animal husbandry (Oelbermann et al. 2004), involves the practice of planting trees along with crops (Patel et al. 2019; Albrecht and Kandji 2003). It has a potential for mitigation of the effects of climate change, adaptation, food security, and crop productivity (Coulibaly et al. 2017; Mbow et al. 2014). In addition to this, the practice plays a role in improving soil quality, water retention, carbon sequestration, agrobiodiversity, and ultimately farmers' income (Zomer et al. 2016; Abbas et al. 2017; Paul et al. 2017). The system is used worldwide as a land-use management system (Pandey 2002). Agroforestry has a high significance in drought prone areas owing to the fact that the deep roots of tree explore a larger soil volume for water and nutrients (Verchot et al. 2007). A system of agroforestry, known as silvopastoral system, is beneficial for livestock, in which leguminous fodder grasses are grown with trees (Reis et al. 2010; Isaac et al. 2005). This makes nutritious green fodder available for farm animals, which is required for their health and productivity.

6.3.2 *Intercropping*

The practice of cultivating more than one crop species on the same field is referred to as intercropping (Singh and Singh 2017). It is considered to be one of the highly productive farming systems (Hu et al. 2017), which utilizes the natural resources, such as land, water, and nutrient, efficiently and increases productivity, biodiversity, resilience, and stability of agroecosystem (Ning et al. 2017). Since more than one crop is used and different crops have different adaptability, this system reduces the climate-driven crop failure (Shava et al. 2009). It has been an ancient practice, especially cultivation of pigeon pea with sorghum (Wang et al. 2010). Carbon sequestration (Kumara et al. 2016), nitrogen fixation (Duchene et al. 2017), reduction of requirement of external nitrogen fertilizers (Singh and Singh 2017), increased availability of nitrogen and phosphorous (Latati et al. 2017; Lazali et al. 2016), reduced soil erosion (Forte et al. 2017) are some of the additional benefits of this system.

6.3.3 Crop Rotation

A traditional practice of growing a sequence of crops on a given land area every growing or planting cycle and season (Dury et al. 2012). Some of the benefits due to this system of agriculture include improvement in soil quality (Liu et al. 2016), soil fertility (Pedraza et al. 2015), carbon sequestration (Triberti et al. 2016), increased yield, effective water use, reduced soil erosion (Huang et al. 2003), and nutrient recycling. The use of leguminous crops reduces dependence on external source of nitrogen fertilizers.

6.3.4 Cover Cropping

A traditional practice of cultivating a crop in order to cover the land for reducing the erosion of soil and loss of nutrients (Dabney et al. 2001). The practice of replacing a bare fallow period through cover cropping is a workable way of runoff control and soil erosion prevention (Alvarez et al. 2017). Such crops, which could be both leguminous and non-leguminous (Cooper et al. 2017), are generally harvested before the plantation of the main crop or even alongside the main crops as a living mulch (Robačer et al. 2016). Many beneficial features have been enlisted, namely, improvement in soil microbial biomass, soil health maintenance, water storage, nutrient cycling, weed control, and carbon sequestration (Pinto et al. 2017; Frasier et al. 2016). However, certain disadvantages, such as additional costs, difficultly in tillage, allelopathy, labour, increased disease risk, need a mention (Dabney et al. 2001).

6.3.5 Composting

Composting is an age-old traditional practice (Oudart et al. 2015) of decomposing organic matter by micro-organisms under controlled conditions (Misra et al. 2003) to produce compost, which can be used as an organic manure (Onwosi et al. 2017). Organic manure can be an excellent source of enhancing soil fertility. Waste materials, such as farmyard manure, kitchen waste, sewage-sludge, and crop residues, can be recycled into useful manure to be used in the agricultural fields and fodder lands. In addition to this, it increases soil carbon sequestration, reduces green-house gas emission (Forte et al. 2017) enhances soil aeration, soil microbial diversity, cation exchange capacity, soil moisture, soil organic matter, soil carbon, or nitrogen levels and minimizes soil-erosion and controls pests and diseases (Liu et al. 2013; Zhang et al. 2012; Ge et al. 2008), makes soils more resistant to drought (Lal 2008). In the current scenario, the popularity of organic products is increasing globally and hence organic manure production is gaining popularity too. Composting is a prevalent practice in Asian countries (Yadav et al. 2017). The use of compost produced from farm yard manure has been a traditional practice in China (Yang et al. 2004), South Africa (Kangalawe et al. 2014), and India (Gopinath et al. 2008). Vermicompost production, as a small-scale venture, is helping rural women folk in India to earn their livelihood and is empowering them in many ways (Hamadani et al. 2020; Baraskar et al. 2018).

6.3.6 Integrated Livestock Farming

One of the oldest practices of integrating livestock farming with agriculture is considered to be the backbone of cultivation in developing countries (Patel et al. 2019). It is an efficient way of resource utilization, wherein a by-product of one venture is utilized as an input of another. One example of integrated dairy farming with agriculture is illustrated in Fig. 6.1, which clearly shows the flow of resources in an integrated manner. The main products from a dairy farm, that is, milk and calves, form a direct source of income to the farmers, whereas the waste product, dung is either sold as such or is recycled to a more valuable vermicompost. The vermicompost, if sold directly, fetches the farmer an additional income or can be applied in the agriculture and fodder lands in place of fertilizers to improve soil fertility as well as production. The main produce from the agricultural land contributes directly to income of the farmer, and the by-products can be utilized in feeding the animals. The fodder produced can be sold, as well as utilized for animal feed production, which can again be sold as well as fed to own animals. The manure can also be used to produce biogas, which can also be utilized at the farm to carry out various operations.

Integrating livestock component to crop sector has a positive impact of agrobiodiversity, food diversity, land resource management, food security, income generation (Singh and Singh 2017). The system also acts as a buffer in times of a crop failure due to natural disasters such as droughts and floods.

6.3.7 Shifting Cultivation

It is also referred to as slash-and-burn cultivation and encompasses a practice of growing crops on a land covered with ashes produced from burning piles of wood obtained by chopping the trees (Muimba-Kankolongo 2018). The burning procedure is carried out just before the onset of the rainy season in order to destroy pests and to fertilize the land with ash. When the soil shows signs of exhaustion, the land is left uncultivated and allowed to grow again into a forest and, till then, the farmer moves to another plot (Alam et al. 2014). The cleared plot is cultivated for 2–3 years and then left fallow for approximately 10–20 years (Brady 1996). The increasing human population pressure demanded decreased fallow period (Thomaz et al. 2014). It has been argued that fallow period less than 10 years may not be sustainable

Fig. 6.1 Illustrated diagram of integrated dairying with crop production showing the utilization of products and by-products efficiently

(Borggaard et al. 2003). The sustainability of this system relies on the length of fallow period. Shorter periods may not allow replenishment of nutrients and longer periods may lead to runoff and soil loss (Thomaz et al. 2014). Further, large amounts of fuel may intensify the fire and cause damage to the top layer of the soil (Thomaz 2009). Other disadvantage of this system includes its implications on the environment in terms of deforestation and air pollution caused due to burning of the forests. Shifting cultivation landscapes (both cultivated and fallows) cover around 280 million hectares worldwide (Heinimann et al. 2017). It has been estimated that there might be a decline in shifting cultivation over the next decades, which may possibly raise issues of livelihood security among people currently depending on shifting cultivation (Heinimann et al. 2017).

6.4 Summary

Traditional farming has been practised by the farmers since ancient times and it has been ever-evolving. Tremendous population expansion, shrinkage of resources, changes in mind-set, and invention of new technologies and tools with passing time have all contributed to this. However, indigenous knowledge passed on by the ancient people across generations is still being used today and has its own merits, especially being in tune with the environment and being less resource intensive. Therefore, such farming practices are gaining attention as the world is looking for new alternatives to our production systems, while facing serious challenges such as climate change, biological magnification, and environmental degradation.

References

Abbas F, Hammad HM, Fahad S, Cerdà A, Rizwan M, Farhad W, Bakhat HF (2017) Agroforestry: a sustainable environmental practice for carbon sequestration under the climate change scenarios—a review. Environ Sci Pol 24(12):11177–11191

Acquaah G (2002) Agricultural production systems. In: Principles of crop production, theories, techniques and technology. Prentice Hall, Upper Saddle River, pp 283–317

Alam A, Rizvi AH, Verma K, Gautam C (2014) The changing scenario in Indian agriculture: a review. Int J Sci Res Agric Sci 2(7):118–127. https://doi.org/10.12983/ijsras-2014-p0118-0127

Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99(1):15–27

Alvarez R, Steinbach HS, De Paepe JL (2017) Cover crop effects on soils and subsequent crops in the pampas: a meta-analysis. Soil Till Res 170:53–65

Baraskar M, Choudhary S, Wankhede A, Jain SK, Verma DK (2018) Impact of socio personal attributes of vermicompost production in terms of income and employment generation in Hoshangabad District (Madhya Pradesh). SSRG Int J Agric Environ Sci 5(4):34–36

Barker, Randolph, Herdt RW, Rose B (1985) The rice economy of Asia resource for the future, in. Washington

Borggaard OK, Gafur A, Petersen L (2003) Sustainability appraisal of shifting cultivation in the Chittagong Hill tracts of Bangladesh. Ambio 32:118–123

Brady NC (1996) Alternatives to slash-and-burn: a global imperative. Agric Ecosyst Environ 58:3–11

Burton S (1998) A history of India. Blackwell Publishing, Chichester. CSIRO 2006 press release on Seed Quest website

Cooper RJ, Aziza JH, Hiscocka KM, Lovetta AA, Dugdalea SJ, Su¨nnenberga G, Noble L, Beamish J, Hovesen P (2017) Assessing the farm-scale impacts of cover crops and noninversion tillage regimes on nutrient losses from an arable catchment. Agric Ecosyst Environ 237:181–193

Coulibaly JY, Chiputwa B, Nakelse T, Kundhlande G (2017) Adoption of agroforestry and the impact on household food security among farmers in Malawi. Agric Syst 155:52–69

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal 32:1221–1250. https://doi.org/10.1081/CSS-100104110

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecologia Balkanica 5(1):31–35

Duchene O, Vian JF, Celette F (2017) Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms: a review. Agric Ecosyst Environ 240:148–161

Dury J, Schaller N, Garcia F, Reynaud A, Bergez JE (2012) Models to support cropping plan and crop rotation decisions: a review. Agron Sustain Dev 32(2):567–580

Forte A, Fagnano M, Fierro A (2017) Potential role of compost and green manure amendment to mitigate soil GHGs emissions in Mediterranean drip irrigated maize production systems. J Environ Manag 192:68–78

Frasier I, Quiroga A, Noellemeyer E (2016) Effect of different cover crops on C and N cycling in sorghum NT systems. Sci Total Environ 562:628–639

Ge Y, Zhang JB, Zhang LM, Yang M, He JZ (2008) Long-term fertilization regimes affect bacterial community structure and diversity of an agricultural soil in Northern China. J Soils Sediments 8:43–50

Gopinath KA, Saha S, Mina BL, Pande H, Kundu S, Gupta HS (2008) Influence of organic amendments on growth, yield and quality of wheat and on soil properties during transition to organic production. Nutr Cycl Agroecosyst 82(1):51–60

Hamadani H, Parrah JD, Hassan N, Dar RA, Sheikh FD (2020) Study of the socioeconomic status of women vermicompost-producing farmers in Kashmir Valley. Int J Curr Microbiol Appl Sci 9(4):1486–1491

Heinimann A, Mertz O, Frolking S, Egelund Christensen A, Hurni K, Sedano F, Parsons Chini L, Sahajpal R, Hansen M, Hurtt G (2017) A global view of shifting cultivation: recent, current, and future extent. PLoS One 12(9):e0184479. https://doi.org/10.1371/journal.pone.0184479

Hu F, Feng F, Zhao C, Chai Q, Yu A, Yin W, Gan Y (2017) Integration of wheat-maize intercropping with conservation practices reduces CO2 emissions and enhances water use in dry areas. Soil Till Res 169:44–53

Huang M, Shao M, Zhang L, Li Y (2003) Water use efficiency and sustainability of different long-term crop rotation systems in the Loess Plateau of China. Soil Till Res 72(1):95–104

Isaac ME, Gordon AM, Thevathasan N, Oppong SK, Quashie-Sam J (2005) Temporal changes in soil carbon and nitrogen in West African multistrata agroforestry systems: a chronosequence of pools and fluxes. Agrofor Syst 65(1):23–31

Kangalawe RY, Noe C, Tungaraza FS, Naimani G, Mlele M (2014) Understanding of traditional knowledge and indigenous institutions on sustainable land management in Kilimanjaro Region, Tanzania. Open J Soil Sci 4(13):469

Kumara PR, Munasinghe ES, Rodrigo VHL, Karunaratna AS (2016) Carbon footprint of rubber/sugarcane intercropping system in Sri Lanka: a case study. Proc Food Sci 6:298–302

Kunju PCA (2013) Agricultural technology development and transfer in the socio economic transformation of Agrarian economies: the Kerala experience with special reference to Kuttanad. Ph.D thesis submitted to Mahatma Gandhi University, Kottayam

Lal R (2008) Carbon sequestration. Philos Trans R Soc B Biol Sci 363(1492):815–830

Latati M, Aouiche A, Tellah S, Laribi A, Benlahrech S, Kaci G, Ounane SM (2017) Intercropping maize and common bean enhances microbial carbon and nitrogen availability in low phosphorus soil under Mediterranean conditions. Eur J Soil Biol 80:9–18

Lazali M, Brahimi S, Merabet C, Latati M, Benadis C, Maougal RT, Ounane SM (2016) Nodular diagnosis of contrasting recombinant inbred lines of Phaseolus vulgaris in multi-local field tests under Mediterranean climate. Eur J Soil Biol 73:100–107

Liu Y, Duan M, Yu Z (2013) Agricultural landscapes and biodiversity in China. Agric Ecosyst Environ 166:46–54

Liu X, Lehtonen H, Purola T, Pavlova Y, Ro¨tter R, Palosuo T (2016) Dynamic economic modelling of crop rotations with farm management practices under future pest pressure. Agric Syst 144:65–76

Ludden D (1996) Archaic formation of agricultural knowledge in South India. In: Peter Robb meanings of agriculture. Oxford University Press, Delhi, pp 35–70

Mbow C, Van Noordwijk M, Luedeling E, Neufeldt H, Minang PA, Kowero G (2014) Agroforestry solutions to address food securityand climate change challenges in Africa. Curr Opin Environ Sustain 6:61–67

Misra RV, Roy RN, Hiraoka H (2003) On-farm composting methods. UN-FAO, Rome

Muimba-Kankolongo A (2018) Chapter 6 - Common cultivation practices. In: Muimba-Kankolongo A (ed) Food crop production by smallholder farmers in Southern Africa. Academic Press, pp 49–58. https://doi.org/10.1016/B978-0-12-814383-4.00006-2

Ning C, Qu J, He L, Yang R, Chen Q, Luo S, Cai K (2017) Improvement of yield, pest control and Si nutrition of rice by rice-water spinach intercropping. Field Crops Res 208:34–43

Oelbermann M, Voroney RP, Gordon AM (2004) Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada. Agric Ecosyst Environ 104(3):359–377

Onwosi CO, Igbokwe VC, Odimba JN, Eke IE, Nwankwoala MO, Iroh IN, Ezeogu LI (2017) Composting technology in waste stabilization: on the methods, challenges and future prospects. J Environ Manag 190:140–157

Oudart D, Robin P, Paillat JM, Paul E (2015) Modelling nitrogen and carbon interactions in composting of animal manure in naturally aerated piles. Waste Manag 46:588–598

Pandey DN (2002) Carbon sequestration in agroforestry systems. Clim Policy 2(4):367–377

Patel SK, Singh A, Singh GS (2019) Food production through traditional agriculture: an urgent need to improve soil health by sustaining soil microbial diversity. Int J Curr Microbiol Appl Sci 8(1):183–196

Paul C, Weber M, Knoke T (2017) Agroforestry versus farm mosaicsystems: comparing land-use efficiency, economic returns and risks under climate change effects. Sci Total Environ 587:22–35

Pedraza V, Perea F, Saavedra M, Fuentes M, Castilla A, Alca'ntara C (2015) Winter cover crops as sustainable alternative to soil management system of a traditional durum wheat-sunflower rotation in Southern Spain. Procedia Environ Sci 29:95–96

Perroni E (2017) Five indigenous farming practices enhancing food security. Food Tank https://foodtank.com/news/2017/08/celebrating-international-day-of-the-worlds-indigenous-peoples/

Pinto P, Long MEF, Pineiro G (2017) Including cover crops during fallow periods for increasing ecosystem services: is it possible in croplands of Southern South America? Agric Ecosyst Environ 248:48–57

Reis GL, Lana ÂMQ, Maurício RM, Lana RMQ, Machado RM, Borges I, Neto TQ (2010) Influence of trees on soil nutrient pools in a silvopastoral system in the Brazilian Savannah. Plant Soil 329(1-2):185–193

Robačer M, Canali S, Kristensen HL, Bavec F, Mlakar SG, Jakop M, Bavec M (2016) Cover crops in organic field vegetable production. Sci Hortic 208:104–110

Shakeel A (2018) Traditional Agriculture and its impact on the environment. Jaran Josh 3–5. https://www.jagranjosh.com/general-knowledge/traditional-agriculture-and-its-impact-on-the-environment-1518096259-1

Shanin T (1976) Peasants and peasant societies. Hormonds worth, Pengiun Book Ltd

Shava S, O'Donoghue R, Krasny ME, Zazu C (2009) Traditional food crops as a source of community resilience in Zimbabwe. Int J Afr Renaiss Stud 4(1):31–48

Shiva V (1996) Agricultural biodiversity, intellectual propert rights and farmers' rights, Economic and Political Weekly, June - 22, pp 60–67

Singh R, Singh GS (2017) Traditional agriculture: a climate-smart approach for sustainable food production. Energy Environ Sci 2(5):296–316. https://doi.org/10.1007/s40974-017-0074-7

Swaminathan MS (1993) Science and famine avoidance strategies of independent India. In: Surendranath KV, Damodaran AK, Unnikrishnan SV (eds) For an Indian model. Essays in homage to - C. Achutha Menon, C. Achutha Menon Foundation, Trivandrum, pp 158–174

Thomaz EL (2009) The influence of traditional steep land agricultural practices on runoff and soil loss. Agric Ecosyst Environ 130:23–30

Thomaz EL, Antoneli V, Doerr SH (2014) Effects of fire on the physicochemical properties of soil in a slash-and-burn agriculture. *Catena* 122(June 2019):209–215. https://doi.org/10.1016/j.catena.2014.06.016

Triberti L, Nastri A, Baldoni G (2016) Long-term effects of crop rotation, manure and mineral fertilisation on carbon sequestration and soil fertility. Eur J Agron 74:47–55

Verchot LV, Van Noordwijk M, Kandji S, Tomich T, Ong C, Albrecht A, Palm C (2007) Climate change: linking adaptation and mitigation through agroforestry. Mitig Adapt Strat Glob Change 12(5):901–918

Wang Q, Li Y, Alva A (2010) Cropping systems to improve carbon sequestration for mitigation of climate change. J Environ Prot 1(03):207

Yadav H, Fatima R, Sharma A, Mathur S (2017) Enhancement of applicability of rock phosphate in alkaline soils by organic compost. Appl Soil Ecol 113:80–85

Yang C, Yang L, Yang Y, Ouyang Z (2004) Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. Agric Water Manag 70(1):67–81

Zhang QC, Shamsi IH, Xu DT, Wang GH, Lin XY, Jilani G, Hussain N, Chaudhry AN (2012) Chemical fertilizer and organic manure inputs in soil exhibit a vice versa pattern of microbial community structure. Appl Soil Ecol 57:1–8

Zomer RJ, Neufeldt H, Xu J, Ahrends A, Bossio D, Trabucco A, van Noordwijk M, Wang M (2016) Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci Rep 6:29987. https://doi.org/10.1038/srep29987

Chapter 7
Soil Organic Matter and Its Impact on Soil Properties and Nutrient Status

Owais Bashir, Tahir Ali, Zahoor Ahmad Baba, G. H. Rather, S. A. Bangroo, Sofi Danish Mukhtar, Nasir Naik, Rehana Mohiuddin, Varsha Bharati, and Rouf Ahmad Bhat

7.1 Introduction

Soil organic matter plays a dynamic role in the improvement and maintenance of physical, chemical, and biological properties of soil. Agriculture is most concerned about these relationships, including the critical limits of soil organic matter with the key soil properties. There has been direct and indirect impact of soil organic matter on the soil properties, including its physical, chemical, and biological properties (Bezuglova et al. 2019; Sachkova et al. 2019; Orlova et al. 2019; Garratt et al. 2018; Zhang et al. 2017; Bhat et al. 2017b). In the physical properties, the soil organic matter affect soil structure, water retention, available water capacity, thermal conductivity, erodibility, infiltration, soil aggregate formation, soil color, soil

---

O. Bashir (✉) · T. Ali · Z. A. Baba · S. A. Bangroo · N. Naik
Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

G. H. Rather
Division of Fruit Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

S. D. Mukhtar
Department of Chemistry, Jamia Millia Islamia, New Delhi, India

R. Mohiuddin
Division of Agronomy, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

V. Bharati
Division of Plant Pathology, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

R. A. Bhat
Division of Environmental Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_7

compaction, soil aeration, saturated and unsaturated hydraulic conductivity (Beck-Broichsitter et al. 2018; Ajayi and Horn 2017; Blanchet et al. 2016; Angin et al. 2013). In the chemical properties, the SOM effect pH, buffering capacity, CEC, base saturation, zeta potential, exchangeable cations, soil fertility, and nutrient release (Garratt et al. 2018; Kwiatkowska-Malina 2018; Sulman et al. 2018). The biological properties include soil microbial population, soil microbial biomass carbon, nitrogen transformation, mycorrhizal population, root length and root growth, dehydrogenase, phosphatase, and urease (Fedoseeva et al. 2019; Orlova et al. 2019; Tikhova et al. 2019; Kallenbach et al. 2019; Wurzburger and Clemmensen 2018; Hazard and Johnson 2018; Parker et al. 2018).

Soil organic matter is a complex system of substance ranging from metabolic products of microbes, products of secondary synthesis components of organic residues undergoing decomposition, and humic substance. Soil organic matter is the plant and animal residues, microbial biomass, partly decomposed biomass fragments, stabilized organic matter, and soluble organic fraction (Zuber et al. 2015; Balesdent et al. 2000; Qadri and Bhat 2020). The soil organic matter generally describes the non-living product of plant and animal origin, but in broader term, it includes the total soil biomass, including the meso and macrofauna (Jiang et al. 2018; Laossi et al. 2008) and the biomass decomposition product. The soil organic matter is the heterogeneous product resulting from the chemical and microbial transformation of organic debris (Sidhu et al. 2016; Streubel et al. 2011; Liang et al. 2006; Mikutta et al. 2006; Dervash et al. 2020; Mushtaq et al. 2018). The soil organic matter has two important constituents: the non-living part, including the decomposed and un-decomposed products, and the living fraction of soil organic matter which is composed mainly of bacteria (10^9 organisms per gram of soil), fungi (10^7 organisms per gram of soil), actinomycetes (10^8 organisms per gram of soil), protozoa (10^6 organisms per gram of soil), algae (10^3 organisms per gram of soil), and nematodes (50 organisms per gram of soil). In the soil organic matter, these microbial populations play an important role in fermentation, mineralization, and humification process (Yuan et al. 2018; Gougoulias et al. 2014; Ahmad et al. 2007; Tiquia 2005; Alfreider et al. 2002; Zaman et al. 1999; Khanday et al. 2016; Singh et al. 2018a, b). The major constituents of the organic inputs are polysaccharides (hemicelluloses, cellulose) and lignin (Hsu et al. 2018; Liu 2014; Torres 2014; Zhu 2010; Kiem and Kögel-Knabner 2003), the others being biopolymers, such as (polyester, protein, tannins, suberin, cutin, and chlorophyll pigments) (Rui et al. 2016; Liu 2010; Bhat et al. 2017a, b). Soil organic matter serves as a substrate for microbial activity, nutrient source, soil conditioner, and major factor for sustaining agricultural productivity (Oldfield et al. 2018; Singh et al. 2020).

Soil organic matter decomposition is directly related to emission of atmospheric carbon, leading to global climate change. Environmental variables (soil moisture and soil temperature), microbial activity, soil chemical properties, and soil organic matter inputs (e.g., root exudates, plant litter, dead fine roots) usually impact decomposition dynamics (Dar et al. 2013, 2016; Genardzielinski et al. 2018; Yang et al. 2018; Dar and Bhat 2020). Apart from the organic inputs, the most influential are microbial activity and soil climate. In the soils, organic matter influences its output through priming effect (Fig. 7.1). The priming effect is small period transition in soil organic carbon turnover caused by the external organic matter input. A positive priming effect accelerates the decomposition rate, while as negative priming effect retards decomposition. The decline in the soil organic matter has a deleterious effect on the soil properties (Matos et al. 2019; Johnson et al. 2017; Huo et al. 2017; Kumar et al. 2016; Pausch et al. 2013; Zimmerman et al. 2011). As predicted in (European Environment Agency 2010) EU Soil Thematic Strategy, a decline of SOM contents is considered among eight main threats for soils. About 108–188 Pg C have been lost since the mid-nineteenth century, mostly from terrestrial ecosystem. However, several mitigating practices in agriculture, such as use of crop residues and residue incorporation into soil, maintain and build up soil organic matter. The mineralization and decomposition of soil organic matter is prejudiced by the land management, especially agricultural lands. Soils easily and quickly lose organic matter when natural soils are converted into agricultural soils. About 20–25% of the soil organic carbon is lost into atmosphere during its conversion and the possible reason is the destruction of soil aggregates. The sustainability in agriculture can be achieved now by the supply of exogenous organic matter. The organic matter having rich carbon pool and poor nitrogen content (e.g., straw, brown coal, wood and tree coniferous) act as substrate for microorganisms and relatively stable energy source (Singh et al. 2018a, b; Wei et al. 2017; Gogoi et al. 2017; Xiang et al. 2015) The current paper reviews the importance of soil organic matter in the

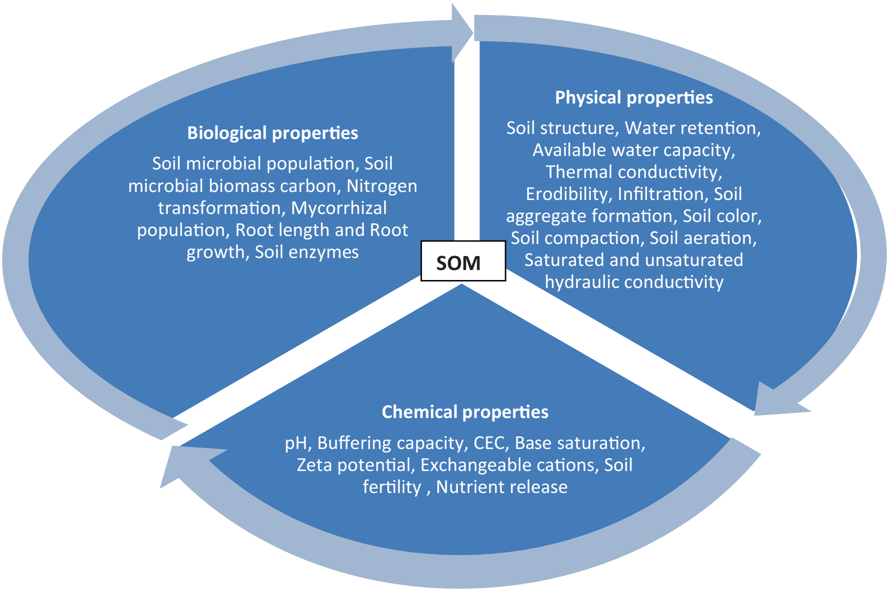


Fig. 7.1 Impact of soil organic matter on soil’s physical, chemical, and biological properties

Table 7.1 Various fractions of the soil organic matter and their relative proportion

Fractions	Source	Composition	Amount (%)	Available form
Living organic matter	Plant biomass	Plant litter and roots	1	Active pool, labile soil carbon, decomposable plant materials (low C:N ratio), resistant plant material (high C:N ratio, high lignin)
	Microbial biomass	Bacteria	1–5	
		Fungi		
Non-living organic matter	Particulate organic matter	Litter	5–20	Labile soil carbon, active pool, decomposable plant materials (low C:N ratio, low lignin), resistant plant material (high C:N ratio, high lignin
		Macro-organic material		
		Light fraction		
	Dissolved organic matter		0.1	
	Humus	Non humic	65–80	Slow soil carbon
		Humic		
	Inert organic matter	Charcoal and biochar	1–5	Passive soil carbon, inert organic material

enhancement and amelioration of physical, chemical, biological, and fertility aspects of the soil (Table 7.1).

7.2 Effect of Soil Organic Matter on Soil Physical Properties

7.2.1 Soil Structure and Aggregate Stability

Soil structure stability indicates the resistance of soil to structural arrangement of particles and to different stresses (compaction/trampling, cultivation, and irrigation). Soil structure is the most important property influencing biological, chemical, and physical processes within soil, such as determining water and nutrient movement, air accessibility, seedling emergence, root penetration, resistance to erosion, and soil drainage (Sandin et al. 2017; Toosi et al. 2017; Jozefaciuk et al. 2015; Mehmood et al. 2019). The soil structure is a property which can be greatly influenced and manipulated by organic agriculture management practice. The organic matter has been associated with improved soil structure through the production of organic acids, biodiversity improvement, chelates, and increased earthworm population (Pylak et al. 2019; Bongiornoa et al. 2019; Moos et al. 2016; Kravchenko et al. 2015; Peng et al. 2015; Regelink et al. 2015). The amount of water stable aggregate is connected to macro-aggregate stability and positively related with labile organic carbon. A minimum of 2% soil organic carbon is necessary to maintain soil structure stability (Liu et al. 2013; Celik et al. 2010; Huang et al. 2010). The concept of soil aggregation and soil structure involving different binding agents have been revealed by the work of many researchers. Fine network of roots and hyphae in soil with high soil organic matter held together large aggregates (200 micron), while as aggregates above this size are held by organic cementing agents. Water stable aggregates of 2–20 micron are bound by living and dead bacterial cells. The idea of aggregate hierarchy reveals that organic matter controls aggregate stability and destruction of large aggregates creating smaller and more stable aggregates (Keller and Håkansson 2010; Moni et al. 2010; Kaiser and Guggenberger 2003; Christensen 2001; Oades 1984). Particulate organic matter acts as a substrate for microbial activity, enhancing the production of microbial bonding material. Fresh and active part of soil organic matter (mono, polysaccharides, exudates, fungal hyphae, and roots) are largely responsible for soil aggregation (De Curtis et al. 2019; Frąc et al. 2018; Plaza-Bonilla et al. 2013; Miao et al. 2009). There has been seen a positive relationship between organic farming systems using FYM, compost, vermicompost, sewage, and sludge with the aggregate stability.

7.2.2 Soil Compaction

Bulk density is an indicator of soil compaction and affects infiltration, soil porosity, plant nutrient availability, available water capacity, and soil microbial activity (Karlen et al. 2019; Nunes et al. 2019; Laiho et al. 2004; Aşkın and Özdemir 2003). The soil compaction is regarded as the most serious problem caused by conventional agriculture and the most difficult type to determine, as it shows no evident marks on the surface (Meurer et al. 2018; Masto et al. 2007; Håkansson and Lipiec 2000). The effects of soil compaction on soil properties are very complex and the state of soil compactness is evident soil attribute and determined mostly by the bulk density and soil strength (Singh et al. 2014; Hati et al. 2007). The bulk density and soil strength gives the direct comparable value of soil compactness. Soil organic matter retains soil water, thus helping the soil to overcome the problem of soil compaction. The adequate amount of organic matter in the soil stabilizes soil structure and makes it more resistant to soil degradation and also decreases the bulk density and increases soil strength (Das et al. 2018; Gharahi-Gheni et al. 2012; Heuscher et al. 2005; Calhoun et al. 2001; Han et al. 2012). The various mechanisms by which the organic matter influences the soil compaction are as follows: (a) binding of mineral particles to soil; (b) aggregate wet ability reduction; and (c) influencing the strength of soil aggregates, which is a measure of inter-particle bond. There has been a varying result between the soil organic matter and soil compactness and different researchers have reported different behavior for the different types of organic matter (Pravin et al. 2013). These differences seem to be due to different types of organic manure, C/N ratio of manure, and degree of resistance to degradation. Soil compactness is more influenced by readily oxidizable soil organic matter than the total organic matter. The organic farming system increases the organic matter in the soil and thus improves the bulk density of soil. Furthermore, using high quantity of organic manure or wastes decreases the bulk density of the soil due to a dilution effect caused by the incorporation of the added organic material with the denser mineral fraction of the soil (Almajmaie et al. 2017; Boizard et al. 2017; Guimarães et al. 2017). The plant residues are the common source of organic matter, but the farmers also use animal manures to reduce the soil compaction in the different organic farming systems (Avnimelech et al. 2001; Curtis and Post 1964; Huntington et al. 1989; Bhat et al. 2018a, b). The elasticity of the manure reduces the transmission of stress toward subsoil thus acting as a buffer to subsoil compaction. Incorporation of 50–100 t/ha of cattle manure in the silty clay loam top soils significantly reduces the effects of load 1–2 passes of 48.5 kW tractor (Mosaddeghi et al. 2000). Green or brown manure may not be an efficient source of nutrient for high-yielding environment, but acts as a beneficial practice in improving soil physical properties in compacted soils. Reddy (1991) observed a decrease in bulk density and soil strength of 0.02 Mg/m^3 and 11.8 kpa in the sandy loam soil due to the incorporation of 10 t/ha of green leaf manure. Incorporation of various organic matters in subsoils may prove a better alternative for stable retention in tackling soil compaction.

7.2.3 Soil Porosity

The architecture of soil refers to arrangement of soil particles and soil pores. The soil organic matter directly influences plant nutrition, penetration, and seedbed preparation, ease of cultivation, improved bulk density, greater aggregate stability, increased water holding capacity, and enhanced porosity (Xu et al. 2016; Ibrahim et al. 2013; Jack et al. 2011; Jarvis et al. 2007; Malkawi et al. 1999; Haynes and Naidu 1998). The organic carbon is mostly located in these pores between mineral grains as discrete particles or adsorbed on these particles. The soil porosity can influence the organic material stability through its effect on aggregate stability, isolation, and entrapment of decomposers and water and oxygen availability (Li et al. 2014; Masri and Ryan 2006). The changes in the pore size distribution are accompanied by the higher rates of organic matter mineralization at equivalent values of air-filled porosity. Rose (1991) studied that FYM not only changes aggregate stability but also affects the inter- and intramicro porosity. By the application of FYM and compost, both the micro porosity and macro porosity has increased (Pagliai and Vittori Antisari 1993). The increase in micro porosity occurs as a result of increase in elongated macropores of the newly formed aggregates. The effect of organic farming system can indirectly enhance soil porosity through the influence of soil fauna whose burrowing and feeding activity modify porosity (Park and Smucker 2005; McCallum et al. 2004). The various organic farming systems can also enhance the soil porosity by reducing soil crusting, clay dispersion, tillage, and compaction (Fig. 7.2).

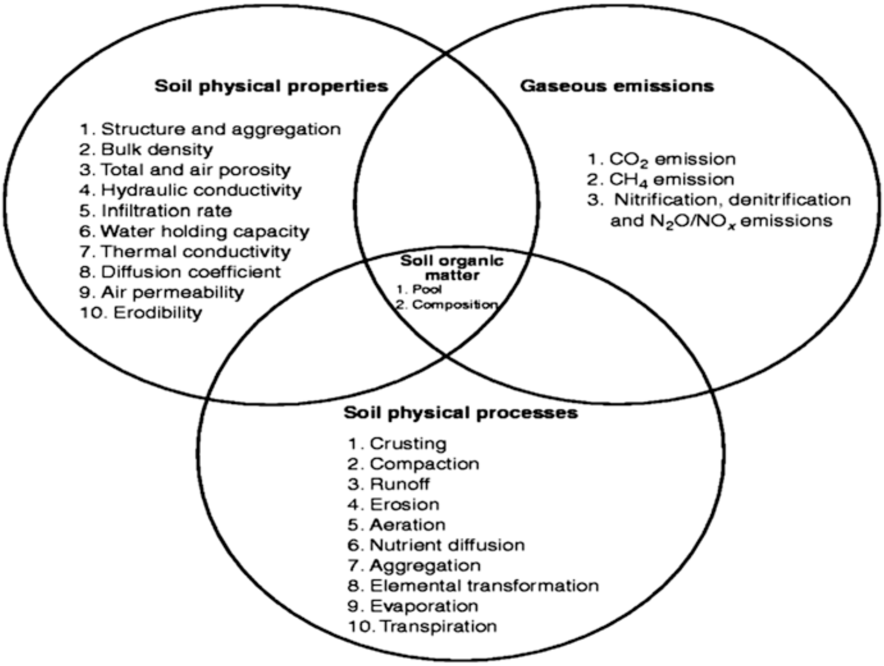


Fig. 7.2 Effect of soil organic matter on the soil's physical properties and processes

7.2.4 Soil Color

A strong relationship exists between soil color and many other important soil properties, including soil fertility mineral composition, soil organic matter soil drainage class, soil moisture, and land suitability (Ben-Dor et al. 2008; Barron and Torrent 1986; Alexander 1971; Brown and O'Neal 1923). The soil color is used to characterize, classify, and differentiate soils. The most convenient way to determine soil color is by the Munsell color chart. The soil color determines the pedogenic process in soil and the most important soil pigmenting agents are organic matter, iron, and manganese (Erskine 2013; He et al. 2003; Ketterings and Bigham 2000). The application of soil organic matter darkens the soil. The concept of Russian chernozem and Mollisol shaving the high organic matter are mostly defined by relative thick, dark surface horizons. The dark brown soils having high amount of soil organic matter are generally considered as an ideal soil. Within similar soil textural class and landscape, the soil color and soil organic matter has a good linear correlation (Ertlen et al. 2015; Kirillova et al. 2015; Kweon et al. 2013; Li et al. 2012; Ertlen et al. 2010; Gao and Xia 2009). The dark color soil having high amount of the organic matter applied by various organic farming systems holds a large amount of water, absorbs more radiation, and affects heat transfer (Sánchez-Marañón et al. 2011; Ketterings and Bigham 2000). The relationship between burned soil color, soil fertility, and fire severity found that color and chroma decreased with increasing heat severity due to decrease of soil organic matter and the soils appeared red, while the light heated soils appeared black due to incomplete burning of soil organic matter (Valeeva et al. 2016).

7.2.5 Water-Holding Capacity

An important soil physical characteristic is the capacity of the soil to supply and store water and air for plant growth. Soil's water holding capacity is the ability of the soil to store water. The soil organic matter increases the water holding capacity of the soil. The effect of organic matter on the water holding capacity is generally assumed to be positive (Ankenbauer and Loheide 2017; Basche et al. 2016; Jordán et al. 2010; Franzluebbers 2002; Bauer 1974; Jamison and Kroth 1958). An increase of 50% water content with per gram addition of organic carbon at −10 kpa suction (Emerson and McGarry 2003; Haynes and Naidu 1998).

The soil organic matter can enhance the hydraulic conductivity by improving the aggregate stability and porosity of the soil (Yang et al. 2014; Xu 2014). The organic manures reduce the compactness of soil, therefore improving water penetration. The effect of organic matter was more pronounced in the coarse-textured soil, followed by medium textured soil, and then the fine soils (Haynes and Naidu 1998). Several researchers have reported that, with an increase of soil organic matter, there is an increase of water holding capacity at both field capacity and wilting point (Sohail-Ur-Raza et al. 2015; Wang et al. 2015; Evrendilek et al. 2004; Matsi et al. 2003). The water holding capacity of soils is mainly dependent on the number of pores and specific surface area of soil. Both these pores and the specific surface area are increased by the application of organic matter. The increased water holding capacity is basically the result of an increase in the number of smaller pores at lower tension (Gülser et al. 2015; Hati et al. 2007; Khaleel et al. 1981). At higher tensions, all the pore space in the soil is filled by air and the water is retained mainly due to specific surface area and the thickness of water film on these surfaces.

7.2.6 Soil Thermal Properties

Soil thermal properties are considered a function of soil organic matter and soil carbon pool. Soil organic matter alters the thermal properties of soil because of its black dark nature. The albedo of soil gets reduced by the potential increase of dark color and more heat gets absorbed. The soils with least organic matter have albedo value of 0.6, while soils with 5% organic matter have albedo value of 0.08. At least, a soil organic matter of 2.5–3.0% is considered significant (Bi et al. 2018; Di Sipio and Bertermann 2018; Cai et al. 2017; Hortensia et al. 2018; Dębska et al. 2016).

Table 7.2 Thermal characteristics of the various soil constituents

Soil constituents	Density	Specific heat capacity	Volumetric heat capacity	Thermal conductivity
	kg/m^3	kJ/kg/°C	kJ/m^3/°C	W/m/°C
Quartz	2.7 × 103	0.8	2 × 103	8.8
Clay minerals	2.7 × 103	0.8	2 × 103	2.9
Water	1.0 × 103	4.2	4.2 × 103	0.6
Air 20 °C	1.2	1	1.2	0.025

The soil organic matter also affects the actual thermal properties of soil, including both its storage and flow of heat (Table 7.2).

The soils with good amount of organic matter have ample germination and higher crop growth because of the favorable temperature. The soil organic matter has substantially different physical characters in view of other soil constituents and with the increase in the soil organic matter the potential change in the soil thermal properties occurs (Bi et al. 2018; Wardani and Purqon 2016; Mondal et al. 2015; Usowicz et al. 2013; Tarnawski et al. 2009). Soil organic matter has the direct effect on the bulk density, which later affects heat conductivity and capacity of the soil. Mostly increase in the soil organic matter decreases the thermal conductivity and the wet soils have higher heat capacity and require lot of heat to raise its temperature. The wet soils are considered to have higher thermal conductivity than the organic and other soils.

7.2.7 Soil Infiltration and Percolation

The soil organic matter influences the infiltration or the admittance of water into a soil, and percolation, or the descendent movement of water, in a soil. The rate of infiltration depends on soil structure, developed soil horizon, soil slope, soil texture, depth of water table, chemical content of water, rate of water applied, and the amount of organic matter. Initially, in any soil, the infiltration rate is higher and then decreases with time (Basche and DeLonge 2019; Korucu et al. 2018; Loecke et al. 2017; Haghnazari et al. 2015). The important characteristic of soil affecting the soil infiltration is porosity of soil. The organic matter has a direct impact on the soil porosity and as the soil organic matter increases the porosity of the soil is also enhanced. The rate of infiltration reduces with time due to deflocculation and breakdown of the peds. The soil organic matter enhances soil aggregate stability and thus allows the greater rate of infiltration. Initial infiltration is higher, but the later infiltration is sometimes superior if there are no macropores on the surface and the soils have good aggregate stability and no surface crusting (Zeng et al. 2019; Acharya et al. 2018; Chavarria et al. 2018; Rodrigo-Comino et al. 2018; Diadin et al. 2018;

Balázs et al. 2018). In the tropics and semi tropics, the infiltration rate is more dependent on hydrous oxides and clay minerals because of having mineral origin of aggregates. In the humid and temperate zones, the infiltration depends on the soil organic matter because the stability of aggregates largely depends on the soil organic matter. The rate of infiltration varies from 0.1 to 5 inches per hour and the general infiltration rate varies from 0.3 to 1.0 inch per hour. The large amount of crop residues, mulches, and soil surfactants can regulate good infiltration rate by breaking droplet size of the rain water.

Percolation or downward movement of water is reliable on uninterrupted pore space in soil. For every doubling of pore size diameter, the rate of percolation in the soil increases by four times. The other factors affecting percolation rate are soil texture, soil structure, soil compaction, and amount of organic matter present. The soil temperature, soil moisture, and depth of soil horizons also affect the percolation rate (Issaka et al. 2018; Bullard et al. 2018; Jakab et al. 2017; Di Prima et al. 2017). The percolation of soil is restricted by the insufficient pans, clay pan, fragipans, plow pans, hard pans, and the presence of higher water table (Gómez et al. 2017; López-Vicente et al. 2016). In general, the percolation rate is considered higher in sandy soils, but the light soils having well stable soil aggregates, good soil structure, and high amount of organic matter have higher percolation rates than the fine sands. Mulches, crop residues, compost, FYM, and other organic soil amendments increase the soil macropores, thus increasing the percolation rate in the soil (Hlavčová et al. 2019; Gómez et al. 2018; Ben-Salem et al. 2018; Lucas-Borja et al. 2018; Fortugno et al. 2017).

7.3 Soil Chemical Properties

7.3.1 Buffering Capacity and Soil pH

Buffering capacity of soil is an important aspect as it assures the stability of soil pH. The buffering capacity of soil is the resistance to change in pH when an acid or base is added. At the pH value between 5 and 7.5, soil organic matter and clay acts as a sink for H and OH and the buffering capacity is governed by exchangeable reaction (Yuan et al. 2011; Nelson and Su 2010; Zhang et al. 2008; Herre et al. 2007). The presence of various functional groups (amine carboxylic, alchoal, phenolic, and amide) in soil organic matter allows it to act as a buffer over a wide range of soil pH (Sohi et al. 2010; Larney et al. 2008). The organic rich surface soils have higher buffering capacity than the mineral soils. James and Riha (1986) reported the buffering capacity of 18–36 $\mathrm{Cmol_c/kg}$ in the forest soils and 1.5–3.5 $\mathrm{Cmol_c/kg}$ in the mineral soils. Bloom (1999) studied that soil organic matter has a buffering capacity of 200 $\mathrm{Cmol_c/kg}$, while buffering capacity of soil organic carbon was reported 300 times in comparison to kaolonite. Cayley et al. (2002) recorded a good relationship between the buffering capacity and soil organic matter and the importance of soil organic matter to maintain soil pH despite certain acidifying factors. A strong correlation existed between initial soil pH value and the buffering capacity of subsurface horizon, and the highly acidic soils were better buffered than less acidic soils (Curtin and Trolove 2013; Lieb et al. 2011; Bowman et al. 2008; De Vries et al. 1989; Bhat et al. 2018a, b). The soils are poorly buffered between 4.5 and 6.5 and well buffered below 4 and above 7. A number of researchers have studied the relationship between soil organic matter and soil pH. The decomposition of young shoots of trees in Ultisols and Oxisols increased soil pH and decrease in exchangeable aluminum content and the acid neutralization was due to aluminum and proton complexation by the organic anions (Wong et al. 2000; Tian et al. 1992; Hue 1992; Vallis and Jones 1973). The under saturation of aluminum adsorption would result in 3 mol of protons consumed for each mol of aluminum dissolved. The aluminum dissolution by the organic anions would result in proton consumption and the pH increase. The pH increase is not the primary cause for the decrease of soluble and exchangeable aluminum, but also due to adsorption of these substances on soil organic matter (Luo et al. 2015) The soil organic matter and the exchangeable aluminum has a negative correlation at greater depths and the effect of soil organic matter was greater at lower pH values. The relationship of soil organic matter and pH was studied when different type of plant material was incubated in top soil and there occurred increase in pH_{kcl} in a few days and the magnitude of which depends on type of soil organic matter and rate of application. The organic anions (malate, citrate, oxalate) balance the plant derived cations and the oxidation of anions consumes H^+ ion and the release of OH^- ion (Najafi and Jalali 2016). When the decomposed organic matter is added to the soil there is rise in pH due to complexation of proton by organic anion. If the undecomposed organic matter is added, the rise in soil pH is due to decarboxylation of organic anions during microbial decomposition. The decomposition of organic matter will transfer organic nitrogen to ammonia and releases OH^- and results in increase in soil pH (Zhang et al. 2013; Qin et al. 2013; Galloway et al. 2008; Ju et al. 2004). The specific adsorption of soil organic matter onto the aluminum and iron hydroxides results in release of OH^- ion. The long-term effect of organic matter increases soil pH as there occurs accumulation of humic material which complexes with aluminum compounds and decreases their solubility and protects soil from toxicity.

7.3.2 Cation Exchange Capacity

Cation exchange capacity of soil is the measure of exchangeable cations that soil can hold and represents negative charge per unit mass of soil. Soils with high cation exchange capacity is favorable as it holds many plant nutrients and this cation exchange capacity is expressed as centimol of positive charge per kilogram of soil (Soares and Alleoni 2008; Wiseman and Puttmann 2006; Adams and Evans 1979). The soils are having two charges: permanent charge CEC_P and pH-dependent charge CEC_v which depends on pH and the soil organic matter (Bache 1976; Bascomb

1964). The addition of organic matter generally causes increase in CEC_v and this increase is due to the presence of certain functional groups in the soil organic matter. The organic compounds with high molecular weight contribute less to cation exchange capacity compared to low molecular weight compounds (Alburquerque et al. 2014; Asai et al. 2009; Bonfante et al. 2010; Das and Varma 2011; McClellan et al. 2007; Lehmann and Rondon 2006). The contribution of soil organic matter to CEC is in the range 25–90% and the variation is mainly due to presence of functional group in soil organic matter and the soil type. There is a greater increase due to addition of soil organic matter to the cation exchange capacity in the coarse-textured soils than the medium- and fine-textured soils. Due to the addition of soil organic matter to mineral soil, there is greater increase of cation exchange capacity than in the surface soil (Schulz and Glaser 2012; Kammann et al. 2011; Peng et al. 2011). The soil organic matter has a cation exchange capacity of 150–250 Cmol(p^+) kg^{-1} and in the arable calcareous soil with high organic matter, the cation exchange capacity ranges from 230 + _ 47 (Wolf and Snyder 2003). In sandy forest soils, soil organic matter contribution to cation exchange capacity is very high in comparison to Vertisols derived from basalt. Stevenson (1982) worked on several laboratory methods to determine the relationship between soil organic matter and cation exchange capacity. The regression equation was developed for predicting the relationship between soil organic matter and cation exchange capacity (Hallsworth and Wilkinson 1958). The cation exchange capacity of soil organic matter varies and it depends on type of functional group present in soil organic matter and the pH of soil. The measure source of negative charge that contributes to cation exchange capacity is the carboxylic groups. The cation exchange capacity of soil organic matter in acid soils was estimated to be 134 Cmol(p^+) kg^{-1} and in chernozem it ranged upto 297 Cmol(p^+) kg^{-1}. The potential sites for cation exchange in soil organic matter are more than the measured as the many sites become unavailable due to the association with polyvalent cations (Table 7.3).

Table 7.3 Cation exchange capacity ($cmol_c\ kg^{-1}$) of the various soil constituents

Soil constituents	Capacity ($cmol_c\ kg^{-1}$)
Kaolinite	1–5
Fe and Al oxides and hydroxides	5–40
Illite	20–40
Allophane/imogolite	20–50
Smectite	80–150
Vermiculite	150–200
Soil organic matter	>200

7.3.3 Adsorption and Complexation

Adsorption reaction due to soil organic matter are dependent mostly on pH as well as cation exchange capacity because similar types of organic carbon species are involved in adsorption reaction (Ahmed et al. 2015; Figueroa-diva et al. 2010; Frossard et al. 2002; Jones and Edwards 1998). The presence of functional groups (COOR, NH_2, OH, NHR, $CONH_2$) are very important for adsorption of ions on humus particles (Wu et al. 2012). The important mechanism for protection of soil organic matter from decomposition is its adsorption with clay particles. The positive relationship between soil organic carbon, clay content and soil surface area illustrates the significance of adsorption of soil organic matter on to the clay particles (Schaumann 2006; Schulten 2002). The interaction of soil organic matter with clay is governed by nature of soil organic matter and type of clay present. The interaction between soil organic matter and positively charged ions is through cation exchange reaction (between positively charged cation and negatively charged carbon group) (Cheng et al. 2014; Schwarz et al. 2012; Ghosh et al. 2000). The complexation of soil organic matter with inorganic material enhances the soil fertility as it increases the availability of soil phosphorus by blocking iron, aluminum, and calcium adsorption sites. Soil organic matter decreases the phosphorus adsorption in oxisols and the greater phosphorus adsorption was observed in cultivated soils (800 mgP/kg) than forest soils (560 mgP/kg) and it is attributed to greater amount of soil organic carbon in the forest soils (Bai et al. 2012). With the exception of few non-crystalline minerals, soil organic matter has the greatest capacity to form bonds with metals and it is associated by a positive association between solubility of metals with soil organic matter content as well as to high amounts of trace metals in organic rich soils compared with the non-organic soils (Sparks 2003). The increased concentration of soil organic matter decreases the concentration of cupric, zinc, and manganese in soil solution and also decreases the extraction of calcium by calcium chloride and acetic acid. The adsorption of copper was much stronger than zinc and manganese in the peat, solid humic acid, and acid washed peat (Klucakova 2012; Barancikova et al. 2003). The organic manures reduce the aluminum toxicity and increases the phosphorus availability and the important organic carbon groups in this complex reaction were low molecular weight aliphatic organic acids and soluble humic molecules as it complexes with the monomeric aluminum. The formation of complexes between polyvalent metal ions and humic substance is due to O-containing functional groups (enolic, phenolic, alcoholic, and carboxylic) as hydroxyl there is also the decreases the sorption of chlorinated aliphatic hydrocarbons and low molecular weight organic acids (fumaric, lactic, oxalic, citric, tartaric, propionic, butyric, acetic and formic acid) which are derived from leaves and from microbial biomass and also forms complex with AL^{3+}. Hydroxyl acids form stronger complexes than carbon groups. The presence of these functional groups in soil organic matter does not only determine sorption capacity but also have certain synergistic effects, such as aromaticity, polarity, and hydrophobicity.

7.4 Soil Biological Properties

7.4.1 Soil Organic Matter as a Driver of Biological Activity

The fundamental function of organic farming system is to supply high amounts of organic matter which provides metabolic energy and drives soil biological process. In the organic farming systems, there is basically the transformation of carbon compounds by macro and microorganisms and plants that provide energy and connects above and below surface energy by the formation of a cycle (Rossiter and Bouma 2018; Wade et al. 2018; Roper et al. 2017; Bonfante and Bouma 2015; Tiquia 2005). The plants assimilate carbon from atmosphere and form glucose and other complex plant biomolecules which, upon plant senescence, enter the soil through roots, litter, and root exudates (Zhang 2013; Zuber et al. 2018; Bashir et al. 2016). The plants supply energy to heterotrophs and, to a less extent, to chemotrophs (microbes, fungi, and earthworms) by the formation of recalcitrant organic matter (Adeniji and Babalola 2019) The carbon source acts as a source of energy and as long as net primary production exceeds respiration the organic carbon will accumulate in the soil (Miranda et al. 2019; Oburger and Jones 2018; Conrad et al. 2018; Mahanty et al. 2014; Dijkstra et al. 2013). The different organic farming systems provide various amounts of soil organic matter in soil, which reflects the balance between carbon produced and carbon leached (Gopalakrishnan et al. 2015). This balance occurs due to energy requirement of biota and is governed by certain factors (temperature, clay content, moisture, humidity, and rainfall). The transformation of labile soil organic matter into more complex form, that is, humus stabilizes this soil organic matter and can be used as a source of energy for longer period in an edaphic environment. The energy released from the soil organic matter decomposition is in the form of heat and the heat losses from 1 hectare is nearly equal to heat value of 1 metric ton coal and the highly productive organic matter soil releases heat of about 12 megagram of coal annually. The soil microorganisms play an immense role in the transformation of organic matter as these microbes carry 80–90% of total soil metabolism (Fernández-Gómez et al. 2019; Cui et al. 2019; Lamprecht et al. 2018; Pascual et al. 2018; Shen et al. 2014). The 1–5% of nitrogen and carbon are being preserved in the microbial tissue. A concept of microbial catabolic evenness (CE) was introduced by Degens et al. (2000) to measure soil microbial diversity by short term respiration response of soil over a certain range of organic compounds. They found a direct relationship between microbial catabolic evenness and soil organic pools and reported higher (CE) in pastures followed by agriculture and horticultural crops and the least was reported in the arable soils (Yuan et al. 2014). It was also found that, with the depletion of soil organic matter or carbon stock, there was greater decline in the microbial catabolic evenness.

7.4.2 Soil Organic Matter and Soil Microbial Population

Soil is species rich habitat on earth having diverse and abundant species which help in the formation and development of soil. The soil biodiversity is indicator of soil health, as greater biodiversity means greater soil stability in terms of certain functions, such as maintenance of soil structure, assimilation of organic wastes, and nutrient cycling (Miranda et al. 2019; Oburger and Jones 2018; Conrad et al. 2018; Mahanty et al. 2014; Bashir et al. 2016; Shen et al. 2014; Dijkstra et al. 2013; Wang et al. 2012; Bhatti et al. 2017). Soil organic matter, soil organic carbon, and soil biodiversity are closely related but distinct. Biodiversity means residing of certain organisms, such as bacteria, fungi, actinomycetes, protozoa, worms, vertebrates, and invertebrates (Oburger and Jones 2018; Conrad et al. 2018). All these organisms depend on soil organic matter for their energy, nutrients, and habitat. The topmost soil of earth, where concentration of organic matter and roots are higher, forms the largest habitat for these organisms (Bashir et al. 2016). A vast diversity of the organisms is present in the soil but only limited microorganism has been explored (Table 7.4).

7.4.3 Soil Enzyme Activity and Soil Organic Matter

Soil enzymes play a key role in organic matter decomposition and its recycling, with their activities being closely related to microbial activity, microbial biomass, soil physical property, and soil organic matter (Oburger and Jones 2018; Mahanty et al. 2014; Bashir et al. 2016; Dijkstra et al. 2013). These enzymes are either intracellular or extracellular, with intracellular being inside the cell in the cytoplasm bound by the cell wall. The extracellular enzymes are permanently immobilized and are being released into the soil on humic and clay colloids through hydrogen bonds, ionic bonds, covalent bonds, and other mechanism. These soil enzymes act as catalyst for decomposition of organic matter and effect agronomic production, environmental quality, and energy transformation (Wade et al. 2018; Rossiter and Bouma

Table 7.4 Number of species of soil flora and fauna and the percent explored from the soil

Group	Known species	Estimated total species	% known
Bacteria	13,000	1,000,000	1
Fungi	18,000–35,000	1,500,000	1–2
Protozoa	1500	200,000	7.5
Nematodes	5000	400,000	1.3
Ants	8800	15,000	58.7
Termites	1600	3000	53.3
Earthworms	3600	No estimate	No estimate
Mites	20,000–30,000	900,000	2.2–3.3
Collembola	6500	24,000	27.1

2018; Roper et al. 2017; Bonfante and Bouma 2015). Soil enzymes are considered best soil detectors because they respond to the soil sooner than physical and chemical parameters.

7.4.4 Soil Organic Matter as Important Nutrient Source

In considering the importance of organic matter as source of nutrients, it is to be mentioned that soil formation is closely related to diverse forms of organic substance on parent material. Soil organic matter provides all the essential nutrients, including primary nutrients such as nitrogen, phosphorus, and sulfur and micronutrients such as iron, manganese, zinc, copper, boron, molybdenum, and chlorine (Nurhidayati et al. 2018; Pravin et al. 2013; Masto et al. 2007; Laiho et al. 2004; Katyal et al. 2001). These nutrients are being made available during mineralization of organic matter during their growing season and the important fraction of soil organic matter fraction which supplies nutrients is particulate organic matter. Ninety percent of soil organic matter is made of carbon, hydrogen, and oxygen, while 50% of remaining elements is made of nitrogen, potassium, and silicon (Gwenzi et al. 2016; Haynes and Naidu 1998; Mahanty et al. 2014; Moco et al. 2009; Reeves 1997; Steller et al. 2008; Stevenson 1994; Von Lutzow et al. 2005). However, the application of fertilizers supplies a major nutrient available to plants, but the organic matter along with the soil microbes, store and cycle large amounts of nutrients required for growth (Liu et al. 2009). Most of the nutrients held in the soil organic matter are not easily assessable to plants and are resistant to decomposition. Only 1–5% of the soil organic matter is decomposed annually and it takes almost a decade for its complete decomposition (Molina-Herrera and Romanya 2015; Haynes and Naidu 1998). Soil organic matter acts as larger reservoir of macronutrients with 90–95% nitrogen and sulfur and 20–75% phosphorus. The 90–95% nitrogen is held in both available and fixed form. The 40–45% of organic nitrogen is quantified and identifiable as amino-sugars and amino acids and the remaining portion consists of unidentifiable structure. The soil Sulfur in organic form is mainly in the form of amino-acids, such as cysteine, cystine, and methionine. Phosphorus is mainly present in ester form and nitrogen is covalently bonded to C–S or C–O–S. The process of net phosphorus mineralization occurs if ratio of C:P is less than 100, whereas ratio of greater than 300 indicate net immobilization. The soil organic matter has impact on phosphorus availability through specific adsorption reaction because the humic fraction shows competitive character on oxide surfaces (Zhao et al. 2019; Liu et al. 2009; ErdalSakin 2012; Gama-Rodrigues et al. 2008; Geeves et al. 1995; Lal 2011; Zhang et al. 2006; Madejón et al. 2003; Powlson et al. 2001). Mineralization and transformation of organic source of phosphorus occur through extracellular hydrolysis or by the oxidation of organic carbon. Decrease in the soil organic carbon pertains to reduced nutrient supply and less than 1% organic matter is considered a threshold value below which there is no nutrient supply. The release of NPS from organic matter depends upon ratio of these elements to carbon. A narrow ratio of these elements to carbon usually allows fast nutrient release and a wide ratio reduces their availability (Guan et al. 2019; Hu et al. 2019; Ma et al. 2019; Cai et al. 2018). There are various schools of thought pertaining to nutrient status of soil organic matter, including its C:N:P:S with ratio of 100:10:1:1, 155:10:0.68:1.4, and 140:10:1.4:1.4. C:N:S ratio in the agricultural soils vary from other soils due to higher carbon mineralization of carbon and greater fertilizer input.

In view of the macronutrients, soil organic matter forms a number of chelates that make metal nutrient elements available over a wide range of pH. The micronutrient chelation has greater significance because of the nature of these elements to become fixed in high pH soils. The most chelates formed in the soil are of iron, copper, and zinc. In the plant's heme group forms the most common chelates, including chlorophyll and iron porphyrin. Oxalic and malic acids are reported to have high chelating properties. The root exudates and complex organic matter form the chelates that remain available to plants for a longer period. Ketogluconic acid has been reported as a highly chelating agent, but probably there are more chelating agents formed by organic matter (Shi et al. 2018; Du et al. 2018; Zhou et al. 2018; Liu et al. 2017; Hu et al. 2016; Guo et al. 2015; Wiatrowska et al. 2013). The organic matter supplied to high pH soils forms chelates and corrects lime-induced chlorosis. The carbon dioxide favors bicarbonate formation, which decreases iron uptake and translocation within plants.

7.5 Conclusion

The diverse nature of soil organic matter plays a defining role in determining the dimensions of various soil processes and properties, including its physical, chemical, and biological properties. This chapter revealed that interaction of soil organic matter with soil properties is very complex. The soil organic matter is considered as an important soil health indicator, as most of the soil properties depend on it. Almost all the soil properties were strengthened with the increase in the soil organic matter. The increase in soil organic matter had clear impact on the soil structure, water retention, thermal conductivity, available water capacity, zeta potential, exchangeable cations, soil fertility, erodibility, infiltration, soil aggregate formation, soil color, soil compaction, soil aeration, pH, buffering capacity, CEC, base saturation, and microbial population. The soil organic matter is an important factor in nutrient cycling, nutrient supply, especially nitrogen, phosphorus, sulfur, and micronutrients. The soil organic matter was more dominant where clay content was low. The important conclusion was that, with the addition of soil organic matter, we can improve many soil properties simultaneously. The certain issues that need to be readdressed in future are as follows: (a) application of soil organic matter to enhance soil health, (b) integrated nutrient management for sustainable agriculture, (c) carbon sequestration for mitigating climate change, and (d) organic residues management concerning recycling and environmental protection.

References

Acharya BS, Kharel G, Zou BP, Wilcox CB, Halihan T (2018) Woody plant encroachment impacts on groundwater recharge: a review. Water 10:1466

Adams JM, Evans S (1979) Determination of the cation-exchange capacity (layer charge) of small quantities of clay minerals by nephelometry. Clay Clay Miner 27:137–139

Adeniji AA, Babalola OO (2019) Phylogeny, useful applications, and avenues for exploitation. Appl Microbiol Biotechnol 103:3669–3682

Ahmad R, Jilani G, Arshad M, Zahir ZA, Khalid A (2007) Bio-conversion of organic wastes for their recycling in agriculture: an overview of perspectives and prospects. Ann Microbiol 57(4):471–479

Ahmed AA, Thiele-Bruhn S, Aziz SG, Hilal RH, Elroby SA, Al-Youbi AO, Leinweber P, Kühn O (2015) Interaction of polar and nonpolar organic pollutants with soil organic matter: sorption experiments and molecular dynamics simulation. Environ Sci Technol 508:276–287

Ajayi AE, Horn R (2017) Biochar-induced changes in soil resilience: effects of soil texture and biochar dosage. Pedosphere 27:236–247

Alburquerque JA, Calero JM, Barrón V, Torrent J, del Campillo MC, Gallardo A, Villar R (2014) Effects of biochars produced from different feedstocks on soil properties and sunflower growth. J Plant Nutr Soil Sci 177(1):16–25

Alexander JD (1971) Color chart for estimating organic carbon in mineral soils in Illinois. Bull. AG-1941. Univ. of Ill. Coop. Ext. Serv., Champaign

Alfreider A, Peters S, Tebbe CC (2002) Microbial community dynamics during composting of organic matter as determined by 16S ribosomal DNA analysis. Compost Sci Util 10:303–312

Almajmaie A, Hardie M, Acuna T, Birch C (2017) Evaluation of methods for determining soil aggregate stability. Soil Tillage Res 167:39–45

Angin I, Aksakal EL, Oztas T, Hanay A (2013) Effects of municipal solid waste compost (MSWC) application on certain physical properties of soils subjected to freeze- thaw. Soil Tillage Res 130:58–61

Ankenbauer K, Loheide SP (2017) The effects of soil organic matter on soil water retention and plant water use in a meadow of the Sierra Nevada, CA. Hydrol Process 31:891–901

Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Horie T (2009) Biochar amendment techniques for upland rice production in Northern Laos: soil physical properties, leaf SPAD and grain yield. Field Crop Res 111(1):81–84

Aşkın T, Özdemir N (2003) Soil bulk density as related to soil particle size distribution and organic matter content. Agriculture 9(2):52–55

Avnimelech Y, Ritvo G, Meijer LE, Kochba M (2001) Water content, organic carbon and dry bulk density in flooded sediments. Aquac Eng 25:25–33

Bache BW (1976) The measurement of cation exchange capacity of soils. J Sci Food Agric 27:273–280

Bai E, Boutton TW, Liu F, Wu XB, Hallmark CT, Archer SR (2012) Spatial variation of soil δ13C and its relation to carbon input and soil texture in a subtropical lowland woodland. Soil Biol Biochem 44:102–112

Balázs B, Bíró T, Dyke GJ, Singh SK, Szabó SZ (2018) Extracting water-related features using reflectance data and principal component analysis of Landsat images. Hydrol Sci J 63:269–284

Balesdent J, Chenu C, Balabane M (2000) Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res 53:215–230

Barancikova G, Klucakova M, Madaras M, Makovnikova J, Pekar M (2003) Chemical structure of humic acids isolated from various soil types and lignite. Humic Subst Environ 3:3–8

Barron V, Torrent J (1986) Use of the Kubelka-Munk theory to study the influence of iron oxides on soil color. Eur J Soil Sci 37:499–510

Basche AD, DeLonge MS (2019) Comparing infiltration rates in soils managed with conventional and alternative farming methods: a meta-analysis. PLoS One 14(9):0215702

Basche AD, Kaspar TC, Archontoulis SV, Jaynes DB, Sauer TJ, Parkin TB (2016) Soil water improvements with the long-term use of a winter rye cover crop. Agric Water Manag 172:40–50

Bascomb L (1964) Rapid method for the determination of the cation exchange capacity of calcareous and non-calcareous soils. J Sci Food Agric 15:821–823

Bashir O, Kamran K, Khalid RH, Naseer AM, Rather GH, Mohiuddin R (2016) Soil microbe diversity and root exudates as important aspects of rhizosphere ecosystem. In: Plant, soil and microbes. Springer International Publishing, Cham, pp 337–357

Bauer A (1974) Influence of soil organic matter on bulk density and available water capacity of soils North Dakota Agricultural Experimental Station. Farm Res 31:44–52

Beck-Broichsitter S, Fleige H, Horn R (2018) Compost quality and its function as a soil conditioner of recultivation layers – a critical review. Int Agrophys 32:11–18

Ben-Dor E, Heller D, Chudnovsky A (2008) A novel method for classifying soil profiles in the field using optical means. Soil Sci Soc Am J 72:1113–1123

Ben-Salem N, Álvarez S, López-Vicente M (2018) Soil and water conservation in rainfed vineyards with common sainfoin and spontaneous vegetation under different ground conditions. Water 10:1058

Bezuglova OS, Gorovtsov AV, Polienko EA, Zinchenko VE, Grinko AV, Lykhman VA, Dubinina MN, Demidov A (2019) Effect of humic preparation on winter wheat productivity and rhizosphere microbial community under herbicide-induced stress. J Soils Sediments 19:2665–2675

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytother 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Bi J, Zhang M, Wu CW, Lu J, Lai Y (2018) A new model to determine the thermal conductivity of fine-grained soils. Int J Heat Mass Transf 123:407–417

Blanchet G, Gavazov K, Bragazza L, Sinaj S (2016) Responses of soil properties and crop yields to different inorganic and organic amendments in a Swiss conventional farming system. Agric Ecosyst Environ 230:116–126

Bloom PR (1999) Soil pH and pH buffering. In: Sumner ME (ed) Handbook of soil science. CRC Press, Boca Raton, pp B333–B352

Boizard H, Peigné J, Sasal MC, de Fátima Guimarães M, Piron D, Tomis V, Vian JF, Cadoux S, Ralisch R, Tavares Filho J, Heddadj D, De Battista J, Duparque A, Franchini JC, Roger-Estrade J (2017) Developments in the "profile cultural" method for an improved assessment of soil structure under no-till. Soil Tillage Res 173:93–103

Bonfante A, Bouma J (2015) The role of soil series in quantitative land evaluation when expressing effects of climate change and crop breeding on future land use. Geoderma 259–260:187–195

Bonfante A, Basile A, Acutis M, De Mascellis R, Manna P, Perego A, Terribile F (2010) SWAP, CropSyst and MACRO comparison in two contrasting soils cropped with maize in Northern Italy. Agric Water Manag 97:1051–1062

Bongiornoa G, Postma J, Bünemann EK, Brussaard L, de Goede RG, Mäder P, Tamm L, Thuerig B (2019) Soil suppressiveness to Pythium ultimum in ten European long-term field experiments and its relation with soil parameters. Soil Biol Biochem 133:174–187

Bowman WD, Cleveland CC, Halada Ĺ (2008) Negative impact of nitrogen deposition on soil buffering capacity. Nat Geosci 1:767–770

Brown PE, O'Neal AM (1923) The color of soils in relation to organic carbon content. Res Bull No. 75. Iowa State College of Agric. and Mechanic Arts, Ames

Bullard JE, Ockelford A, Strong CL, Aubault H (2018) Impact of multi-day rainfall events on surface roughness and physical crusting of very fine soils. Geoderma 313:181–192

Cai G, Liu S, Puppala AJ (2017) Investigation on thermal characteristics and prediction models of soils. Int J Heat Mass Transf 106:1074–1086

Cai X, Lin ZW, Penttinen P, Li YF, Li YC, Luo Y (2018) Effects of conversion from a natural evergreen broadleaf forest to a Moso bamboo plantation on the soil nutrient pools, microbial biomass and enzyme activities in a subtropical area. For Ecol Manag 422:161–171

Calhoun FG, Smeck NE, Slater BL, Bigham JM, Hall GF (2001) Predicting bulk density of Ohio soils from morphology, genetic principles, and laboratory characterization data. Soil Sci Soc Am J 65:811–819

Cayley JWD, McCaskill MR, Kearney GA (2002) Changes in pH and organic carbon were minimal in a long-term field study in the Western District of Victoria. Aust J Agric Res 53:115–126

Celik I, Gunal H, Budak M, Akpinar C (2010) Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. Geoderma 160:236–243

Chavarria DN, Pérez-Brandan C, Serri DL, Meriles JM, Restovich SB, Andriulo AE, Jacquelin L, Vargas-Gil S (2018) Response of soil microbial communities to agroecological versus conventional systems of extensive agriculture. Agric Ecosyst Environ 264:1–8

Cheng G, Zhu L, Sun M, Deng J, Chen H, Xu X, Lou L, Chen Y (2014) Desorption and distribution of pentachlorophenol (PCP) on aged black carbon containing sediment. J Soils Sediments 14(2):344–352

Christensen BT (2001) Physical fractionation of soil and structural and functional complexity in organic matter turnover. Eur J Soil Sci 52:345–353

Conrad KA, Dalal RC, Dalzell SA, Allen DE, Fujinuma R, Menzies NW (2018) Soil nitrogen status and turnover in subtropical leucaena-grass pastures as quantified by δ15N natural abundance. Geoderma 313:126–134

Cui Y, Bing H, Fang L, Wu Y, Yu J, Shen G et al (2019) Diversity patterns of the rhizosphere and bulk soil microbial communities along an altitudinal gradient in an alpine ecosystem of the eastern Tibetan Plateau. Geoderma 338:118–127

Curtin D, Trolove S (2013) Predicting pH buffering capacity of New Zealand soils from organic matter content and mineral characteristics. Soil Res 51:494–502

Curtis RO, Post BW (1964) Estimating bulk density from organic matter content in some Vermont forest soils. Soil Sci Soc Am Proc 28:285–286

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from Fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Das SK, Varma A (2011) Role of enzymes in maintaining soil health. In: Shukla G, Varma A (eds) Soil enzymology, Soil biology, vol 22. Springer-Verlag, Berlin Heidelberg

Das A, Lyngdoh D, Ghosh PK, Lal R, Layek J, Idapuganti RG (2018) Tillage and cropping sequence effect on physico-chemical and biological properties of soil in Eastern Himalayas, India. Soil Tillage Res 180:182–193

De Curtis F, Ianiri G, Raiola A, Ritieni A, Succi M, Tremonte P, Castoria R (2019) Integration of biological and chemical control of brown rot of stone fruits to reduce disease incidence on fruits and minimize fungicide residues in juice. Crop Prot 119:158–165

De Vries W, Posch M, Kämäri J (1989) Simulation of the long-term soil response to acid deposition in various buffer ranges. Water Air Soil Pollut 48:349–390

Dębska B, Długosz J, Piotrowska-Długosz A, Banach-Szott M (2016) The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration—results from a field-scale study. J Soils Sediments 16:2335–2343

Degens BP, Schipper LA, Sparling GP, Vojvodic-Vukovic M (2000) Decreases in organic C reserves in soils can reduce the catabolic diversity of soil microbial communities. Soil Biol Biochem 32:189–196

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Di Prima S, Bagarello V, Lassabatere L, Angulo-Jaramillo R, Bautista I, Burguet M, Cerda A, Iovino M, Prosdocimi M (2017) Comparing Beerkan infiltration tests with rainfall simulation experiments for hydraulic characterization of a sandy-loam soil. Hydrol Process 31:3520–3532

Di Sipio E, Bertermann D (2018) Thermal properties variations in unconsolidated material for very shallow geothermal application (ITER project). Int Agrophys 32:149–164

Diadin D, Vystavna Y, Vergeles Y (2018) Quantification of nitrate fluxes to groundwater and rivers from different land use types. Hung Geogr Bull 67:333–341

Dijkstra FA, Carrillo Y, Pendall E, Morgan JA (2013) Rhizosphere priming: a nutrient perspective. Front Microbiol 4:216

Du H, Huang Q, Peacock C, Tie B, Lei M, Liu X, Wei X (2018) Competitive binding of Cd, Ni and Cu on goethite organo-mineral composite made with soil bacteria. Environ Pollut 243:444–452

Emerson WW, McGarry D (2003) Organic carbon and soil porosity. Aust J Soil Res 41:107–118

ErdalSakin (2012) Organic carbon organic matter and bulk density relationships in arid-semi arid soils in Southeast Anatolia region. Afr J Biotechnol 11(6):1373–1377

Erskine WD (2013) Soil colour as a tracer of sediment dispersion from erosion of forest roads in Chichester State Forest, NSW, Australia. Hydrol Process 27:933–942

Ertlen D, Schwartz D, Trautmann M, Webster R, Brunet D (2010) Discriminating between organic matter in soil from grass and forest by near-infrared spectroscopy. Eur J Soil Sci 61:207–216

Ertlen D, Schwartz D, Brunet D, Trendel JM, Adam P, Schaeffer P (2015) Qualitative near infrared spectroscopy, a new tool to recognize past vegetation signature in soil organic matter. Soil Biol Biochem 82:127–134

European Environment Agency (2010). Annual report 2010 and Environmental statement 2011. European Environment Agency Kongens Nytorv 6 1050 Copenhagen K Denmark. file:///C:/Users/User/Downloads/Annual-Report-2010.pdf

Evrendilek F, Celik I, Kilic S (2004) Changes in soil organic carbon and other physical soil properties along adjacent Mediterranean forest, grassland, and cropland ecosystems in Turkey. J Arid Environ 59(4):743–752

Fedoseeva E, Stepanov A, Yakimenko O, Patsaeva S, Freidkin M, Khundzhua D, Terekhova V (2019) Biodegradation of humic substances by microscopic filamentous fungi: chromatographic and spectroscopic proxies. J Soils Sediments 19:2676–2687

Fernández-Gómez B, Maldonado J, Mandakovic D, Gaete A, Gutiérrez RA, Maass A (2019) Bacterial communities associated to Chilean altiplanic native plants from the Andean grassland's soils. Sci Rep 9:1042

Figueroa-diva RA, Vasudevan D, Mackay AA (2010) Trends in soil sorption coefficients within common antimicrobial families. Chemosphere 79:786–793

Fortugno D, Boix-Fayos C, Bombino G, Denisi P, Quiñonero Rubio JM, Tamburino V, Zema DA (2017) Adjustments in channel morphology due to land-use changes and check dam installation in mountain torrents of Calabria (southern Italy). Earth Surf Process Landf 42:2469–2483

Frąc M, Hannula SE, Bełka M, Jędryczka M (2018) Fungal biodiversity and their role in soil health. Front Microbiol 9:707

Franzluebbers A (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res 66:197–205

Frossard E, Skrabul P, Sinaj S, Bangerter F, Traore O (2002) Forms and exchangeability of inorganic phosphate in composted solid organic wastes. Nutr Cycl Agroecosyst 62:103–113

Galloway JN, Townsend AR, Erisman JW (2008) Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science 320:889–892

Gama-Rodrigues EF, Barros NF, Viana AP, Santos GA (2008) Microbial biomass and activity in soil and forest litter of eucalyptus plantations and native vegetation in southeastern Brazil. Rev Bras Cienc Solo 32:1489–1499

Gao F, Xia J (2009) Soil organic-mineral complex status and distribution of organic carbon in tea plantations of different planting year. J Soil Water Conserv 23:50–53

Garratt MPD, Bommarco R, Kleijn D, Martin E, Mortimer SR, Redlich S, Senapathi D, Steffan-Dewenter I, Świtek S, Takacs V, van Gils S, van der Putten WH, Potts SG (2018) Enhancing soil organic matter as a route to the ecological intensification of European arable systems. Ecosystems 21:1404–1415

Geeves GW, Cresswell HP, Murphy BW, Gessler PE, Chartres CJ, Little IP, Bowman GM (1995) The physical, chemical and morphological properties in the wheat-belt of south eastern New South Wales and north eastern Victoria. CSIRO Division of Soils, Canberra and NSW Department of Conservation and Land Management

Genardzielinski AC, Boissard C, Ormeño E, Lathière J, Reiter IM, Wortham H (2018) Seasonal variations of Quercus pubescens isoprene emissions from an in natura forest under drought stress and sensitivity to future climate change in the Mediterranean area. Biogeosciences 15:4711–4730

Gharahi-Gheni N, Nemes A, Verdoodt A, van Ranst E, Cornelis WM, Boeckx P (2012) Nonparametric techniques for predicting soil bulk density of tropical rainforest topsoils in Rwanda. Soil Sci Soc Am J 76:1172–1183

Ghosh U, Gillette JS, Luthy RG, Zare RN (2000) Microscale location, characterization, and association of polycyclic aromatic hydrocarbons on harbor sediment particles. Environ Sci Technol 34:1729–1736

Gogoi A, Sahoo UK, Singh SL (2017) Assessment of biomass and total carbon stock in a tropical wet evergreen rainforest of eastern Himalaya along a disturbance gradient. J Plant Biol Soil Health 4(1):8

Gómez JA, Francia JR, Guzmán G, Vanwalleghem T, Durán Zuazo VH, Castillo C, Barrón V (2017) Lateral transfer of organic carbon and phosphorus by water erosion at hillslope scale in southern Spain olive orchards. Vadose Zone J 16:1–15

Gómez JA, Campos M, Guzmán G, Castillo-Llanque F, Van walleghem T, Lora A, Giráldez JV (2018) Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. Environ Sci Pollut Res 25:977–989

Gopalakrishnan S, Sathya A, Vijayabharathi R, Varshney RK, Gowda CL, Krishnamurthy L (2015) Plant growth promoting rhizobia: challenges and opportunities. 3 Biotech 5:355–377

Gougoulias C, Clark MJ, Shaw LS (2014) The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. J Sci Food Agric 94:2362–2237

Guan S, Liu SJ, Liu RY, Zhang JJ, Ren J, Cai HG, Li XX (2019) Soil organic carbon associated with aggregate-size and density fractions in a Mollisol amended with charred and uncharred maize straw. J Integr Agric 18(7):1496–1507

Guimarães RML, Lamandé M, Munkholm LJ, Ball BC, Keller T (2017) Opportunities and future directions for visual soil evaluation methods in soil structure research. Soil Tillage Res 173:104–113

Gülser C, Candemir F, Kanel Y, Demirkaya S (2015) Effect of manure on organic carbon content and fractal dimensions of aggregates. Eur J Soil Sci 4(1):1–5

Guo XJ, Zhu NM, Chen L, Yuan DH, He LS (2015) Characterizing the fluorescent properties and copper complexation of dissolved organic matter in saline-alkali soils using fluorescence excitation-emission matrix and parallel factor analysis. J Soils Sediments 15:1473–1482

Gwenzi W, Muzava M, Mapanda F, Tauro TP (2016) Comparative short-term effects of sewage sludge and its biochar on soil properties, maize growth and uptake of nutrients on a tropical clay soil in Zimbabwe. J Integr Agric 15:1395–1406

Haghnazari F, Shahgholi H, Feizi M (2015) Factors affecting the infiltration of agricultural soils: review. Int J Agron Agric Res 6(5):21–35

Håkansson I, Lipiec J (2000) A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil Tillage Res 53:71–85

Hallsworth EG, Wilkinson GK (1958) Contribution of clay and organic matter to cation exchange capacity of soil. J Agric Sci 51:1–3

Han GZ, Zang GL, Gong ZT, Wang GF (2012) Pedotransfer functions for estimating soil bulk density in China. Soil Sci 177:158–164

Hati KM, Swarup A, Dwivedi AK, Misra AK, Bandyopadhyay KK (2007) Changes in soil physical properties and organic carbon status at the topsoil horizon of a vertisol of central India after 28 years of continuous cropping, fertilization and manuring. Agric Ecosyst Environ 119:127–134

Haynes RJ, Naidu R (1998) Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr Cycl Agroecosyst 51(2):123–137

Hazard C, Johnson D (2018) Does genotypic and species diversity of mycorrhizal plants and fungi affect ecosystem function? New Phytol 220:1122–1128

He X, Vepraskas MJ, Lindbo DL, Skaggs RW (2003) A method to predict soil saturation frequency and duration from soil color. Soil Sci Soc Am J 67:961–969

Herre A, Lang F, Siebe CH, Dohrmann R, Kaupenjohann M (2007) Mechanisms of acid buffering and formation of secondary minerals in vitric Andosols. Eur J Soil Sci 58:431–444

Heuscher SA, Craig C, Brandt CC, Jardine PM (2005) Using soil physical and chemical properties to estimate bulk density. Soil Sci Soc Am J 69:1–7

Hlavčová K, Danáčová M, Kohnová S, Szolgay J, Valent P, Výleta R (2019) Estimating the effectiveness of crop management on reducing flood risk and sediment transport on hilly agricultural land—a Myjava case study, Slovakia. Catena 172:678–690

Hortensia BV, Jose MSD, Edmundo GM, Armando GV, Bernardo JAG (2018) Physico-chemical properties of soil and pods (Theobroma cacao L.) in cocoa agroforestry systems. J Agron 17:48–55

Hsu TH, Lawrence CR, Winnick MJ, Bargar JR, Maher K (2018) A molecular investigation of soil organic carbon composition across a subalpine catchment. Soil Syst 2:6

Hu S, Lu C, Zhnag C, Hang Y, Yau M, Wu Y (2016) Effects of fresh and degraded dissolved organic matter derived from maize straw on copper sorption onto farmland loess. J Soils Sediments 16:327–338

Hu J, Wu J, Sharaf A, Sun J, Qu X (2019) Effects of organic wastes on structural characterizations of fulvic acid in semiarid soil under plastic mulched drip irrigation. Chemosphere 234:830–838

Huang S, Peng XX, Huang QR, Zhang WJ (2010) Soil aggregation and organic carbon fractions affected by long-term fertilization in a red soil of subtropical China. Geoderma 154:364–369

Hue NV (1992) Correcting soil acidity of a highly weathered Ultisol with chicken manure and sewage sludge. Commun Soil Sci Plant Anal 23:241–264

Huntington TG, Johnson CE, Jonhson AH, Sicama TG, Ryan DF (1989) Carbon, organic matter and bulk density relationships in a forested spodosol. Soil Sci 148:380–386

Huo C, Luo Y, Cheng W (2017) Rhizosphere priming effect: a meta-analysis. Soil Biol Biochem 111:78–84

Ibrahim H, Hatira A, Pansu M (2013) Modelling the functional role of microorganisms in the daily exchanges of carbon between atmosphere, plants and soil. Procedia Environ Sci 19:96–105

Issaka Z, Li H, Yue J, Tang P, Darko RO (2018) Water-smart sprinkler irrigation, prerequisite to climate change adaptation: a review. J Water Clim Chang 9:383–398

Jack ALH, Rangarajan A, Culman SW, Sooksa-Nguan T, Thies JE (2011) Choice of organic amendments in tomato transplants has lasting effects on bacterial rhizosphere communities and crop performance in the field. Appl Soil Ecol 48:94–101

Jakab G, Madarász B, Szabó JA, Tóth A, Zacháry D, Szalai Z, Kertész Á, Dyson J (2017) Infiltration and soil loss changes during the growing season under ploughing and conservation tillage. Sustainability 9:1726

James BR, Riha SJ (1986) pH buffering in forest soil organic horizons: relevance to acid precipitation. J Environ Qual 15:229–234

Jamison V, Kroth E (1958) Available moisture storage capacity in relation to textural composition and organic matter content of several Missouri soils. Soil Sci Soc Am J 22:189–192

Jarvis N, Larsbo M, Roulier S, Lindahl A, Persson L (2007) The role of soil properties in regulating non-equilibrium macropore flow and solute transport in agricultural topsoils. Eur J Soil Sci 58:282–292

Jiang T, Chen XS, Wang DY, Liang J, Bai WY, Zhang C, Wang QL, Wei SQ (2018) Dynamics of dissolved organic matter (DOM) in a typical inland lake of the Three Gorges Reservoir area: fluorescent properties and their implications for dissolved mercury species. J Environ Manag 206:418–429

Johnson SP, Miller ZJ, Lehnhoff EA, Miller PR, Menalled FD (2017) Cropping systems modify soil biota effects on wheat (*Triticum aestivum*) growth and competitive ability. Weed Res 57:6–15

Jones DL, Edwards AC (1998) Influence of sorption on the biological utilisation of two simple carbon substrates. Soil Biol Biochem 30:1895–1902

Jordán A, Zavala LM, Gil J (2010) Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. Catena 81:77–85

Jozefaciuk G, Czachor H, Lamorski K, Hajnos M, Swieboda R, Franus W (2015) Effect of humic acids, sesquioxides and silica on the pore system of silt aggregates measured by water vapour desorption, mercury intrusion and microtomography. Eur J Soil Sci 66:992–1001

Ju X, Liu X, Zhang F, Roelcke M (2004) Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. Ambio 33:300–305

Kaiser K, Guggenberger G (2003) Mineral surfaces and soil organic matter. Eur J Soil Sci 54:219–236

Kallenbach CM, Wallenstein MD, Schipanksi ME, Stuart Grandy A (2019) Managing agroecosystems for soil microbial carbon use efficiency: ecological unknowns, potential outcomes, and a path forward. Front Microbiol 10:1146

Kammann CI, Linsel S, Gößling JW, Koyro HW (2011) Influence of biochar on drought tolerance of Chenopodium quinoa Willd and on soil–plant relations. Plant Soil 345(1–2):195–210

Karlen DL, Veum KS, Sudduth KA, Obrycki JF, Nunes MR (2019) Soil health assessment: past accomplishments, current activities and future opportunities. Soil Tillage Res 195:104365

Katyal JC, Rao NH, Reddy MN (2001) Critical aspects of organic matter management in the tropics: the example of India. Nutr Cycl Agroecosyst 61(1–2):77–88

Keller T, Håkansson I (2010) Estimation of reference bulk density from soil particle size distribution and soil organic matter content. Geoderma 154:398–406

Ketterings QM, Bigham JM (2000) Soil color as an indicator of slash-and-burn fire severity and soil fertility in Sumatra, Indonesia. Soil Sci Soc Am J 64:1826–1833

Khaleel R, Reddy KR, Overcash MR (1981) Changes in soil physical properties due to organic waste applications: a review. J Environ Qual 10(2):133–141

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kiem R, Kögel-Knabner I (2003) Contribution of lignin and polysaccharides to the refractory carbon pool in C-depleted arable soils. Soil Biol Biochem 35:101–118

Kirillova NP, Vodyanitskii YN, Sileva TM (2015) Conversion of soil color parameters from the Munsell system to the CIE-L*a*b* system. Eurasian Soil Sci 48:468–475

Klucakova M (2012) Comparative study of binding behaviour of Cu(II) with humic acid and simple organic compounds by ultrasound spectrometry. Open Colloid Sci J 5:5–12

Korucu T, Shipitalo MJ, Kaspar TC (2018) Rye cover crop increases earthworm populations and reduces losses of broadcast, fall-applied, fertilizers in surface runoff. Soil Tillage Res 180:99–106

Kravchenko AN, Negassa WC, Guber AK, Rivers ML (2015) Protection of soil carbon within macro-aggregates depends on intra-aggregate pore characteristics. Sci Rep 5:16261

Kumar A, Kuzyakov Y, Pausch J (2016) Maize rhizosphere priming: field estimates using 13C natural abundance. Plant Soil 409:1–11

Kweon G, Lund E, Maxton C (2013) Soil organic matter and cation-exchange capacity sensing with on-the-go electrical conductivity and optical sensors. Geoderma 199:80–89

Kwiatkowska-Malina J (2018) Qualitative and quantitative soil organic matter estimation for sustainable soil management. J Soils Sediments 18:2801–2812

Laiho R, Penttilä T, Laine J (2004) Variation in soil nutrient concentrations and bulk density within peatland forest sites. Silva Fenn 38(1):29–41

Lal R (2011) Organic matter, effects on soil physical properties and processes. In: Gliński J, Horabik J, Lipiec J (eds) Encyclopedia of agrophysics, Encyclopedia of earth sciences series. Springer, Dordrecht

Lamprecht A, Semenchuk PR, Steinbauer K, Winkler M, Pauli H (2018) Climate change leads to accelerated transformation of high-elevation vegetation in the central Alps. New Phytol 220:447–459

Laossi KR, Barot S, Carvalho D, Desjardins T, Lavelle P, Martins M, Mitja D, Rendeiro AC, Rousseau G, Sarrazin M, Velasquez E, Grimaldi M (2008) Effects of plant diversity on plant biomass production and soil macrofauna in Amazonian pastures. Pedobiologia 51:397–407

Larney FJ, Olson AF, Miller JJ, DeMaere PR, Zvomuya F, McAllister TA (2008) Physical and chemical changes during composting of wood chip-bedded and straw-bedded beef cattle feedlot manure. J Environ Qual 37(2):725–735

Lehmann J, Rondon M (2006) Bio-char soil management on highly weathered soils in the humid tropics. In: Biological approaches to sustainable soil systems. CRC Press, Boca Raton, pp 517–530

Li D, Chen XZ, Peng ZP, Chen SS, Chen WQ, Han LS, Li YJ (2012) Prediction of soil organic matter content in a litchi orchard of South China using spectral indices. Soil Tillage Res 123:78–86

Li J, Pu L, Zhu M, Zhang J, Li P, Dai X, Xu Y, Liu L (2014) Evolution of soil properties following reclamation in coastal areas: a review. Geoderma 226–227:130–139

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizão FJ, Petersen J, Neves EG (2006) Black carbon increases cation exchange capacity in soils. Soil Sci Soc Am J 70:1719–1730

Lieb AM, Darrouzet-Nardi A, Bowman WD (2011) Nitrogen deposition decreases acid buffering capacity of alpine soils in the southern Rocky Mountains. Geoderma 164:220–224

Liu E (2010) Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158:173–180

Liu S (2014) Differential responses of crop yields and soil organic carbon stock to fertilization and rice straw incorporation in three cropping systems in the subtropics. Agric Ecosyst Environ 184:51–58

Liu M, Hu F, Chen X, Huang Q, Jiao J, Zhang B, Li H (2009) Organic amendments with reduced chemical fertilizer promote soil microbial development and nutrient availability in a subtropical paddy field: the influence of quantity, type and application time of organic amendments. Appl Soil Ecol 42:166–175

Liu YR, Li X, Shen QR, Xu YC (2013) Enzyme activity in water-stable soil aggregates as affected by long-term application of organic manure and chemical fertilizer. Pedosphere 23:111–119

Liu B, Ai S, Zhang W, Huang D, Zhang Y (2017) Assessment of the bioavailability, bioaccessibility and transfer of heavy metals in the soil-grain-human systems near a mining and smelting area in NW. Sci Total Environ 609:822–829

Loecke TD, Burgin AJ, Riveros-Iregui DA, Ward AS, Thomas SA, Davis CA (2017) Weather whiplash in agricultural regions drives deterioration of water quality. Biogeochemistry 133:7–15

López-Vicente M, García-Ruiz RG, Guzmán G, Vicente-Vicente JL, Van Wesemael B, Gómez JA (2016) Temporal stability and patterns of runoff and runon with different cover crops in an olive orchard (SW Andalusia, Spain). Catena 147:125–137

Lucas-Borja ME, Zema DA, Carrà BG, Cerdà A, Plaza-Alvarez PA, Cózar JS, de las Heras J (2018) Short-term changes in infiltration between straw mulched and non-mulched soils after wildfire in Mediterranean forest ecosystems. Ecol Eng 122:27–31

Luo WT, Nelson PN, Li MH (2015) Contrasting pH buffering patterns in neutral-alkaline soils along a 3600 km transect in northern China. Biogeosciences 12:7047–7056

Ma RT, Hu FN, Liu YF, Xu CY, Yang ZH, Wang ZL, Zhao SW (2019) Evolution characteristics of soil surface electrochemical properties during vegetation restoration in the Loess Plateau. Acta Pedol Sin:1–12

Madejón E, Burgos P, López R, Cabrera F (2003) Agricultural use of three organic residues: effect on orange production and on properties of a soil of the "Comarca Costade Huelva" (SWSpain). Nutr Cycl Agroecosyst 65(3):281–288

Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A, Tribedi P (2014) Biofertilizers: a potential approach for sustainable agriculture development. Environ Sci Pollut Res 24:3315–3335

Malkawi AIH, Alawneh AS, Abu-Safaqah OT (1999) Effects of organic matter on the physical and the physicochemical properties of an illitic soil. Appl Clay Sci 14:257–278

Masri Z, Ryan J (2006) Soil organic matter and related physical properties in a Mediterranean wheat-based rotation trial. Soil Tillage Res 87:146–154

Masto RE, Chhonkar PK, Singh D, Patra AK (2007) Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol. Agric Ecosyst Environ 118:130–142

Matos CC, Costa MD, Silva IR, Silva AA (2019) Competitive capacity and rhizosphere mineralization of organic matter during weed-soil microbiota interactions. Planta Daninha 37:e019182676

Matsi T, Lithourgidis AS, Gagianas AA (2003) Effects of injected liquid cattle manure on growth and yield of winter wheat and soil characteristics. Agron J 95(3):592–596

McCallum MH, Kirkegaard JA, Green TW, Cresswell HP, Davies SL, Angus JF, Peoples MB (2004) Improved subsoil macroporosity following perennial pastures. Aust J Exp Agric 44:299–307

McClellan AT, Deenik J, Uehara G, Antal M (2007) Effects of flash carbonized macadamia nutshell charcoal on plant growth and soil chemical properties. In: Proceedings American Society of Agronomy Conference. Abstracts. 3–7 November, New Orleans, LA. ASA, Madison, WI

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Meurer KHE, Haddaway NR, Bolinder MA, Kätter T (2018) Tillage intensity affects total SOC stocks in boreo-temperate regions only in the topsoil—a systematic review using an ESM approach. Earth Sci Rev 177:613–622

Miao SJ, Qiao YF, Zhou LR (2009) Aggregation stability and microbial activity of China's black soils under different long-term fertilisation regimes. N Z J Agric Res 52:57–67

Mikutta R, Kleber M, Torn MS, Jahn R (2006) Stabilization of soil organic matter: association with minerals or chemical recalcitrance? Biogeochemistry 77:25–56

Miranda V, Rothen C, Yela N, Aranda-Rickert A, Barros J, Calcagno J, Fracchia S (2019) Subterranean desert rodents (genus Ctenomys) create soil patches enriched in root endophytic fungal propagules. Microb Ecol 77:451–459

Moco MKS, Gama-Rodrigues EF, Gama-Rodrigues AC, Machado RCR, Baligar VC (2009) Soil and litter fauna of cacao agroforestry systems in Bahia, Brazil. Agrofor Syst 76:127–138

Molina-Herrera S, Romanya J (2015) Synergistic and antagonistic interactions among organic amendments of contrasted stability, nutrient availability and soil organic matter in the regulation of C mineralisation. Eur J Soil Biol 70:118–125

Mondal S, Padmakumar GP, Sharma V, Singh DN, Baghini MS (2015) A methodology to determine thermal conductivity of soils from flux measurement. Geomech Geoeng 11:73–85

Moni C, Rumpel C, Virto I, Chabbi A, Chenu C (2010) Relative importance of sorption versus aggregation for organic matter storage in subsoil horizons of two contrasting soils. J Soil Sci 61:958–969

Moos JH, Schrader S, Paulse HM, Rahmann G (2016) Occasional reduced tillage in organic farming can promote earthworm performance and resource efficiency. Appl Soil Ecol 103:22–30

Mosaddeghi MR, Hajabbasi MA, Hemmat A, Afyuni M (2000) Soil compactibility as affected by soil moisture content and farmyard manure in central Iran. Soil Tillage Res 55:87–97

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–178

Najafi S, Jalali M (2016) Effect of heavy metals on pH buffering capacity and solubility of Ca, Mg, K, and P in non-spiked and heavy metal-spiked soils. Environ Monit Assess 188:1–11

Nelson PN, Su N (2010) Soil pH buffering capacity: a descriptive function and its application to some acidic tropical soils. Aust J Soil Res 48:210–207

Nunes MR, Pauletto EA, Denardin JE, Suzuki LEAS, van-Es HM (2019) Dynamic changes in compressive properties and crop response after chisel tillage in a highly weathered soil. Soil Tillage Res 186:183–190

Nurhidayati N, Machfudz M, Murwani I (2018) Direct and residual effect of various vermicompost on soil nutrient and nutrient uptake dynamics and productivity of four mustard Pak-Coi (Brassica rapa L.) sequences in organic farming system. Int J Recycl Org Waste Agric 7(2):173–181

Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. Plant Soil 76:319–337

Oburger E, Jones DL (2018) Sampling root exudates–mission impossible? Rhizosphere 6:116–133

Oldfield EE, Wood SA, Bradford MA (2018) Direct effects of soil organic matter on productivity mirror those observed with organic amendments. Plant Soil 423:63–373

Orlova N, Abakumov E, Orlova E, Yakkonen K, Shahnazarova V (2019) Soil organic matter alteration under biochar amendment: study in the incubation experiment on the Podzol soils of the Leningrad region (Russia). J Soils Sediments 19:2708–2716

Pagliai M, Vittori Antisari L (1993) Influence of waste organic matter on soil micro and macrostructure. Bioresour Technol 43:205–213

Park EJ, Smucker A (2005) Saturated hydraulic conductivity and porosity within macroaggregates modified by tillage. Soil Sci Soc Am J 69:38–45

Parker TC, Sanderman J, Holden RD, Blume-Werry G, Sjögersten S, Large D, Castro-Díaz M, Street LE, Subke JA, Wookey PA (2018) Exploring drivers of litter decomposition in a greening Arctic: results from a transplant experiment across a treeline. Ecology 99:2284–2294

Pascual J, Blanco S, Ramos JL, van Dillewijn P (2018) Responses of bulk and rhizosphere soil microbial communities to thermoclimatic changes in a Mediterranean ecosystem. Soil Biol Biochem 118:130–144

Pausch J, Zhu B, Kuzyakov Y, Cheng W (2013) Plant inter-species effects on rhizosphere priming of soil organic matter decomposition. Soil Biol Biochem 57:91–99

Peng X, Ye LL, Wang CH, Zhou H, Sun B (2011) Temperature- and duration dependent rice straw-derived biochar: characteristics and its effects on soil properties of an Ultisol in southern China. Soil Tillage Res 112(2):159–166

Peng X, Horn RF, Hallett PD (2015) Soil structure and its functions in ecosystems: phase matter & scale matter. Soil Tillage Res 146:1–3

Plaza-Bonilla D, Alvaro-Fuentes J, Cantero-Martinez C (2013) Soil aggregate stability as affected by fertilization type under semiarid no-tillage conditions. Soil Sci Soc Am J 77:284–292

Powlson DS, Hirsch PR, Brookes PC (2001) The role of soil microorganisms in soil organic matter conservation in the tropics. Nutr Cycl Agroecosyst 61(1/2):41–51

Pravin RC, Dodha VA, Vidya DA, Manab C, Saroj M (2013) Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. Int J Sci Res Publ 3:2250–3153

Pylak M, Oszust K, Frąc M (2019) Review report on the role of bioproducts, biopreparations, biostimulants and microbial inoculants in organic production of fruit. Rev Environ Sci Biotechnol 18:597–616

Qadri H, Bhat RA (2020) The concerns for global sustainability of freshwater ecosystems (2019). In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 1–15

Qin Z, Zhang Y, Zhou Z, Shi X, Guo T (2013) Characteristics of mineralization and nitrification in neutral purple paddy soil from a long-term fertilization experiment. Sci Agric Sin 46:3392–3400

Reddy MS (1991) Effects of soil amendments on the hardening of red sandy loams (chalka soils) of Andhra Pradesh. Ann Agric Res 12:174–176

Reeves DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res 43:131–167

Regelink IC, Stoof CR, Rousseva S, Weng L, Lair GJ, Kram P, Nikolaidis NP, Kercheva M, Banwart S, Comans RNJ (2015) Linkages between aggregate formation, porosity and soil chemical properties. Geoderma 247–248:24–37

Rodrigo-Comino J, Neumann M, Remke A, Ries JB (2018) Assessing environmental changes in abandoned German vineyards. Understanding key issues for restoration management plans. Hung Geogr Bull 67:319–332

Roper WR, Osmond DL, Heitman JL, Wagger MG, Reberg-Horton SC (2017) Soil health indicators do not differentiate among agronomic management systems in North Carolina soils. Soil Sci Soc Am J 81:828–843

Rose DA (1991) The effects of long-continued manuring on some physical properties of soils. In: Wilson WS (ed) Advances in soil organic matter research: the impact on agriculture and the environment. Royal Society of Chemistry, Cambridge, pp 197–205

Rossiter DG, Bouma J (2018) A new look at soil phenoforms–definition, identification, mapping. Geoderma 314:113–121

Rui Y, Murphy DV, Wang X, Hoyle FC (2016) Microbial respiration, but not biomass, responded linearly to increasing light fraction organic matter input: consequences for carbon sequestration. Sci Rep 6:354–396

Sachkova AS, Kovel ES, Churilov GN, Stom DI, Kudryasheva NS (2019) Biological activity of carbonic nano-structures-comparison via enzymatic bioassay. J Soils Sediments 19:2689–2696

Sánchez-Marañón M, Martín-García JM, Delgado R (2011) Effects of the fabric on the relationship between aggregate stability and color in a Regosol-Umbrisol soils cape. Geoderma 162:86–95

Sandin M, Koestel J, Jarvis N, Larsbo M (2017) Post-tillage evolution of structural pore space and saturated and near-saturated hydraulic conductivity in a clay loam soil. Soil Tillage Res 165:161–168

Schaumann GE (2006) Soil organic matter beyond molecular structure part I: macromolecular and supramolecular characteristics. J Plant Nutr Soil Sci 169:145–156

Schulten HR (2002) New approaches to the molecular structure and properties of soil organic matter: humic-, xenobiotic-, biological-, and mineral bonds. Dev Soil Sci 28:351–381

Schulz H, Glaser B (2012) Effects of biochar compared to organic and inorganic fertilizers on soil quality and plant growth in a greenhouse experiment. J Plant Nutr Soil Sci 175(3):410–422

Schwarz J, Thiele-Bruhn S, Eckhardt KU, Schulten HR (2012) Sorption of sulfonamide antibiotics to soil organic sorbents: batch experiments with model compounds and computational chemistry. ISRN Soil Sci 2012:10

Shen C, Liang W, Shi Y, Lin X, Zhang H, Wu X (2014) Contrasting elevational diversity patterns between eukaryotic soil microbes and plants. Ecology 95:3190–3202

Shi W, Lu C, He J, En H, Gao M, Zhao B (2018) Nature differences of humic acids fractions induced by extracted sequence as explanatory factors for binding characteristics of heavy metals. Ecotoxicol Environ Saf 15:59–68

Sidhu V, Sarkar D, Datta R (2016) Effects of biosolids and compost amendment on chemistry of soils contaminated with copper from mining activities. Environ Monit Assess 188(3):176

Singh J, Salaria A, Kaul A (2014) Impact of soil compaction on soil physical properties and root growth: a review. Int J Food Agric Vet Sci 5(1):22–32

Singh SL, Sahoo UK, Kenye A, Gogoi A (2018a) Assessment of growth, carbon stock and sequestration potential of oil palm plantations in Mizoram, Northeast India. J Environ Prot 9:912–931

Singh DV, Bhat JIA, Bhat RA, Dervash MA, Ganei SA (2018b) Vehicular stress a cause for heavy metal accumulation and change in physico-chemical characteristics of road side soils in Pahalgam. Environ Monit Assess 190:353. https://doi.org/10.1007/s10661-018-6731-2

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Soares MR, Alleoni LRF (2008) Contribution of soil organic carbon to the ion exchange capacity of tropical soils. J Sustain Agric 32:439–462

Sohail-Ur-Raza M, Ahmed ZI, Malik MA, Ijaz SS (2015) Effective soil additives for improved soil water retention. Pak J Agric Sci 52(1):463–468

Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Adv Agron 105:47–82

Sparks DL (2003) Kinetics of Soil Chemical Processes. In. Environmental Soil Chemistry (Second Edition) 2003, Pages 207-244. https://doi.org/10.1016/B978-012656446-4/50007-4

Steller RM, Jelinsk NA, Kucharik CJ (2008) Developing models to predict soil bulk density in southern Wisconsin using soil chemical properties. J Int Biosci 6:53–63

Stevenson FJ (1982) Humus Chemistry. New York, Wiley

Stevenson FJ (1994) Humus chemistry. Genesis, composition, reactions. Wiley, New York

Streubel JD, Collins HP, Garcia-Perez M, Tarara J, Granatstein D, Kruger CE (2011) Influence of contrasting biochar types on five soils at increasing rates of application. Soil Sci Soc Am J 75(4):1402–1413

Sulman BN, Moore JAM, Abramoff R, Averill C, Kivlin S, Georgiou K, Sridhar B, Hartman MD, Wang G, Wieder WR, Bradford MA, Luo Y, Mayes MA, Morrison E, Riley WJ, Salazar A, Schimel JP, Tang J, Classen AT (2018) Multiple models and experiments underscore large uncertainty in soil carbon dynamics. Biogeochemistry 141:109–123

Tarnawski VR, Momose T, Leong WH (2009) Assessing the impact of quartz content on the prediction of soil thermal conductivity. Géotechnique 59:331–338

Tian G, Kang BT, Brussaard L (1992) Biological effects of plant residues with contrasting chemical compositions under humid tropical conditions-decomposition and nutrient release. Soil Biol Biochem 24:1051–1060

Tikhova VD, Deryabina YM, Vasilevich RS, Lodygin ED (2019) Structural features of tundra and taiga soil humic acids according to IR EXPERT analytical system data. J Soils Sediments 19:2697–2707

Tiquia SM (2005) Microbiological parameters as indicators of compost maturity. J Appl Microbiol 99:816–828

Toosi ER, Kravchenko AN, Mao J, Quigley MY, Rivers ML (2017) Effects of management and pore characteristics on organic matter composition of macroaggregates: evidence from characterization of organic matter and imaging. Eur J Soil Sci 68:200–211

Torres IF (2014) The role of lignin and cellulose in the carbon-cycling of degraded soils under semiarid climate and their relation to microbial biomass. Soil Biol Biochem 75:152–160

Usowicz B, Lipiec J, Usowicz JB, Marczewski W (2013) Effects of aggregate size on soil thermal conductivity: comparison of measured and model-predicted data. Int J Heat Mass Transf 57:536–541

Valeeva AA, Aleksandrova AB, Koposov GF (2016) Color estimation of forest-steppe soils by digital photography under laboratory conditions. Eurasian Soil Sci 49:1033–1037

Vallis I, Jones RJ (1973) Net mineralisation of nitrogen in leaves and leaf litter of Desmodium intortum and Phaseolus atropurpureus mixed with soil. Soil Biol Biochem 5:391–398

Von Lutzow M, Kogel-Knabner I, Ekschmitt K, Matzner E, Guggenberger G, Marschner B, Flessa H (2005) Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions—a review. Eur J Soil Sci 57:426–445

Wade J, Culman SW, Hurisso TT, Miller RO, Baker L, Horwath WR (2018) Sources of variability that compromise mineralizable carbon as a soil health indicator. Soil Sci Soc Am J 82:243–252

Wang J, Soininen J, He J, Shen J (2012) Phylogenetic clustering increases with elevation for microbes. Environ Microbiol Rep 4:217–226

Wang X, Ciu H, Shi J, Zhao Y, Wei Z (2015) Relationship between bacterial diversity and environmental parameters during composting of different raw materials. Bioresour Technol 198:395–402

Wardani AK, Purqon A (2016) Thermal conductivity prediction of soil in complex plant soil system using artificial neural networks. J Phys Conf Ser 739:012–017

Wei Z, Zhongmin HU, Shenggong LI, Guo Q, Yang H, Zang T (2017) Impact of land use conversion on soil organic carbon stock in an agro-pastoral ecotone of Inner Mongolia. J Geogr Sci 27:999–1010

Wiatrowska K, Komisarek J, Dłużewski P (2013) Metal enrichment of particulate organic matter in soil contaminated by metallurgical fallout in Poland. Fresenius Environ Bull 11:3424–3432

Wiseman CLS, Puttmann W (2006) Interactions between mineral phases in the preservation of soil organic matter. Geoderma 134:109–118

Wolf B, Snyder GH (2003) Sustainable soils: the place of organic matter in sustaining soils and their productivity. Food Products Press of the Haworth Press, New York

Wong MTF, Gibbs P, Nortcliff S, Swift RS (2000) Measurement of the acid neutralizing capacity of agroforestry tree prunings added to tropical soils. J Agric Sci 134:269–276

Wu LM, Zhou CH, Keeling J, Tong DS, Yu WH (2012) Towards an understanding of the role of clay minerals in crude oil formation, migration and accumulation. Earth Sci Rev 115:373–386

Wurzburger N, Clemmensen KE (2018) From mycorrhizal fungal traits to ecosystem properties – and back again. J Ecol 106:463–467

Xiang H, Zhang L, Wen D (2015) Change of soil carbon fractions and water-stable aggregates in a forest ecosystem succession in South China. Forests 6(8):2703–2718

Xu Z (2014) Study on ecological function evaluation and biodiversity of typical forest stands in Jinxi of the Loess Plateau. Master's thesis, Beijing Forestry University, Beijing, China

Xu X, Shi Z, Li D, Rey A, Ruan H, Craine JM, Liang J, Zhou J, Luo Y (2016) Soil properties control decomposition of soil organic carbon: results from data-assimilation analysis. Geoderma 262:235–242

Yang F, Zhang GL, Yang JL, Li DC, Zhao YG, Liu F (2014) Organic matter controls of soil water retention in an alpine grassland and its significance for hydrological processes. J Hydrol 519:3086–3093

Yang H, Zhao X, Liu C, Bai L, Zhao M, Li L (2018) Diversity and characteristics of colonization of root-associated fungi of *Vaccinium uliginosum*. Sci Rep 8:15283

Yuan JH, Xu RK, Zhang H (2011) The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresour Technol 102:3488–3497

Yuan Y, Si G, Wang J, Luo T, Zhang G (2014) Bacterial community in alpine grasslands along an altitudinal gradient on the Tibetan Plateau. FEMS Microbiol Ecol 87:121–132

Yuan DH, An YC, He XS, Yan CL, Jia YP, Wang HT, He LS (2018) Fluorescent characteristic and compositional change of dissolved organic matter and its effect on heavy metal distribution in composting leachates. Environ Sci Pollut Res 25:18866–18878

Zaman MD, Di HJ, Cameron KC, Frampton CM (1999) Gross nitrogen mineralization and nitrification rates and their relationships to enzyme activities and the soil microbial biomass in soils treated with dairy shed effluent and ammonium fertilizer at different water potentials. Biol Fertil Soils 29(2):178–186

Zeng J, Yue FJ, Wang ZJ, Wu Q, Qin CQ, Li SL (2019) Quantifying depression trapping effect on rainwater chemical composition during the rainy season in karst agricultural area, southwestern China. Atmos Environ 218:116998

Zhang J (2013) Agricultural land use affects nitrate production and conservation in humid subtropical soils in China. Soil Biol Biochem 62:107–114

Zhang M, Heaney D, Henriquez B, Solberg E, Bittner E (2006) A four-year study on influence of biosolids/MSW co-compost application in less productive soils in Alberta: nutrient dynamics. Compost Sci Util 14:68–80

Zhang HM, Wang BR, Xu MG (2008) Effects of inorganic fertilizer inputs on grain yields and soil properties in a long-term wheatcorn cropping system in South China. Commun Soil Sci Plant Anal 39:1583–1599

Zhang N, Yu X, Pradhan A, Puppala AJ (2017) A new generalized soil thermal conductivity model for sand–kaolin clay mixtures using thermo-time domain reflectometry probe test. Acta Geotech 12:739–752

Zhao ZJ, Chang E, Lai P, Dong Y, Xu RK, Fang DM, Jiang J (2019) Evolution of soil surface charge in a chronosequence of paddy soil derived from Alfisol. Soil Tillage Res 192:144–150

Zhou T, Wu L, Luo Y, Christie P (2018) Effects of organic matter fraction and compositional changes on distribution of cadmium and zinc in long-term polluted paddy soil. Environ Pollut 232:514–522

Zhu H (2010) Improving fertility and productivity of a highly-weathered upland soil in subtropical China by incorporating rice straw. Plant Soil 331:427–437

Zimmerman A, Gao B, Ahn M-Y (2011) Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biol Biochem 43:1169–1179

Zuber SM, Behnke GD, Nafziger ED, Villamil MB (2015) Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agron J 107:971–978

Zuber SM, Behnke GD, Nafziger ED, Villamil MB (2018) Carbon and nitrogen content of soil organic matter and microbial biomass under long-term crop rotation and tillage in Illinois, USA. J Agric 8:37

Chapter 8
Sustainable Agricultural Practices

S. J. A. Bhat, Syed Maqbool Geelani, Zulaykha Khurshid Dijoo, Rouf Ahmad Bhat, and Mehraj ud din Khanday

8.1 Introduction

Organic farming is an all-inclusive food production managing system which endorses and improves agro-ecosystem well-being, overall biodiversity, organic cycles, besides soil biological activity (FAO/WHO 2011). It gives importance to the local managing practices in place and provides inclination to the practice of off-farm ideas, such as agronomic, biological, and mechanical methods. Organic farming helps to yield healthy food and signifies an emergent source of revenue for industrialized and emerging countries. By the nineteenth century, globally, maximum food was organically produced by means of biological fertilizers, that is, manures (White 1970).

S. J. A. Bhat
Faculty of Forestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Benhama, Ganderbal, Jammu and Kashmir, India

S. M. Geelani · R. A. Bhat
Division of Environmental Science, Sher-e-Kashmir University of Agricultural Science and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

Z. K. Dijoo (✉)
Department of Environmental Science/Centre for Research and Development, University of Kashmir, Srinagar, Jammu and Kashmir, India

M. u. d. Khanday
Division of Soil Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Srinagar, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_8

8.2 Current Status

Currently, 31 million hectares of agricultural land is under cultivation through organic farming practices. This is being made possible by more than 600,000 farmers working globally. Also, more than 62 million areas are certified. Countries with most organic land are shown below.

8.2.1 Prerequisite of Organic Farming

1. Together, in developing as well as developed nations, demand for organic agronomy is increasing with an average growth of 20–25% annually.
2. Excessive use of pesticides affect biodiversity, human and animal health, besides creating pollution in the environment.
3. Expensive contributions in established farming.
4. Deteriorating factor efficiency.
5. Scarcity of essential soil micronutrients.
6. Increase in concentration of carbon dioxide and temperature due to pollution created by use of fertilizers.
7. Agricultural production (1.5%) not meeting population growth rate.
8. Risk of poor harvest.

8.2.2 Sources of Plant Nutrients

Aimed at the improvement of yield output, Indian agricultural lands require 30% of the nutrients. This need is fulfilled by diverse organic sources. Crop production can be sustained by conventional riches such as farm animal droppings which provide added nitrogen content than chemical-based nitrogen fertilizers. The evaluation of NPK from natural sources is founded on over-all nutrient. Collective usage of chemical fertilizers plus organic fertilizers ensures better throughput and improved soil quality on an extensive basis (Chhonkar 2002; Dar et al. 2013; Bhat et al. 2017a, b). Besides providing NPK to plants, organic fertilizers deliver elemental nitrogen, bound phosphates, other required micronutrients, as well as decomposed organic remains in a form accessible to plants.

Application of organic nutrients to plants enhances plant growth and development besides increasing the activity of mycorrhizae and other beneficial soil microbes, therefore aiding to relieve the deficit of micronutrients and consequently support high productivity together with soil health (Nambiar et al. 1992; Bhatti et al. 2017; Qadri and Bhat 2020). High economic gains to farmers are obtained from organically produced crops, such as *Oryza sativa*, *Pisium sativum*, and *Allium cepa*, due to their demand in international markets (Kalyan 2005). In FYM (Farm

Yard Manure), nutrient concentrations are usually small and vary based on duration and storage. Because of inconstant nature, production and storage; FYM have N, P, and K contents stretching from 0.01% to 1.9% on dry weight basis.

The fine decomposed FYM contains 0.2% of P_2O_5, 0.5% N, and 0.5% of K_2O (Inoko 1984; Zhu et al. 1984; Tandon 1992); 112 kg of N, 56 kg P_2O_5, and 112 kg K_2O ha^{-1} can be added to soil by applying 25 t ha^{-1} of farm yard manure (Gaur 1992). Globally, numerous researchers have revealed countless profits on the use of FYM on soil properties as well as crop productivity (Prabhakar et al. 2010; Dar et al. 2016; Bhat et al. 2017a, b). Usually the farmers make use of harvested crop chaffs as animal feed and bedding; however, chaff is also put to use for trapping urine in order to enhance N cycling. Wet straw collected daily from the sheds is composted to manure which is either applied during the on-going season or is stored for the following season (Timsina and Connor 2001).

8.3 Practices in Organic Farming

Besides dealing with potential difficulties triggered with chemical fertilizers, organic farming improves soil fertility and likewise increases crop productivity.

8.3.1 Composting

Crop residues, animal wastes are properly decomposed for 1–6 months to form compost. Still sometimes, additional months are required depending upon the composting process used, accessibility of labour, management period, and investment.

8.3.2 Vermicomposting

A specialized and modified method of composting, vermicomposting, uses earthworms which consume farm wastes and turn them into high quality compost in 2 months. Besides an organic fertilizer, vermicompost is exercised for production of compost tea, which is used as a prophylactic against numerous pests and diseases. Vermi-wash, a by-product of vermicompost, is served for the same purpose. Proper sieving of compost should be carried out by applying it in fields. Non-indigenous earthworms are used in vermicomposting, which swiftly colonize and dictate the indigenous species. Indigenous earthworm species can also be used by collecting them from fields using collection baits and form heaps. In traditional way, vermicomposting is practiced all around the world and most places in India; however, it is labour insensitive and requires infrastructure which is beneficial for small compost as compared to large fields which find it expensive.

8.4 Biofertilizers

Biofertilizers improve nutrient availability of the soil through better nitrogen fixation. The microorganisms are added to the rhizosphere of the plant in order to enhance their activity by choosing effective varieties and with this their efficacy to absorb nutrients can be improved. These organisms are cultured and added directly to the soil through seeds. Bioinoculants or biofertilizers employ eco-friendly fungal and bacterial strains of *Azotobacter*, *Azospirillium*, *Azolla*, and phosphate solubilizers.

8.4.1 Rhizobium Inoculants

Rhizobial nitrogen fixation is beneficial for legume production as by fulfilling nitrogen requirement and by enriching soil for successive crops. Rhizobium inoculation gains greatest benefit of nitrogen in the shortest of time and hence should be considered as superlative green manure. Microbial inoculations of *Azotobacter*, *Azospirillum*, and *Pseudomonas* are still at the field trials though good responses in wheat, rice, sugarcane, and mustard have been observed.

8.4.2 Phosphate Solubilizing Microorganisms

Variety of fungi and bacteria having ability to solubilize and transform inorganic phosphate from insoluble sources as well as from organic acids, for example, *Aspergillus*, *Pencillium*, and *Trichoderma*. Besides solubilisation of phosphorus, these microorganisms mineralize lacked up organic phosphate into soluble available forms. In rhizosphere, these microorganisms bring more phosphorus into solution form and provide it to the plant which they can use for their own growth. The efficacy of these microorganisms are subject to availability of sufficient energy source, carbon in the soil, phosphorus concentration, temperature, and moisture.

8.4.3 Mycorrhiza

Mycorrhiza is a symbiotic association of plants and fungi. Fungi acquire carbon as provided by the host plant while the plant is profited by fundamental nutrients, such as phosphorus, potassium, ammonium ions, zinc, and copper, which are otherwise difficult to absorb. In the preponderance of cultivated crops, excluding those fitting to Chenopodiaceae*, Amaranthaceae, Caryophyllaceae, Polygonaceae,* *Brassicaceae, Commelinaceae, Juncaceae*, *and Cyperaceae families,* the fungi are discovered to be allied. The fungal species are omnipresent in distribution in plants growing in temperate and tropical regions. Arbuscular mycorrhizal (AM) fungi are generally found in cultivated soils and report for 5–50% of the soil microbial biomass (Olsson et al. 1999; Bhat et al. 2018a, b; Singh et al. 2018). Glomalin, an organic carbon generated by the fungi surpasses soil microbial biomass by a factor of 10–20. Mineral extraction from soil is reflected to be the primary role of mycorrhizae fungi besides other important properties.

8.5 Mulching, Green Manuring, and Cover Cropping

Organic materials are put to use for covering the soil specifically round the plants in order to check water loss and enrichment of nutrients. Mulching is an inexpensive practice aimed at enhancing the number of earthworms, checking soil loss by erosion besides checking weed growth. Green manuring is a customary exercise predominant from the earliest stretches. It is advantageous in dual ways: (I) for the fixation of nitrogen, and (II) assisting in improving the soil quality in terms of its texture and water holding ability. Green manuring of leaves can also be done if ample leguminous plant leaves are accessible. Atmospheric nitrogen fixation can be carried out by growing legumes, clover, and pea at a rate of 20–200 kg N/ha (Adjei-Nsiah et al. 2008; Bhat et al. 2018a, b; Khanday et al. 2016; Singh et al. 2020), chiefly if soil is deficient in mineral nitrogen.

Loss of phosphorus and nitrogen by leaching and run-off can be prevented by cultivating non-leguminous plants, such as oats, barley, rye-grass, sorghum, rapeseed, and mustard, which trap phosphorus plus nitrogen. Many biocide plants such as *Brassica* Species *B. napus*, *B. nigra*, and *B. alba* decrease infestation of some fungi, such as *Rhizoctonia* spp., and nematodes, *Pratylencus penetrans*, by producing isothiocyanates (Brown et al. 2008; Bhat et al. 2017a, b) due to myrosinase enzyme. Fusion of grasses with legumes provides tolerance to non-leguminous species by enhancing rate of N_2 fixation. Depending upon the temperature requirement, cover crops can be seeded in autumn, late winter, or early spring and typically in summer at the initiation of flowering stage of crops when the C:N ratio is lesser than 20:1.

8.6 Crop Rotation

Sowing different crops together is crop rotation. Mixed cropping of cereals and legumes, for example, mustard and rice, is the example of crop rotation in temperate conditions (Fig. 8.1).

Fig. 8.1 Mustard (*rabi*) crop followed by rice (*Kharief*) crop in Jammu and Kashmir

8.7 Multicropping

Multicropping is the concurrent farming of two or more crops. In Indian farming practice, it is well-known that as numerous as 15 varieties of crops are cultivated at a time, for example, multicropping of tomatoes and onions.

8.8 Intercropping

Intercropping is the cultivation of another crop between two crops, for example, coconut, banana, pineapple, ginger, leguminous fodder, medicinal, or aromatic plants are cultivated by using the mentioned technique. Inter-cropping additionally allows for potential use of available resources plus it helps in controlling pest populations. Amalgamation of fallen leaves and previous crop remains enhances the soil nutrients or compost heap nutrient quality as they develop into additional nutritional resources available to plants.

8.9 Effective Microorganisms

Effective microorganisms are both aerobic and anaerobic and are supportive in diverse ways, such as enhancing of soil nutrients, repelling numerous pests acting as a prophylactic, and in animal feeds.

8.10 Biopesticides

Biopesticides are useful in integrated pest management and organic agriculture practices as they are harmless for mammals and other non-target species, have high target specificity besides being environmentally more compatible, and aim at reducing the use of harmful chemical pesticides, for example, Bt (*Bacillus thuringiensis*) formulations have been helpful in controlling destructive species of Lepidopteraee and *Trichoderma*. *Verticillium lechanii* is employed for regulating the whiteflies, aphids, thrips, and other insect *populations*; *Bauveria bassiana* for controlling thrips plus other harmful insects; *Paecelomices fumosoroseus* for monitoring different insects primarily beetles, fire ants, and nematodes; *Corynebacterium paurometabolum* to keep nematodes and other pest populations in check; *Metarhizium anisopliae* for checking termites, several destructive coleoptera insect species, leaf hoppers, and aphids.

8.11 Use of Agro-Industry Remains

Waste from agriculture activities, such as weed residues, cotton litters, biogas slurry, hay, and mushroom waste, supply considerable amount of NPK to the soil in addition to various primary and secondary soil-needed micronutrients.

8.11.1 Oil Cakes as Organic Manure

Inedible oil cakes of castor, neem, and karanji (*Pongamia pinnata*) and edible cakes of groundnut, mustard are extensively utilized in India as organic manure because of their good NPK content. Similarly, animal wastes, such as bone meal and fish meal, rich in nutrients are also widely utilized in organic farming.

8.12 Naturally Occurring Mineral Amendments

According to Alimentarius Commission (Codex), some naturally occurring mineral amendments, such as rock phosphate, potassium, sulphate, guano, basic slag, gypsum (calcium sulphate), Epsom salt (magnesium sulphate), calcite lime, dolomite lime are permissible for use (Singh and Dabas 2012).

8.13 Permanent Grass

Permanent grass helps soil in the following ways: addition of organic matter, nitrogen fixation, nutrient entrapping, checking soil erosion, preventing leaching of nitrate, and nutrient runoff as well as enhancing accessibility of essential nutrients, such as potassium, phosphate, and magnesium (Schliemann et al. 1983; Mushtaq et al. 2018). In addition to this, the association of fruit trees and grass species improve the signs of leaf chlorosis because of Fe insufficiency. The quantity of organic material replaced annually by the plant mass is comparatively easy to estimate. Balesdent and Balabane (1996) stated, though the projected above-ground organic matter (345 g C m^{-2} $year^{-1}$) was better than the below-ground (152 g C m^{-2} $year^{-1}$) in corn residue, the latter added more to the soil organic matter than the former. Similarly, cultivation of alley grasses decreased the frequency of downy mildew plus powdery mildew in grape (Marangoni et al. 2001).

Nutrient release from grass litter at dissimilar rates varies with the mineral type, for example, K is released approximately following 5 weeks, whereas N, Ca, and P release takes months (Tagliavini et al. 2007). The application of mowed grass as mulch in organic farming is not much suggested in fruits, such as Pome, owing to negative effects following harvest. All the approaches aimed at prevention of excessive nutrient accumulation in soils, like that of K or P, must be implemented. Controlling iron concentrations in fruit trees is a key concern in calcareous soils, therefore inhibition of diseases such as leaf chlorosis needs to be accomplished by proper agronomic practices such as introducing resilient rootstocks and enhancement in organic material concentration in soils. Orchard management using grasses, such as species of *Festuca*, can diminish or inhibit Fe chlorosis by producing phytosiderophores and compounds, such as mugineic acid (Klair et al. 1995; Dervash et al. 2020), that chelate the insoluble iron present in the soil.

8.14 Nutrient Management and Fruit Quality

Currently, in this age of aggressive marketing, consumers are aware of their rights and concerned about the quality of the food products. Therefore, the price of organically farmed fruits, such as apples, almonds, cashew nuts, and walnuts, has increased by considerable amounts in comparison to traditionally grown fruits. The effect of organic farming on superiority and chiefly on the nutritional significance of fruits is immensely argued. In comparison to traditional farming, organic fruit management has been established to enhance the concentration of phenols, flavanols in apples (Weibel et al. 2000). Overall, reductions in the concentration of secondary metabolic products such as organic acids and polyphenolic compounds, which are deliberated as advantageous to the human health, are obtained from organic cultivation practices (Winter and Davis 2006). The fruits obtained from organic farming enhance the productivity of plant polyphenols which have resistance mechanisms against harmful insecticides and fungicides (Asami et al. 2003; Chassy 2007) with an enhancement in protein content (Brandt and Mølgaard 2001).

8.15 Role of Soil Organic Matter

Organic matter consisting of plant and animal remains is considered to be an essential constituent of the soil. In the breakdown process, many materials are synthesized biologically from the decomposition products. These materials are categorized as humic and non-humic materials. The organic matter in soil is amorphous, hydrophilic, acidic, partially aromatic, and complex in nature. Humic materials comprises three components: (i) humic acid that is alkali soluble and acid insoluble; (ii) fulvic acid, which is the humic part remaining as a solution when the alkaline fraction acidifies; and (iii) humin, the humic fraction that is not extractable by using dilute base or acid. Soil organic matter (SOM) comprises humic substances as the largest component (85–90%), and non-humic substances as the lesser fraction comprising (10–15%) of the total percentage. The importance of SOM stems from the following points:

- Organic matter is an important nutrient reservoir for soil microbes.
- Organic matter is a repository of numerous plant macro- and micronutrients, especially N, P, S.
- Low inorganic nitrogen quantity is available in the soil, therefore much of it is acquired through conversion from organic forms which makes plants reliant on soil organic matter to supplement their nutritional requirement.
- Soil organic matter has a noteworthy function of improving physical characteristics of the soil, such as soil texture, moisture holding capacity, permeability, and soil drainage.
- Soil organic matter aids in improvising the numerous chemical properties of the soil such as accelerating soil cation exchange capacity that is helpful in enhancing the rate of chelation of nutrients, such as calcium, magnesium, zinc, potassium, copper, and iron.
- Soil organic matter supports soil buffering.
- Soil organic matter benefits in increase in nutrient release from the soil, hence aids in nutrient obtainability.

- Plant growth and development are stimulated by the physiological activities of organic matter.
- The organic material available to plants influence different soil processes, resulting in soil formation.

8.16 Organic Matter as Soil Structure Builder and Storehouse of Nutrients

Organic matter content of cultivated soils is intricately associated with soil productivity, tilth, and fertility. In semi-arid soils, organic matter is comparatively less, within a range of 0.5–3% of the total organic matter, but its impact on soil properties has a considerable implication. Organic matter at low concentrations is the prime substance assisting soil accretion and soil structure stability. Good soil structures are helpful in efficient air and water intake helps as well in protecting soils from erosion by means of wind and water. It also endures root structure. Dark coloured humic component of the soil promotes the capacity of the soil for increasing the heat absorption rate which helps the soil to warm up easily in the spring after harsh winter conditions. Therefore, organic matter is the main reservoir for most fundamental plant nutrients in semiarid soils.

The N, P, and S content of the semi-arid soils is 0.12%, 0.05%, and 0.03%, respectively, with 95% of the total N, 40% of the total P, and 90% of the total S being provided from the soil organic matter. Furthermore, the soil organic matter comprises the principal reservoir of plant nutrients, and variability within this reservoir is of foremost importance for storing and cycling of nutrients. In some dry land cropping systems, more than or equal to 50% of the nitrogen is compulsory for the plants and it arrives from SOM mineralization. The decomposition is facilitated by microbes and releasing of nutrients is controlled by numerous other means, for example, wetting of the soil, tillage, adding plant and animal residues. These affect the overall dynamics of soil and result in escalation of the size of microbes and improve nutrient release.

8.17 Role of Organic Nutrient Sources in Enhancing Nutrient-Use Efficiency

Organic substances play a chief function of maintaining soil buffering capacity, its physical and biological properties. An array of factors, such as soil temperature, water content, and chemical composition of the organic matter, affects the release of N from the soil. Monitoring N release from organic materials is dependent on its amount and quality of nutrients, properties of soil, the many environmental as well as management factors (Singh et al. 2001; Mehmood et al. 2019;

Dar and Bhat 2020). The accumulation of organic material in the soil is essential to increase the N mineralization potential. The task in optimization of N intake of organic as well as cover crop-based systems do not wholly depend on development of organic matter pools but also have an impact on the rate and timing of N mineralization.

The rate of N mineralization in soil is subjected to various interactions amongst contributions of manure, cover crops, fertilizers, and organic matter (Horwath et al. 2006). Owing to gradual releasing characteristics of organic N, it often shows slight improvement on crop growth during the initial time of the cultivable year. After application, the uptake of N increases resulting in the enrichment of the overall N content of the soil. This practice proves the durable competence of organic fertilizers. Nevertheless, in terms of mineral fertilizer equivalents, short-term N release from organic sources contrasts between 0% (with some material) to 100% (with urine). Application of green manure and NPK is encouraging throughout the first three seasons, whereas FYM and NPK were superior throughout later three seasons, signifying long-term usage of FYM for improved yields in inter-cropping practices in vertisols (Subbaiah et al. 2006).

Soil fertility shows a remarkable improvement by making use of FYM and poultry in comparison to the initial status. Unifying nutrient enhancement practices, that is, using leaf manure of sababul, neem, and melia with N fertilizer, can significantly enhance nitrogen uptake, agronomic efficiency, and increased yield in sunflower plants (Panneer and Bheemaiah 2005). When residues were incorporated in the groundnut and maize cropping system, it resulted in enhancing the successive maize yield and an increasing N recycling efficiency was observed (Sakonnakhon et al. 2005). In chick-pea, making use of residue as soil manure significantly improved the physical and fertility parameters of the soil. In maize, the nitrogen uptake effectiveness can be improved by incorporating *Glyricidia sepium* pruning 4 weeks before planting. On the residual effect of linseed and rice, the application of *Sesbania rostrata* proved beneficial as compared to paddy straw. The combined action of urea and green manure increase yield and N uptake. In Rice, N content as high as 50% can be attained by using 1 t/ha (dry weight) *Sesbania rostrate* (Singh et al. 1999).

8.18 Conclusion

Organic farming is system sustainable and environmentally sensitive; therefore, it is essential for achieving sustainable development. For improving productivity and fertility of soil, the various techniques of organic farming such as vermicomposting, integrated nutrient management, and nutrient use efficiency, the part of organic matter in improving soil health, are of critical importance and offer a better scope of sustainable agriculture.

References

Adjei-Nsiah S, Kuyper TW, Leeuwis C, Abekoe MK, Cobbinah J, Sakyi-Dawson O, Giller KE (2008) Farmers' agronomic and social evaluation of productivity, yield and N_2-fixation in different cowpea varieties and their subsequent residual N effects on a succeeding maize crop. Nutr Cycl Agroecosyst 80:199–209

Asami DK, Hong YJ, Barret DM, Mitchell AE (2003) Comparison of the total phenolic and ascorbic acid content of freeze-dried and air-dried marionberry, strawberry, and corn grown using conventional, organic, and sustainable agriculture practices. J Agric Food Chem 51:1237–1241

Balesdent J, Balabane M (1996) Major contribution of root to soil, carbon storage inferred from maize cultivated soils. Soil Biol Biochem 28:1261–1263

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017a) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017b) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza – nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Brandt K, Mølgaard JP (2001) Organic agriculture: does it enhance or reduce the nutritional value of plant foods? J Sci Food Agric 81:924–931

Brown BD, Gibson RC, Geary B, Morra MJ (2008) Bio fumigant biomass, nutrient content and glucosinolate response to phosphorus. J Plant Nutr 31:743–757

Chhonkar PK (2002) Organic farming myth and reality. In: Proceedings of the FAI seminar on fertilizer and agriculture meeting the challenges, New Delhi, India, December 2002

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from Fish Rohu (Labeo rohita) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 183–196

FAO/WHO (Food and Agriculture Organization/World Health Organization) (2011) *Codex alimentarius:* guidelines for the production, processing, labelling and marketing of organically produced foods. CAC/GL 32. FAO/WHO, Paris

Gaur AC (1992) Bulky organic manures and crop residues. In: Tandon HLS (ed) Fertilizer organic manures recyclable wastes and bio-fertilizers. Fertiliser Development and Consultation Organisation, New Delhi

Horwath W, Kabir Z, Reed K, Kaffka S, Miyao G, Kent (2006) Long-term assessment of N use and loss in irrigated organic, low-input and conventional cropping systems. In: 18th world congress of soil science, held during 9–15 July, Philadelphia, PA, USA

Inoko A (1984) Compost as source of plant nutrients. In: Banta S, Mendoza CV (eds) Organic matter and rice. IRRI, Los Banos, Philippines, pp 137–146

Kalyan S (2005) Development of sustainable farming system model for the Irrigated agro-ecosystem of Eastern UP, ICAR, Adhoc project. Final Annual Report, Department of Agronomy, Institute of Agricultural Science, Banaras Hindu University, Varanasi, India

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Klair S, Adams Z, Hider RC, Leigh RA (1995) The role of phytosiderophores in iron uptake by cereal plants. J Inorg Biochem 59:109–109

Marangoni B, Toselli M, Venturi A, Fontana M, Scudellari D (2001) Effects of vineyard soil management and fertilization on grape diseases and wine quality. IOBC/WPRS Bull 243:53–358

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–178

Nambiar KKM, Soni PN, Vats MR, Sehgal DK, Mehta DK (1992) AICRP on long term fertilizer experiments. Annual Reports 1987–88 and 1988–89, IARI, New Delhi, India

Olsson PA, Thingstrup I, Jakobsen I, Baath E (1999) Estimation of the biomass of arbuscular mycorrhizal fungi in a linseed field. Soil Biol Biochem 31:1879–1887

Panneer S, Bheemaiah G (2005) Effect of integrated nutrient management practices on productivity, nutrient uptake and economics of sunflower intercropped with *Azadirachtaindica* and *Melia azadirach* trees. J Oilseeds Res 22(1):231–234

Prabhakar RT, Umadevi M, Chandrasekhar RP (2010) Effect of fly ash and farm yard manure on soil properties and yield of rice grown on an inceptisol. Agric Sci Dig 30:281–285

Qadri H, Bhat RA (2020) The concerns for global sustainability of freshwater ecosystems (2019). In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 1–15

Sakonnakhon SPN, Toomsan B, Cadisch G, Baggs EM, Vityakon P, Limpinuntana V, Jogloy S, Patanothai A (2005) Dry season groundnut stover management practices determine nitrogen cycling efficiency and subsequent maize yields. Plant Soil 272(1/2):183–199

Schliemann GK, Terblanche JH, De Koch IS (1983) Preparation and cultivation of plum soil. DFGA 1:20–27

Singh YV, Dabas JPS (2012) Hormonize organic farming and food security. Kurukshetra 60:29–34

Singh AP, Tripathi RS, Mittra BN (1999) Integrated nitrogen management in rainfed rice-linseed cropping system. Trop Agric Res Ext 2(2):83–86

Singh U, Giller KE, Palm CA, Ladha JK, Breman H (2001) Synchronizing N release from organic residues: opportunities for integrated management of N. In: 2nd international nitrogen conference, held during 14–18 October 2001 at Potomac, Maryland, the USA

Singh DV, Bhat JIA, Bhat RA, Dervash MA, Ganei SA (2018) Vehicular stress a cause for heavy metal accumulation and change in physico-chemical characteristics of road side soils in Pahalgam. Environ Monit Assess 190:353. https://doi.org/10.1007/s10661-018-6731-2

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 319–339

Tagliavini M, Tonon G, Scandellari F, Quiñones A, Palmieri S, Menarbin G, Gioacchini P, Masia A (2007) Nutrient recycling during the decomposition of apple leale (*Malus domestica*) and mowed grasses in an orchard. Agric Ecosyst Environ 118:191–200

Tandon HLS (1992) Fertilizers and their integration and organics and bio-fertilizers. In: Tandon HLS (ed) Fertilizers, organic manures, recyclable wastes and bio-fertilizers. Fertiliser Development Consultation Organisation, New Delhi, pp 32–36

Timsina J, Connor DJ (2001) Productivity and management of rice-wheat cropping systems: issues and challenges. Field Crop Res 69:93–132

Weibel F, Bickel R, Leuthold S, Alföldi T (2000) Are organically grown apple tastier and healthier? A comparative field study using conventional and alternative methods to measure fruit quality. Acta Hortic 517:417–426

White KD (1970) Fallowing, crop rotation, and crop yields in Roman times. Agric Hist 44:281–290

Winter CK, Davis SF (2006) Organic food. J Food Sci 9:117–124

Zhu ZI, Liu CQ, Jiang BF (1984) Mineralization of organic nitrogen, phosphorus and sulphur in some paddy soils in China. In: Organic matter and rice. International Rice Research Institute, Los Baños, Laguna/Manila, Philippines, pp 259–272

Chapter 9
Values of Composting

Umair Riaz, Shazia Iqbal, Faizan Rafi, Madiha Batool, Nadia Manzoor, Waqas Ashraf, and Ghulam Murtaza

9.1 Introduction

Compost served as a source of nutrients, and it has numerous advantages as well as disadvantages due to its organic nature. Compost is used as a soil conditioner, added essential humus and humic acid in the soil, and is used as a fertilizer and pesticide for cropland. In a simple method of compost formation, the heap of organic matter is formed, and that material changes to humus after a few months. Different types of waste products, e.g., municipal sewage, cattle manure, tree bark, and root waste, are used for compost formation (Gaind 2014).There are three elements of composting: human management, production of internal heat, and the presence of air. Carbon is required for energy production in composting. Heat is produced at the result of oxidation of carbon by microorganisms (Vidović and Runko Luttenberger 2019; Bhat et al. 2018a). Nitrogen is required for the reproduction and growth of the organism for the oxidation of carbon. Oxygen is used in the decomposition process for the oxidation of carbon, and water is also required during decomposition. At the carbon-to-nitrogen ratio of 25:1, the maximum composting occurs (Tilley 2014). In

---

U. Riaz (✉)
Soil and Water Testing Laboratory for Research, Agriculture Department,
Government of Punjab, Bahawalpur, Pakistan
e-mail: umair.riaz@uaf.edu.pk

S. Iqbal · F. Rafi · M. Batool · G. Murtaza
Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan

N. Manzoor
Department of Soil Chemistry, Regional Agricultural Research Institute,
Bahawalpur, Pakistan

W. Ashraf
Department of Plant Pathology, University College of Agriculture and Environmental
Sciences, Islamia University of Bahawalpur, Bahawalpur, Pakistan

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_9

hot container composting, the compost is produced quickly because heat remains inside the container (Haug 2018). The carbon-to-nitrogen ratio should be 30–35 for the decomposition of feedstock, and the production of raw material is considered as the initial step of decomposition (Gil et al. 2008; Bhat et al. 2017a, b; Sofi et al. 2017). Aeration, moisture, type of feedstock, and C:N ratio are said to be the main factors that affect the process of composting. If the condition is anaerobic, it would lead to fermentation, and if the C:N ratio is not correct, it will increase the length of the composting process.

The growth of microorganisms will be affected if the moisture is low in the composting process (Füleky and Benedek 2010). The layout of composting process is shown in Fig. 9.1. The windrow method is said to be the most convenient method of composting. In this method, the raw material is set in parallel rows; the piles are allowed to rotate for the increase of oxygen supply. The moisture of piles is also removed by turning the windrows. The windrows are rotated twice a week usually. Another system used for composting of organic matter is called aerated static piles; in this system, the organic matter is placed in perforated pipes, and the material does not move to another place for aeration (Wang and Li 2009; Bhat et al. 2017a, b, 2018a, b; Qadri and Bhat 2020).

The atmospheric nitrogen-fixing bacteria and archaea are the main microorganisms that transform nitrogen during the composting process (Pepe et al. 2013). In the compost formation, fungi are found during the initial and last stage of the process. *Aspergillus*, *Penicillium*, *Mortierella*, and *Acremonium* are the essential genera (Anastasi et al. 2005). In the degradation of a complex organic compound, actinobacteria play a significant role because it can grow in high temperatures. In the fermentation process, available carbon converts into unavailable carbon due to actinobacteria (Shilev et al. 2007). In the initial stage of composting, the breakdown of organic nitrogen occurs into small compounds, and many types of bacteria, fungi, and other microorganisms take part. In the organic matter to be composted, the microorganisms are present, which convert the protein into amino acids by the release of proteases (Vargas-García et al. 2010; Dervash et al. 2020; Khanday et al. 2016).

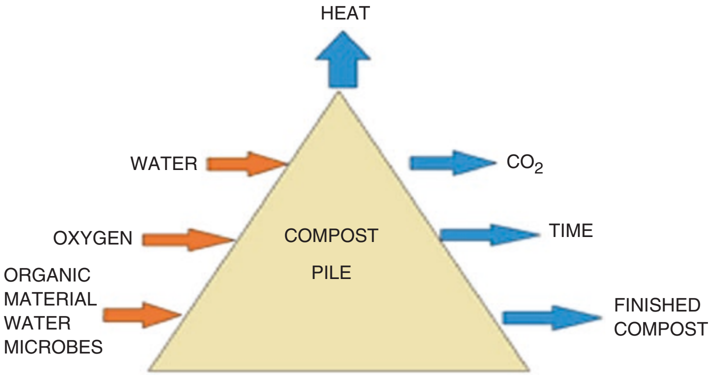


Fig. 9.1 The composting process

9.2 Historical Background and Perspectives

About 6000 years ago, the first pits were built in Sumerian cities; the organic matter of these piles was used to apply in fields for the sake of agriculture. These piles were built outside the houses (Waldron and Nichols 2009). People of India, China, and South America use animal and human residues in agriculture as a source of fertilizer (Howard 1942). Sir Albert Howard was the first person who worked on the management of composting in India, and he also made advancements in modern composting (Howard 1933). Indore process was developed by Sir Howard in collaboration with other persons. Firstly, only animal manures were used in this process, but then human feces and other materials were also used (Brunt 1949). Indore method was improved and named Bangalore process by the Indian Council of Agricultural Research in Bangalore (Diaz and De Bertoldi 2007). In China composting was studied by Scott and some other people, and they used night soil in 1935, but they stopped their studies due to World War II. Later, they mentioned the issue of composting human waste (Scott 1952).

An experiment was performed by Waksman and others from 1926 to 1941 on the formation of compost in the presence of air using vegetables. They studied the effect of different temperatures on degradation and studied the part of microorganisms in the decomposition of organic matter (Stotzky 1965). From 1920 to 1930, Beccari process was adopted by the USA, Florida, and New York. In Scarsdale, a plant was developed, and the awful smell was observed when the doors of the plant were opened. This lousy smell was produced because of anaerobic conditions developed in the plant. The New York Health Department failed to control these issues, so they stopped this facility, unfortunately (University of California 1950).

In the USA, the Frazer process was used in 1949; the organic matter was filed in a digester having an aerobic environment. The organic matter was mixed thoroughly and then moved to screening. The material was sent back to the composting process after screening (Eweson 1953). The composting of biosolids was started in 1973 by the USDA (Willson and Walker 1973). The static pile method of composting was introduced by Beltsville in 1975 (Epstein et al. 1976). Much work had been done on the formation and use of compost in Japan in 1970 and 1980 (Yoshida and Kubota 1979). Composting is being used by gardeners and farmers for many centuries. Composting has been used in agriculture to improve fertility from the time no one knows. The manure from animals and organic materials from vegetables were thrown in piles and placed into pits. These were then decomposed by the microorganisms present in the soil naturally. The time taken by this process ranged from 6 months to a year. The simple techniques to cover it with soil or turning all the materials were utilized. In China, the fecal material of humans, along with that of animal and vegetable manure, is in use for almost 4000 years. This led to an increase in soil fertility that supported a dense human population. A layer of green manures together with river silt, animal waste, and rice straw with superphosphate has been in use in a primitive method called "pit manure." In this method, a rectangular or a circular pit was dug. The area of this pit was almost 10m^2. The moisture was conserved by wetting an upper layer of mud. It not only conserved moisture but assisted in avoiding loss of nutrients and maintenance of temperature. All the material was turned three times per month. The anaerobic conditions were maintained throughout the process (Lopez-Real 1996).

9.3 Types of Compost

The quality and type of compost are one of the essential criteria in its use as an organic amendment and a recycling process for organic waste (Lasaridi et al. 2006). The composts are used extensively in agriculture, mostly due to enormous organic matter and mineral components that are found in manure, municipal waste, sewage sludges, etc. These assist in the reclamation of soil and for better crop production. This is all done after running them through appropriate processes of stabilization (Campitelli and Ceppi 2008).

The following are the types of compost:

(a) *Aerated static pile composting*
(b) *Windrow composting*
(c) *Vermicomposting*
(d) *In-vessel composting*

9.3.1 *Aerated Static Pile Composting*

The distinguishing feature of this composting system is the use of a grid for aeration pipes (Fig. 9.2). It is done for forced aeration. The pile is aerated by a fan or blower. This type of composting involves the mixing of dehydrated sludge with wood chips,

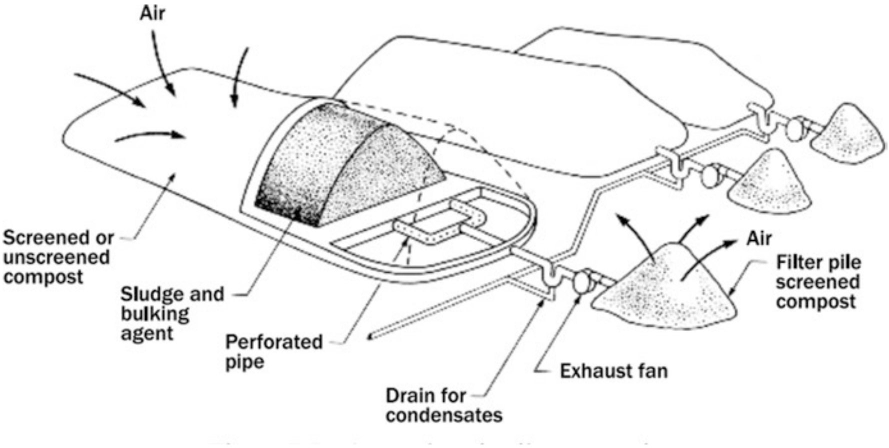


Fig. 9.2 Lay out of an aerated static pile composting

which is used as a bulking agent. The other process is followed by the building of a pile of compost above the grid of aeration pipes, composting, filtering of the compost, curing, and then storage. The following is the procedure of aerated static pile composting. The 100–150 mm plastic pipes are used to make aeration grid. These are then fitted in the 1 ft plenum of wood chips. The wood chips assist in even distribution of air and for absorbance of moisture from the pile. The height of the pile ranges from 6 to 8 ft. The temperature and oxygen are controlled by forced air in aerated static pile composting (Metcalf 2003).

9.3.2 *Windrow Composting*

In this process, the composting material is thoroughly mixed with a bulking agent. These are then formed in long rows. These parallel rows are called windrows. The height of a windrow ranges from 3 to 6 ft with 6–14 ft width at the base. The height and width depend on the types of equipment used for turning and mixing of the windrows. This type of composting is done on open sites. The rows are continuously turned upside down to expose composting materials properly. The movement of air is eased by it. The moisture is also decreased by it. The most used machine for turning windrows is a front-end loader, which is shown in Fig. 9.3.

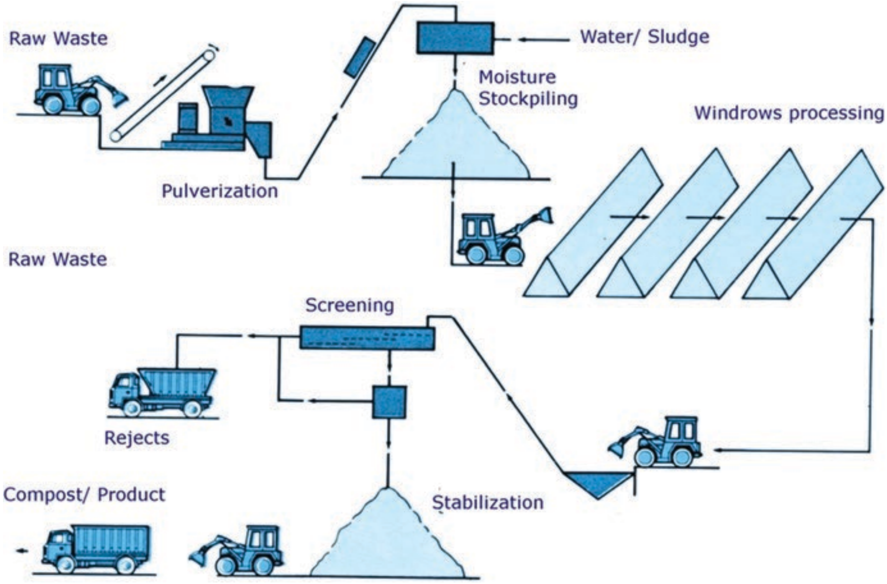


Fig. 9.3 Lay out of an open windrow composting

9.3.3 Vermicomposting

A finely powdered peat-like mature substance which is produced as a result of the non-thermophilic procedure and engaging interaction between earthworms and microbes is known as vermicomposting. This results in stabilization and oxidation of organic matter. The primary process of vermicomposting revolves around the conversion of solid organic waste into vermicompost through the non-thermophilic procedure. This is one of the eco-friendliest technologies that are used as an organic fertilizer. The most found bacteria in vermicomposting are from *Rhizobium*, *Pseudomonas*, *Nitrosomonas*, *Azotobacter*, and *Bacillus*. The nutrition provided to plants by vermicompost is higher than other composts (Joshi et al. 2015) (Fig. 9.4).

9.3.4 In-Vessel Composting

In-vessel composting is done inside a container. A more consistent and stabilized compost can be made by this process in lesser time because environmental conditions like oxygen, airflow, and temperature are controlled. The odors produced as the result of this process are also contained in in-vessel composting. There are two classes of this type, namely, dynamic reactors and agitated reactors. The following schematic diagram (Fig. 9.5) shows this type of composting.

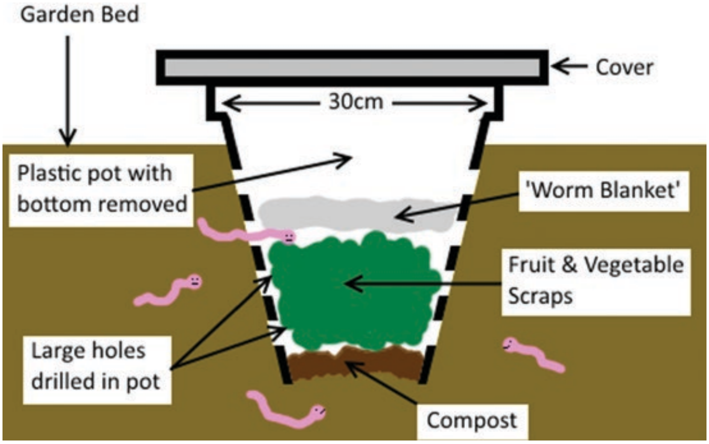


Fig. 9.4 A schematic diagram of a worm tunnel for the production of vermin compost

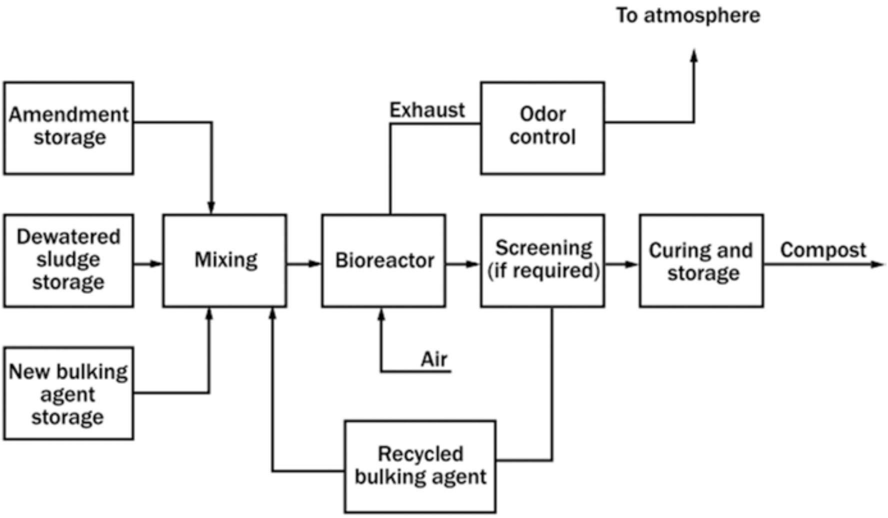


Fig. 9.5 Schematic diagram of in-vessel composting

9.4 Compost: A Viable Tool for Sustainable Agriculture

Compost can be incorporated to the soil, to recover degraded soils; to control plant disease; to increase or maintain soil fertility to reduce negative impacts and production costs of chemical fertilizers, pesticides, and fuel; to sequester carbon into the soil; and to reduce global warming (Dar et al. 2013; Scotti et al. 2016; Sánchez et al. 2017; Vázquez and Soto 2017; Mushtaq et al. 2018). Compost helps to improve microbial activity, organic matter, and bring back dead soil to life. It serves as a mulching material, nursery cultivation substrate, a growing medium, or porous absorbent material that holds moisture and soluble minerals and provides nutrients and support to help plants flourish. Composting can be a well-thought-out C-based system, like agricultural management practices, reforestation, or other waste management industries and an alternative to landfill (Brown et al. 2008; Quirós et al. 2014). Compost possesses little physical similarity to the originated raw material, but its nutrient content differs with the type of materials used for the initial mass preparation. Final compost characterization of generally hinge on initial C:N ratio of used materials (Arbab and Mubarak 2016). Compost provides nutrients to the soil for a long time. Compost acts as a slow nutrient release fertilizer and improves nutrient use efficiency. It takes at least 3 years to establish its full value. As a rule, compost releases 40% of phosphorus, 20% of nitrogen, and 80% potassium in the first year of application. Organic nitrogen released at a constant rate with continuous application of compost from the accumulated humus and increased nitrogen use efficiency of chemical fertilizers over 50% over the years. Phosphorus availability is sometimes much higher than that of inorganic fertilizers (Sinha et al. 2012; Singh et al. 2020). Compared to the separate addition of biochar or compost, their combined application was more effective to improve soil pH, organic matter, organic carbon, and available potassium (Tang et al. 2020). The on-farm composting process resembles the recent indication and provision of the European Commission on agricultural biomass recycling for production and application of organic-based fertilizer in soil to the management of the organic matter. These approaches are supposed to signify an important influence and valuable chance to advance the circular economy at local as well as regional scale (European Commission 2017). The compost application in agriculture could encounter the European Union country's target objective to cut the organic waste quantity going to landfill sites by 50% by 2050 (European Commission 1999).

Compost helps to conserve soil and water, balance the soil pH in a way that diminishes plant stress, control soil runoff and erosion, and improve chemical properties of soil and invigorate degraded soils and ecosystems (Hernadez et al. 2015). It improves availability to plants by nutrient mobilization, soil structure water-holding capacity, and aeration, suppresses soilborne diseases, and promotes microbial life in soil (Tejada et al. 2009; Hadar 2011; Macci et al. 2012). Vermicompost, human compost, and cow compost affected soil chemical properties in the cultivated green bean plot. A significant increase in soil EC, soil pH, and organic carbon of soil and green bean yield under human compost was observed than in other composts for 0–15 cm depth. This proves that the fertilizer value of the sanitary products was higher than that of vermicompost and cow compost. Sanitary products (human waste) can be used as a soil amendment and nutrient source, but it is high in salinity (Uwamahoro et al. 2019).

Application of green manure and compost (0, 10, and 20 t ha^{-1}) alone or in combination with mineral nitrogen (0, 43, and 86 kg N ha^{-1}) recovers soil properties and improves growth and yield of sweet pepper. In this context, compost was better than green manure (Mahgoub 2014). Composted poultry manure application along with some microbial inoculation improved nutrient status of calcareous soil (Iqbal et al. 2016). Additionally, application of wheat straw and cow manure compost at the ratio of 3:1 alone (0, 4, 8, 12, and 16 ton fed^{-1}) or in combination with chemical fertilizers 86 kg N ha^{-1} and 43 kg P_2O_5 ha^{-1} for wheat and 86 kg N ha^{-1} for okra crop had significantly improved soil properties. Nutrient uptake increased significantly by plant and improved the yield and growth for wheat and okra. The combination of chemical fertilizers with compost (16 ton fed^{-1}) gave the highest nutrient content, grain yield, crude protein, potassium, and phosphorus percent (Eltayeb 2018). However, this high amount of compost is not good from an economic point of view. The application of sewage sludge compost is helpful in enlightening soil conditions and the yield of sorghum fodder. The combination of sludge compost with recurrent irrigation can upsurge yield by more than 47% compared to air-dry sludge treatment (Shashoug et al. 2017).

The use of compost is a sustainable approach to mitigate, control, or prevent harmful plant diseases and pests. It affects vascular, foliar, as well as root pathogens. Compost can decrease crop losses by soilborne diseases by disease suppression. On the other hand, it acts as a shelter and food source for the enemies of plant pathogens and stimulates their proliferation (Hadar 2011). Disease control by compost largely depends on the substrate or soil properties, i.e., biotic and physicochemical parameters, the composting process used, and raw material composition in the preparation of compost, and on the quality and maturity of the compost (Janvier et al. 2007). Long periods of compost maturation can decrease microbial activity and, therefore, decrease the disease suppression ability (Zmora-Nahum et al. 2008). Bacteria belonging to genera *Enterobacter* spp., *Bacillus* spp., *Streptomyces* spp., *Trichoderma* spp., *Pseudomonas* spp., as well as several *Penicillium* spp., isolates, and other fungi have been recognized as biocontrol agents in compost-amended substrates (Pugliese et al. 2008). Sterilization or heat treatments can drop the suppressive effect of the compost (Pugliese et al. 2011). However, insufficient research is found about the direct effect of compost on pest management. For instance, both indirect and direct links were found between aphids, predators, and compost. Compost-treated plots confirmed lower aphid population numbers pointedly when predators' numbers are suggestively higher. Aphids were also lower significantly than in plots without compost (Bell et al. 2008). The compost teas have an extensive series of microflora like actinomycetes, bacteria, fungi, etc., with variable occurrence and population. Most of the microfloras are potential antagonists against different disease agents such as *Alternaria alternata*. Individually, actinomycetes and anaerobic bacterial isolates were proved more effective than some others (Praveena and Reddy 2013).

9.5 Compost Application in Peri-urban Areas

Peri-urban agriculture is an integral part of the twenty-first-century economy. It is a rural-urban transition zone. Because of the increasing population and spread in urbanized areas, agriculture farms once sited in rural areas are now surrounded by urban areas (Cohen and Reynolds 2015). Peri-urban agriculture is the livestock rearing or crop production for sale or consumption within the city areas. It is well-known that peri-urban agriculture addresses the threefold security global goals (FAO 2008), i.e., (i) sustainable management and use of natural resources, (ii) sustainable increases in food production and availability, and (iii) economic and social progress (Bougnom et al. 2014). Peri-urban agriculture plays a role in the urban social, economic, and ecological systems (Mougeot 2002). Achieving food security requires an increase in production in the cities, along with a sustainable farming system. Peri-urban agriculture requires a large number of inputs, such as plant nutrients. Chemical fertilizers are usually suggested to maintenance farmers, but they are expensive to use. Chemical fertilizers and pesticides are persistent and remain in water and soil. They will cause pollution by accumulation in soils, runoff, and horticultural crops, by the accumulation of organic compounds and heavy metals in aquatic life, by seepage into aquifers, by airborne chemicals, and by direct contact. Therefore, to replace inorganic fertilizers, composting material is used in many areas of the world. Composting seems to be a possible way to handle organic waste management in the cities and to provide peri-urban agriculture with organic fertilizers (Bougnom et al. 2014; Dar et al. 2016). Compost lessens transportation costs because some of the waste can go into the compost piles as a replacement for landfilling (Eureka Recycling 2001), while composting without an understanding of the adverse effects on neighbors can have damaging effects on communities (Krasa et al. 2017).

The commercial compost contains the raw material from various sources and may have a considerable amount of heavy metals in their composition (Riaz et al. 2017). Seven different composting mixtures from fresh vegetable leaves and fallen tree leaves mixed with maize or grass straw (0%, 10%, 30%, and 50% w/w) are common in peri-urban areas of Harare. The composts with a 30% straw mixture effectively reduced nitrogen losses and had higher potential as a soil amendment in the peri-urban areas of Harare (Mhindu et al. 2013). Raw fecal sludge and wood chips and maize cobs from three peri-urban communities were composted. The results showed that the total N and carbon contents of all materials decreased. At the end of the composting process, the experiment showed lower phosphorus and potassium (K) available concentrations than in the original substrate materials. Maize cob that contained more phosphorus, nitrogen, potassium, and carbon is the most ideal (Appiah-Effaha et al. 2016).

9.6 Compost Versus Environmental and Soil Pollution

Human activities, such as mining, chemical manufacturing, smelting, fertilizer application, fossil fuel combustion, and tanning, are the main reasons of heavy metal, pesticide, harmful chemical, and oil-based hydrocarbon accumulation and pollution in soil (Liu et al. 2019a, b; Tang et al. 2019). Heavy metals and other chemicals are generally not degradable, and their buildup in the soil causes pollution and threatens human health (Liu et al. 2019c; Bhatti et al. 2017). Many countries have been endangered by heavy metal pollution in soil, including China, the USA, Italy, Mexico, etc. (Tang et al. 2019). Many studies have been done on removal or immobilization of heavy metals in soil with numerous inorganic and organic additives (Lu et al. 2017). Compost can lessen exchangeable and mobile metal fraction of contaminated soil and has been used as a highly effective heavy metal removal amendment (Liang et al. 2017; Dar and Bhat 2020). Compost comprises a large number of humic substances, which can form stable organometallic complexes with metal ions in the soil to reduce the mobility of metals (Arif et al. 2018; Gusiatin and Kulikowska 2016). Moreover, compost with low carbon-to-N ratio and a high proportion of humic substances to TOC can more effectively reduce the mobility of heavy metals in soil (Gusiatin and Kulikowska 2016). Conversely, some heavy metals such as Cu may be activated by humic acid (Zeng et al. 2015). The increase in available P by composting decreased heavy metal availability, possibly by complexation and with phosphate precipitation (Ahmad et al. 2012). More phosphate availability increased arsenate availability because of the same chemical nature (Beesley et al. 2014). Compost increases soil organic matter, and it acts as an essential heavy metal (Cd and Zn) adsorbent because of the presence of many functional groups, such as –OH and –COOH. These functional groups can bind metal ions and form stable anti-desorption complexes (Yang et al. 2016). Compost with biochar remediates the heavy metal pollution in soil. Compost and biochar significantly reduced the availability of Zn and Cd but activated Cu and As slightly. Also, soil enzyme, catalase, dehydrogenase, and urease activities were activated by compost (Tang et al. 2020). Combined compost and plant technology can remove 50% of hexavalent chromium in chromium eluted soil (Mangkoedihardjo et al. 2008). The use of vegetal material compost has been encouraged strongly and better explored gradually for the remediation of the contaminated soil. Vegetal materials compost caused vertical transport and rapid mobilization of As and trace metals (Beesley and Dickinson 2010). Green waste composts comprise carboxylate groups (8.8%) and inorganic ash (46.1%) and immobilized Cu soils contaminated by metals (Tsang et al. 2014).

Animal manure compost with more than 50% inorganic fraction (high phosphorous) decreased the amounts of water-soluble lead by over 88% compared to the soil without compost. However, the microbial enzyme activity levels were the same or less than those in the control soil. Animal manure compost with 25% inorganic fraction did not suppress the water-soluble lead existed during the first 30 days, but it improved microbial enzyme activities (Katoh et al. 2016; Mehmood et al. 2019).

Pesticides are used for pest and weed control. However, it affects the soil and air quality as these chemicals can drift to other sites (Arias-Estéveza et al. 2008). Pesticides induce detectable changes in structure, functionality, and size of the microbial community, thus changing life dynamics, functions, and biodiversity of soil organisms (Yañez-Ocampo et al. 2011; Chen et al. 2015; Cruz et al. 2015). Composting can stabilize pesticides in soils through microbial degradation and can improve soil quality (Chen et al. 2015). Biochar and compost, two frequent amendments, were used to investigate their combined influence on enzymatic activities and microbial communities in organic-polluted wetlands. Compost application (2% and 10%) enhanced degradation efficiency of sulfamethoxazole by 0.033% and 0.222%, respectively, along with biochar due to the upsurge of biomass and enzymes (Liang et al. 2020). Composts of cow dung, yard manure, corn stalks, corn fermentation by-product, and sawdust have been used to improve the herbicide removal of trifluralin, metolachlor, and atrazine in contaminated soils (Moorman et al. 2001). Compost addition to soil has improved degradation of herbicides, MCPA (4-chloro-2-methylphenoxyacetic acid), and benthiocarb (S-4-chlorobenzyl diethylthiocarbamate). Composting of contaminated sawmill soil degraded chlorophenols effectively (Megharaj et al. 2011). Composting pile produced out of straw compost and chlorophenol-contaminated soil degraded more than 90% of the chlorophenols (Chen et al. 2015).

Rumen residue and yard waste alteration accelerate the aromatic and aliphatic fractions of petroleum hydrocarbon degradation in crude oil-contaminated soil as the primary substrate in the composting process. Petroleum hydrocarbon degradation efficiency was 31 times higher in soils added with rumen residue and yard waste mixture than contaminated soil, which satisfied the quality standard of soil (6974.58 mg kg^{-1}). The total petroleum hydrocarbon degradation might be completed by *Bacillus* sp. and *Bacillus cereus* as the main bacteria at the end of the composting process (Sari and Trihadiningrum 2019).

Motor oil pollution in the soil is a major environmental issue related to illegal dumping and improper handling of industrial waste. A combined alternative biological treatment that focuses on composting the polluted soil with yard trimmings was done. A 12% degradation of total petroleum hydrocarbons present in motor oil after a 9-week composting process was achieved. An additional 50% decrease in total petroleum hydrocarbons was reached after planting *Lolium perenne* with the highest microbial count, 2.8 × 107 CFU, of bacterial species, *Azotobacter vinelandii*, *Bacillus brevis*, *Burkholderia cepacia*, and *Stenotrophomonas maltophilia* (Escobar-Alvarado et al. 2015).

Composting decreases environmental problems related to waste management by decreasing waste volumes and by killing potentially dangerous organisms. Composting can effectively recycle valuable organic matter nutrients that are trapped in the environment. Landfills generate emissions, mostly containing methane, a more toxic greenhouse gas than carbon dioxide. Landfilling is considered a significant contributor to the increase in greenhouse gas emission. Developing countries caused about 29% of these emissions in the year 2000, and this is predicted to increase to 64% in 2030 and 76% in 2050 (Monni et al. 2006). Moreover, landfills produce hazardous leachate that can degrade habitats and water quality as well as poison flora and fauna if it enters water sources. The US Composting Council notes that although barriers are often put in place in an attempt to prevent emissions and leachate escaping, if these liners break down, contaminants can be leaked into surface runoff and groundwater. By diverting organic wastes from landfills, the lifespan of municipal landfills can be lengthened, reducing the need to create new landfills. Keeping organics out of waste stream continually can extend the life of municipal landfills. This improves the air quality by reduced emission processing as well as anthropogenic greenhouse gas production (EPA, CalRecycle, Clean Air Council, Global Alliance for Incinerator Alternatives, US Composting Council).

Composting, as an alternative to waste incineration, has huge inferences for civilizing environmental quality. The Environmental Protection Agency and the US Composting Council reported that aerobic composting does not expressively add to an increase in CO_2 emissions. The Global Alliance for Incinerator Alternatives reported that waste incinerators produce more CO_2 emissions compared to coal, oil, or natural gas-fueled power plants. Any emissions from aerobic composting are considered part of the natural carbon cycling. Aerobic compost can also be used as a landfill cover to reduce methane emissions. Aerobic compost as a bio-filter can eliminate 80–90% of volatile organic compounds from gas streams. It sequesters carbon in the ground, acts as a carbon sink, and promotes soil structural stability and fertility (EPA, US Composting Council, the Global Alliance for Incinerator Alternatives).

During composting, microorganisms consume oxygen and decompose organic materials, generating water vapor heat and carbon dioxide. During decomposition, mineral nutrients such as sulfur, P, and N are released, and a substantial amount of potent greenhouse gasses (i.e., methane and nitrous oxide), ammonia, and NOx are produced during composting as well. Several strategies have been established to diminish greenhouse gas emissions and N losses from composting (Chowdhury et al. 2014; Wang et al. 2014). A recent study showed the influence of biochar and bean dreg addition during pig manure composting on the emission of N, greenhouse gas, and ammonia. During pig manure composting, the combined application of biochar and bean dregs decreased N loss (24.26%), greenhouse emissions (29.56%), and ammonia emissions (33.71%) (Yang et al. 2020).

The use of straw from vegetable waste composting reduced total N loss by 33% and from manure composting by 27–30% (Vu et al. 2015). High C:N materials, for example, straw, sawdust, and biochar, decreased N_2O emissions by 37–43% and methane emissions by 70–90% from composting (Jiang et al. 2011; Chowdhury et al. 2014; Vu et al. 2015). Aeration is another option for mitigating N losses and greenhouse gas emissions from composting because it reduces the presence of anaerobic hotspots in a composting pile. Anaerobic compost method decreased total N losses by 70% and ammonia emissions by 90% (Sagoo et al. 2007). A decrease of 72–78% N losses was reported by composting (Shah et al. 2012, 2016), and N losses of less than 2% of the initial total N by leachates were reported under relatively higher aeration rates (De Guardia et al. 2010). Nonmixing of cow manure compost produced 3.5 times less N_2O compared to the unturned pile composting method (Ahn et al. 2011). However, in another study, the mixed composting method increased ammonia volatilization and reduced N_2O emissions to the environment (Szanto et al. 2007). The emission of N_2O from soil was increased by sludge or biomass composting (He et al. 2016). Frequent turning of compost pile increased the total N losses by more than double compared to less frequent turning. More aeration increase N loss by ammonia volatilization (Cook et al. 2015). An increase of over 88% in total N was recorded during higher aeration. Methane emission is decreased by composting (Chowdhury et al. 2014).

9.7 Conclusion

Compost is used in agricultural soil as a soil amendment and conditioner. Compost improves the soil structure, organic matter content, and water relations. It helps to remediate the soil from heavy metals, polyaromatic hydrocarbons, pesticide, and herbicide residues by making complexes. Nutrients such as P content are improved by compost that also helps in remediating the soil from heavy metal, especially arsenate, by making complexes. Compost releases many greenhouse gasses to the environment and causes pollution. Different amendments and different types of composting materials helped to reduce the emission of greenhouse gasses. Agriculture farm practices near cities known as peri-urban agriculture recently used compost as a soil amendment, but due to the much civil legislation and neighbor's rights legislation, its use is under restriction in many areas of the world. However, it is used in many peri-urban areas as fertilizers successfully.

References

Ahmad M, Lee SS, Yang JE, Ro HM, Lee YH, Ok YSJE, Safety E (2012) Effects of soil dilution and amendments (mussel shell, cow bone, and biochar) on Pb availability and phytotoxicity in military shooting range soil. Ecotoxicol Environ Saf 79:225–231

Ahn HK, Mulbry W, White JW, Kondrad SL (2011) Pile mixing increases greenhouse gas emissions during composting of dairy manure. Bioresour Technol 102:2904–2909

Anastasi A, Varese G, Marchisio V (2005) Isolation and identification of fungal communities and compost and vermicompost. Mycologia 97:33–44

Appiah-Effaha E, Nyarkoa KB, Antwi EO, Awuahc E (2016) Effect of bulking materials and mixing ratios on concentration of nutrients during composting of raw faecal sludge from peri-urban areas. Water Pract Technol 11(1):234–242

Arbab KMA, Mubarak AR (2016) Characterization of compost as affected by manipulation of C/N ratio. Agric Sci Dig 36(1):44–47

Arias-Estéveza M, López-Periagoa E, Martínez-Carballob E, Simal-Gándarab J, Mejutoc J, García-Ríod L (2008) The mobility and degradation of pesticides in soils and the pollution of groundwater resources. Agric Ecosyst Environ 123:247–260

Arif MS, Riaz M, Shahzad SM, Yasmeen T, Ashraf M, Siddique M, Mubarik MS, Bragazza L, Buttler A (2018) Fresh and composted industrial sludge restore soil functions in surface soil of degraded agricultural land. Sci Total Environ 619:517–527

Beesley L, Dickinson NM (2010) Carbon and trace element mobility in an urban soil amended with green waste compost. J Soils Sediments 10:215–222

Beesley L, Inneh OS, Norton GJ, Moreno-Jimenez E, Pardo T, Clemente R, Dawson JJ (2014) Assessing the influence of compost and biochar amendments on the mobility and toxicity of metals and arsenic in a naturally contaminated mine soil. Environ Pollut 186:195–202

Bell JR, Traugott M, Sunderland KD, Skirvin DJ, Mead A, Kravar-Garde L, Reynolds K, Fenlon JS, Symondson WOC (2008) Beneficial links for the control of aphids: the effects of compost applications on predators and prey.J. Appl Ecol 45(4):1266–1273

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytother 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Bougnom BP, Boyomo O, Nwaga D, Ngang JJE, Etoa FX (2014) Compost: a tool to sustainable urban and peri-urban agriculture in sub-Saharan Africa? In: Maheshwari DK (ed) Composting for sustainable agriculture. Sustainable development and biodiversity 3. Springer International Publishing, Cham, pp 269–283

Brown S, Kruger C, Subler S (2008) Greenhouse gas balance for composting operations. Environ Qual 37:1396–1141

Brunt L (1949) Municipal composting. Publication No. 2a. Albert Howard Foundation of Organic Husbandry, London

Campitelli P, Ceppi S (2008) Chemical, physical and biological compost and vermicompost characterization: a chemometric study. Chemom Intell Lab Syst 90(1):64–71

Chen M, Xu P, Zeng G, Yang C, Huang D, Zhang J (2015) Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: applications, microbes and future research needs. Biotechnol Adv 33:745–755

Chowdhury MA, de Neergaard A, Jensen LS (2014) Potential of aeration flow rate and biochar addition to reduce greenhouse gas and ammonia emissions during manure composting. Chemosphere 97:16–25

Cohen N, Reynolds K (2015) Resource needs for a socially just and sustainable urban agriculture system: Lessons from New York City. Renewable Agric Food Syst 30(1):103–114

Cook KL, Ritchey EL, Loughrin JH, Haley M, Sistani KR, Bolster CH (2015) Effect of turning frequency and season on composting materials from swine high-rise facilities. Waste Manag 39:86–95

Cruz E, Cruz A, Vaca R, delÁguila P, Lugo J (2015) Assessment of soil parameters related with soil quality in agricultural systems. Life Sci J 12:154–161

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balk 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

De Guardia A, Mallard P, Teglia C, Marin A, Le Pape C, Launay M, Benoist JC, Petiot C (2010) Comparison of five organic wastes regarding their behaviour during composting: part 2, nitrogen dynamic. Waste Manag 30:415–425

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Diaz L, De Bertoldi M (2007) History of composting. In: Waste management series, vol 8. Elsevier publisher, pp 7–24 (ISBN 9780080439600)

Eltayeb NEH (2018) Effect of compost and inorganic fertilizers on yield and yield components of wheat and okra. Ph.D. Thesis, Faculty of Agricultural Sciences, University of Gezira, Wad Medani

EPA, CalRecycle, Clean Air Council, Global Alliance for Incinerator Alternatives, US Composting Council

EPA, US Composting Council, the Global Alliance for Incinerator Alternatives

Epstein E, Willson G, Burge W, Mullen D, Enkiri N (1976) A forced aeration system for composting wastewater sludge. J Water Pollut Control Fed 48:688–694

Escobar-Alvarado L, Vaca-Mier M, Rojas-Valencia N, López R, Flores J (2015) Degradation efficiency and bacterial species in soil polluted with used motor oils, treated by composting with yard trimmings and phytoremediation with Lolium perenne. J Agric Eng Biotechnol 3(2):72–78

Eureka Recycling (2001) Environmental benefits of recycling and composting. Eureka Recycling. Retrieved from http://makedirtnotwaste.org/sites/default/files/composting_factsheet_0.pdf

European Commission (1999) Council Directive 1999/31/EC on the landfill of waste. Available on http://ec.europa.eu/environment/waste/landfill_index.htm

European Commission (2017) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan. Available on http://ec.europa.eu/environment/circular-economy/implementation_report.pdf

Eweson E (1953) Profitable garbage disposal by composting. University of Kansas Publications. The Bulletin of Engineering and Architecture 29

FAO (2008) Urbanization and food security in Sub Saharan Africa. Information paper for the FAO 25th African regional conference. ftp://ftp.fao.org/docrep/fao/meeting/012/k1915e.pdf

Füleky G, Benedek S (2010) Composting to recycle biowaste. In: Sociology, organic farming, climate change and soil science. Springer, Dordrecht, pp 319–346

Gaind S (2014) Effect of fungal consortium and animal manure amendments on phosphorus fractions of paddy-straw compost. Int Biodeterior Biodegradation 94:90–97

Gil M, Carballo M, Calvo L (2008) Fertilization of maize with compost from cattle manure supplemented with additional mineral nutrients. Waste Manag 28(8):1432–1440

Gusiatin ZM, Kulikowska D (2016) Behaviors of heavy metals (Cd, Cu, Ni, Pb and Zn) in soil amended with composts. Environ Technol 37:2337–2347

Hadar Y (2011) Suppressive compost: when plant pathology met microbial ecology. Phytoparasitica 39:311–314

Haug R (2018) The practical handbook of compost engineering. Routledge, London

He S, Li A, Wang L (2016) Effect of sewage sludge and its biomass composting product on the soil characteristics and N_2O emission from the tomato planting soil. Int J Agric Biol 18:501–508

Hernadez T, Garcia E, García C (2015) A strategy for marginal semiarid degraded soil restoration: a sole addition of compost at a high rate. A five-year field experiment. Soil Biol Biochem 89:61–71

Howard A (1933) The waste products of agriculture: their utilization as humus. J R Soc Arts 82(4229):84–121

Howard A (1942) An Agricultural Testament. J Environ Qual 37:1396–1410

Iqbal S, Khan MY, Asghar HN, Akhtar MJ (2016) Combined use of phosphate solubilizing bacteria and poultry manure to enhance the growth and yield of mung bean in calcareous soil. Soil Environ 35(2):146–154

Janvier C, Villeneuve F, Alabouvette C, Edel-Hermann V, Mateille T, Steinberg C (2007) Soil health through soil disease suppression: which strategy from descriptors to indicators. Soil Biol Biochem 39:1–23

Jiang T, Schuchardt F, Li G, Guo R, Zhao Y (2011) Effect of C/N ratio, aeration rate and moisture content on ammonia and greenhouse gas emission during the composting. J Environ Sci 23(10):1754–1760

Joshi R, Singh J, Vig AP (2015) Vermicompost as an effective organic fertilizer and biocontrol agent: effect on growth, yield and quality of plants. Rev Environ Sci Biotechnol 14(1):137–159

Katoh M, Kitahara W, Sato T (2016) Role of inorganic and organic fractions in animal manure compost in lead immobilization and microbial activity in soil. Appl Environ Soil Sci 2016:7872947

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Krasa AJ, Preston BP, Carbonneau B, Bograd NA (2017) Northborough composting: a peri-urban land conflict. Retrieved from https://digitalcommons.wpi.edu/iqp-all/1076

Laboratory BSER (1950) Composting for disposal of organic refuse, vol 1 & 37. University of California, Institute of Engineering Research, Berkeley

Lasaridi K, Protopapa I, Kotsou M, Pilidis G, Manios T, Kyriacou A (2006) Quality assessment of composts in the Greek market: the need for standards and quality assurance. J Environ Manag 80(1):58–65

Liang J, Yang Z, Tang L, Zeng G, Yu M, Li X, Wu H, Qian Y, Li X, Luo Y (2017) Changes in heavy metal mobility and availability from contaminated wetland soil remediated with combined biochar-compost. Chemosphere 181:281–288

Liang J, Tanga S, Gonga J, Zenga G, Tanga W, Songa B, Zhanga P, Yanga Z, Luoa Y (2020) Responses of enzymatic activity and microbial communities to biochar/compost amendment in sulfamethoxazole polluted wetland soil. J Hazard Mater 385:121533

Liu J, Li N, Zhang W, Wei X, Tsang DC, Sun Y, Luo X, Bao Z, Zheng W, Wang J, Xu G, Hou L, Chen Y, Feng Y (2019a) Thallium contamination in farmlands and common vegetables in a pyrite mining city and potential health risks. Environ Pollut 248:906–915

Liu J, Luo X, Sun Y, Tsang DC, Qi J, Zhang W, Li N, Yin M, Wang J, Lippold H, Chen Y, Sheng G (2019b) Thallium pollution in China and removal technologies for waters: a review. Environ Int 126:771–790

Liu J, Yin M, Luo X, Xiao T, Wu Z, Li N, Wang J, Zhang W, Lippold H, Belshaw N, Feng Y, Chen Y (2019c) The mobility of thallium in sediments and source apportionment by lead isotopes. Chemosphere 219:864–874

Lopez-Real J (1996) Composting of agricultural wastes. In: The science of composting. Springer, Dordrecht, pp 542–550

Lu K, Yang X, Gielen G, Bolan N, Ok YS, Niazi NK, Xu S, Yuan G, Chen X, Zhang X (2017) Effect of bamboo and rice straw biochars on the mobility and redistribution of heavy metals (Cd, Cu, Pb and Zn) in contaminated soil. J Environ Manag 186:285–292

Macci C, Doni S, Peruzzi E, Masciandaro G, Mennone C, Ceccanti B (2012) Almond tree and organic fertilization for soil quality improvement in southern Italy. J Environ Manag 95:215–222

Mahgoub MMA (2014) Effect of compost, green manure and fertilizer nitrogen on growth and yield of sweet pepper (Capsicum annuum L.) and some soil properties of the Gezira soil, Sudan. Ph.D. Thesis. Faculty of Agricultural Sciences, University of Gezira, Wad Medani

Mangkoedihardjo L, Ratnawati R, Alfianti N (2008) Phytoremediation of hexavalent chromium polluted soil using Pterocarpus indicus and Jatropha curcas. World Appl Sci J 4:338–342

Megharaj M, Ramakrishnan B, Venkateswarlu K, Sethunathan N, Naidu R (2011) Bioremediation approaches for organic pollutants: a critical perspective. Environ Int 37:1362–1375

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Metcalf E (2003) Wastewater engineering, treatment and reuse. McGraw-Hill, New York

Mhindu RL, Wuta M, Ngorima E (2013) Composting of selected organic wastes from peri-urban areas of Harare, Zimbabwe. Int J Recycl Org Waste 2(14):1–12

Monni S, Pipatti R, Lehtilä A, Savolainen I, Syri S (2006) Global climate change mitigation scenarios for solidwaste management. VTT Publications 603, Julkaisija Publisher, Helsinki. Available from: http://www.vtt.fi/inf/pdf/publications/2006/P603.pdf. Accessed 13-04-2020

Moorman TB, Cowan JK, Arthur EL, Coats JR (2001) Organic amendments to enhance herbicide biodegradation in contaminated soils. Biol Fertil Soils 33:541–545

Mougeot LJA (2002) Urban agriculture: definition, presence, potentials and risks, and policy challenges. Retrieved from http://hdl.handle.net/10625/26429

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 152–178

Pepe O, Ventorino V, Blaiotta G (2013) Dynamic of functional microbial groups during mesophilic composting of agro-industrial wastes and free-living (N_2)-fixing bacteria application. Waste Manag 33(7):1616–1625

Praveena DK, Reddy PN (2013) Compost teas - an organic source for crop disease management. Int J Innov Biol Res 2:51–60

Pugliese M, Liu BP, Gullino ML, Garibaldi A (2008) Selection of antagonists from compost to control soil-borne pathogens. J Plant Dis Prot (Zeitschrift fur Pflanzenkrankheiten und Pflanzenschutz) 115:220–228

Pugliese M, Liu BP, Gullino ML, Garibaldi A (2011) Microbial enrichment of compost with biological control agents to enhance suppressiveness to four soil - borne diseases in greenhouse. J Plant Dis Prot 118:45–50

Qadri H, Bhat RA (2020) The concerns for global sustainability of freshwater ecosystems. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 1–15

Quirós R, Villalba G, Muñoz P, Colón J, Font X, Gabarrell X (2014) Environmental assessment of two home composts with high and low gaseous emissions of the composting process. Resour Conserv Recycl 90:9–20

Riaz U, Murtaza G, Saifullah Farooq M (2017) Comparable effect of commercial composts on chemical properties of sandy clay loam soil and accumulation of trace elements in soil-plant system. Int J Agric Biol 20:85–92

Sagoo E, Williams JR, Chambers BJ, Boyles O, Matthews R, Chadwick DR (2007) Integrated management practices to minimise losses and maximise the crop nitrogen value of broiler litter. Biosyst Eng 97:512–519

Sánchez ÓJ, Ospina DA, Montoya S (2017) Compost supplementation with nutrients and microorganisms in composting process. Waste Manag 69:136–153. https://doi.org/10.1016/j.wasman.2017.08.012

Sari GL, Trihadiningrum Y (2019) Bioremediation of petroleum hydrocarbons in crude oil contaminated soil from wonocolo public oilfields using aerobic composting with yard waste and rumen residue amendments. J Sustain Dev Energy Water Environ Syst 7(3):482–492

Scott JC (1952) Health and agriculture in China. A fundamental approach to some of the problems of world hunger. Faber & Faber, London

Scotti R, Pane C, Spaccini R, Palese AM, Piccolo A, Celano G, Zaccardelli M (2016) On-farm compost: a useful tool to improve soil quality under intensive farming systems. Appl Soil Ecol 107:13–23

Shah GM, Groot JCJ, Oenema O, Lantinga EA (2012) Covered storage reduces losses and improves crop utilisation of nitrogen from solid cattle manure. Nutr Cycl Agroecosyst 94:299–312

Shah GM, Shah GA, Groot JCJ, Oenema O, Raza AS, Lantinga EA (2016) Effect of storage conditions on losses and crop utilization of nitrogen from solid cattle manure. J Agric Sci 154:58–71

Shashoug MSA, Abdalla MA, Ehadi EA, Rezig FAM (2017) Response of fodder sorghum (Sorghum bicolor L.) to sewage sludge treatment and irrigation intervals in a dry land condition. Eurasian J Soil Sci 6(2):144–153

Shilev S, Naydenov M, Vancheva V, Aladjadjiyan A (2007) Composting of food and agricultural wastes. In: Utilization of by-products and treatment of waste in the food industry. Springer, Boston, pp 283–301

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Sinha RK, Valani D, Chauhan K, Brijal K, Agarwal S (2012) Earthworm vermicompost: a nutritive biofertilizer and powerful biopesticide for promoting organic farming while protecting farm soils and mitigating global warming. In: Singh RP (ed) Organic fertilizers. Nova Science Publishers, Inc, Hauppauge, pp 163–205

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Stotzky G (1965) Microbial respiration. In: Methods of soil analysis. Part 2. Chemical and microbiological properties, Agronomy Monographs, vol 9, pp 1550–1572

Szanto GL, Hamelers HM, Rulkens WH, Veeken AHM (2007) NH_3, N_2O and CH_4 emissions during passively aerated composting of straw-rich pig manure. Bioresour Technol 98:2659–2670

Tang J, Zhang J, Ren L, Zhou Y, Gao J, Luo L, Yang Y, Peng Q, Huang H, Chen A (2019) Diagnosis of soil contamination using microbiological indices: a review on heavy metal pollution. J Environ Manag 242:121–130

Tang J, Zhang L, Zhang J, Ren L, Zhou Y, Zheng Y, Luo L, Yang Y, Huang H, Chen A (2020) Physicochemical features, metal availability and enzyme activity in heavy metal-polluted soil remediated by biochar and compost. Sci Total Environ 701:134751

Tejada M, Hernandez MT, Garcia C (2009) Soil restoration using composted plant residues: effects on soil properties. Soil Tillage Res 10(21):109–117

Tilley E (2014) Compendium of sanitation systems and technologies. Eawag, Dübendorf

Tsang DCW, Yip ACK, Olds WE, Weber PA (2014) Arsenic and copper stabilization in a contaminated soil by coal fly ash and green waste compost. Environ Sci Pollut Res 21:10194–10204

Uwamahoro L, Nyagatare G, Shingiro C (2019) Effect of different composts on soil chemical conditions and green bean yield in Bugesera District, Eastern Province of Rwanda. Agric Biol Sci J 5(4):132–137

Vargas-García M, Suárez-Estrella F, López M, Moreno J (2010) Microbial population dynamics and enzyme activities in composting processes with different starting materials. Waste Manag 30(5):771–778

Vázquez MA, Soto M (2017) The efficiency of home composting programmes and compost quality. Waste Manag 64:39–50

Vidović I, Runko Luttenberger L (2019) The contribution of home composting to environmental protection

Vu QD, de Neergaard A, Tran TD, Hoang HTT, Vu VHK, Jensen LS (2015) Greenhouse gas emissions from passive composting of manure and digestate with crop residues and biochar on small-scale livestock farms in Vietnam. Environ Technol 36(23):2925–2934

Waldron K, Nichols E (2009) Composting of food-chain waste for agricultural and horticultural use. In: Handbook of waste management and co-product recovery in food processing. Woodhead Publishing Limited, Elsevier, Cambridge UK, pp 583–627

Wang L, Li Y (2009) Sequencing batch reactors. In: Wang LK, Pereira NC, Hung YT (eds) Biological treatment processes. Handbook of environmental engineering series. Humana Press, New York

Wang J, Hu Z, Xu X, Jiang X, Zheng B, Liu X, Pan X, Kardol P (2014) Emissions of ammonia and greenhouse gases during combined pre-composting and vermicomposting of duck manure. Waste Manag 34:1546–1552

Willson GB, Walker JM (1973) Composting sewage sludge, how? Compost Sci. J. Waste Recycling 30, September–October

Yañez-Ocampo G, Sanchez-Salinas E, Ortiz-Hernandez ML (2011) Removal of methyl parathion and tetrachlorvinphos by a bacterial consortium immobilized on tezontle-packed up-flow reactor. Biodegradation 22:1203–1213

Yang J, Yang F, Yang Y, Xing G, Deng C, Shen Y, Luo L, Li B, Yuan H (2016) A proposal of "core enzyme" bioindicator in long-term Pb-Zn ore pollution areas based on topsoil property analysis. Environ Pollut 213:760–769

Yang Y, Awasthia MK, Dua W, Rena X, Leia T, Lva J (2020) Compost supplementation with nitrogen loss and greenhouse gas emissions during pig manure composting. Bioresour Technol 297:122435

Yoshida T, Kubota H (1979) Gel chromatography of water extract from compost. J Ferment Technol 57:582

Zeng G, Wu H, Liang J, Guo S, Huang L, Xu P, Li Y, Yuan Y, He X, He Y (2015) Efficiency of biochar and compost (or composting) combined amendments for reducing Cd, Cu, Zn and Pb bioavailability, mobility and ecological risk in wetland soil. RSC Adv 5:34541–34548

Zmora-Nahum S, Danon M, Hadar Y, Chen Y (2008) Compost curing reduces suppression of plant diseases. Compost Sci Util 16:250–256

Chapter 10
Introduction to Microbiota and Biofertilizers

Bisma Nisar, Sumaira Rashid, Lone Rafiya Majeed, Heena Nisar Pahalvi, and Azra N. Kamili

10.1 Introduction

With an annual growth rate of 1.8% per year, the world populace is perpetually pacing up which is expected to grow from the contemporary population of 7.4 billion to 9.6 billion by 2050. It is casted that the total food demand will grow in proportion to world population (United Nations 2013). These days, crop production is coming across challenges due to increase in population, change in climate, and also an increased demand for sustainable output. A large chunk of productive soils are being reserved for other requirements due to increased urbanization which produces high pressure to expand agriculture; most of the fertile soils in favorable environments are being diverted to other uses. The agrochemicals cannot increase the crop output past a certain limit. Besides, because of paucity of knowledge, farmers put in more synthetic fertilizers than actually recommended. The over usage of synthetic chemicals prompts an otherwise effect on health of consumer and further results in reduction of soil fertility as they augment salt substance to the soil (Swapna 2013; Dar et al. 2013; Bhat et al. 2017; Bhatti et al. 2017). Such unsustainable cropping practices have imposed new challenges to agricultural output. Plant pathogens, low temperatures, high temperatures, excess nutrients, deficient nutrients, soil salinity, excess water, and deficient water are among a multitude of biotic and abiotic factors affecting the production of crops. In order to push up the actual output of different crops, it is a dire need to change biotic and abiotic factors so as to put our

---

B. Nisar (✉) · S. Rashid · H. N. Pahalvi
Department of Environmental Sciences, University of Kashmir,
Srinagar, Jammu and Kashmir, India

L. R. Majeed
Vivekananda Global University, Jaipur, India

A. N. Kamili
Centre of Research for Development, University of Kashmir, Srinagar, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_10

agricultural demands at par, where the traditional farming practices baffle. As of late, harmful impacts of synthetic fertilizers on the environment and human life have moved the attention on environmental-friendly options. The traditional agriculture has a pivotal role with regard to fulfilling the staple needs for a perpetually pacing up human populace, prompting an expanding reliance on the utilization of synthetic fertilizers and pesticides for production enhancement (Santos et al. 2012). Synthetic fertilizers are scientifically made preparations, the utilization of which results in pollution of air, water, and subsequently the nutrient enrichment of water bodies (Youssef and Eissa 2014; Dar et al. 2016). However, the act of utilizing synthetic fertilizers and pesticides quickens acidification of soil (Chun Li et al. 2014; Bhat et al. 2017; Mushtaq et al. 2018; Dar and Bhat 2020); it likewise represents the danger of polluting the environment and groundwater (Mehmood et al. 2019; Dar et al. 2020). Besides, it also debilitates the plant roots consequently making them defenseless to certain pathogenic diseases. Therefore, advancement of biofertilizer-based organic farming is required direly as interest for residue-free and safe food is pacing up tremendously. In this context, the use of microbial inoculants is among the potential methods of realizing this objective (Calvo et al. 2014; Pertot et al. 2016; Singh et al. 2016; Bhat et al. 2018). Because of the proven possibility of microorganisms as biopesticides as well as biofertilizers, a rising demand has been felt to include them as one of the choices replacing chemical products in cultivation methods (Mendes et al. 2013; Mitter et al. 2016; Rashid et al. 2019).

Biofertilizers are appended by the living microbes which inhabit the roots endogenously, thereby boosting the delivery of nutrients to the host crops, thereby enhancing the growth and development of plants, once put into operation with seeds, plant surfaces, or soils (Vessey 2003; Bardi and Malusa 2012; Malusa and Vassilev 2014). The chosen processes of microbes are widely accelerated by biofertilizers which increase the nutrient availability for easy uptake by the plant. By converting the ambient nitrogen into usable forms and solubilizing the inaccessible phosphorus into phosphates, they enhance soil fertility by secreting plant development promoting chemicals in the soil (Mazid and Khan 2015; Dervash et al. 2020). The primary job of biopesticides or biofertilizers is to avert or inhibit the diseases of plants. Under normal conditions rhizosphere and aboveground plant parts are inhabited by protozoa, bacteria, algae, actinomycetes, and fungi. Bacteria constitute 95% of colonizing microorganisms (Glick 2012; Khanday et al. 2016). The development of plant is profoundly influenced by direct and indirect processes carried out by bacteria which inhabit the roots of plants either exogenously or endogenously constituting the plant growth-promoting bacteria or rhizobacteria, thereby making them eligible to be called as biopesticides and biofertilizers (Glick 2012). The soil encompassing plant roots is a principal source of bacterial agents advancing growth and development of plants.

Secretion of chemicals by the roots of plants helps in proliferating soil microbes found in the surroundings of their roots (Walker et al. 2003; Bhat et al. 2018). Stage of development, health, fitness, and plant genotype determine the properties and composition of root exudates. Particular microbiomes have been distinguished for every organ (Vorholt 2012; Philippot et al. 2013; Hardoim et al. 2015) and plant species (Berg and Smalla 2009) in spite of functional and taxonomic overlap within the plant microbiota (Bai et al. 2015). The fortification of microorganisms by the plant root is certainly not an arbitrary but rather a focused process (Johnston-Monje et al. 2016; Adam et al. 2016) and the attraction of microbes to roots by supplements such as carbohydrates and amino acids in combination with plant-specific secondary metabolites (Moe 2013; Weston and Mathesius 2013). Differences in plant root exudates assume a significant job in the working of both chemoattractants and repellents (Badri and Vivanco 2009). Plant defense signaling assumes an extra role in these processes (Doornbos et al. 2012).

10.2 Types of Biofertilizers

Biofertilizers can be grouped based on their function and nature in the below mentioned groups (Fig. 10.1). These biofertilizers have been upgraded to bring in the processes of mobilization of nutrients which are biologically accessible, thereby enhancing the fertility status of soils enormously and subsequently the yield of crops (Pandey and Singh 2012).

10.2.1 Nitrogen-Fixing Biofertilizer (NFB)

Being copious and omnipresent in atmosphere, nitrogen still turns out to be a limiting nutrient owing to its non-fixation as molecular nitrogen and difficulty in uptake by plants, though some microbes which live in association with roots or in the soil around the roots are able to fix nitrogen significantly. This microbial association prevents nitrogen losses by denitrification and reduces chances of leaching and volatilization that aids effective uptake of fixed nitrogen by plants. These microbes can be:

10.2.1.1 Free-Living

Though it is difficult to evaluate the fixation of nitrogen by free-living bacteria, it has been found to range in between 3 kg N/hectare and 10kgN/hectare in plants like *Medicago sativa*. In addition to slime production which aggregates soil, *Azotobacter chroococcum* is estimated to fix 2–15 milligram of nitrogen per gram of carbon source in cultivable soils. Nevertheless, *Frankia* has been found to fix nitrogen in the root zone from atmosphere in their host as well as non-host plants (Thomas and Singh 2019). Potential of cyanobacteria has been utilized in cultivating paddy in India under ideal conditions producing approximately 20–30 kg N/hectare (Kannaiyan 2002).

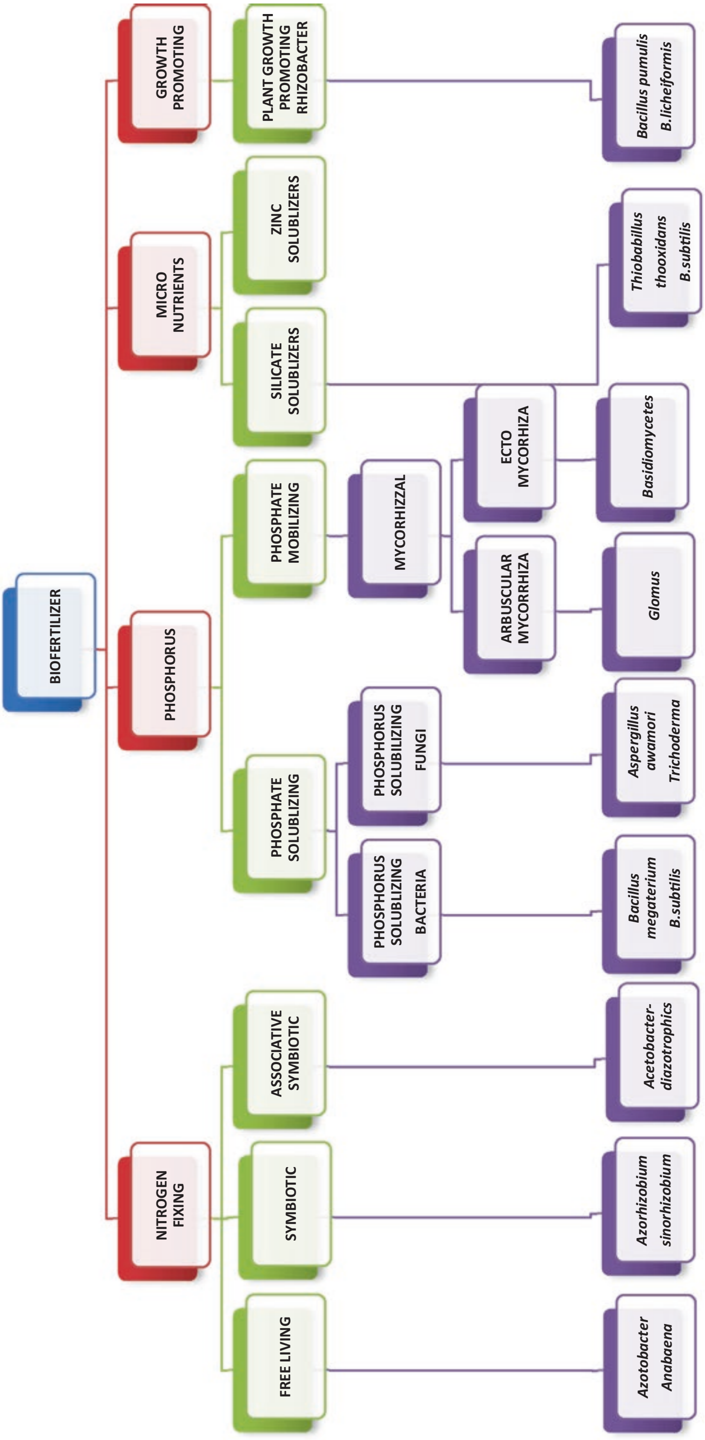


Fig. 10.1 Classification of microbial fertilizers

10.2.1.2 Symbiotic Associations

A significant group of organisms like *Sinorhizobium*, *Allorhizobium*, *Bradyrhizobium*, etc. by forming nodules in the roots of host legume species can show nitrogen fixation efficiency of up to 450 kilograms of nitrogen for each hectare of land (Graham and Vance 2000; Unkovich and Patat 2000; Thomas and Singh 2019). Granular, liquid, and powder preparations in various aseptic carriers of charcoal, peat, perlite, and mineral soil may be used for the rhizobial biofertilizers (Stephens and Rask 2000). *Frankia* being an *actinomycete* also fixes atmospheric nitrogen like *Rhizobia* by forming nodules in the roots of many woody plants (Wall 2000). This bacterium forming mycelium lives in symbiotic association with roots of many nonlegume plants like *Alder*, *Casuarina*, *Myrica*, etc. The inoculation of *Frankia* in perturbed or dry environments is regarded as beneficial (Sprent and Parsons 2000). In addition, *Xanthomonas* and *Mycobacterium* living symbiotically in the internal cavities of the leaves of *Ardisia* fix nitrogen turning such leaves into a pool of nitrogen for the soil (Miller 1990). Another ecologically viable group is the blue-green algae (BGA) of cyanobacteria, some of them contribute to around 36% of the world's nitrogen fixation, such as *Trichodesmium*, *Nostoc*, *and Anabaena*, and have been found to help improve rice crop fertility in many parts of the world (Gallon 2001; Irisarri et al. 2001). BGA is also known as a potential advantageous remedy for dry environments or flood-prone ecosystems (Malam Issa et al. 2001; Sofi et al. 2017). However, inadequately developed application and production of blue-green algae are ought to be regarded as a biofertilizing agent in sustainable agriculture for different environs (Hashem 2001; Thomas and Singh 2019).

10.2.1.3 Associative Symbiotic (Without Endophytic Symbioses)

These nitrifying microorganisms are distantly associated to roots compared to endophytic symbionts. *Acetobacter diazotrophicus* and *Herbaspirillums* are the examples of associative symbiotic nitrogen fixers which are associated with plants like sugarcane, maize and sorghum (Boddey et al. 2000), species of *Bacillus, Herbaspirillum*, *Klebsiella*, *Pseudomonas* are associated with rice & maize and species of *Azoarcus* with kallar grass (James 2000); and *Azospirillum* with large host specificities including a broad range of perennial and annual plants. Many studies have reported that fixation of nitrogen and secretion of growth-promoting chemicals by *Azospirillum* has improved the yield and growth in cotton, oak, sugar beet, carrot, pepper, eggplant, and wheat (Thomas and Singh 2019). *Azospirillum* inoculum can be manufactured at low cost with a simple formulation of peat (Broek et al. 2000). *Acetobacter diazotrophicus* biofertilizer has been found to supply almost 70% nitrogenous demand for sugarcane by fixing approximately 150 kilograms of nitrogen for each hectare of land annually. As a result, nitrogen fixation capability makes them the potential choice for biofertilizer application (Thomas and Singh 2019).

10.3 Phosphorus Biofertilizers

10.3.1 Phosphorus-Solubilizing Biofertilizers (PSB)

Though the phosphorus concentration is high in the soils, most of it remains in unavailable states making phosphorus the second most deficient nutrient in the plants after nitrogen. The phosphorus-solubilizing biofertilizers can be grouped in two categories:

10.3.1.1 The Phosphorus-Solubilizing Bacteria (PSB)

Bacteria that solubilize phosphorus such as *Bacillus* and *Pseudomonas* function by solubilizing insoluble phosphate forms within soil, thereby increasing the supply of phosphorus to plant species (Richardson 2001).

10.3.1.2 The Phosphorus-Solubilizing Fungi (PSF)

Penicillium and *Aspergillus* also increase the phosphorus available to plants by mobilizing it out of nonavailable states in the soil. Bacteria and fungi secrete organic acids which bring down pH in their vicinity, causing bound phosphates in the soil to disintegrate (Fig.10.2). The use of *Bacillus megaterium* var. *phosphaticum*, along with the cheaper rock phosphate, was found to increase the quality and yield of sugar cane by 12.6 percent and to reduce the requirement of phosphorus by 25 percent, thus further reducing the costly superphosphate consumption by 50 percent (Sundara et al. 2002).

10.4 Phosphate-Mobilizing Biofertilizers (PMB)

They operate through the scavenging and mobilization of phosphates from soil layers into soil; such biofertilizers are applied to like mycorrhiza. Occasionally, phosphate-solubilizing biofertilizers can behave as phosphate mobilizers too (Chang and Yang 2009). The phosphate-mobilizing biofertilizers have a broad spectrum. Figure 10.3 shows the activation of soil phosphorus and its immobilization by bacteria. The mycorrhizal biofertilizers are discussed in the following section.

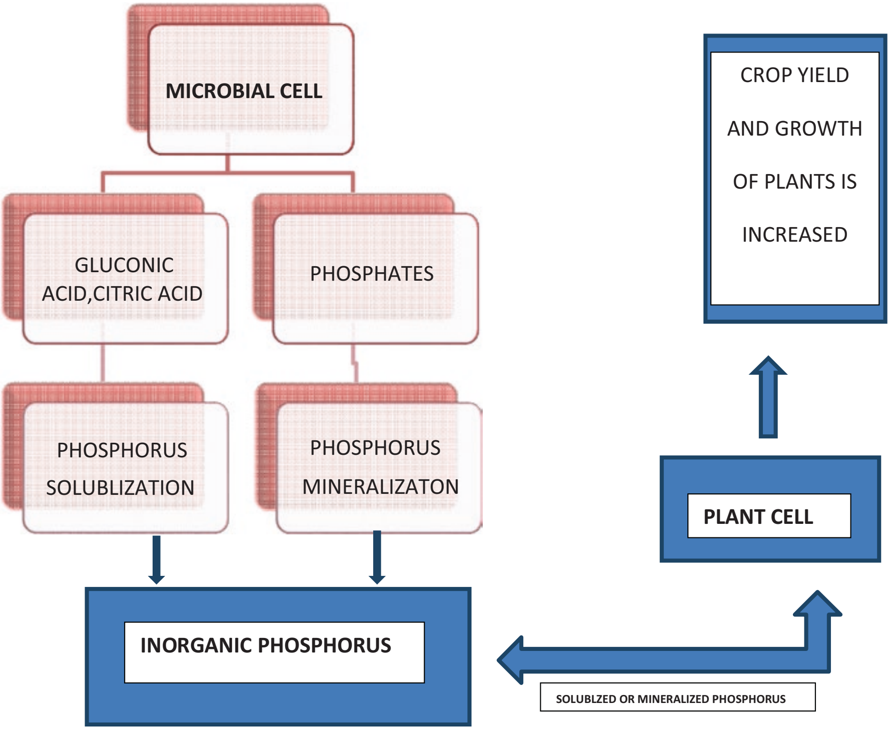


Fig. 10.2 Solubilization of inorganic phosphorus by phosphate-solubilizing bacteria and fungi

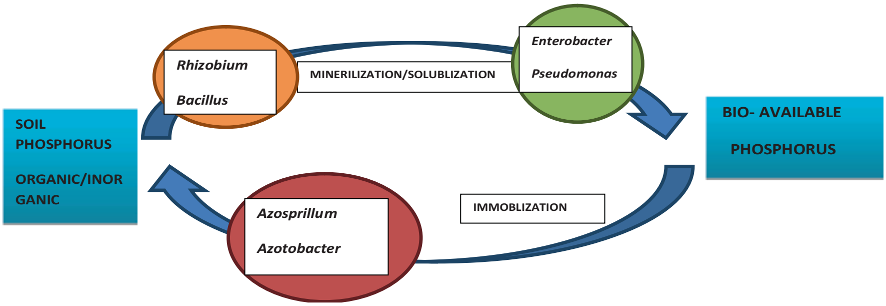


Fig. 10.3 Diagrammatic representation of phosphorus mobilization and immobilization by the soil microbes

10.5 Mycorrhizal Biofertilizers

These biofertilizers are also known as phosphate absorbers that help in mobilizing phosphorus. Here the fungus lives obligately or facultatively in association with almost 80% plants resulting in mutualistic symbiosis where the fungal component derives phosphates and energy; plant component derives a wide variety of benefits from the fungus it hosts (Thakur and Singh 2018). Fungal mycelium stretches from the host root surfaces to soil and thereby enhances the surfaces of the plant, deriving energy from insoluble phosphorus, other sources such as calcium, copper, zinc, etc. helping in more efficient nutrient access and acquisitions to the plant (Singh and Gira 2017). Besides, such biofertilizers improve and enhance the aeration process in the soil, improve the fertility status of the soil, balance the water dynamics of the plant, augment the sequestering potential for heavy metals, and increase the tolerance of plant species to drought, thereby making them less susceptible to pathogenic diseases and herbivory (Rillig et al. 2002; Thakur and Singh 2018). It means that these fungi have a high potential for use in forestry, soil conservation, or habitat restoration (Thomas and Singh 2019). The two types are as follows:

10.5.1 Arbuscular Mycorrhizal (AM)

The fungi such as the *Glomus* are intercellular, nonspecific mandatory symbionts living endogenously bearing vesicles in roots as special structures functioning as an extended root providing water to the crop as well as different microniche nutrients to the soil in addition to the increased phosphorus accessibility and availability helping plant to grow and develop adequately. Obligate association and nonculturability of arbuscular mycorrhiza has made inoculation not been consistent with broad-scale industrial agriculture and may thus necessitate additional research (Ryan and Graham 2002). Nonetheless, adjusted uniform growth of crop has been made possible by inoculating AM proving beneficial for the development of nursery stocks. The source of inoculums determines the colonizing potential of fungi in certain host plants which can vary for agricultural purposes (Klironomos and Hart 2002). The process of inoculating the host plant or cultured root organs with AM is an effective symbiotic way of producing infective propagules, but the high cost involved in its production in addition to prolonged turnover and challenges of excluding some pathogens of roots turns out to be some of the limitations. The most reliable inoculation of AM is done in the form of spores. For some taxa, effective inoculums are applied as fragments of AM colonizing the roots. In addition, a combination of both these methods can be used where the mycelium in soil in combination with pumice, perlite, and vermiculite as carrier substrate can be inoculated (Klironomos and Hart 2002; Gaur and Adholeya 2000; Thomas and Singh 2019; Singh et al. 2020).

10.5.2 Ectomycorrhiza

Basidiomycetes in *Eucalyptus*, peach, and pine penetrate internally in intercellular spaces in the cortex forming a mantle on the surface of root where plant-secreted sugars advance the nutritional availability to the plants. These fungi absorb water, minerals, and inorganic nutrients by increasing the surface area of roots and secrete chemicals which act as antimicrobials providing protection to plants against a broad range of root pathogens. Ectomycorrhizal symbiosis has been found to be important for the growth and nutrient acquisition in tree plantations in particular for larger inocular practices in nurseries or forest areas (Thomas and Singh 2019).

10.5.3 Biofertilizers for Micronutrients

Excluding nitrogen and phosphate, soil microbes are also used as biofertilizers for the supply of different micronutrients as zinc, silicates, etc. Such biofertilizers can be categorized in the following two groups:

10.5.3.1 Zinc Solubilizers

As zinc is found in the crust of the earth in minute concentration, its low occurrence forces the farmers to have an external application of it as the costliest soluble zinc sulfate to resolve its deficiencies in the plants. *Saccharomyces*, *Bacillus subtilis*, and *Thiobacillus thiooxidans* are among the bacteria which solubilize less costly oxides, carbonates, and sulfides of zinc in the soil (Ansori and Gholami 2015).

10.5.3.2 Silicate Solubilizers

These are some microorganisms that hydrolyze aluminum silicates by adding protons and form cationic complexes by secreting organic acids, thereby keeping silicates in dissolved form which benefits plants during metabolism. For example, increased rice growth and the yield of grain were observed by increased silica and soil nutrients using *Bacillus* sp. combining rice paw, rice husk, and black ash with silica residues (Cakmakci et al. 2007).

10.5.3.3 Plant Growth-Promoting Biofertilizer (PGPB)

In addition to a nitrogen-fixing (Fig. 10.4) and phosphorus-solubilizing microbe, some microbes ideal for biofertilizers stimulate growth of plants by synthesizing chemicals which have been found to generate significant amounts of host plant

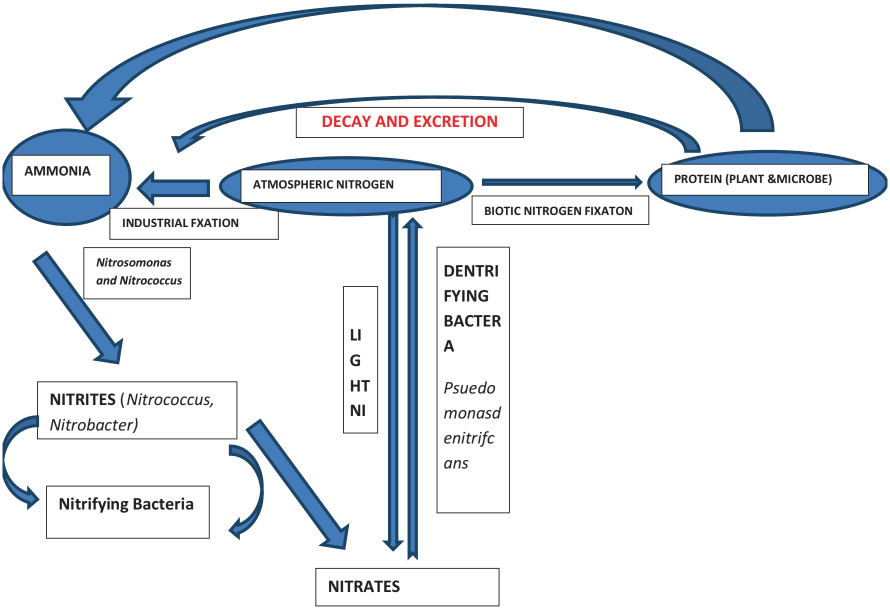


Fig. 10.4 Schematic representation of nitrogen cycle

hormones with significant physiological activity (Gutierez-Manero et al. 2001; Thomas and Singh 2019), e.g., rhizospheric *Bacillus pumilus* and *Bacillus licheniformis*. However, *Paenibacillus polymyxa* showed a broad range of beneficial property, like fixation of nitrogen, phosphorus solubility, antibiotic production, cytokinase, hydrolytic enzymes, chitinase and other enzymes, and soil porosity enhancement.

In addition, plant hormones were reported for certain *Azospirillum* species (Thomas and Singh 2019). The synthesis of antimicrobial metabolites by rhizobacteria, such as enzymes that have the ability to degrade fungal cells, causing cytolysis, ion leakage, membrane disruption and inhibition of mycelial growth and protein synthesis, are among the antagonastic mechanisms of phytopathogenic microorganisms which helps in improving plant health (Idriss et al. 2007; Lugtenberg and Kamilova 2009). For example, antifungal metabolites such as phenazines, pyrrolnitrin, pyoluteorin, or cyclic viscosinamide lipopeptides can be produced in *Pseudomonas* strains to prevent *Pythium ultimum* sugar beet infections. The *Pseudomonas fluorescens* synthesizes siderophores such as pseudobactin and pyoverdine which bind and take up ferric ions, making them more competitors of iron and thus preventing pathogenic microbes such as *Pythium ultimum*, *Fusarium*, and *Rhizoctonia bataticola* (Hultberg et al. 2000), which prevent them from growing and proliferating (Hultberg et al. 2000). Siderophores like pyoverdine, pyochelin, and salicylic acid are produced by *Pseudomonas aeruginosa*, and resistance is further inducted against *Botrytis cinerea* (on tomato and bean) and *Colletotrichum lindemuthianum* (on bean) (Audenaert et al. 2002). Nevertheless, some *Pseudomonas* species make the *Fusarium solani* mycelia to break with extracellular chitinase and laminase. Biofertilizers also provide protection from certain soil diseases and insect pests and plant diseases, such as the use of antibiotics in *Azotobacter* to limit the spread of soil pathogens such as *Pythium* and *Phytophthora* (Wani et al. 2013).

10.6 Microbiota Used in Biofertilizers

Organisms that are mostly used as biofertilizer components include nitrogen fixers, phosphorus solubilizer, and phosphorus mobilizers used solely or in combination with fungi. Majority of the bacteria used in biofertlizers have a close association with roots of plants for example Rhizobacterium which dwell in rhizosphere are having a symbiotic association with the roots of legumes (Khosro and Yousef 2012). Most of the time, bacteria and fungi make insoluble phosphorus accessible to the plants (Gupta 2004). A few soil fungi and many bacteria have the capacity to change insoluble phosphate in soil into dissolvable structures by secreting organic acids. These acids bring down the soil pH and achieve the disintegration of bound forms of phosphate (Gupta 2004). While Cyanobacteria, *Rhizobium* and *Azolla* are crop specific, bioinoculants such as PSB, *Azospirillum*, *Azotobacter* and VAM could be viewed as wide-spectrum biofertilizers (Gupta 2004). VAM being fungi improves the buildup of nutrients in plants by being associated with most of the agricultural crops (Khosro and Yousef 2012; Wani et al. 2013). It has been recommended to stimulate plant by physiological impacts or by diminishing the seriousness of infections brought about by soil pathogens. The following are the microbiota that are commonly found in biofertilizers:

10.6.1 Bacteria

Bacteria are life forms that have just a single cell and, hence, microscopic. There are about 100 million to 1 billion microbes in only a teaspoon of damp, fertile soil. They decompose dead plant material and natural waste. The process of decomposition discharges supplements that different living beings could get to (Abu Bakar et al. 2013). The bacteria do this by converting the nutrients from non-usable to usable structures. This course of action is essential in the phosphorus and nitrogen cycles.

10.6.2 Actinomycetes

They are also soil microorganisms like the bacteria and fungi and have attributes connecting them to the two classes. They are frequently accepted to be the missing evolutionary connection between fungi and bacteria; however they share a greater number of attributes practically with bacteria than they do with fungi. Actinomycetes contribute to soil its peculiar smell. They have likewise been the source of a few huge helpful medicines (Shukla and Livleen 2015).

10.6.3 Fungi

Fungi bunch themselves into sinewy strings called hyphae; hyphae further branches into mycelium which are 0.8 mm wide but can get up to a few meters. They are useful, yet could likewise be destructive, to soil creatures. Fungi are useful in light of the fact that they can breakdown supplements that different life forms cannot (Nutongkaew 2014). They at that point discharge them into the soil, and different life forms find a good place to use them. Significant development of the plant can occur when fungi live in symbiotic association with plant. This is an advantageous association called mycorrhizal. The fungi help the plant by giving it required nutrients, and these organisms get sugars from the plant. The soil fungi perform some important functions.

- Saprophytic fungi act as decomposers and help in breaking the dead organic matter into carbon dioxide and organic acids and converting some portion into fungal biomass.
- Mycorrhizal fungi act as mutualists by colonizing the roots of the plants. They convert bound forms of phosphorus to soluble forms and nitrogen, water, and micronutrients to the plant they are in association with. Ectomycorrhizae are found in trees where it grows on the surface layer of roots while endomycorrhizae are found in vegetables and grasses where it grows endogenously in the root cell.

10.6.4 Algae

They are living in the vast majority of the soils where dampness and daylight are accessible. Their number ranges from 100 to 10,000 for each gram of soil. They are equipped for photosynthesis, whereby they acquire carbon dioxide from the environment and sunlight from daylight and synthesize their own food. The significant functions of algae in soil are:

- Playing a significant role in the upkeep of soil richness, particularly in tropical soils.
- In the uncultivated soils, it prevents leaching and drainage of nitrates, hence keeping a check on loss of nitrates.
- Adding organic content to soil when they die and accordingly increasing the amount of natural carbon in soil.

- By secreting slime, it helps in binding particles of soil, hence diminishing and forestalling erosion of soil.
- Helping to build the water retention limit of soil for longer timespans.
- It encourages submerged aeration by releasing ample oxygen in the soil environment via photosynthesis.
- By secreting organic acids, it accelerated rock weathering and hence proves valuable in the buildup of soil structure.

10.6.5 Protozoa

These are drab, single-celled animal-like organisms. They are bigger than microscopic organisms, changing from a couple of microns to a couple of millimeters. Their population in arable soil ranges from 10,000 to 100,000 for every gram of soil, and they are abundant in surface soil (Johns 2017). They can endure hostile soil conditions, as they are portrayed by an ensured torpid stage in their life cycle. The major functions, roles, and features of protozoa are:

- Many protozoans get their food from feeding or ingesting soil microorganisms, and in this way they assume a significant job in keeping up microbial/bacterial balance in the soil.
- Some protozoa have been as of late utilized as natural control agents against life forms that cause detrimental maladies in plants.

10.6.6 Viruses

Soil viruses are critical, as they may impact the nature of soil organic networks through both a capacity to move genes from host to host and as a potential reason for microbial mortality. Accordingly, viruses are significant players in worldwide cycles, affecting the turnover and convergence of nutrients and gases. Soils most likely harbor numerous novel viral species that, together, may speak to a huge repository of genetic diversity (Johns 2017). A few specialists accept that researching this generally unexplored diversity of soil viruses can possibly change our comprehension of the virus infections in worldwide biological systems and the advancement of microbial life itself.

10.6.7 Nematodes

Nematode worms are normally 50 microns in breadth and one millimeter long. Species responsible for plant infections have gotten a lot of consideration; however far less is known about a great part of the nematode network, which assumes useful jobs in soil. A staggering variety of nematodes have been found to work at several levels of the soil food web. Primary level nematodes feed on the algae and plants, secondary level nematodes feed on fungi and bacteria, and higher level nematodes feed on other nematodes. Free-living nematodes can be separated into four general gatherings dependent on their eating regimen. Bacterial feeders expend microscopic organisms. Contagious feeders feed by puncturing the cell walls of fungi and sucking out the internal contents. Predatory nematodes eat a wide range of nematodes and protozoa. They eat little living beings entirely or append themselves to the cuticle of bigger nematodes, scratching endlessly until the prey's interior body parts can be extricated. Like protozoa, nematodes are significant in mineralizing, or discharging, supplements in plant-accessible forms. At the point when nematodes eat microscopic organisms or parasites, ammonium is discharged on the grounds that fungi and bacteria contain considerably more nitrogen than the nematodes require. Nematodes may likewise be valuable pointers of soil quality due to their colossal diversity and their investment in numerous capacities at various degrees of the soil food web (Johns 2017).

10.7 Functions of Plant Microbiota as Biofertilizers

The individuals from plant microbiome include advantageous, neutral, or pathogenic microorganisms. The following are the significant functions which are performed by plant microbiota as biofertilizers:

(a) Plant growth-promoting bacteria secrete auxin, gibberellins, and cytokinin affecting growth of plants through endogenous modulation of hormone levels, thereby advancing plant development by either immediate or aberrant mechanisms.
(b) Nitrogen fixation, phosphate solubilization, indole acetic acid, growth and stress tolerance, and mechanisms involved in improved uptake of nutrients are some important plant growth promotion properties that have been found in soybean roots and wheat harboring *Pantoea* spp., *Paraburkholderia* spp., and *Pseudomonas* spp. (Rascovan et al. 2016).
(c) *Arthrobacter* spp. and *Bacillus* spp. are some of the plant growth-promoting bacteria that secrete an enzyme, 1-aminocyclopropane-1-carboxylate deaminase, which enhances growth of plant by reducing ethylene level, i.e., the main stress hormone in the plant.
(d) Some microorganisms can cause infection manifestations through the secretion of phytohormones, phytotoxic mixes, and proteins. *Erwinia amylovora* is a

pathogenic bacterium that causes fire blight disease of ornamentals plants and fruit trees. *Pseudomonas syringae* is a notable plant pathogen having an exceptionally expansive host range including olive, tobacco, green bean, and tomato. *Xylella fastidiosa*, *Xanthomonas* species, and *Ralstonia solanacearum* are likewise connected with numerous significant maladies of banana and potato (Mansfield et al. 2012). The seriousness of plant infection relies upon the combination of numerous components like pathogen populace size, susceptibility of host, plant microbiota, and favorable environment that by and large decide the result of plant-pathogen interaction (Brader et al. 2017).

(e) Both subterranean and aboveground plant-related microorganisms have been found to improve resistance of host against pathogen disease either through interaction of commensal pathogen or through plant defense modulation (Rudrappa et al. 2008; de Vrieze et al. 2018). Production of siderophores, antibiotics, pathogen inhibiting volatile compounds, and lytic enzymes are some of the activities which protect the plant against disease progression and invasion of pathogen (Hopkins et al. 2017; Berg and Koskella 2018). Specifically, genera like *Paraburkholderia*, *Paenibacillus*, *Pseudomonas*, *Bacillus*, *Enterobacter*, *Pantoea*, *Streptomyces*, and *Burkholderia* have been reported for their role in pathogen suppression (Gomez et al. 2017; Schlatter et al. 2017). The nonstop utilization of agricultural soils can facilitate pathogen pressure and can likewise create malady suppressive soils containing microorganisms interceding suppression of diseases (Santhanam et al. 2015; Duran et al. 2018). *Firmicutes*, *Acidobacteria*, and *Actinobacteria* controlled the attack of *Fusarium* wilt at a continental scale (Trivedi et al. 2017). Soil disease suppressiveness of *Paraburkholderia graminis* PHS1 against fungal root pathogen was accounted to synthesis of cysteine desulfurase and dimethyl sulfoxide reductase (Carrion et al. 2018). *Enterobacter* and *Serratia* were found to be the best possible endospheric community of bacteria for suppression of take-all diseases, i.e., *Gaeumannomyces graminis* (Duran et al. 2018).

10.8 Factors Affecting Plant Microbiota

A number of biotic and abiotic factors, including the abundance of microbial predators (e.g., protists or nematodes) and the amount of carbon available, can impact the total amount of microbial biomass found in soil at any given time. On a global scale, availability of soil moisture is the best indicator of total soil microbial biomass. The wetter ecosystems of the world like tropical rainforests harbor larger quantities of microbial biomass (Serna-Chavez et al. 2013). However, not all microbial taxa are equally abundant in soil. Bacteria and fungi are commonly the predominant microorganisms found in soil; these groups usually have 102–104 times more biomass than the other significant components of the soil microbiome (protists, archaea, and infections) (Lynch and Neufield 2015).

There is no typical soil microbiome. The relative abundances of major bacterial and archaeal taxa found in the soil microbiome can vary considerably depending on the soil type. This is true even for the soil samples collected from sites that are just a few centimeters apart (O'Brien 2016). This variation in the composition of the microbiome can be attributed to spatial variability in the soil environment; it also depends on the taxa in question and the type of soil being analyzed. Thus, there is no single biotic or abiotic factor that is reliably the most significant in determining the soil microbial composition. Among abiotic factors, soil pH is usually taken as the best indicator of bacterial and archaeal community composition (Lauber et al. 2009; Griffiths 2011). Yet these pH impacts may not be apparent when soil samples cover a smaller range of pH values and not all taxa react to soil pH changes. Apparently there are many variables which can directly or indirectly affect the spatial structure of microbial soil communities. In addition to soil pH, the most important factors with significant influences on the structure of soil bacterial communities are most likely nitrogen availability (Cederlund 2014), organic carbon content of soil (Sul 2013), temperature (Oliverio et al. 2017), redox status (Ridge and Firestone 2005), and salinity (Fierer 2017). Nature of exudate, morphology of root, and rhizodeposits associated with different genotypes are the factors determining the composition of microbiome harbored by plant species (Hartmann et al. 2009; Ladygina and Hedlund 2010; Chaparro et al. 2014; Reinhold-Hurek et al. 2015). Plant species growing in the similar soil environment recruit significantly different microbial communities in both rhizosphere and root compartments (Hacquard 2016; Samad et al. 2017; Aleklett et al. 2015).

10.9 Mechanism of Action of Various Biofertilizers

The static lifestyle of plants forces them to optimize their well-being within the biotic environment they are a part of. The microbes in soil influence the plant fitness besides making use of the host plants for their proliferation. This has led to a very strong plant-microbe association. The coevolution of microbes and their host plants has produced mechanisms that control the growth and development of both plants as well as microbes (Jones and Dangl 2006; Oldroyd 2013). The plant roots have strong affinity toward a variety of microorganisms. The microbes in soil are regulated by the root exudates (like p-hydroxy acids, quinones, cytokinins, and flavonoids). This is the first step in root colonization where microbes show chemotactic response toward a number of root exudates (Zhengand and Sinclair 1996). The complex interactions that a plant experience are physical, chemical, and biological interactions. These interactions take place in rhizosphere of the plant. It includes root-root and root-microbe interactions.

The rhizospheric microbiome is the major determinant of plant growth and development. It helps the plant in nutrient uptake, gives protection against diseases, and also helps in abiotic stress resistance (Berendsen et al. 2012; Bulgarelli et al. 2013; Dubbey et al. 2018; Sasse et al. 2018). Thus, the interaction between the microorganisms and their host plants is utmost important for improving plant growth and maintaining appropriate soil conditions. The plant science has already recognized the significance of root exudates in maintaining these biological interactions (Baetz and Martinoia 2014). A few examples are secretion of isoflavones by soybean roots which attract a mutualist (*Bradyrhizobium japonicum*) and a pathogen (*Phytophthora sojae*) (Sasse et al. 2018). The chemotactic response of *Pseudomonas fluorescens* towards the root exudates of tomato plant drives colonization in them (de Weert et al. 2002). There are some endophytic bacteria which show fivefold increase in the chemotaxis in the presence of exudates of rice roots. Due to the diverse functional characters of PGPR such as enzyme synthesis, hormone production, solubilization of nutrients, and effective root colonization for sustainable agriculture, it attains a unique and extraordinary position among the varied microbial communities. The symbiotic relationship between plants and microbes can be seen as an integrated ecological unit called as holobiont (Vandenkoornhuyse et al. 2015). The varying microbial composition of soil is attributed to differences in root exudate chemistry (Bais et al. 2006; Rasmann and Turlings 2016) and in plant nutrient uptake rates (Bell et al. 2015). Knowledge and understanding of ecology, growth-promoting features, mechanism of action, and application of naturally occurring microbial communities are essential to plant growth. There is still wide scope to understand the various types of plant-microbe interactions.

10.10 Types of Biofertilizer Formulation

Biofertilizer is a live, viable microbial cell designed to boost soil fertility. They are formulated to make them viable and at the same time to increase growth of plant, fertility of soil, and yield of crops. The biofertilizer preparation method is carried out through multilevel processes, in which several strains are combined with some additives which protect cells all through the storage cycle (Herrmann and Lesueur 2013). The type of formulation has a significant function in biofertilizer preparation. Besides enhancing the activity of microbes at larger pace in host plant when inoculated, an efficient formulation also proliferates the number of soil microbes (Arora et al. 2010). Better biofertilizer formulations, hence, are needed in order to produce in the market a new, more reliable, safe, and better-quality biofertilizers that meet the needs of farmers (Bashan et al. 2014). Various enviable characteristic properties of good-quality formulation are as follows:

(i) Good formulation must be allowing nutrient adding, easily adjustable pH, and adequate supply and availability of reasonably low priced raw material (Catroux et al. 2001; Hermann and Lesueur 2013).
(ii) It should be environmentally gracious, i.e., biodegradable, non-pollutant, and nontoxic, in line with contemporary environmental issues concerning the usage of chemicals which alter characteristics of soil.

(iii) Release of bacteria into the soil must be speedy and regulated, and it may be used with regular seeding equipment (Malusa et al. 2012).
(iv) Biofertilizers should be endured and metabolized under harsh conditions in a high number (Malusa et al. 2012). Most commonly used formulations are tourbillon, oil, granules, and lyophilized powders.

10.10.1 Peat Formulations

Peat consists of decayed plants that have partly collapsed over the years. This allows spectacular range of microbes to grow, which are covered by particles and in the colonies of their cells, as well as creates a nutrient-enriched and protective habitat (Bashan et al. 2014). Foremost advantageous characteristics a peat formulation must contain are its nontoxicity, extreme absorptivity, lofty organic content, enhanced water retentivity, economic affordability, and easy to sterilize. Peat is indeterminate and dynamic matrix of various substances showing variability in its capacity for maintaining growth and survival of cells (Malusa et al. 2012). Survival and growth of inoculated microbes may also get impacted by sterilization of toxic chemicals. It could lead to problems in ensuring clear output and field outcomes (Bashan et al. 2014).

10.10.2 Liquid Formulations

Aqueous (broth crops), mineral and organic, and water-based oils, or polymer-based suspensions, are the basis for fluid formulation. The easy handling and use of liquid biofertilizers, either on seeds or in soil, has become more popular (Herman and Lesueur 2013). Generally they hold high number of cells that contain high concentrations of cells, but the lower levels of formulations can also be applied. In addition, in contrast to solid formulation, liquid formulation enables a manufacturer to add sufficient nutrient quantity, cell protective agents to advance performance (Sahu and Brahmaprakash 2016). In case of a large farm machinery, including air seeders or seed augers, it has been reported that these are non-contamination formulations, have longer shelf life, and improved protection against environmental stress compared to peat formulations. Further, large farm machinery find liquid formulations easy to carry (Bashan et al. 2014). In addition, small-scale biofertilizer farmers, who do not have the capacity to handle peat as carrier, are preferred (Singleton et al. 2002). In most developing countries, however, other restrictions have now prohibited their use. Broth-based biofertilizers lack supporting security and quickly lose seed viability. The addition of certain other ingredients such as gum arabic, saccharose, and glycerol may, however, enhance the continued existence of liquid microbes (John et al. 2011).

10.10.3 Granules

Granules consist of tourbillons or little grains of calcite, marble, and silica, wetted adhesively and mixed by means of powder-specific inoculations. Granules are impregnated or coated by target microorganisms (Bashan et al. 2014). Granulate dimensions vary, but the relation between population density and quality of the end product is straightforward. Better mother culture gives better final product (Herman and Lesueur 2013). The benefits of granules in comparison to peat include the following: less sandy, easy handling, easy applicability. These biofertilizers are placed in a groove next to seed in order to have lateral – root interaction with the seed, however, there is no proximity with the chemicals/pesticides that are toxic to microbes (Bashan et al. 2014). There are however other drawbacks, such as the bulker type, which makes transportation and storage costly. In order to achieve this desired result, the application rate must also be increased (Herman and Lesueur 2013).

10.10.4 Lyophilized Powders

Dry biofertilizers produced using soil, organic, or inert carrier have been used in certain cases (Bashan et al. 2014).

10.11 Potential Significance of Beneficial Microbiome in Sustainable Agriculture

Suggestions have been put forward that utilization of transfer therapy of customized central microbiome for its benefits in agribusiness can prove to be a prospective methodology for overseeing plant maladies in various crops (Gopal et al. 2013). The metagenomic study gives the individual, the core rhizosphere, and endophytic microbiomes action in *Arabidopsis thaliana* utilizing 454 sequencing (Roche) of 16S rRNA quality amplicons (Hirsh and Mauchline 2012). Rhizospheric microbial networks as alternative replacing synthetic manures turn to be a subject matter of incredible enthusiasm for economical agriculture and biosafety programs.

For each gram of root, 10^{11} microbial cells are present in constricted zone of soil encompassing plant roots commonly recognized as rhizosphere (Egamberdieva et al. 2008) or above 3×10^3 species of prokaryotes that, by and large, advance productivity of plant (Mendes et al. 2013). Microbiome is an aggregate genome found in rhizosphere microbial network surrounding the plant roots and is bigger in comparison to host plant (Bulgarelli et al. 2013), the interactions of which decide the crop well-being in characteristic agrobiological systems by offering various types of services to crop plants, viz., nutrient procurement, water assimilation, cycling of nutrients, control of weeds and pests, and decomposition of organic matter (Berg et al. 2013). Biofertilizers form additional constituent in soil and cultivation traditions, in other words soil fertility renewal, rotation of crops, maintenance of tillage, organic adjustments, crop residue recycling, control of pathogens by bioagents, and management of pests, whose operations can serve to sustain the productivity of different crops (Sahoo et al. 2013b). The PGPRs found to increase in the soil without the treatment of tillage or minimum tillage include cyanobacteria *Azotobacter*, *Rhizobium*, *Azospirillum*, phosphorous, and K-solubilizing microbes; some PGPRs are the mycorrhizae present in soils facing no tillage or minimum tillage (Dògan et al. 2011; Aziz et al. 2012). In *Helianthus annus*, significant amounts of nitrogen may be produced by efficient strains of *Azospirillum*, *Azotobacter*, Phosphobacter and *Rhizobacter*; also an increase in height of the plant, leaf number, diameter of the stem and dry seed weight has also been observed (Dhanasekar and Dhandapani 2012). Likewise, in rice, physiology and root morphology get enhanced by incorporating *Azotobacter*, *Azospirillum*, and *Rhizobium* (Choudhury and Kennedy 2004). By utilizing beneficial microbes for sustainable crop production, safe, secure, eco-accommodating strategies will hold a significant focal point in the near future (Nina et al. 2014). In general, these microbes include various natural microorganisms which when inoculated in soil ecosystems promote physicochemical properties of soils, crop productivity, soil health, soil biodiversity of microbes, growth of plants, and development (Sahoo et al. 2013a). Microbial crops that are agriculturally useful include rhizobacteria that promote plant growth, cyanobacteria fixing nitrogen, mycorrhiza, bacteria that suppress plant maladies, and endophytes that promote stress tolerance and biodegrade microbes (Singh et al. 2011). As *Azotobacter* has a number of metabolic functions, it performs significant function in the process of nitrogen cycle (Sahoo et al. 2013a). *Azotobacter* has an ability to make thiamine, riboflavin (vitamins), as well as cytokinin, auxins, and gibberellins (plant hormones) (Abd EL-Fattah et al. 2013) in addition to playing a role in nitrogen fixation (Revillas et al. 2000). *Azotobacter chroococcum* increases seed germination and promotes root development, thereby promoting growth of the entire plant (Gholami et al. 2009) by repressing pathogens found in the vicinity of root frameworks in different crops (Mali and Bodhankar 2009). *Azotobacter nigricans*, *Azotobacter vinelandii*, and *Azotobacter paspali* are applied as biofertilizers for coffee, jute, rice, sorghum, coconuts, etc. (Wani et al. 2013).

Azospirillum is another free-living, gram-variable, and flood-prone aerobic bacterium (Sahoo et al. 2014), promoting various plant growth and development aspects (Bhattacharyya and Jha 2012). In both greenhouse and field trials, *Azospirillum* has proven to have beneficial effects on crop and plant growth (Saikia et al. 2013). Different *Azospirillum* species including *A. brasilense, A. amazonense, A. lipoferum, A. halopraeferens* and *A. irakense* have been found to improve productivity of different crops (Sahoo et al. 2014). Interestingly, inoculation of *Azospirillum* can alter the root morphology through the production by siderophore production of crop regulatory substances (Bashan et al. 2004; Sahoo et al. 2014). The lateral roots are increased as well, and root hair formations are enhanced so that more root surface areas are used to absorb enough nutrients (Mehdipour-Moghaddam et al. 2012).

This enhances the plant's water status and helps the nutrient profile of plant growth to grow (Ilyas et al. 2012).

Azospirillum brasilense and *Rhizobium meliloti* plus 2,4-D were co-inoculated, and the grain yield and N, P, and K content of *Triticum aestivum* increased significantly (Askary et al. 2009). For many years, rhizobium has been used as an effective nitrogen fixer. The transformation of atmospheric nitrogen into usable form plays a key role in increasing yields (Sharma et al. 2011). Rhizobium normally enters the root hair, multiplies there, and forms nodules (Nehra et al. 2007). The grain yield of Bengal grams and the lentil (Rashid et al. 2012) by rhizobium inoculants in different places and soil types has been significantly increased. Such wild rice-derived rhizobium isolates have been reported to provide nitrogen to the rice plant for growth and development (Peng et al. 2008). A *Rhizobium meliloti* 1021 species infects nonleguminous plants such as rice to support growth through increased endogenous plant hormone levels as well as photosynthesis to confer plant stress tolerance (Chi et al. 2010). In groundnut, the rhizobium strain IRC-6 has resulted in enhancing several useful characteristics in 50 DAI (days after inoculation) such as increasing the number of color pink nodules, reductase activity in nitrate, and leghemoglobin content (Sharma et al. 2011). Plants like the Mexican bean beetle (Thamer et al. 2011) and the greenhouse whitefly *Trialeurodes vaporariorum* (Menjivar et al. 2012) are shielded against pathogens and herbivores by rhizobial symbiosis.

10.12 Important Uses of Biofertilizers

10.12.1 Biofertilizer Boosts Up Photosynthetic Activity

Enhanced plant growth is shown by higher photosynthesis, as about 90 percent biomass in plant is derived by assimilating carbon dioxide during the process of photosynthesis (Long et al. 2006). Biofertilizer inoculation in particular *Rhizobium* sp., *Bradyrhizobium* species IRBG 271, and *R. leguminosarum* augmented photosynthesis rate for a single leaf in comparison with plant left without inoculation, i.e., control. The IRBG strain showed average increases in photosynthetic activity in all three candidates tested (14 percent) in the plant relative to the control (Peng et al. 2002). Some test strains were reported to significantly enhance plant surface area, gross photosynthetic rate, stomatal conductance, and water quality, demonstrating that rhizobial rice inoculation is able to boost the plant's photosynthetic ability significantly (Mia and Shamsuddin 2010). A few reactive oxygen species are caused by water stress, leading to photosynthetic apparatus damage to the plant (Heidari and Golpayegani 2012). The mixture of *Pseudomonas*, *A. brasilense*, and *Bacillus lentus* was found to increase both antioxidant expression and the content of chlorophyll in stress leaves (Heidari and Golpayegani 2012), as a consequence of which photosynthetic machinery gets fully developed. Therefore, biofertilizer will improve plant's photosynthesis, allowing the plant to grow well even under stress.

10.12.2 PGPR Reduces Contamination of Soil with Pesticides in a Sustainable Way

Plant diseases are regulated or prevented by nematicides, insecticides, herbicides, and fungicides. Pesticide application is imperative to modern agriculture because they control pesticides economically. Continuous undue application of pesticides however is harmful to the environment, posing an impending risk to plant kingdom in addition to human race since it can easily pass into tissue and thus cause biomagnifications (Akhtar et al. 2009; Kumar and Puri 2012). Bioremediation methods attracted substantial consideration in treatment of contamination by pesticides owing to its eco-accommodating nature, economical efficacy, and noticeable decontamination of the environment (Nawaz et al. 2011). Therefore, researching bacterial strains degrading pesticides offers a considerable alternative in mitigating harmful effects of pesticides. Numerous studies have been made so far on the potential role of PGPR in agriculture, horticulture, forestry, and conservation of the environment. Consequently, a set of investigations have been made to study the PGPR role in pesticide bioremediation. Microorganisms such as *Enterobacter*, *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Klebsiella*, *Serratia*, *Bacillus*, etc. have been found capable of attenuating pesticide toxicity (Shaheen and Sundari 2013). Apart from these species, actinomycetes also have significant potential in transforming and degrading pesticide biologically. For pesticide degradation, the enzymatic lysis is the principal process of microorganisms. Three main enzyme systems associated with the majority of degradation of pesticides are as follows: first-stage hydrolyses; mixed function oxidases (MFO) and esterases; and second-stage glutathione-S-transferases (Ortiz-Hernández et al. 2013). In addition, a varied number of reactions, including hydrolyzing, oxidation, addition of an amino group to a nitro group, dehalogenation, nitro group reduction to an amino group, oxygen substitution of the sulfur, cleavage of ring, and side chain metabolism have also been researched to attenuate pesticidal toxicity (Ramakrishnan et al. 2011). On the basis of various studies, PGPR shows a promising approach to the sustainable reduction of pesticide contamination in soil.

10.12.3 Variation in the PGPR Microbial Population Varies the Type of Amino Acid Secretion in the Plant

Rhizosphere (du Jardin 2015) is the region of ground around the root system, and rhizobacterias are a community of rhizosphere bacteria colonizing the vicinity of roots (Shahaby et al. 2016). Besides providing anchorage to plant, helping in uptake of nutrients and water, roots of plant synthesize and exude a broad range of chemicals including amino acids (Wălker et al. 2003; Westŏn et al. 2012; Moê 2013). Root exudates are usually referred to as the chemical products that roots secrete into soils. Plant root secretion products serve as chemicals attracting a large number of heterogeneous microbial communities. Exuding various chemicals alters physicochemicals of soil and, hence, greatly controls composition of the microbial soil culture in its direct surroundings (Bulgarelli et al. 2013; Huang et al. 2014). There is therefore a reliance on plant species and associated microorganics to the plant for type of amino acids plus the chemical constitution of radically secreted exudates (Kang et al. 2010; Bardgett and Putten 2014). Hence, the kind of amino acid secretion from the plant varies significantly with the variability in the adhering microbial PGPR population.

10.12.4 Role of Biofertilizers in Remediation of Heavy Metal Toxicity

Metals exist naturally in soils, many of which are needed as micronutrients for growth of plants. Nevertheless, unceasing anthropological activities, intensive agriculture, and rapidly growing industries have contributed to many environmental problems through the release of heavy metals, toxic waste, agricultural contaminants, and so on (Shinwari et al. 2015). Inorganic heavy metal pollutants are water soluble and nondegradable and get amassed in the soil (Akhtar et al. 2013). Toxic heavy metals like cadmium, nickel, mercury, arsenic, zinc, and chromium exist in different valence states. Although some metals are required by plants as micronutrients, disproportionately high concentration of heavy metals is harmful to most of the plants. When high levels of heavy metal ions occur, the root system quickly absorbs and relocates to the shoots and leaves, causing stress to metabolism, decreasing growth, or even causing plant mortality (Mehes et al. 2013). In addition, heavy metal concentrations above threshold in soil decrease fertility of soil affecting microbial communities as well (Lenart and Volny 2013).

Attenuating heavy metals in soil is difficult, considering that they are not organically degradable. Only by altering the oxidation state can it be detoxified. Most heavy metals are oxidized and reduced in toxicity (Wuana and Okiemen 2011). So far, various methods like physical, chemical, and biological treatments have been put forth to treat metal pollutants; bioremediation still continues to occupy forefront owing to its easy and economical application when compared to various costly detoxifying methods (Lim et al. 2014). Role of PGPR in bioremediating metal toxicity has been explored by various researchers, and various microorganisms have been identified to decrease or detoxify heavy metal toxicity (Dixit et al. 2015). *Brevibacillus* sp., *Ralstonia metallidurans*, *Achromobacter xylosoxidans*, and *Psycrobacter* sp., are some of the most important PGPRs among the wide range of PGPRs in heavy metal bioremediation (Shinwari et al. 2015). A well-known finding that toxicity is caused by heavy metal induces plant stress which in turn inhibits production of ethylene when found at high level (Hossain et al. 2012). One of the most important defensive mechanisms exercised in PGPR is 1-aminocyclopropane-1-carboxylate synthesis that decreases ethylene production in plants (Singh et al.

2015). Therefore, ACC deaminase production through PGPR provides efficient protection for the host plant against heavy metal toxicity stress response.

Production of microbial siderophores is one more successful mechanism used by the PGPR for reducing toxicity of metals (Radzki et al. 2013). Siderophores contribute in reducing stress of plant by complexing with noxious metals like zinc, copper, lead, copper, and cadmium (Dimpka et al. 2009; Saha et al. 2016). In addition, through the biosorption process, PGPR can also help to reduce metal toxicity either by metabolism-dependent or metabolism-independent methods (Dary et al. 2010).

10.12.5 Microbial Biofertilizers Exert a Significant Nematicidal Activity

El-hadad et al. (2011) have confirmed that three strains of *Bacillus megaterium*, four strains of *Paenibacillus polymyxa*, nitrogen-fixing bacteria, and phosphorus-solubilizing bacteria have been individually inoculated in plants of tomato infested with the root nematode *M. incognita* in potted sandy soil with significant nematicidal action wherein *P. polymyxa NFB7*, *B. circulans KSB2*, and *B. megaterium PSB2* inoculation demonstrated a high decrease in number of nematodes compared to infested control of the uninoculated nematode.

In contrast to nematode-infested tomato plant that did not get inoculated by biologically fertilized agent, these biofertilizers often increase the length of stem (cm), leaf number, stem dry weight, and root dry weight (g). Inoculation with *Azospirillum* and *Azotobacter* augmented productivity and quality of nematode infested capsicum (Khan et al. 2012). Six Egyptian trade biofertilizers (BFs) have been tested by Ismail and Hasabo (2000) for regulation of blue-green algae, microbien, nitrobien, serealin, phosphorine, and rhizobacterin for controlling *M. incognita* in sunflower. The nematode population was significantly reduced by all the biofertilizers studied. Rhizobacterin therapy followed by phosphorine and nitrobial drugs was the fastest suppressors in the nematode populations. The use of biofertilizer-like bacteria to prevent parasite nematodic growth in plants has been found to commonly produce many volatile compounds, hydrogen sulfide, fatty acids, enzymes, alcohol, hormones, and phenolic compounds which hamper nematodic growth. Such materials may be nematodically toxic or may alter the rhizosphere climate, indirectly resulting in a decline of nematodes (Youssef and Eissa 2014).

10.12.6 Effect of Biofertilizers on Ecosystem

Though biofertilizers have found extensive agricultural usage in recent decades, colonizing and ecology knowledge are not well illustrated. Moreover, the interaction mechanism between the plants and the resident microbial community remains a question of people's curiosity. The presence of indigenous microflora in rhizosphere is the main factor determining the biofertilizer's effectiveness in the natural ecosystem. Survival and growth in plants by biofertilizer application can be influenced by this highly competitive culture with different rhizosphere species (Hibbing et al. 2010). Along with this, seed and seedling bacterization or soil modifications might produce change in indigenous microfloral community which will have to be taken into consideration as far as the safety of bacterial introduction in the environment is considered (Dey et al. 2012). Therefore, it becomes imperative to assess nontarget impacts on ecosystem and populations before biofertilizer is released in the environment, and therefore, before changing agricultural practices, a detailed study of the effects of organic fertilizers is certainly important. Finally, impact on biogeochemical cycles, soil texture, soil properties including water retaining capacity, fertility, porosity, and erosion prevention must be taken into account properly (Pereg and Mcmillan 2015). Although there is some study on the effect of biofertilizer on soil rhizosphere and food web nontargets, the magnitude of changes in the rhizosphere and the importance of them on the ecological function of these products remain unreportable due to the introduction of rhizosphere inoculants (Martinez-Viveros et al. 2010). The questions as to which species are selected in the indigenous microflora in biofertilizer competitions and which are beneficial or harmful to the host and resident microbial community are still unanswered and yet unfounded. Attempts to find answers are therefore unavoidable, while further experiments and studies are planned with the inoculation of microorganisms in the soil. The impact of the introduction of biofertilizers into the home communities is stated to be based on various factors, including soil characteristics, application method of biofertilizers, and a different environment (Dey et al. 2012). Nevertheless, there have been very few research carried out to date over a longer period, which is very important to determine the effectiveness of bioinoculants as well as their risk factors. It is, therefore, clear that extensive studies must be performed before bioinoculants are released safely for commercial purposes to study the longer-term impact of bioinoculants on nontarget species. In addition, both a culturally dependent and culturally indigenous method, including genetic and physiological tests, has investigated the impact of biofertilizer on nontarget communities. Evaluation of microbial structures of organisms by both plating and cytochemical methods is a good way of researching the impact of biofertilizer on the resident microflora. The use of the latest technologies is necessary for investigating the impact of biofertilizers on native microflora and soil functions. While DNA is a valid and effective marker on population diversity and potential, recent successful mRNA reports are sufficient to include the experiment with biofertilizer for risk and efficiency assessment studies. In addition, a mRNA-based approach would consider a real functional diversity of biofertilizers at any given level. Hence, high-performance and higher-resolution methods and traditional multidimensional analysis techniques must be used to assess biofertilizers in the efficacy, diversity, and risk assessment studies prior to their release into the ecosystem (Sharma et al. 2012).

10.12.7 Effect of Biofertilizer in Soil Reclamation of Degraded Land Ecosystem

Mining of mineral resources leads to serious soil degradation, changes in microbial ecosystems, and damage to vegetation, which lead to the loss of a large amount of land (Juwarkar and Jambhulkar 2008; Sheoran et al. 2010). Gradual growth in such landscapes can not only threaten the productivity of agro-forest but also disrupt the ecosystems and the ecological balance. It has been reported on several occasions that nutrients are leached during various mining processes due to accelerated erosion rates that destroy soil productivity (Sheoran et al. 2010). Reclamation is the process in such vulnerable circumstances that restores ecological integrity in these disturbed mining areas. The advancement of a functioning indigenous microbial network responsible for the improvement of soil structure helpful for plant and plant nutrient production by a variety of biogeochemical cycles is key to successful recovery of mine spoil dumps (Juwarkar et al. 2001; Juwarkar and Singh 2007; Kumar et al. 2013). A mining site's rehabilitation process is troublesome as such mining sites loose fertility status, productivity, as well as their capacity to support plant and associated microbial networks (Chaubey and Prakash 2014) that have a significant role in balancing ecosystem productivity. Restoration of disturbed land systems may somehow return to their predisturbed state with assistance of tree ranches along with organic amendments, in this manner, improving fertility and productivity. The soil of mining sites becomes extremely acidic due to the practice of mining, which affects plant growth. This is possible by incorporating organic modifications, which not only increase the pH of soil but also improve the quality of the soil and its ability to maintain water and to slowly release fertilizer (Diacono and Montemurro 2010). It can therefore be said that for the soil recovery of the mining sites, it is necessary to keep leguminous plants in the plant community and to have a proper microbial population.

10.13 Benefits and Limitations of Biofertilizers

Biological practices can offer a wide scope of opportunities for the improvement of better agrarian practices because of the benefits and advantages provided for the soil, crops, and the farmers. However, restrictions of these practices are additionally all around examined and perceived, which infers that attainability studies ought to be completed to discover better answers for every specific case in farming exercises. A portion of the advantages and constraints are referenced to feature the need of future research on certain issues.

10.13.1 Benefits of Biological Fertilizers

1. Biological fertilizers can prepare supplements that favor the development of natural processes in soils.
2. Maintenance of plant well-being is upgraded by the expansion of adequate nutrients.
3. Food supply is given, and development of microorganisms and helpful soil worms is prompted.
4. Because of the good structure given to the soil, root development is promoted.
5. The organic matter in soil is higher than ordinary levels.
6. Biological fertilizers promote the improvement of mycorrhizal affiliations, which expands the accessibility of phosphorus (P) in the soil.
7. Biological fertilizers help to dispose of plantar sicknesses and give ceaseless stockpile of micronutrients to the dirt.
8. Biological fertilizers contribute to the maintenance of stable nitrogen (N) and phosphorus (P) concentrations (Chen 2006).

10.13.2 Limitations of Biofertilizers

1. The biofertilizers nutrient composition is highly variable; the expense is highly contrasted with some synthetic fertilizers.
2. Extensive and long-haul application may bring about salt accumulation and heavy metal accumulation that could cause antagonistic impacts on plant development, growth of life forms of the soil, water quality, and human well-being.
3. Large volumes are required for land application because of low nutrient content, in correlation with synthetic fertilizers.
4. Main macronutrients may not be available in adequate amounts for development and improvement of plants.
5. The nutrient release rate is too slow to fulfill crop requirements in a short time, which could lead to nutrient deficiency.

10.14 Future Perspectives of Biofertilizers

The utilization of different biofertilizers as a fundamental part of agricultural practice is the new rising field nowadays. These microbes are as of now being effectively utilized in many nations and are required to develop further with time (Weekley et al. 2012). Consequently, it is sensible to anticipate that later on, the extensive utilization of biofertilizers will offer different effective techniques for by and large advancement of farming field. However, widespread usage of biofertilizers will require handling few issues with more consideration and necessary actions to solve the issues (Gamalero et al. 2008).

1. Efficient multifunctional biofertilizers need to be produced for different varieties of crops.
2. From lab experiments to commercializing, the use of biofertilizers needs a number of latest techniques for formulation, maintenance, storage, shipping, and application of these microbes.
3. It is important to instruct individuals and farmers about the long-term advantage of utilizing biofertilizers in place of synthetic fertilizers. The unfriendly and hazardous impacts of synthetic fertilizers should also be featured before farmers. The misguided judgment about microbes that they only cause diseases should be cleared to farmers so that they will use biofertilizers on a large scale.
4. Although initial biofertilizers are likely to be non-transformed bacterial strains which have been chosen for certain positive attributes, development of genetically designed strains which are increasingly effective in invigorating plant development is required. In any case, researchers should demonstrate to both people in general and administrative organizations worldwide that genetically designed strains do not present any new perils or hazards.
5. A quality control framework should exist for the creation of inoculants and their application in the field to ensure and explore the advantages of plant-microbe's beneficial interaction. "Biofertilizer Act" and strict guideline should be established for quality control in business sectors and application.
6. The microbial survival of biofertilizers in soil under disturbed conditions needs to be examined. Agronomic, soil, and monetary assessment of biofertilizers should be carried out for the different agricultural outputs.

10.15 Conclusion

Biofertilizers are an essential part of organic farming in modern agricultural practices in terms of best alternative to synthetic fertilizers which pose different environmental hazards. Biofertilizers are capable of fixing atmospheric nitrogen in soil and root nodules and consequently make it available to plants. They help in solubilizing phosphate (from insoluble sources such as aluminum phosphates) into accessible form, moving phosphates from one soil layer to another, synthesizing hormones and antibodies to help in plant growth and resistance against diseases. They also help in the decomposition of organic matter, thus taking part in soil mineralization. This leads to expanded crop yields, increased soil structure (influencing soil particle aggregation for a better water relationship), and induced plant dry spell resilience (increasing leaf water and turgor capacity, keeping up stomatal functioning, and increasing root development). Nevertheless, increased demand and understanding among farmers and growers regarding the use of biofertilizers will definitely pave the way for new businesses to join the manufacturing of biofertilizers, which additionally needs consolation and backing from governments. Biofertilizer innovation, which is an essential part of sustainable agriculture, must be reasonable for users' social and infrastructural conditions, monetarily plausible and feasible, stable in the long term, suitable to various sections of society. Therefore, it is clear that by proper training of dealers and farmers, comprehension of the significance and monetary suitability of applying biofertilizer innovation must be expanded.

References

Abd El-Fattah DA, Ewedab WE, Zayed MS, Hassaneina MK (2013) Effect of carrier materials, sterilization method, and storage temperature on survival and biological activities of Azotobacter chroococcum inoculants. Ann Agric Sci 58:111–118

Abu-Bakar, Nurul-Ain, Ibrahim N (2013) Indigenous microorganisms production and the effect on composting process. AIP conference proceedings 1571: 283–286. Academic Search Premier. Web. 12 Dec 2015

Adam E, Bernhart M, Mu¨ller H (2016) The *Cucurbita pepo* seed microbiome: genotype-specific composition and implications for breeding. Plant Soil. https://doi.org/10.1007/s11104-016-3113-9

Akhtar MS, Chali B, Azam T (2013) Bioremediation of arsenic and lead by plants and microbes from contaminated soil. Res Plant Sci 1(3):68–73

Aktar W, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol 2(1):1–12

Aleklett K, Leff JW, Fierer N, Hart M (2015) Wild plant species growing closely connected in a subalpine meadow host distinct root-associated bacterial communities. Peer J 3:e804

Ansori A, Gholami A (2015) Improved nutrient uptake and growth of maize in response to inoculation with Thiobacillus and mycorrhiza on an alkaline soil. Commun Soil Sci Plant Anal 46:2111–2126

Arora NK, Khare E, Maheshwari DK (2010) Plant growth promoting rhizobacteria: constraints in bioformulation, commercialization and future strategies. In: Plant growth and health promoting bacteria. Springer, Berlin/Heidelberg, pp 97–116

Askary M, Mostajeran A, Amooaghaei R, Mostajeran M (2009) Influence of the co-inoculation Azospirillum brasilense and Rhizobium meliloti plus 2, 4-D on grain yield and N, P, K content of Triticum aestivum (cv. Baccros and Mahdavi). Am Eurasian J Agric Environ Sci 5:296–307

Audenaert K, Pattery T, Cornelis P, Höfte M (2002) Induction of systemic resistance to *Botrytis cinerea* in tomato by Pseudomonas aeruginosa 7NSK2: role of salicylic acid, pyochelin, and pyocyanin. MPMI 15:1147–1156

Aziz G, Bajsa N, Haghjou T, Taule C, Valverde A, Mariano J, Arias A (2012) Abundance, diversity and prospecting of culturable phosphate solubilizing bacteria on soils under crop–pasture rotations in a no-tillage regime in Uruguay. Appl Soil Ecol 61:320–326

Badri DV, Vivanco JM (2009) Regulation and function of root exudates. Plant Cell Environ 32:666–681

Baetz U, Martinoia E (2014) Root exudates: the hidden part of plant defense. Trends Plant Sci 19:90–98. https://doi.org/10.1016/j.tplants.2013.11.006

Bai Y, Mu¨ller DB, Srinivas G (2015) Functional overlap of the *Arabidopsis* leaf and root microbiota. Nature 528:364–369

Bais HP, Weir TL, Perry LG et al (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. Annu Rev Plant Biol. https://doi.org/10.1146/annurev.arplant.57.032905.105159

Bardgett RD, van der Putten WH (2014) Belowground biodiversity and ecosystem functioning. Nature 515(7528):505–511

Bardi L, Malusà E (2012) Drought and nutritional stresses in plant: alleviating role of rhizospheric microorganisms abiotic stress: new research. Nova Science Publishers Inc., Hauppauge, pp 1–57

Bashan Y, Holguin G, Bashan LE (2004) Azospirillum-plant relationships: agricultural, physiological, molecular and environmental advances (1997–2003). Can J Microbiol 50:521–577

Bashan Y, de Bashan LE, Prabhu SR, Hernandez JP (2014) Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). Plant Soil 378:1–33

Bell CW, Asao S, Calderon F (2015) Plant nitrogen uptake drives rhizosphere bacterial community assembly during plant growth. Soil Biol Biochem 85:170–182. https://doi.org/10.1016/j.soilbio.2015.03.006

Berendsen RL, Pieterse CMJ, Bakker PAHM (2012) The rhizosphere microbiome and plant health. Trends Plant Sci 17:478–486. https://doi.org/10.1016/j.tplants.2012.04.001

Berg M, Koskella B (2018) Nutrient- and dose-dependent microbiome-mediated protection against a plant pathogen. Curr Biol 28:2487–2492

Berg G, Smalla K (2009) Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. FEMS Microbiol Ecol 68:1–13

Berg G, Zachow C, Müller H, Phillips J, Tilcher R (2013) Next-generation bio-products sowing the seeds of success for sustainable agriculture. Agronomy 3:648–656

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018) Biopesticide Techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhattacharyya PN, Jha DK (2012) Plant growth-promoting rhizobacteria (PGPR): emergence in agriculture. World J Microbiol Biotechnol 28:1327–1350

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Boddey RM, Da Silva LG, Reis V, Alves BJR, Urquiaga S (2000) Assessment of bacterial nitrogen fixation in grass species. In: Triplett EW (ed) Prokaryotic nitrogen fixation: a model system for analysis of a biological process. Horizon Scientific Press, Wymondham, pp 705–726

Brader G, Compant S, Vescio K, Mitter B, Trognitz F, Ma L-J (2017) Ecology and genomic insights into plant-pathogenic and plant-nonpathogenic endophytes. Annu Rev Phytopathol 55:61–83

Bulgarelli D, Schlaeppi K, Spaepen S, Loren V, van Themaat E, Schulze-Lefert P (2013) Structure and functions of the bacterial microbiota of plants. Annu Rev Plant Biol 64:807–838

Cakmakci R, Dönmez MF, Erdoğan Ü (2007) The effect of plant growth promoting rhizobacteria on barley seedling growth, nutrient uptake, some soil properties, and bacterial counts. Turk J Agric For 31:189–199

Calvo P, Nelson L, Kloepper JW (2014) Agricultural uses of plant biostimulants. Plant Soil 383:3. https://doi.org/10.1007/s11104-014-2131-8

Carrión VJ, Cordovez V, Tyc O, Etalo DW, Bruijn ID, Jager CL, de Victor (2018) Involvement of Burkholderiaceae and sulfurous volatiles in disease suppressive soils. ISME J 12:2307–2321

Catroux G, Hartmann A, Revellin C (2001) Trends in Rhizobial inoculant production and use. Plant Soil 230(1):21–30

Cederlund H (2014) Soil carbon quality and nitrogen fertilization structure bacterial communities with predictable responses of major bacterial phyla. Appl Soil Ecol 84:62–68

Chang CH, Yang SS (2009) Thermotolerant phosphate solubilizing microbes for multifunctional bio-fertilizer preparation. Bio/Technology 100(4):1648–1658

Chaparro JM, Badri DV, Vivanco JM (2014) Rhizosphere microbiome assemblage is affected by plant development. ISME J. https://doi.org/10.1038/ismej.2013.196

Chaubey OP, Prakash R (2014) Bio-reclamation of degraded ecosystem. Int J Bio-Sci Bio-Technol 6(4):145–154

Chen JH (2006) The combined use of chemical and organic fertilizers and/or bio-fertilizer for crop growth and soil fertility. International workshop on sustained management of the soil rhizosphere system for efficient crop production and fertilizer use. Taiwan: National Chung Hsing University. Available online at http://www.agnet.org/library/tb/174/

Chi F, Yang P, Han F, Jing Y, Shen S (2010) Proteomic analysis of rice seedlings infected by Sinorhizobiummeliloti 1021. Proteomics 10:1861–1874

Choudhury MA, Kennedy IR (2004) Prospects and potentials for system of biological nitrogen fixation in sustainable rice production. Biol Fertil Soils 39:219–227

Chun-Li W, Shiuan-Yuh C, Chiu-Chung Y (2014) Present situation and future perspective of biofertilizer for environmentally friendly agriculture. Ann Rep:1–5

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecologia Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish Fuana. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 51–68

Dary M, Chamber-Pérez MA, Palomares AJ, Pajuelo E (2010) "In situ" phytostabilisation of heavy metal polluted soils using Lupinus luteus inoculated with metal resistant plant-growth promoting rhizobacteria. J Hazard Mater 177(1):323–330

de Vrieze M, Germanier F, Vuille N, Weisskopf L (2018) Combining different potato associated Pseudomonas strains for improved biocontrol of Phytophthora infestans. Front Microbiol 9:2573

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

deWeert S, Vermeiren H, Mulders IHM (2002) Flagella-driven chemotaxis towards exudate components is an important trait for tomato root colonization by *Pseudomonas fluorescens*. Mol Plant Microb Interact 15(11):1173–1180

Dey R, Pal KK, Tilak KV (2012) Influence of soil and plant types on diversity of rhizobacteria. Proc Natl Acad Sci India B Biol Sci 82(3):341–352

Dhanasekar R, Dhandapani R (2012) Effect of biofertilizers on the growth of Helianthus annuus. Int J plant Anim Environ Sci 2:143–147

Diacono M, Montemurro F (2010) Long term effects of organic amendments on soil fertility: a review. Agron Sustain Dev 30(2):401–422

Dimkpa CO, Merten D, Svatoš A, Büchel G, Kothe E (2009) Metal induced oxidative stress impacting plant growth in contaminated soil is alleviated by microbial siderophores. Soil Biol Biochem 41(1):154–162

Dixit R, Malaviya D, Pandiyan K, Singh UB, Sahu A, Shukla R, Singh BP, Rai JP, Sharma PK, Lade H, Paul D (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability 7(2):2189–2212

Dogan K, KamailCelik I, Mustafa Gok M, Ali C (2011) Effect of different soil tillage methods on rhizobial nodulation, biomass and nitrogen content of second crop soybean. Afr J Microbiol Res 5:3186–3194

Doornbos RF, Van Loon LC, Bakker PA (2012) Impact of root exudates and plant defense signaling on bacterial communities in the rhizosphere. A review. Agron Sustain Dev 32:227–243

Dubey A, Kumar A, AbduAllah EF et al (2018) Growing more with less: breeding and developing drought resilient soybean to improve food security. Ecol Indic. https://doi.org/10.1016/j.ecolind.2018.03.003

Durán P, Tortella G, Viscardi S, Barra PJ, Carrión VJ, Mora LA (2018) Microbial community composition in take-all suppressive soils. Front Microbiol 9:2198

Egamberdieva D, Kamilova F, Validov S, Gafurova L, Kucharova Z, Lugtenberg B (2008) High incidence of plant growth stimulating bacteria associated with the rhizosphere of wheat grown on salinated soil in Uzbekistan. Environ Microbiol 10:1–9

El-Haddad ME, Mustafa MI, Selim SM, El-Tayeb TS, Mahgoob AE, Aziz NH (2011) The nematicidal effect of some bacterial biofertilizers on Meloidogyne incognita in sandy soil. Braz J Microbiol 42(1):105–113

Fierer N (2017) Embracing the unknown: disentangling the complexities of the soil microbiome. Nat Rev Microbiol 15:579–590

Gallon JR (2001) N_2 fixation in phototrophs: adaptation to a specialized way of life. Plant Soil 230:39–48

Gamalero E, Berta G, Massa N, Glick BR, Lingua G (2008) Synergistic interactions between the ACC deaminase producing bacterium Pseudomonas putida UW4 and the AM fungus Gigaspora rosea positively affect cucumber plant growth. FEMS Microbiol Ecol 64(3):459–467

Gaur A, Adholeya A (2000) Effects of the particle of soil-less substrates upon AM fungus inoculum production. Mycorrhiza 10:43–48

Gholami A, Shahsavani S, Nezarat S (2009) The effect of Plant Growth Promoting Rhizobacteria (PGPR) on germination seedling growth and yield of maize. Int J Biol Life Sci 5:1

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012:963401. https://doi.org/10.6064/2012/963401

Gómez Expósito R, Bruijn ID, Postma J, Raaijmakers JM (2017) Current insights into the role of rhizosphere bacteria in disease suppressive soils. Front Microbiol 8:2529

Gopal M, Gupta A, Thomas GV (2013) Bespoke microbiome therapy to manage plant diseases. Front Microbiol 5:15

Graham PH, Vance CP (2000) Nitrogen fixation in perspective: an overview of research and extension needs. Field Crops Res 65:93–106

Griffiths RI (2011) The bacterial biogeography of British soils. Environ Microbiol 13:1642–1654

Gupta AK (2004) The complete technology book on biofertilizer and organic farming. National Institute of Industrial Research Press India, New Delhi, pp 242–253

Gutierez-Mañero FJ, Ramos-Solano B, Probanza A, Mehouachi J, Tadeo FR, Talon M (2001) The plant-growth-promoting rhizobacteria Bacillus pumilus and Bacillus licheniformis produce high amounts of physiologically active gibberellins. Physiol Plant 111:206–211

Hacquard S (2016) Disentangling the factors shaping microbiota composition across the plant holobiont. New Phytol 209:454–457

Hardoim PR, van Overbeek LS, Berg G, Pirttilä AM, Compant S, Campisano A (2015) The hidden world within plants: ecological and evolutionary considerations for defining functioning of microbial endophytes. MMBR 79:293–320

Hartmann A, Schmid M, van Tuinen D, Berg G (2009) Plant-driven selection of microbes. Plant Soil 321:235–275

Hashem MA (2001) Problems and prospects of cyanobacterial biofertilizer for rice cultivation. Aust J Plant Physiol 28:881–888

Heidari M, Golpayegani A (2012) Effects of water stress and inoculation with plant growth promoting rhizobacteria (PGPR) on antioxidant status and photosynthetic pigments in basil (Ocimum basilicum L.). J Saudi Soc Agric Sci 11(1):57–61

Herrmann L, Lesueur D (2013) Challenges of formulation and quality of biofertilizers for successful inoculation. Appl Microbiol Biotechnol 97(20):8859–8873

Hibbing ME, Fuqua C, Parsek MR, Peterson SB (2010) Bacterial competition: surviving and thriving in the microbial jungle. Nat Rev Microbiol 8(1):15–25

Hirsch PR, Mauchline TH (2012) Who's who in the plant root microbiome? Nat Biotechnol 30:961–962

Hopkins SR, Wojdak JM, Belden LK (2017) Defensive symbionts mediate host–parasite interactions at multiple scales. Trends Parasitol 33:53–64

Hossain MA, Piyatida P, da Silva JA, Fujita M (2012) Molecular mechanism of heavy metal toxicity and tolerance in plants: central role of glutathione in detoxification of reactive oxygen species and methylglyoxal and in heavy metal chelation. J Bot 37. https://doi.org/10.1155/2012/872875

Huang XF, Chaparro JM, Reardon KF, Zhang R, Shen Q, Vivanco JM (2014) Rhizosphere interactions: root exudates, microbes, and microbial communities. Botany 92(4):267–275

Hultberg M, Alsanius B, Sundin P (2000) In vivo and in vitro interactions between Pseudomonas fluorescens and Pythium ultimum in the suppression of damping-off in tomato seedlings. Biol Control 19:1–8

Idris EE, Iglesias DJ, Talon M, Borriss R (2007) Tryptophan-dependent production of indole-3-acetic acid (IAA) affects level of plant growth promotion by Bacillus amyloliquefaciens FZB42. MPMI 20:619–626

Ilyas N, Bano A, Iqbal S, Raja NI (2012) Physiological, biochemical and molecular characterization of Azospirillum spp. isolated from maize under water stress. Pak J Bot 44:71–80

Irisarri P, Gonnet S, Monza J (2001) Cyanobacteria in Uruguayan rice fields: diversity, nitrogen fixing ability and tolerance to herbicides and combined nitrogen. J Biotechnol 91:95–103

Ismail AE, Hasabo SA (2000) Evaluation of some new Egyptian commercial biofertilizers, plant nutrients and a biocide against Meloidogyne incognita root knot nematode infecting sunflower. Pak J Nematol 18:39–49

James EK (2000) Nitrogen fixation in endophytic and associative symbiosis. Field Crops Res 65:197–209

Jardin P (2015) Plant biostimulants: definition, concept, main categories and regulation. Sci Hortic 196:3–14

John RP, Tyagi RD, Brar SK, Surampalli RY, Prévost D (2011) Bioencapsulation of microbial cells for targeted agricultural delivery. Crit Rev Biotechnol 31(3):211–226

Johns C (2017) Living soils: the role of microorganisms in soil health. Future Directions International

Johnston-Monje D, Lundberg DS, Lazarovits G (2016) Bacterial populations in juvenile maize rhizospheres originate from both seed and soil. Plant Soil 405:337–355

Jones JDG, Dangl JL (2006) The plant immune system. Nature 444:323–329. https://doi.org/10.1038/nature05286

Juwarkar AA, Jambhulkar HP (2008) Phytoremediation of coal mine spoil dump through integrated biotechnological approach. Bioresour Technol 99(11):4732–4741

Juwarkar AA, Singh SK (2007) Utilisation of municipal solid waste as an amendment for reclamation of coal mine spoil dump. Int J Environ Technol Manag 7:407–420

Juwarkar AA, Dubey K, Khobragade R, Nimje M, Singh SK (2001) Integrated biotechnological approach for phytoremediation of copper mine spoil dumps and tailing. In: Proceeding of international conference on industrial pollution and control technologies (ICIPACT- 2001). JNTU, Hyderabad 7–10

Kang BG, Kim WT, Yun HS, Chang SC (2010) Use of plant growth promoting rhizobacteria to control stress responses of plant roots. Plant Biotechnol Rep 4(3):179–183

Kannaiyan S (ed) (2002) Biotechnology of biofertilizers. Alpha Science Int'l Ltd, Pangbourne

Khan Z, Tiyagi SA, Mahmood I, Rizvi R (2012) Effects of N fertilization, organic matter, and biofertilizers on the growth and yield of chilli in relation to management of plant-parasitic nematodes. Turk J Bot 36(1):73–78

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir

M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Khosro M, Yousef S (2012) Bacterial bio-fertilizers for sustainable crop production: a review. APRN J Agric Biol Sci 7(5):237–308

Klironomos JN, Hart MM (2002) Colonization of roots by arbuscular mycorrhizal fungi using different sources of inoculum. Mycorrhiza 12:181–184

Kumar M, Puri A (2012) A review of permissible limits of drinking water. Indian J Occup Environ Med 16(1):40

Kumar S, Chaudhuri S, Maiti SK (2013) Soil dehydrogenase enzyme activity in natural and mine soil-a review. Middle-East J Sci Res 13(7):898–906

Ladygina N, Hedlund K (2010) Plant species influence microbial diversity and carbon allocation in the rhizosphere. Soil Biol Biochem 42:162–168

Lauber C, Knight R, Hamady M, Fierer N (2009) Soil pH as a predictor of soil bacterial community structure at the continental scale: a pyrosequencing-based assessment. Appl Environ Microbiol 75:5111–5120

Lenart A, Wolny-Koładka K (2013) The effect of heavy metal concentration and soil pH on the abundance of selected microbial groups within ArcelorMittal Poland steelworks in Cracow. Bull Environ Contam Toxicol 90(1):85–90

Lim KT, Shukor MY, Wasoh H (2014) Physical, chemical, and biological methods for the removal of arsenic compounds. Biomed Res Int 2014:9

Long SP, Zhu XG, Naidu SL, Ort DR (2006) Can improvement in photosynthesis increase crop yields? Plant Cell Environ 29(3):315–330

Lugtenberg B, Kamilova F (2009) Plant-growth-promoting rhizobacteria. Annu Rev Microbiol 63:541–556

Lynch MDJ, Neufeld JD (2015) Ecology and exploration of the rare biosphere. Nat Rev Microbiol 13:217–229

MalamIssa O, Stal LJ, Défarge C, Couté A, Trichet J (2001) Nitrogen fixation by microbial crusts from desiccated Sahelian soils (Niger). Soil Biol Biochem 33:1425–1428

Mali GV, Bodhankar MG (2009) Antifungal and phytohormone production potential of Azotobacter chroococcum isolates from groundnut (Arachis hypogaea L.) rhizosphere. Asian J Exp Sci 23:293–297

Malusa E, Vassilev N (2014) A contribution to set a legal framework for biofertilisers. Appl Microbiol Biotechnol 98(15):6599–6607

Malusa E, Sas-Paszt L, Ciesielska J (2012) Technologies for beneficial microorganisms inocula used as biofertilizers. Sci World J 2012:491206

Mansfield J, Genin S, Magori S, Citovsky V, Sriariyanum M, Ronald P (2012) Top 10 plant pathogenic bacteria in molecular plant pathology. Mol Plant Pathol 13:614–629

Martínez-Viveros O, Jorquera MA, Crowley DE, Gajardo G, Mora ML (2010) Mechanisms and practical considerations involved in plant growth promotion by rhizobacteria. J Soil Sci Plant Nutr 10(3):293–319

Mazid M, Khan TA (2015) Future of bio-fertilizers in Indian agriculture: an overview. Int J Agric Food Res 3(3):10–23

Mehdipour-Moghaddam MJ, Emtiazi G, Salehi Z (2012) Enhanced auxin production by Azospirillum pure cultures from plant root exudates. J Agric Sci Technol 14:985–994

Mehes-Smith M, Nkongolo K, Cholewa E (2013) Coping mechanisms of plants to metal contaminated soil. In: Environmental change and sustainability, Intech, pp 978–953. https://doi.org/10.5772/55124

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess Environ 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mendes R, Garbeva P, Raaijmakers JM (2013) The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS Microbiol Rev 37:634–663

Menjivar RD, Cabrera JA, Kranz J, Sikora RA (2012) Induction of metabolite organic compounds by mutualistic endophytic fungi to reduce the greenhouse whitefly Trialeurodes vaporariorum (Westwood) infection on tomato. Plant Soil 352:233–241

Mia MB, Shamsuddin ZH (2010) Nitrogen fixation and transportation by rhizobacteria: a scenario of rice and banana. Int J Bot 6:235–242

Miller IM (1990) Bacterial leaf nodule symbiosis. Adv Bot Res 17:163–234

Mitter B, Pfaffenbichler N, Sessitsch A (2016) Plant–microbe partnerships in 2020. Microb Biotechnol 9:635–640

Moe LA (2013) Amino acids in the rhizosphere: from plants to microbes. Am J Bot 100:1692–1705

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 152–178

Nawaz K, Hussain K, Choudary N, Majeed A, Ilyas U, Ghani A, Lin F, Ali K, Afghan S, Raza G, Lashari MI (2011) Eco-friendly role of biodegradation against agricultural pesticides hazards. Afr J Microbiol Res 5(3):177–183

Nehra K, Yadav SA, Sehrawat AR, Vashishat RK (2007) Characterization of heat resistant mutant strains of Rhizobium sp. (Cajanus) for growth, survival and symbiotic properties. Indian J Microbiol 47:329–335

Nina K, Thomas WK, Prem SB (2014) Beneficial organisms for nutrient uptake. VFRC report 2014/1, virtual fertilizer research center. Wageningen Academic Publishers 63, Washington, DC

Nutongkaew T (2014) Effect of inoculum size on production of compost and enzymes from Palm Oil Mill Biogas Sludge mixed with Shredded Palm empty fruit bunches and Decanter cake. Songklanakarin J Sci Technol 36.3:275–281. Academic Search Premier. Web. 13 Dec. 2015

O'Brien SL (2016) Spatial scale drives patterns in soil bacterial diversity. Environ Microbiol 18:2039–2051

Oldroyd GED (2013) Speak, friend, and enter: signalling systems that promote beneficial symbiotic associations in plants. Nat Rev Microbiol 11:252–263. https://doi.org/10.1038/nrmicro2990

Oliverio AM, Bradford MA, Fierer N (2017) Identifying the microbial taxa that consistently respond to soil warming across time and space. Glob Change Biol 23:2117–2129

Ortiz-Hernández ML, Sánchez-Salinas E, Dantán-González E, Castrejón- Godínez ML (2013) Pesticide biodegradation: mechanisms, genetics and strategies to enhance the process. Biodegradation-life science. Intech-publishing, Rijeka, pp 251–287

Pandey J, Singh A (2012) Opportunities and constraints in organic farming: an Indian perspective. J Sci Res 56:47–72

Peng S, Biswas JC, LadhaJ K, Gyaneshwar P, Chen Y (2002) Influence of rhizobial inoculation on photosynthesis and grain yield of rice. Agron J 94(4):925–929

Peng G, Yuan Q, Li H, Zhang W, Tan Z (2008) Rhizobium oryzae sp. nov., isolated from the wild rice Oryza alta. Int J Syst Evol Microbiol 58:2158–2163

Pereg L, McMillan M (2015) Scoping the potential uses of beneficial microorganisms for increasing productivity in cotton cropping systems. Soil Biol Biochem 80:349–358

Pertot I, Alabouvette C, Hinarejos Esteve E, Franca S (2016) Focus group Soil-Borne Diseases mini-paper – the use of microbial biocontrol agents against soil - borne diseases. Agric Innov 117:11

Pett-Ridge J, Firestone MK (2005) Redox fluctuation structures microbial communities in a wet tropical soil. Appl Environ Microbiol 71:6998–7007

Philippot L, Raaijmakers JM, Lemanceau P, van der Putten WH (2013) Going back to the roots: the microbial ecology of the rhizosphere. Nat Rev Microbiol 11:789–799

Radzki W, Manero FG, Algar E, García JL, García-Villaraco A, Solano BR (2013) Bacterial siderophores efficiently provide iron to iron starved tomato plants in hydroponics culture. Antonie Van Leeuwenhoek 104(3):321–330

Ramakrishnan B, Megharaj M, Venkateswarlu K, Sethunathan N, Naidu R (2011) Mixtures of environmental pollutants: effects on microorganisms and their activities in soils. In: Reviews of environmental contamination and toxicology, vol 211. Springer, New York, pp 63–120

Rascovan N, Carbonetto B, Perrig D, Díaz M, Canciani W, Abalo M (2016) Integrated analysis of root microbiomes of soybean and wheat from agricultural fields. Sci Rep 6:28084

Rashid MH, Schafer H, Gonzalez J, Wink M (2012) Genetic diversity of rhizobia nodulating lentil (Lens culinaris) in Bangladesh. Syst Appl Microbiol 35:98–109

Rashid A, Bhat RA, Qadri H, Mehmood MA (2019) Environmental and socioeconomic factors induced blood lead in children: an investigation from Kashmir, India. Environ Monit Assess 191(2):76. https://doi.org/10.1007/s10661-019-7220-y

Rasmann S, Turlings TCJ (2016) Root signals that mediate mutualistic interactions in the rhizosphere. Curr Opin Plant Biol 32:62–68. https://doi.org/10.1016/j.pbi.2016.06.017

Reinhold-Hurek B, Bünger W, Burbano CS, Sabale M, Hurek T (2015) Roots shaping their microbiome: global hotspots for microbial activity. Annu Rev Phytopathol 53:403–424

Revillas JJ, Rodelas B, Pozo C, Martinez-Toledo MV, Gonzalez LJ (2000) Production of B-group vitamins by two Azotobacter strains with phenolic compounds as sole carbon source under diazotrophic and adiazotrophic conditions. J Appl Microbiol 89:486–493

Richardson AE (2001) Prospects for using soil microorganisms to improve the acquisition of phosphorus by plants. Aust J Plant Physiol 28:897–906

Rillig MC, Wright SF, Eviner VT (2002) The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: comparing effects of five plant species. Plant Soil 238:325–333

Rudrappa T, Czymmek KJ, Paré PW, Bais HP (2008) Root-secreted malic acid recruits beneficial soil bacteria. Plant Physiol 148:1547–1556

Ryan MH, Graham JH (2002) Is there a role for arbuscular mycorrhizal fungi in production agriculture? Plant Soil 244:263–271

Saha M, Sarkar S, Sarkar B, Sharma BK, Bhattacharjee S, Tribedi P (2016) Microbial siderophores and their potential applications: a review. Environ Sci Pollut Res 23(5):3984–3999

Sahoo RK, Ansari MW, Dangar TK, Mohanty S, Tuteja N (2013a) Phenotypic and molecular characterization of efficient nitrogen fixing Azotobacter strains of the rice fields. Protoplasma. https://doi.org/10.1007/s00709-013-0547-2

Sahoo RK, Bhardwaj D, Tuteja N (2013b) Biofertilizers: a sustainable eco-friendly agricultural approach to crop improvement. In: Tuteja N, Gill SS (eds) Plant acclimation to environmental stress. Springer Science plus Business Media, New York, pp 403–432

Sahoo RK, Ansari MW, Pradhan M, Dangar TK, Mohanty S, Tuteja N (2014) Phenotypic and molecular characterization of efficient native Azospirillum strains from rice fields for crop improvement. Protoplasma. https://doi.org/10.1007/s00709-013-0607-7

Sahu PK, Brahmaprakash GP (2016) Formulations of biofertilizers approaches and advances. In: Microbial inoculants in sustainable agricultural productivity. Springer India, New Delhi, pp 179–198

Saikia SP, Bora D, Goswami A, Mudoi KD, Gogoi A (2013) A review on the role of Azospirillum in the yield improvement of non-leguminous crops. Afr J Microbiol Res 6:1085–1102

Samad A, Trognitz F, Compant S, Antonielli L, Sessitsch A (2017) Shared and host specific microbiome diversity and functioning of grapevine and accompanying weed plants. Environ Microbiol 19:1407–1424

Santhanam R, van Luu T, Weinhold A, Goldberg J, Oh Y, Baldwin IT (2015) Native root-associated bacteria rescue a plant from a sudden-wilt disease that emerged during continuous cropping. Proc Natl Acad Sci U S A 112:E5013–E5020

Santos VB, Araujo SF, Leite LF (2012) Soil microbial biomass and organic matter fractions during transition from conventional to organic farming systems. Geodderma 170:227–231

Sasse J, Martinoia E, Northen T (2018) Feed your friends: do plant exudates shape the root microbiome? Trends Plant Sci. https://doi.org/10.1016/j.tplants.2017.09.003

Schlatter D, Kinkel L, Thomashow L, Weller D, Paulitz T (2017) Disease suppressive soils: new insights from the soil microbiome. Phytopathology 107:1284–1297

Serna-Chavez HM, Fierer N, van Bodegom PM (2013) Global drivers and patterns of microbial abundance in soil. Global Ecol Biogeog 22:1162–1172

Shahaby AF, Alharthi AA, El Tarras AE (2016) Screening of natural bacterial flora of pomegranate roots (*Punica granatum L.)* and their antibiotic activity in Taif, Saudi Arabia. Int J Curr Microbiol App Sci 5(2):1–6

Shaheen S, Sundari KS (2013) Exploring the applicability of PGPR to remediate residual organophosphate and carbamate pesticides used in agriculture fields. Int J Agric Food Sci Technol 4(10):947–954

Sharma P, Sardana V, Kandola SS (2011) Response of groundnut (Arachis hypogaea L.) to Rhizobium inoculation. Libyan Agric Res Centre J Int 2:101–104

Sharma S, Gupta R, Dugar G, Srivastava AK (2012) Impact of application of biofertilizers on soil structure and resident microbial community structure and function. In: Bacteria in agrobiology: plant probiotics. Springer, Berlin/Heidelberg, pp 65–77

Sheoran V, Sheoran AS, Poonia P (2010) Soil reclamation of abandoned mine land by revegetation: a review. Int J Soil Sediment Water 3(2):13

Shinwari KI, Shah AU, Afridi MI, Zeeshan M, Hussain H, Hussain J, Ahmad O (2015) Application of plant growth promoting rhizobacteria in bioremediation of heavy metal polluted soil. Asian J Multidiscip Stud 3(4):179

Shukla, Livleen (2015) Economically viable mass production of Lignocellulolytic Fungal inoculum for rapid degradation of agrowaste. Curr Sci (00113891) 107.10 (2014):1701–1704. Academic Search Premier. Web. 13 Dec. 2015

Singh I, Giri B (2017) Arbuscular mycorrhiza mediated control of plant pathogens. In: Mycorrhiza–nutrient uptake, biocontrol, ecorestoration. Springer, Cham, pp 131–160

Singh JS, Pandey VC, Singh DP (2011) Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. Agric Ecosyst Environ 140:339–353

Singh RP, Shelke GM, Kumar A, Jha PN (2015) Biochemistry and genetics of ACC deaminase: a weapon to “stress ethylene” produced in plants. Front Microbiol 6:1255

Singh DP, Singh HB, Prabha R (2016) Microbial inoculants in sustainable agricultural productivity. Springer, New York

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Singleton P, Keyser H, Sande E (2002) Development and evaluation of liquid inoculants. Inoculants and nitrogen fixation of legumes in Vietnam. Australian Centre for International Agricultural Research, Canberra, pp 52–66

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Sprent JI, Parsons R (2000) Nitrogen fixation in legume and non-legume trees. Field Crops Res 65:183–196

Stephens JHG, Rask HM (2000) Inoculant production and formulation. Field Crops Res 65:249–258

Sul WJ (2013) Tropical agricultural land management influences on soil microbial communities through its effect on soil organic carbon. Soil Biol Biochem 65:33–38

Sundara B, Natarajan V, Hari K (2002) Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugar cane and sugar yields. Field Crops Res 77:43–49

Swapna AL (2013) Development of biofertilizers and its future perspective. J Pharm 4:327–332

Thakur P, Singh I (2018) Biocontrol of soilborne root pathogens: an overview. In: Root biology, soil biology. Springer, pp 181–220. https://doi.org/10.1007/978-3-319-75910-4_7

Thamer S, Schädler M, Bonte D, Ballhorn DJ (2011) Dual benefit from a belowground symbiosis: nitrogen fixing rhizobia promote growth and defense against a specialist herbivore in a cyanogenic plant. Plant Soil 34:1209–1219

Thomas L, Singh I (2019) Microbial biofertilizers: types and applications

Trivedi P, Delgado-Baquerizo M, Trivedi C, Hamonts K, Anderson IC, Singh BK (2017) Keystone microbial taxa regulate the invasion of a fungal pathogen in agroecosystems. Soil Biol Biochem 111:10–14

United Nations (2013) World population prospects: the 2012 revision, highlights and advance tables. Working paper no. ESA/P/WP. 228. http://www.un.org/en/development/desa/population. Accessed 22 Apr 2016

Unkovich MJ, Pate JS (2000) An appraisal of recent field measurements of symbiotic N2 fixation by annual legumes. Field Crops Res 65:211–228

Vandenkoornhuyse et al (2015) The importance of the microbiome of the plant holobiont. New Phytol 206:1196–1206. https://doi.org/10.1111/nph.13312

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Vorholt JA (2012) Microbial life in the phyllosphere. Nat Rev Microbiol 10:828–840

Walker TS, Bais HP, Grotewold E, Vivanco JM (2003) Root exudation and rhizosphere biology. Plant Physiol 132(1):44–51

Wall LG (2000) The actinorhizal symbiosis. J Plant Growth Regul 19:167–182

Wani SA, Chand S, Ali T (2013) Potential use of Azotobacter chroococcum in crop production: an overview. Curr Agric Resour J 1(1):35–38

Weekley J, Gabbard J, Nowak J (2012) Micro-level management of agricultural inputs: emerging approaches. Agronomy 2(4):321–357

Weston LA, Mathesius U (2013) Flavonoids: their structure, biosynthesis and role in the rhizosphere, including allelopathy. J Chem Ecol 39:283–297

Weston LA, Ryan PR, Watt M (2012) Mechanisms for cellular transport and release of allelochemicals from plant roots into the rhizosphere. J Exp Bot 63:3445

Wuana RA, Okieimen FE (2011) Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecol 2011:20

Youssef MM, Eissa MF (2014) Biofertilizers and their role in management of plant parasitic nematodes. A review. E3 J Biotechnol Pharm Res 5(1):1–6

Zheng XY, Sinclair JB (1996) Chemotactic response of Bacillus megaterium strain B153-2-2 to soybean root and seed exudates. Physiol Mol Plant Pathol 48:21–35. https://doi.org/10.1006/pmpp.1996.0003

Chapter 11
Fungi and Their Potential as Biofertilizers

Irfan-ur-Rauf Tak, Gowhar Hamid Dar, and Rouf Ahmad Bhat

11.1 Introduction

Fungi which include about 144,000 known species belong to the kingdom Fungi and include yeasts, nuts, smuts, mildews, mushrooms, and molds. Besides this, there are many other fungus-like organisms that include slime molds and oomycetes which normally are not included in the kingdom Fungi but are often called as fungi. These fungus-like organisms are included in the kingdom Chromista (Park et al. 2005; Pereira et al. 2007; Shenoy et al. 2007). It is a known fact that fungi are among the most widely distributed organisms that are present on earth and also are of great environmental as well as medical importance. Fungi are mainly free-living in soil and water, and also some other form parasitic as well as symbiotic relationships with plants and animals (Dar et al. 2013, 2020; Mehmood et al. 2019). The cells of fungi contain membrane-bound organelles besides well-defined nuclei, that is, they are eukaryotic organisms (Khanday et al. 2016; Rashid et al. 2019; Soares and Barreto 2008; Than et al. 2008a, b). Fungi are different from all other living organisms including animals because of their principal modes of vegetative growth as well as the phenomenon of their nutrient intake. In addition, they were historically included in the kingdom Fungi, but because they lack chlorophyll and the area is also different because of their unique physiological and structural features, they were separated from plants. Fungi are also unique because they grow from the tips

---

I. Tak (✉)
Department of Zoology, S.P. College, Cluster University Srinagar, Jammu and Kashmir, India

G. H. Dar
Department of Environmental Science, Sri Pratap College, Cluster University Srinagar, Higher Education Department, Jammu and Kashmir, India

R. A. Bhat
Division of Environmental Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_11

of their filaments (hyphae) that are responsible for making up the bodies of the organisms (mycelia), and they have the characteristic of digesting the organic matter externally before absorbing that organic matter into their mycelia.

Fungi are ubiquitous with some of them having beneficial effects on plants, while some may also be detrimental (Anderson and Cairney 2004; Bhat et al. 2017a; Ipsilantis and Sylvia 2007). It has been observed that a constant decrease in the yield of crops which occurs as a result of plant disease and for which the causative agent is a pathogen is considered as a negative effect. A few fungi are found to be the main pathogens which are responsible for plant diseases and also are responsible for very high yield losses (Park et al. 2005; Pereira et al. 2007; Shenoy et al. 2007; Soares and Barreto 2008; Than et al. 2008a, b). During the recent years, there have been many ways in order to reduce yield losses which are caused by the fungal disease, which include the application of chemical fungicides that is considered at present the most common method (Rosslenbroich and Stuebler 2000; Sofi et al. 2017; Than et al. 2008a). It has however been seen that chemical fungicides have a negative effect on both the human health and environment (Bhat et al. 2018a; Bhatti et al. 2017; Calhelha et al. 2006; Gavrilescua and Chisti 2005; Haggag and Mohamed 2007; Soytong et al. 2005; Voorrips et al. 2004). Development of resistance in plant pathogenic fungi has also been observed because of the application of chemical fungicides over a long period of time (Agrios 2005; Benítez et al. 2004; Kim and Hwang 2007). The chemical fungicides become ineffective when this happens, and in that case the use of other fungicides should be undertaken for effective disease control. A potentially effective alternative method is the use of microorganisms as the potential biological control agents in order to control the plant diseases (Alabouvette et al. 2006; Bhat et al. 2017a, b; Emmert and Handelsman 1999; Kulkarni et al. 2007; Mitchell et al. 2008; Raghukumar 2008; Tejesvi et al. 2007).

During the last 30 years, microorganisms have been characterized as well as tested for being used as biological control agents against the diseases that are caused by soilborne soil pathogens. During the recent past, plant diseases have been controlled by using biological control agents and more importantly antagonistic fungi with more than 90% of their application being formulated using various strains of *Trichoderma* which includes *T. harzianum*, *T. virens*, and *T. viride* (Benítez et al. 2004). A number of species have also been found to be antagonistic against various soil microorganisms which include many species of *Chaetomium*, e.g., *C. globosum*, *C. cupreum*, and *C. cochlioides* (Kanokmedhakul et al. 2002, 2006; Soytong et al. 2001). Besides this, a number of biocontrol agents have been developed and have been used commercially as mycofungicide products (Benítez et al. 2004; Fravel 2005; Kim and Hwang 2004). The USA and France are considered to be the two main biofungicide users, although it has been seen that many other countries are also promoting biocontrol of agents because of bans that has been put on synthetic chemical pesticide residues that they have on agricultural products (Ecobichon 2001; Mushtaq et al. 2018; Ricard and Ricard 1997; Spadaro and Gullino 2005; Wesseling et al. 2005). It has been observed that in the early stages of mycofungicide development, there is a collection of fungal isolates and that there is screening of these mycofungicides for the purpose of identifying the effective strains that are helpful against target plant pathogens both in the greenhouse and laboratory and also in the field. Along these lines, it has been seen that the most important consideration in their mass production is given to the compatibility of the product with regard to both the formulation and their application techniques (Jenkins et al. 1998; Khetan 2001).

Another and a very effective alternative way in order to increase the crop yield in addition to using chemical fertilizers is the use of biofertilizers. These are the substances that are found to contain living microbes which were when applied to seed or soil or plants were found to help in promoting the growth through the supply of very essential nutrients which include nitrogen, phosphorous, and other important mineral nutrients. Besides this, they are also helpful in promoting increased absorption of essential nutrients in plants (Chen 2006; Hart and Trevors 2005; Vessey 2003). Biofertilizers mainly include substances that are obtained from living organisms and also from microbial sources (Chen 2006; Rola 2000). Biofertilizers are also known to have various other benefits, which mainly include helping plants in increasing their access to nutrients, providing them growth-promoting factors, and besides this they are also very useful in composting and efficient recycling of solid wastes (Das et al. 2007; Gaur and Adholeya 2004). Microbial inoculants are the common name of biofertilizers and are normally produced from cultures of some soil organisms which help in the improvement of soil fertility and also crop productivity such as mycorrhizae (Dervash et al. 2020; Malik et al. 2005; Marin 2006). Mycorrhizae which normally forms mutualistic relationships with roots of plants and help to improve the absorption of nutrients and water. Besides, it helps in controlling plant diseases and also help in the improvement of soil structure (Chandanie et al. 2006; Das et al. 2007; Gaur and Adholeya 2004; Rinaldi et al. 2008; Rola 2000; Zhao et al. 2003). It has also been observed that plants which are colonized by mycorrhizae are found to grow better than those which are colonized without them and also have been found to be beneficial in natural as well as agricultural systems (Adholeya et al. 2005; Marin 2006; Singh et al. 2008; Yeasmin et al. 2007).

11.2 Role of Microbial Technology in Sustainable Agriculture

Biofertilizers are usually microbial inoculants which are normally considered as a preparation that contain live and dormant cells of usually very effective strains of nitrogen-fixing, P-solubilizing, and other cellulolytic microorganisms. When we compare them with chemical fertilizers, they are normally considered as viable microorganisms which usually are not considered to be a source of nutrients but instead help plants in accessing the nutrients that are available in the rhizospheric region. In the recent years, many microorganisms are used as biofertilizers which include nitrogen-fixing soil bacteria, e.g., *Azotobacter* and *Rhizobium*; also nitrogen-fixing cyanobacteria, e.g., *Anabaena*; P-solubilizing bacteria, e.g., *Pseudomonas* sp.; and AM fungi. Besides this, several other phytohormone-producing bacteria and cellulolytic microorganisms are also used as biofertilizers. These formulations of microbes are normally used in order to enhance different microbial process so as to make the nutrients available in a form that can easily be assimilated by plant. Biofertilizers are normally considered as a source of nutrients that are of low cost and are also renewable.

Biofertilizers during the recent past have been seen to have gained momentum because of their advantages such as they help in maintaining the soil health and also bring down the environmental pollution by making use of different chemicals in the agriculture (Dar et al. 2016; Dar and Bhat 2020; Muraleedharan et al. 2010). For proper growth of plants, it is necessary that they should be provided essential nutrients in sufficient quantities, but it has been seen that only a small portion of nutrients are released from the soil every year through various biological and chemical processes. Besides this, it is the type of fertilizer used that determines the crop yield which is basically used to enhance the essential nutrients that are important for normal plant growth and development (Rinaldi et al. 2008; Rola 2000; Zhao et al. 2003). It is therefore natural that the main use of fertilizers is to basically supplement the nutrients that are already present in the soil. In addition to the nutrient supplementation, it has been seen that biofertilizers have various other important benefits which mainly include controlling the soilborne diseases and helping the improvement of soil health which ultimately results in higher yield rates. During the recent past, a number of commercial biofertilizers have been found to be available in diverse formulations, and in this regard various strategies have been employed in order to make sure that there is maximum viability of the microorganisms that is used in such formulations. The various strategies include application of biofertilizers in the liquid form, the necessary optimization of their formulations, and also the use of thermotolerant and genetically modified strains. In the production of biofertilizers, different types of microorganisms and their associations with various crop plants are being exploited, and in this regard, they are grouped in different ways which mainly depend on their nature and function (Das et al. 2007; Gaur and Adholeya 2004).

Mycorrhiza is an association of fungus with the roots of higher plants, and in spite of being a mystery, it has been found to be helpful in serving as a model system that has helped to understand the mechanism that occurs as result of mycorrhizal inhabitation which ultimately leads to the stimulation of growth in the root cells (Malik et al. 2005; Marin 2006). Mycorrhiza has been found to secrete bioactive ligands like Myc factors and Nod factors which are then perceived by host roots in order to trigger the signal transduction pathway which in turn initiates other signal transduction pathways which ultimately have been seen to trigger release of Ca^{2+} in the cytosol through some unknown receptors. It has been found that DM1 proteins play an essential role in helping to maintain the periodic oscillation of calcium ions which occurs inside and outside of the nucleus, while nuclear pore complex and some other proteins like NUP have been found to play a very important role in calcium spiking. Besides this, Ca^{2+} channel proteins have been seen to facilitate this process with the help of various transporters.

11.3 Sustainable Production Through Biotechnological Tools

If we see in a strict sense, biofertilizers are not considered as fertilizers but instead are used for crop plants in order to supply nitrogen to them. The most commonly used biofertilizers among microorganisms are bacteria, fungi, and blue-green algae as these are added to the rhizosphere of plant in order to enhance their activity in the soil (Chen 2006; Hart and Trevors 2005; Vessey 2003). These microorganisms indirectly help the plants by helping them in enhanced nitrogen fixation and also increasing the nutrient availability in the soil, and besides this, it has been seen that they can be applied alone or in combination when it comes to observing their mode of action. Systematic research has made it possible to identify the efficient cultures which are then able to grow in particular soil and climatic conditions.

For the purpose of distributing these cultures to farmers, they are prepared at large scale in the laboratory, and for increasing their shelf life, they are packed in peat and lignite powder. Biofertilizers during the recent past have gained tremendous momentum, and as already known that only small part of the nutrients are released from soil every year through biological and chemical processes, it therefore becomes necessary to make use of the fertilizers in order to supplement the nutrients that are already present in the soil (Bhat et al. 2018a, b; Chen 2006). In accelerating the microbial processes which mainly include controlling soilborne diseases and improving the soil health, microorganisms of biofertilizers have been found to play a very important role. For realizing the ultimate goal of the farmers which is the goal of increasing crop productivity, biofertilizers have been found to provide an economically feasible option as these are of low cost and are also considered to be renewable sources of plant nutrients which overall help in supplementing the chemical fertilizers.

11.4 Fungi and Sustainable Agriculture

Biofertilizers are considered to be eco-friendly as well as inexpensive besides also being an important source of nutrients for plants. They are also important in increasing the soil fertility and playing a very important role in the improvement of soil nutrient status which ultimately leads to increased crop productivity (Adholeya et al. 2005; Marin 2006; Pal and Gardener 2006; Singh et al. 2020). When applied in a natural field system whether alone or in combination, fungal biofertilizers are known to cause a very important beneficial impact on the development of plants besides having impact on its growth as well as yield (Gentili and Jumpponen 2006). Differences in plant roots among diffrenet plant groups which include herbs, shrubs, and other terrestrial plants normally grow in natural conditions but have been found to develop various types of mycorrhizal associations when they are grown in conditions that are found to have low bioavailability of necessary essential elements that mainly include phosphorous, zinc, iron, and copper (Zhu et al. 2008).

Among the various types of fungal biofertilizers, P-solubilizing biofertilizers are the most commonly employed as biological agents in order to improve plant growth and also help in its development besides helping in phosphorous uptake in plants. It has been seen that fungi possess a property of phosphate solubilization which mainly contributes to the availability of phosphates that are present in the soil to the plants (Zhu et al. 2008). Seven P-solubilizing fungi have been found from Teff rhizosphere soil which have been found to enhance the phosphate availability to plants, and besides this, it has been found that fungi which belong to *Aspergillus* genera have also been found to be reported from the rhizospheric region of various plants (Gizaw et al. 2017). The most commonly employed fungi that is used for biofertilizer production is *Trichoderma* that is usually found in agricultural soils. The rhizospheres which are inhabited by *Trichoderma* sp. have been seen to interact and also parasitize other fungi, and these have also been recognized because of their ability to enhance the plant productivity by helping the plants to enhance their crop nutrition as well as nutrient acquisition (Chang et al. 1986; Harman 2000; Lindsey and Baker 1967; Vinale et al. 2008; Yedidia et al. 2001). Inoculation of soil with *Trichoderma* sp. and their subsequent utilization as a culture filtrate have been seen to increase plant growth, and as far as its ease of cultivation under laboratory conditions is concerned, it has been seen that this species of fungus can act as model organism not only for its good benefits with regard to plant microbe interaction but also it has been seen that it can act as a good and enhanced tool for increasing the plant productivity (Varma et al. 1999).

As far as the biological properties of the yeast are concerned, its application as biofertilizer has recently gained tremendous interest, and also it is safe to both humans as well as the natural environment (Agamy et al. 2013). Keeping this thing in mind, it has been seen that *Saccharomyces cerevisiae* which is also called as Brewer's yeast has been considerably used as a biofertilizer. The use of yeasts either live or dead has been found to increase the availability of nitrogen and phosphorous to the roots of sugarcane plants. This yeast has been found to be less expensive biological fertilizer because it increases or enhances the plant nutrient status and also the potential of plants and therefore helps in the overall nutrient uptake as well as the growth of plants (Lonhienne et al. 2014). During the recent past, the use of microbially synthesized indole acetic acid which is a type of phytohormone in plant microbe interactions has gained tremendous importance (Singh et al. 2008). Among the bacteria (Idris et al. 2007; Radhakrishnan et al. 2013; Sachdev et al. 2009), fungi and yeasts which are found to be capable of IAA synthesis have been seen to promote plant growth and therefore have been recommended for their use as biofertilizers (Ahmad et al. 2008; El-Tarabily 2004; Sasikala and Ramana 1997; Waqas et al. 2012). It was seen that under laboratory conditions, the synthesis of IAA by yeast was under the control of changes in temperature and pH of the medium (El-Tarabily 2004; Sasikala and Ramana 1997). It has been observed that most of the plant species have mutualistic association with arbuscular mycorrhizal fungi (AMF), and it was seen that complete or partial degeneration of activity of AMF in the soil can cause tremendous changes in the properties of the soil which helped in the overall increase in the agricultural production (Varma et al. 2012). It was observed that AMF helps in conferring resistance to plants against different types of pathogens and heavy metals besides helping them in combating environmental stress and also facilitating the growth of plants by alleviating the bad effects of disease-causing factors. Above all, the AMF interaction helps the plants by reducing the chances of development of disease that is caused by different phytopathogens (Ene and Mioara 2008; Hildebrandt et al. 2007).

11.5 Ectomycorrhiza as Potential Biofertilizers

It has been observed that there is a history of technique development regarding the incorporation of ectomycorrhizal fungal inoculation into various nursery plantation practices (Mikola 1969, 1970; White 1941; Wilde 1944) and in this regard, the importance of EM symbiosis which was found to be helpful for normal growth of trees and nutrient acquisition which was already proposed by Frank (1885). It was long observed that tree plantations will not be successful until and unless endemic or inoculated EM fungi were available on site, and in this regard the proper selection was largely based on enhancement of tree crop and their application for a very large-scale inoculum practices (Smith and Read 1997). Although various alternatives have been used and surveyed, the most widespread inoculum programs have been developed for *Pisolithus tinctorius*. The advantages for the use of *P. tinctorius* included its wide host range and extensive geographic distribution, as well as its occurrence on sites burdened by recent disturbance, drought, high temperatures, and/or chemical contaminants. *P. tinctorius* inoculum can be produced and applied as vegetative mycelium in a peat vermiculite carrier. The nutrient solution, which is necessary for the vegetative growth of *P. tinctorius* throughout the substrate, will also facilitate the competitive exclusion of other root-colonizing fungi (Smith and Read 1997). Various alternative techniques and formulations for inoculation have been developed (Marx and Kenney 1982; Marx et al. 1984). Although liquid or spore suspension techniques would avoid the problems resulting from bulky solid inoculum production and storage, they often suffer from delayed EM establishment or mycelial fragmentation and shredding.

Inoculation programs with EM fungi have had some success. However, as with AM or bacterial inoculum applications, there seems to be no single fungal species or strain that could be universally applied across different sites and host species. When compared to local strains and species in the north-western USA, the *P. tinctorius* strain that had proven extremely favorable for seedling growth and establishment elsewhere seemed less beneficial (Perry et al. 1987). In many cases, the strains that easily colonize seedlings in the nurseries and are easy to manipulate have only limited positive effects on the performance of the planted seedlings (Jackson et al. 1995; le Tacon et al. 1992; Perry et al. 1987). The limited success of the fungi, which have been selected for the inoculation programs, may be simply due to the ubiquitous presence of endemic mycorrhizal fungi in reforested sites and the competitive exclusion of the nursery-inoculated fungi in the field.

Accordingly, the inoculation with EM fungi may be most important on sites with poor reforestation history or on plantations, which will be established on previously non-forested sites. In the research focusing on the development of the forest nursery inoculation programs, one issue that has received relatively little attention is the impact that imported and possibly invasive EM fungi have on the endemic fungi and their community composition. The inoculated fungi may persist in the root systems for extended periods of time and outcompete less invasive endemic strains and species (de la Bastide et al. 1994). Although no direct evidence for such competitive exclusion currently exists, introductions may homogenize local fungal populations and communities.

11.6 Potential of Mycorrhiza as Biofertilizer

AM fungi are microorganisms which are symbiotic in nature as they are not able to grow on synthetic media without the host plant (Hart and Trevors 2005). It is therefore necessary that these fungal inocula must be produced with the host plants though their association, and it has been observed that there are a number of constraints when it comes to their large-scale commercial production. They are produced on a large scale with the process of pot culture either in greenhouse or through growth chambers (Bagyaraj et al. 2002; Gentili and Jumpponen 2006; Kapoor et al. 2008; Marin 2006; Raja 2006). When it comes to their preparation, it is through the process of multiplication of the selected fungi in the roots of susceptible host plants that are grown in the sterilized soil or substrates (Naqvi and Mukerji 2000). Its spores and hyphae have been seen that they can be isolated from the rhizosphere of the soil and then later mixed with carrier substrates, and when it comes to the inocula of AM fungi, it has been seen that it can be applied as spores as well as fragments of colonized roots (Gentili and Jumpponen 2006). It has been found that the spore inocula are resistant and have been seen to withstand unfavorable environmental conditions and also has been observed that they are able to colonize new root systems more slowly than other preparations. It is because of this reason that both inocula and the spores fragments of colonized roots are combined when it comes to their commercial production (Marin 2006).

For the production of fungal biofertilizers on a commercial level, some important steps are essential, and they include first the selection and then the large-scale production. After this, there is the selection of the carrier and its preparation which is followed by mixing and curing. Finally there is the proper maintenance of desired number of inocula which is then followed ultimately by strong quality control (Malik et al. 2005). It has been kept in mind that the criteria which are being employed for the selection of AM fungi will mainly depend on the local environment and the condition of soil and host plants of that area. For obtaining better results, the AM fungi must be able to colonize the roots rapidly soon after the inoculation and should also be in a position to absorb phosphates from the soil. Besides this, it should also be able to transfer phosphorous to the plants and help in increasing the plant growth. Finally it should be able to persist in the soil and should also be able to re-establish the mycorrhizal symbiosis during the subsequent seasons besides forming propagules that would remain viable during and also after the production of inocula (Tanu et al. 2012).

During the recent years, commercially producing the mycorrhizal inocula has evolved very quickly, and it has also been found that there are different types of microbial cultures as well as inoculants that are today available in the market and have rapidly increased because of the tremendous advances in the field of biotechnology (Douds et al. 2000; Raja 2006). There are currently more than 30 companies that are present throughout the world that are involved in the marketing of mycorrhizal products, and among these, some have been found to be composed of one or more than one mycorrhizal fungal inoculum. The products are found to be promoters of plant growth and are utilized in mainly agriculture and forestry (Schwartz et al. 2006).

11.7 Some Other Potential Biological Biofertilizers

Recently several fungal biofertilizers have been used in order to increase the growth of plants, and these mainly include *Penicillium* species. It has been seen that these species are mainly P-solubilizing microorganisms which have found to improve phosphorous absorption and also stimulate the growth in plants (Pradhan and Sukla 2005; Wakelin et al. 2004). It has been seen that *Penicillium bilaiae* when applied increases the dry matter, phosphorous uptake besides also increasing the seed yield in *Brassica napus* commonly known as canola and as a result it has been used as a commercial product which is named as Jumpstart. It was then released into the outside market in the form of a wettable powder in 1999 (Burton and Knight 2005; Grant et al. 2002). Besides this *P. radicum* and *P. italicum* have also been found to be P-solubilizing taxa (El-Azouni 2008; Wakelin et al. 2004; Whitelaw et al. 1999), and it has been seen that *P. radicum* when isolated from the rhizosphere of roots of wheat, has shown a good promise with regard to the plant growth promotion (Whitelaw et al. 1999). In the case of *P. italicum* isolated from rhizosphere soil and it's evaluation for the ability to solubilize tricalcium phosphate (TCP) has been found to promote the growth of soybean (El-Azouni 2008).

It has been reported that a number of species of *Aspergillus* are involved in the process of solubilization of inorganic phosphates which include *A. flavus* and *A. niger* (Akintokun et al. 2007). These have been found to solubilize the inorganic phosphates through the process of producing acids which mainly include citric and gluconic acid (Barroso et al. 2006). Also it has been reported that another species of *Aspergillus*, that is, *A. fumigates*, is normally isolated from compost and has been found to be a potassium-releasing fungus (Lian et al. 2008). Apart from this, a product of *Chaetomium* species has been found to be a fungal biofertilizer which mainly includes Ketomium which is mainly produced from *C. globosum* and C. *cupreum* and has been found to be not only a mycofungicide but has also been reported to be a growth stimulant because a number of plants which include tomato, corn, and pepper when treated with Ketomium have been reported to show a greater plant growth and also high yields as compared to the nontreated plants (Soytong et al. 2001).

11.8 Future of Fungal Biofertilizers

A number of reports are there which suggest the success with regard to the ability of the fungus to control plant diseases and to promote plant growth as biofertilizers. As far as the use of fungi as potential fungicides as well as biofertilizers, it has been found that most of them have been developed during the last two decades. Fungal biofertilizers along with mycofungicides have been found to help in minimizing the use of synthetic chemical fungicides as well as chemical fertilizers, and this has been reported to be very beneficial because these synthetic chemical compounds have probable disastrous effects on both humans and the environment (Calhelha et al. 2006; Haggag and Mohamed 2007). As compared to the chemical compounds, mycofungicides and chemical fertilizers are used on a very large scale, and as far as the development of fungal products is concerned, there has been a very little investment because it has been found that they have very poor effects in the field (Tang et al. 2001). However, it has been seen that there is a comparatively bigger gap between the unpublished research that is carried out in the laboratories and those which are developed for their use in the field. It is therefore necessary that the research should make it mandatory that the fungal products must have a suitable impact when it comes to their field applications and when they should remain in a stable form. Regarding this, the things that should be kept in mind are first making a note of strains of fungi that are used and also making it sure that they are cheap when it comes to their production on a large scale. It should also be kept in mind that they should not have detrimental effects on the environment and above all should be safe to both humans and the environment. To make it possible, there is need for communication between various agencies that mainly include researchers and industry especially during the early stages of the development.

In spite of the fact that there are numerous biocontrol products available, still many problems need to be overcome in order to achieve the successful commercialization of potential biocontrol products. It has been observed that some of the biocontrol agents have a greater efficacy when it comes to their application in the field as compared to their effects in the field (Tang et al. 2001). As far as the control of fungal diseases by biological means with the help of fungal antagonists is concerned, it continues to remain a challenge for further research (Spadaro and Gullino 2005). Keeping this thing in mind, a number of species of fungal antagonists have been developed and then subsequently registered as commercial products, and it has been seen that these products are used on a small scale because of their limited capacity to control plant diseases in the field (Paulitz and Belanger 2001; Tang et al. 2001). When it comes to the use of secondary metabolites, it has been observed that a number of biological control agents are able to produce these metabolites which have the capacity to control different plant diseases. It is because of this fact that secondary metabolites are developed as mycofungicides but should however be tested and should also be harmless to both humans and the environment. With the advances in the field of molecular genetics, the genetic studies of biocontrol agent strains have proven to be a powerful tool that has helped to increase the effectiveness of biological control activity and also the utilization of genetic potential of fungal antagonists (Haggag and Mohamed 2007; Irtwange 2006; Paterson 2006). Research should be carried out which would find the potential of fungal biofertilizers when it comes to their application in the soil as it has been seen that they help to increase the crop yield and also make the soil quality better (Tanu et al. 2012). When it comes to the advantages of fungal biofertilizers, it has been found that they have a number of advantages both in terms of nutrient supply and crop growth besides also being safe to the environment (Smith and Zhu 2001). It should be kept in mind with regard to the development of new strains of fungi that they should help in the improvement of nutrient uptake and should also be fast growing, and as far as their production on a large scale is concerned, the cost should be low (Marin 2006). The future research on the development of fungal biofertilizers should therefore be on the production of more stable strains with the help of traditional and molecular techniques (Tanu et al. 2012; Marin 2006).

11.9 Future Perspectives

Various fungi provide a battery of extracellular enzymes, which may be utilized for improved crop yields and reduced costs for inorganic fertilizers (Tang et al. 2001). The emphasis should be on the field trials that use multiple inoculations of different organisms, and besides this, it should be kept in mind that the combinations must be of tremendous value when it comes to using different organisms that have different benefits for the purpose of integrating them with the crop plants (Irtwange 2006; Paterson 2006). It has been observed through the integration of various microbial capabilities that have been integrated into combined biofertilizers, and it has been observed that they have tremendous potential when it comes to their yield promoting effect. It is most likely being made possible by approaching the application of biofertilizers besides keeping in mind their applications at a scale which is very much relevant to the current agricultural practices. In this direction, the first step is basically finding the suitable avenues and then at the second stage funding the desired collaboration that is between the research facilities and biotechnological industries. It is basically the large-scale production of inocula that is very much important for achieving the desired goals of research, and it has been observed that the connection that is present between the industries and research makes it possible for the inoculum production that is suitable for field trials (Paulitz and Belanger 2001; Tang et al. 2001). Finally the major emphasis should be on the establishment of international guidelines for the trade and production of inoculum, and in this direction, the end user of inocula should be protected, and efforts should be made for the safe choice of commercial inocula that is possible only through collaboration among different research facilities and farmers. It is because of such innovation that will allow a positive start for the production of commercially and economically viable biofertilizers which will be ready for marketing directly to the target consumers.

11.10 Conclusion

We can conclude by saying that using the fungi as biofertilizers will lead ultimately to the decrease in the occurrence of plant diseases which will be made possible only through preventing the growth and decreasing the inocula of pathogens. It will also emphasize on increase in the nutrient uptake from the soil and finally producing various economically important bioactive compounds and enzymes which will lead to better plant growth. These all will lead to increase in the crop production. Currently there are a number of commercial fungal biofertilizers that are present throughout the world, and using these offers an economically and environmentally favorable choice when compared to the use of chemical fertilizers. It has however been reported that there are still certain limitations while using these products which mainly is understood by the fact that their rate of success is determined by the environmental factors. Also the difficulties in their applications coupled with their limited shelf life and a very slow action have been a hurdle when compared to the chemicals and as a result can lead to farmers discouraging the use of these biofertilizers. It is because of these reasons that more research need to be done in order to produce more effective products that have both a rapid action and a larger shelf life.

References

Adholeya A, Tiwari P, Singh R (2005) Large scale inoculum production of arbuscular mycorrhizal fungi on root organs and inoculation strategies. In: Declerck S, Strullu D-G, Fortin A (eds) Soil biology, in vitro culture of mycorrhizae, vol 4. Springer-Verlag, Berlin Heidelberg, pp 315–338

Agamy R, Hashem M, Alamri S (2013) Effect of soil amendment with yeasts as bio-fertilizers on the growth and productivity of sugar beet. Afr J Agric Res 8:46–56

Agrios GN (2005) Plant pathology, 5th edn. Academic Press, San Diego, p 922

Ahmad F, Ahmad I, Khan MS (2008) Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. Microbiol Res 163:173–181

Akintokun AK, Akande GA, Akintokun PO, Popoola TOS, Babalola AO (2007) Solubilization on insoluble phosphate by organic acid-producing fungi isolated from Nigerian soil. Int J Soil Sci 2:301–307

Alabouvette C, Olivain C, Steinberg C (2006) Biological control of plant diseases: the European situation. Eur J Plant Pathol 114:329–341

Anderson CI, Cairney WGJ (2004) Diversity and ecology of soil fungal communities: increased understanding through the application of molecular techniques. Environ Microbiol 6: 69–779

Bagyaraj DJ, Mehrotra VS, Suresh CK (2002) Vesicular arbuscular mycorrhizal biofertilizer for tropical forest plants. In: Kannaiyan S (ed) Biotechnology of biofertilizers. Kluwer Academic Publishers, Boston, pp 299–311

Barroso CB, Pereira GT, Nahas E (2006) Solubilization of CAHPO4 and ALPO4 by *Aspergillus niger* in culture media with different carbon and nitrogen sources. Braz J Microbiol 37:434–438

Benítez T, Rincón MA, Limón MC, Codón CA (2004) Biocontrol mechanisms of *Trichoderma* strains. Int Microbiol 7:249–260

Bhat RA, Shafiq-ur-Rehman MM, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017a) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017b) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA (ed) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Mamta, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Burton EM, Knight SD (2005) Survival of *Penicillium bilaiae* inoculated on canola seed treated with Vitavax RS and Extender. Biol Fertil Soils 42:54–59

Calhelha RC, Andrade JV, Ferreira IC, Estevinho LM (2006) Toxicity effects of fungicide residues on the wine-producing process. Food Microbiol 23:393–398

Chandanie WA, Kubota M, Hyakumachi M (2006) Interactions between plant growth promoting fungi and arbuscular mycorrhizal fungus *Glomus mosseae* and induction of systemic resistance to anthracnose disease in cucumber. Plant Soil 286:209–217

Chang YC, Baker R, Kleifeld O, Chet I (1986) Increased growth of plants in the presence of the biological control agent T. harzianum. Plant Dis 70:145–148

Chen JH (2006) The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility. International workshop on sustained management of the soil-rhizosphere system for efficient crop production and fertilizer use. 16–20 October 2006, Land Development Department, Bangkok 10900 Thailand, pp 1–11

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish fauna. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 51–68

Das A, Prasad R, Srivastava A, Giang HP, Bhatnagar K, Varma A (2007) Fungal siderophores: structure, functions and regulation. In: Varma A, Chincholkar SB (eds) Soil biology volume 12 microbial siderophores. Springer-Verlag, Berlin Heidelberg, pp 1–42

de la Bastide PY, Kropp BR, Piché Y (1994) Spatial and temporal persistence of discrete genotypes of the ectomycorrhizal fungus *Laccaria bicolor* (Maire) Orton. New Phytol 127:547–556

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Douds DD, Gadkar JV, Adholeya A (2000) Mass production of VAM fungus biofertilizer. In: Mukerji KG, Singh J, Chamola BP (eds) Mycorrhizal biology. Kluwer Academic/Plenum Publishers, New York, pp 197–214

Ecobichon DJ (2001) Pesticide use in developing countries. Toxicology 160:27–33

El-Azouni IM (2008) Effect of phosphate solubilising fungi on growth and nutrient uptake of soybean (Glycine Max L.) plants. J Appl Sci Res 4:592–598

El-Tarabily KA (2004) Suppression of *Rhizoctonia solani* diseases of sugar beet by antagonistic and plant growth-promoting yeasts. J Appl Microbiol 96:69–75

Emmert EAB, Handelsman J (1999) Biocontrol of plant disease: a (Gram-) positive perspective. Microbiol Lett 171:1–9

Ene M, Mioara A (2008) Microscopical examination of plant reaction in case of infection with *Trichoderma* and Mycorrhizal fungi. Rom Biotechnol Lett 13:13–19

Frank AB (1885) Ueber den gegenwärtigen Stand der Trüffelfrage und die damit zusammenhängende Ernährung gewisser Bäume durch Wurzelpilze. Gart Ztg 4:423–426

Fravel RD (2005) Commercialization and implementation of biocontrol. Annu Rev Phytopathol 43:337–359

Gaur A, Adholeya A (2004) Prospects of arbuscular mycorrhizal fungi in phytoremediation of heavy metal contaminated soils. Curr Sci 86:528–534

Gavrilescua M, Chisti Y (2005) Biotechnology-a sustainable alternative for chemical industry. Biotechnol Adv 23:471–499

Gentili F, Jumpponen A (2006) Potential and possible uses of bacterial and fungal biofertilizers. In: Rai MK (ed) Handbook of microbial biofertilizers. Food Products Press, New York, pp 1–28

Gizaw B, Tsegay Z, Tefera G, Aynalem E, Wassie M, Abatneh E (2017) Phosphate solubilizing fungi isolated and characterized from Teff rhizosphere soil collected from North Showa zone, Ethiopia. Afr J Microbiol Res 11:687–696

Grant CA, Bailey LD, Harapiak JT, Flore NA (2002) Effect of phosphate source, rate and cadmium content and use of *Penicillium bilaii* on phosphorus, zinc and cadmium concentration in durum wheat grain. J Sci Food Agric 82:301–308

Haggag WM, Mohamed HAA (2007) Biotechnological aspects of microorganisms used in plant biological control. Am Eurasian J Sustainable Agric 1:7–12

Harman GE (2000) Myths and dogmas of biocontrol: changes in perception derived from research on *Trichoderma harzianum* T-22. Plant Dis 84:377–393

Hart MM, Trevors JT (2005) Microbe management: application of mycorrhizal fungi in sustainable agriculture. Front Ecol Environ 3:533–539

Hildebrandt U, Regvar M, Bothe H (2007) Arbuscular mycorrhiza and heavy metal tolerance. Phytochemistry 68:139–146

Idris EES, Iglesias DJ, Talon M, Borriss R (2007) Tryptophan-dependent production of indole-3-acetic acid (IAA) affects level of plant growth promotion by *Bacillus amyloliquefaciens* FZB42. Mol Plant-Microbe Interact 20:619–626

Ipsilantis I, Sylvia DM (2007) Abundance of fungi and bacteria in a nutrient-impacted Florida wetland. Appl Soil Ecol 35:272–280

Irtwange VS (2006) Application of biological control agents in pre- and postharvest operations. Agric Eng Int: CIGR J 3:1–12

Jackson RM, Walker C, Luff S, McEvoy C (1995) Inoculation of Sitka spuce and Douglas fir with ectomycorrhizal fungi in the United Kingdom. Mycorrhiza 5:165–173

Jenkins EN, Heviefo G, Langewald J, Cherry JA, Lomer JC (1998) Development of mass production technology for aerial conidia for use as mycopesticides. Biocontrol News Inf 19:21–31

Kanokmedhakul S, Kanokmedhakul K, Phonkerd N, Soytong K, Kongsaree P, Suksamrarn A (2002) Antimycobacterial anthraquinone chromanone compound and diketopiperazine alkaloid from the fungus *Chaetomium globosum* KMITL-N0802. Planta Med 68:834–836

Kanokmedhakul S, Kanokmedhakul K, Nasomjai P, Louangsysouphanh S, Soytong K, Isobe M, Kongsaeree P, Prabpai S, Suksamran A (2006) Antifungal azaphilones from *Chaetomium cupreum* CC3003. J Nat Prod 69:891–895

Kapoor R, Sharma D, Bhatnagar AK (2008) Arbuscular mycorrhizae in micropropagation systems and their potential applications. Sci Hortic 116:227–239

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Khetan SK (2001) Microbial pest control. Marcel Dekker, Inc, New York, Basel, p 300

Kim BS, Hwang BK (2004) Biolofungicides. In: Dilip KA (ed) Fungal biotechnology in agricultural, food, and environmental applications. M. Dekker, Cop, New York, pp 123–133

Kim BS, Hwang BK (2007) Microbial fungicides in the control of plant diseases. J Phytopathol 155:641–653

Kulkarni M, Chaudhari R, Chaudhari A (2007) Novel tensio-active microbial compounds for biocontrol applications. In: Ciancio A, Mukerji KG (eds) General concepts in integrated pest and disease management. Springer, Berlin, pp 295–304

le Tacon F, Alvarez IF, Bouchard D, Henrion B, Jackson RM, Luff S, Parlade JI, Pera J, Stenström E, Villeneuve N, Walker C (1992) Variations in field response of forest trees of nursery ectomycorrhizal inoculation in Europe. In: Read DJ, Lewis DH, Fitter AH, Alexander IJ (eds) Mycorrhizas in ecosystems. CAB International, Wallingford, pp 119–134

Lian B, Wang B, Pan M, Liu C, Teng HH (2008) Microbial release of potassium from K bearing minerals by thermophilic fungus *Aspergillus fumigatus*. Geochim Cosmochim Acta 72:87–98

Lindsey DL, Baker R (1967) Effect of certain fungi on dwarf tomatoes grown under gnotobiotic conditions. Phytopathology 57:1262–1263

Lonhienne CP, Lonhienne TGA, Yeoh YK, Webb RI, Lakshmanan P, Chan CX, Lim PE, Ragan MA, Schmidt S, Hugenholtz P (2014) A new species of *Burkholderia* isolated from sugarcane roots promotes plant growth. Microb Biotechnol 7:142–154

Malik KA, Hafeez FY, Mirza MS, Hameed S, Rasul G, Bilal R (2005) Rhizospheric plant – microbe interactions for sustainable agriculture. In: Wang Y-P, Lin M, Tian Z-X, Elmerich C, Newton WE (eds) Biological nitrogen fixation, sustainable agriculture and the environment. Springer, The Netherlands, pp 257–260

Marin M (2006) Arbuscular mycorrhizal inoculation in nursery practice. In: Rai MK (ed) Handbook of microbial biofertilizers. Food Products Press, New York, pp 289–324

Marx DH, Kenney DS (1982) Production of ectomycorrhizal fungus inoculum. In: Schenck NC (ed) Methods and principles of mycorrhizal research St. American Phytopathological Society, Paul, pp 131–146

Marx DH, Cordell CE, Kenney DS, Mexal JG, Artman JD, Riffle JW, Molina RJ (1984) Commercial vegetative inoculum of *Pisolithus tinctorius* and inoculation techniques for development of ectomycorrhizae on bareroot tree seedlings. For Sci 25:1–101

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mikola P (1969) Mycorrhizal fungi of exotic forest plantations. Karstenia 10:169–176

Mikola P (1970) Mycorrhizal inoculation in afforestation. Int Rev For Res 3:123–196

Mitchell AM, Strobel GA, Hess WM, Vargas PN, Ezra D (2008) *Muscodor crispans*, a novel endophyte from *Ananas ananassoides* in the Bolivian Amazon. Fungal Divers 31:37–43

Muraleedharan H, Seshadri S, Perumal K (2010) Booklet on bio-fertilizer (Phosphobacteria). Shri AMM Murugappa Chettiar Research Centre Taramani, Chennai, pp 10–11

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and Remediation. Cambridge Scholars Publishing, Cambridge, pp 152–178

Naqvi NS, Mukerji KG (2000) Mycorrhizal technology in plant micropropagation system. In: Mukerji KG, Chamola BP, Singh J (eds) Mycorrhizal biology. Kluwer Academic/Plenum Publishers, New York, pp 217–233

Pal K, Gardener BM (2006) Biological control of plant pathogens. Plant Health Instructor APSnet:1–25. https://doi.org/10.1094/PHI-A-2006-1117-02

Park JH, Choi GJ, Jang SK, Lim KH, Kim TH, Cho YK, Kim JC (2005) Antifungal activity against plant pathogenic fungi of chaetoviridins isolated from *Chaetomium globosum*. FEMS Microbiol Lett 252:309–313

Paterson RRM (2006) Fungi and fungal toxins as weapons. Mycol Res 110:1003–1010

Paulitz TC, Belanger RR (2001) Biological control in greenhouse system. Annu Rev Phytopathol 39:103–133

Pereira OL, Barreto RW, Cavallazzi JRP, Braun U (2007) The mycobiota of the cactus weed *Pereskia aculeata* in Brazil, with comments on the life-cycle of *Uromyces pereskiae*. Fungal Divers 25:127–140

Perry DA, Molina R, Amaranthus MP (1987) Mycorrhizae, mycorrhizospheres and reforestation: current knowledge and research needs. Can J For Res 17:929–940

Pradhan N, Sukla L (2005) Solubilization of inorganic phosphates by fungi isolated from agriculture soil. Afr J Biotechnol 5:850–854

Radhakrishnan R, Shim KB, Lee BW, Hwang CD, Pae SB, Park CH (2013) IAA-producing *Penicillium sp*. NICS01 triggers plant growth and suppresses *Fusarium sp*.-induced oxidative stress in sesame (*Sesamum indicum* L.). *J Microbiol Biotechnol* 23:856–863

Raghukumar C (2008) Marine fungal biotechnology: an ecological perspective. Fungal Divers 31:19–35

Raja P (2006) Status of endomycorrhizal (AMF) biofertilizer in the global market. In: Rai MK (ed) Handbook of microbial biofertilizers. Food Products Press, New York, pp 395–416

Rashid A, Bhat RA, Qadri H, Mehmood MA (2019) Environmental and socioeconomic factors induced blood lead in children: an investigation from Kashmir, India. Environ Monit Assess 191(2):76. https://doi.org/10.1007/s10661-019-7220-y

Ricard JL, Ricard TJ (1997) The ethics of biofungicides – A case study: *Trichoderma harzianum* ATCC 20476 on Elsanta strawberries against *Botrytis cinerea* (gray mold). Agric Hum Values 14:251–258

Rinaldi AC, Comandini O, Kuyper TW (2008) Ectomycorrhizal fungal diversity: separating the wheat from the chaff. Fungal Divers 33:1–45

Rola CA (2000) Economic perspective for agricultural biotechnology research planning. Philippine Institute for Development Studies, Makati, p 28

Rosslenbroich HJ, Stuebler D (2000) *Botrytis cinerea* – history of chemical control and novel fungicides for its management. Crop Prot 19:557–561

Sachdev D, Chaudhari H, Kasture VM, Dhavale DD, Chopade BA (2009) Isolation and characterization of indole acetic acid (IAA) producing Klebsiella pneumonia strains from rhizosphere of wheat (*Triticum aestivum*) and their effect on plant growth. Indian J Exp Biol 47:993–1000

Sasikala C, Ramana C (1997) Biodegradation and metabolism of unusual carbon compounds by Anoxygenic phototrophic Bacteria. Adv Microb Physiol 39:339–377

Schwartz MW, Hoeksema JD, Gehring CA, Johnson NC, Klironomos JN, Abbott LK, Pringle A (2006) The promise and the potential consequences of the global transport of mycorrhizal fungal inoculum. Ecol Lett 9:501–515

Shenoy BD, Jeewon R, Hyde KD (2007) Impact of DNA sequence-data on the taxonomy of anamorphic fungi. Fungal Divers 26:1–54

Singh S, Pandey A, Palni LMS (2008) Screening of arbuscular mycorrhizal fungal consortia developed from the rhizospheres of natural and cultivated tea plants for growth promotion in tea (*Camellia sinensis* (L.) O. Kuntze). Pedobiologia 52:119–125

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Smith SE, Read DJ (1997) Mycorrhizal symbiosis. Academic Press, London

Smith SE, Zhu YG (2001) Application of arbuscular mycorrhizal fungi: potentials and challenges. In: Stephen BP, Hyde KD (eds) Bio-exploitation of filamentous fungi, Fungal Diversity Research Series, vol 6. Fungal Diversity Press, Hong Kong, pp 291–308

Soares DJ, Barreto RW (2008) Fungal pathogens of the invasive riparian weed *Hedychium coronarium* from Brazil and their potential for biological control. Fungal Divers 28:85–96

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Soytong K, Kanokmadhakul S, Kukongviriyapa V, Isobe M (2001) Application of *Chaetomium* species (Ketomium®) as a new broad spectrum biological fungicide for plant disease control: a review article. Fungal Divers 7:1–15

Soytong K, Srinon W, Rattanacherdchai K, Kanokmedhakul S, Kanokmedhakul K (2005) Application of antagonistic fungi to control anthracnose disease of grape. Int J Agric Technol 1:33–41

Spadaro D, Gullino LM (2005) Improving the efficacy of biocontrol agents against soil borne pathogens. Crop Prod 24:601–613

Tang W, Yang H, Ryder M (2001) Research and application of *Trichoderma* spp. in biological control of plant pathogen. In: Pointing SB, Hyde KD (eds) Bio-exploitation of filamentous fungi, Fungal Diversity Research Series, vol 6. Fungal Diversity Press, Hong Kong, pp 403–435

Tanu, Deobagkar DD, Khandeparker R, Sreepada RA, Sanaye SV, Pawar HB (2012) A study on bacteria associated with the intestinal tract of farmed yellow seahorse, Hippocampus kuda (Bleeker 1852): characterization and extracellular enzymes. Aquacult Res 43:386–394

Tejesvi MV, Kini KR, Prakash HS, Subbiah V, Shetty HS (2007) Genetic diversity and antifungal activity of species of Pestalotiopsis isolated as endophytes from medicinal plants. Fungal Divers 24:37–54

Than PP, Prihastuti H, Phoulivong S, Taylor PWJ, Hyde KD (2008a) Chilli anthracnose disease caused by *Colletotrichum* species. J Zhejiang Univ Sci B9:764–778

Than PP, Shivas RG, Jeewon R, Pongsupasamit S, Marney TS, Taylor PWJ, Hyde KD (2008b) Epitypification and phylogeny of *Colletotrichum acutatum* J.H. Simmonds. Fungal Divers 28:97–108

Varma A, Verma S, Sudha SN, Butehorn B, Franken P (1999) *Piriformospora indica*, a cultivable plant-growth-promoting root endophyte. Appl Environ Microbiol 65:2741–2744

Varma A, Bakshi M, Lou B, Hartmann A, Oelmueller R (2012) *Piriformospora indica*: a novel plant growth-promoting mycorrhizal fungus. Agric Res 1:117–131

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255: 571–586

Vinale F, Sivasithamparam K, Ghisalberti EL, Marra R, Woo SL, Lorito M (2008) *Trichoderma* plant pathogen interactions. Soil Biol Biochem 40:1–10

Voorrips RE, Finkers R, Sanjaya L, Groenwold R (2004) QTL mapping of anthracnose (*Colletotrichum* spp.) resistance in a cross between *Capsicum annuum* and *C. chinense*. Theor Appl Genet 109:1275–1282

Wakelin SA, Werren PR, Ryder HM (2004) Phosphate solubilization by *Penicillium* spp. closely associated with wheat root. Biol Fertil Soils 40:36–43

Waqas M, Khan AL, Kamran M, Hamayun M, Kang S, Kim Y, Lee I (2012) Endophytic Fungi produce gibberellins and indole acetic acid and promotes host-plant growth during stress. Molecules 17:10754–10773

Wesseling C, Corriols M, Bravo V (2005) Acute pesticide poisoning and pesticide registration in Central America. Toxicol Appl Pharmacol 207:S697–S705

White DP (1941) Prairie soil as a medium for tree growth. Ecology 22:398–407

Whitelaw MA, Hardena TJ, Helyar KR (1999) Phosphate solubilisation in solution culture by the soil fungus *Penicillium radicum*. Soil Biol Biochem 3:655–665

Wilde HE (1944) Mycorrhizae and silviculture. J For 42:290

Yeasmin T, Zaman P, Rahman A, Absar N, Khanum NS (2007) Arbuscular mycorrhizal fungus inoculum production in rice plants. Afr J Agric Res 2:463–467

Yedidia I, Srivastva AK, Kapulnik Y, Chet I (2001) Effect of *Trichoderma harzianum* on microelement concentrations and increased growth of cucumber plants. Plant Soil 235:235–242

Zhao ZW, Wang GH, Yang L (2003) Biodiversity of arbuscular mycorrhizal fungi in tropical rainforests of Xishuangbanna, southwest China. Fungal Divers 13:233–242

Zhu GS, Yu ZN, Gui Y, Liu ZY (2008) A novel technique for isolating orchid mycorrhizal fungi. Fungal Divers 33:123–137

Chapter 12
Bacillus thuringiensis as a Biofertilizer and Plant Growth Promoter

Jorge Delfim and Zulaykha Khurshid Dijoo

12.1 Introduction

Phosphorus (P) is amongst the chief macronutrients for the plants as well as an important growth-limiting nutrient. In fact, it participates in various functions of plants besides being a constituent of ATP molecules and plant DNA structure (Khan et al. 2014). Nevertheless, the solubility of P is low for most arable land in the world, and this problem directly affects crop production and food supply. Moreover, to get greater productivity, it is obligatory to use a large quantity of P fertilizers. Also, about 5–25% of the used P chemical fertilizer is absorbed by crop, while 75–95% is retained as unavailable forms in soil colloids forming Fe, Al, Ca and organic matter complexes (Dar et al. 2013; Stevenson and Cole 1999). On the other hand, the concentration of bioavailable P in many soils is lower. In this regard *Bacillus thuringiensis* has the capacity to turn the insoluble P into soluble form. In this contest the application of phosphate-solubilizing bacteria (PSB) as inoculant results in increased P utilization in plants. In fact, *Bacillus* strains are amongst the utmost used and potent P solubilizers (Rodríguez and Fraga 1999).

In addition, the inoculation with *B. thuringiensis* is an environmentally friendly practice as it increases solubility of P in soil (Dar and Bhat 2020; Delfim et al. 2018). Soil microorganisms (*B. thuringiensis*) execute a prodigious part in soil P cycle. It also participates in processes of mineralization and immobilization besides

---

J. Delfim (✉)
Instituto de Investigação Agronômica, Huambo, Angola

Programa de Pós-Graduação em Agronomia, Centro de Ciências Agrárias, Universidade Estadual de Londrina, Londrina, PR, Brazil

Z. K. Dijoo
Department of Environmental Sciences/Centre of Research for Development, University of Kashmir, Srinagar, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_12

controlling plant diseases plus tolerance stress. The beneficial effect of the *B. thuringiensis* as biofertilizer and plant growth promoter (PGP) in different crops has been demonstrated in laboratory, greenhouse as well as field trials (Armada et al. 2015; Delfim et al. 2018; Khanday et al. 2016; Wang et al. 2014). Inoculation with *B. thuringiensis* in *L. dentata* has increased the root growth by 412% in drought conditions when compared to non-inoculated conditions (Armada et al. 2016; Bhat et al. 2018) and increment in the tissue percentage of nutrients in maize crop (Armada et al. 2015) as well as improved soil Olsen available P in peanut and wheat rhizosphere (Delfim et al. 2018; Wang et al. 2014).

12.2 Bacillus thuringiensis

B. thuringiensis is a microorganism principally utilized for its biologically insecticidal properties. It is also used as a biological fertilizer and PGP. *B. thuringiensis* is a Gram-positive, aerobic, spore-forming bacterium. At the end of its vegetative phase, it produces parasporal crystals (Sanahuja et al. 2011). The insecticidal and phosphate-solubilizing properties of *B. thuringiensis* were documented several years earlier when the bacterium was discovered and recognized. Few studies have hinted that *B. thuringiensis* spores were used in ancient Egypt. This bacterial strain was isolated in 1901 by Shigetane Ishiwatari, a Japanese biologist, while studying wilt disease in silk worms, and he named it *Bacillus sotto*. After a period of 10 years, it was again isolated by Ernst Berliner from a diseased Mediterranean flour moth (*Ephestia kuehniella*). It was isolated in the German region of Thuringia hence; it was named as *Bacillus thuringiensis* (Siegel 2001).

B. thuringiensis has the capacity to produce diverse extracellular compounds such as insecticidal, antifungal and organic acids used by crop defence and plant development (Stabb et al. 1994). Nonetheless, the harmless utilization of *B. thuringiensis* globally on several agricultural crops for biocontrol argues strongly that this bacterium can be utilized as biofertilizer and biostimulator (Cherif et al. 2001; Rashid et al. 2019).

Amongst the most usefully reported microorganisms in various researches, bacteria of the type *Bacillus* are popular. In soil, the *Bacillus* represents an extensive group of the microorganism community (Qiao et al. 2014). Numerous studies indicate that the presence of *B. thuringiensis* in the rhizosphere of plants like cereals and legumes imparts positive bearings on crop establishment. It promotes growth, is tolerant to drought stress and increases nutrient absorption and utilization (Armada et al. 2014; Bhat et al. 2017). The synthesis and productions of enzymes, antibiotics or siderophores, organic acids, phytohormones and P solubilization have also been observed (Cherif-Silinil et al. 2016; Raddadi et al. 2008). The process of creating diverse biological composts plus the culturing of bacteria in regulated settings (laboratory) is imperative. Moreover, the ability of sporulation by the *Bacillus* and resistance to environmental settings offers them a great lead in persisting in the rhizosphere of the plants. It also extends multiplicity to their modes of action resulting in extraordinary stability potentials when used as biofertilizers or as PGP (Qiao et al. 2014; Sofi et al. 2017).

The beneficial and effective use of *B. thuringiensis* should not be limited to its function as a biocontrol, and it should be also used to control diseases and pests. *B. thuringiensis* investigations are principally appointed on its biological control properties and application. However, studies showing on the biofertilizer and biostimulation characteristics and application, including its interactions with plants in varied environments, are limited (Azizoglu 2019). *B. thuringiensis* isolated in different rhizosphere plants and soils is shown in Table 12.1. In addition, Cherif-Silinil et al. (2016) isolated 35 strains including *B. thuringiensis* from the wheat rhizosphere; the strain had the potential to mobilize phosphates at the rate of 15.05–16.65 µg mL^{-1}. The strains isolated from arid and alkaline soils were extremely effective in the making of compounds like IAA (Indole-3-acetic acid), siderophores and 1-aminocyclopropane-1-carboxylate deaminase (ACC deaminase) (Cherif-Silinil et al. 2016).

Lyngwi et al. (2016) collected and analysed soils from five different sacred groves of Meghalaya, and bacterial isolation was performed. One reference microorganism strain was *B. thuringiensis* strain (MTCC 8996); it provided enlarged pieces of the anticipated size for all the PGP genes screened. This presented various PGP genetic characters that exist in these isolates which proposed that these isolates are able to demonstrate characters that have an important impact on biofertilization, biostimulation, bioprotection and biocontrol undertakings. This can be investigated for agro-biotechnological practices.

12.3 Phosphorus Availability in Soil

Soil fraction P exists as organic and inorganic forms. The organic P is signified principally by inositol or phytates and phosphoesters, while the mineral P comes from rock phosphates, calcium phosphates and hydroxyapatites (Jones and Oburger 2011; Rodríguez and Fraga 1999). Many reports are considerate regarding the quick drop of the global P stores by reason of incessant mining of P (Van Vuuren et al. 2010). In several soils, enormous quantity of inorganic and organic P is present in unavailable (fixed or retained) and immobilized form.

Agricultural soils comprise great quantity of unavailable P coming from chemical fertilizers inaccessible after application because the process of fixation and precipitation in soil is largely reliant on pH and soil type (Rodríguez and Fraga 1999; Singh et al. 2020). Thus, at lower pH, aluminium-phosphorus and iron-phosphorus dominate, whereas at higher pH, calcium-phosphorus is predominantly present. In this context, Lindsay (1979) reported that superphosphate encompasses an adequate quantity of calcium to precipitate and quasi- phosphorus as dicalcium phosphate or dicalcium phosphate dihydrate.

P is an essential nutrient for plant development and yield. Consequently, its accessibility is restricted in various agricultural lands and as a result by plants.

Table 12.1 *Bacillus thuringiensis* isolated from rhizosphere/soil of different plants

Isolate code	Host plant	Organic acid	P solubilizing	IAA	ACC	Phosphatase	References
B1	Wheat	Yes	Yes	Yes	No	Not determined	Cherif-Silinil et al. (2016)
B2	Wheat	Yes	Yes	No	No	Not determined	Cherif-Silinil et al. (2016)
B7	Wheat	Yes	Yes	Yes	No	Not determined	Cherif-Silinil et al. (2016)
B10	Wheat	Yes	Yes	Yes	Yes	Not determined	Cherif-Silinil et al. (2016)
BA3	Wheat	Ye	No	Yes	No	Not determined	Cherif-Silinil et al. (2016)
B1	Tea	Yes	Yes	Not determined	Not determined	Not determined	Wang et al. (2014)
Not determined	Autochthonous shrub species	Yes	Yes	Yes	Yes	Not determined	Armada et al. (2016)
GDB-1	*Pinus sylvestris* L.	Yes	Yes	Yes	Yes	Not determined	Babu et al. (2013)
KR1	*Kudzu*	Yes	Yes	Yes	Not determined	Not determined	Selvakumar et al. (2008)
Not determined	Not determined	Yes	Yes	Yes	No	Not determined	Lyngwi et al. (2016)
BMG1.7 and HD22	Not determined	Yes	Yes	Yes	Yes	Yes	Raddadi et al. (2008)
KVS25	*B. juncea*	No	Yes	Yes	Yes	Not determined	Vishwakarma et al. (2018)
2P1M3	Pea	Not determined	Yes	Yes	Not determined	Yes	Freitas et al. (1997)
KTCIGM2	*Gigaspora margarita* spores	Not determined	Yes	Not determined	Not determined	Not determined	Cruz and Ishii (2012)

Yes solubilize or produce, *No* no solubilize or produce, *IAA* indole-3-acetic acid, *ACCdeaminase* 1-aminocyclopropane-1-carboxylate deaminase

Microorganisms execute a significant role in P cycle by making its mineralization and accessibility easy for the crops. P availability in the soil is regulated by soil pH, soil type and sorption, desorption plus content of organic matter (Dervash et al. 2020; Jones and Oburger 2011).

12.4 Phosphorus-Solubilizing Mechanisms

The main P solubilization mechanisms used by *B. thuringiensis* include production of organic acids, siderophores, changing the pH of medium, acid and alkaline phosphatase production (Cherif-Silinil et al. 2016; Freitas et al. 1997; Raddadi et al. 2008; Vishwakarma et al. 2018; Wang et al. 2014).

As per Freitas et al. (1997), *B. thuringiensis* can be represented as that rhizosphere bacterial class of P solubilizing that acidifies the pH of medium. In fact, Wang et al. (2014) showed that dropping of pH coincides with the incremental performance of P mobilizing action. A greater reduction in pH was connected with a greater extent of P solubilization, for instance, in *B. thuringiensis* B1, in which a considerable quantity of P was liberated from $AlPO_4$ (321.12 mg L^{-1}) which was ensued by a substantial drip in pH. Still, no noteworthy link has been established vis-à-vis pH and soluble P concentration. This is established with several prior findings (Jorquera et al. 2008; Lin et al. 2001).

A wide variety of compounds derived from *B. thuringiensis* can considerably modify the soil pH which results in several nutrients becoming available for uptake by plants. Whereas, only a few studies reported phosphate solubilizing via acidification or alkalinization by *B. thuringiensis* (Cherif-Silinil et al. 2016; Freitas et al. 1997; Vishwakarma et al. 2018; Wang et al. 2014). The mineralization of organic P in soil is accomplished mostly by phosphatases (acid or alkaline is dependent the soil pH) and phytases. These compounds play an important role in dephosphorylating reactions (Nannipieri et al. 2011) and enzyme hydrolysis. In addition, the quantity and quality of extracellular soil phosphatases come from the microorganism masses (Dodor and Tabatabai 2003). On the other hand, *B. thuringiensis* isolates present the genetic elements for acid phosphatase and siderophore making, along with hydrolysing mineral P (Raddadi et al. 2008).

Cherif-Silinil et al. (2016) assessed 35 strains of *Bacillus* including *B. thuringiensis.* These were isolated from the rhizosphere of wheat plants growing in various arid and semi-arid areas of Algeria. These strains were examined for several characteristics including their biofertilization (phosphate solubilization) and conclude that 78% of the strains had the ability to mobilize phosphates on Pikovskaya medium having tricalcium phosphate (Ca_3HPO_4) as the exclusive supplier of P.

Numerous soils, particularly those with high clay percentage, have high adsorption capability of soil P. In addition, it scarcely supplies sufficient P for the development of plants. It is debatable which inorganic P form is efficient for plant growth growing in clayey soil. However, Al-P and Fe-P forms are largely predominated in acid soil and are often treated with soluble P fertilizer for optimal plant

Table 12.2 *Bacillus thuringiensis* grown on insoluble mineral phosphate substrates

Bacillus thuringiensis strains	Substrate					References
	$CaHPO_4$	$Ca_3(PO_4)_2$	$AlPO_4$	Hydroxy-apatite	Rock phosphate	
B1	nd	nd	+	nd	nd	Wang et al. (2014)
BMG1.7	nd	+	nd	nd	nd	Raddadi et al. (2008)
HD22	nd	+	nd	nd	nd	Raddadi et al. (2008)
Bt	nd	+	nd	nd	nd	Armada et al. (2016)
SG1	nd	+	nd	nd	nd	Lyngwi et al. (2016)
SG5	nd	+	nd	nd	nd	Lyngwi et al. (2016)
SG6	nd	+	nd	nd	nd	Lyngwi et al. (2016)
SG11	nd	+	nd	nd	nd	Lyngwi et al. (2016)
SG17	nd	+	nd	nd	nd	Lyngwi et al. (2016)
KVS25	nd	+	nd	nd	nd	Vishwakarma et al. (2018)
nd	nd	+	nd	nd	nd	Dangar (2008)
2P1M3	+	nd	nd	nd	nd	Freitas et al. (1997)

+ solubilize, *nd* not determined or indicated

growth. If *B. thuringiensis* terminate other strains, this can lead to solubilization of the soil fixed P; they also discharge compounds to mobilize the Al and Fe layering which surrounds the soil occluded P (Delfim et al. 2020; Gong et al. 2010). Some studies have reported that *B. thuringiensis* could solubilize the soil $AlPO_4$, Ca_3HPO_4 and other sources producing organic acid and siderophores, thus resulting in increment of soil accessible P (Armada et al. 2015; Cherif-Silinil et al. 2016; Wang et al. 2014).

Some strains of *B. thuringiensis* are able to solubilize phosphate both in solid and liquid medium. But, the P solubilization by *B. thuringiensis* can depend too on the P source or substrate type Table 12.2, the forms and P fractions in soil (Delfim et al. 2020).

Various microorganisms like *B. thuringiensis* suggest a biological saving system proficient of mobilizing the insoluble inorganic P of soil followed by making it accessible to the plants (Lyngwi et al. 2016). The capability of *B. thuringiensis* to turn difficult to get P into a reachable form is a vital characteristic of a vegetable growth promoter bacterium for enhancing crop yield and environmentally sustainable.

12.5 Biological Fertilizer

Biological fertilizers are microorganisms that increment nutrient availability to plants, improving plant nutrition for either favouring nutrient absorption or increasing nutrient solubility in the rhizosphere, thus improving soil health.

The rhizosphere refers to adhered soil area around plant roots. Generally, this region features great microbial population and activity. Rhizosphere is exposed to varied microorganisms which influence the number of nutrients obtained by way of the root exudates (Bhatti et al. 2017; Bowen and Rovira 1999).

B. thuringiensis enhance the solubility of P that is previously existent in the soil although inaccessible. In a way these reduce the soil P reservoirs, but considering the low utilization efficiency of P fertilizers, *B. thuringiensis* execute vital part in intensifying the efficacy of P, plummeting build-up in soil and circumvent water pollution (Dar et al. 2016, 2020; Mehmood et al. 2019). In addition, *B. thuringiensis* solubilize P portions that are very stable in soil (extracted by conc. HCl and HCl 1 mol L^{-1}) (Delfim et al. 2020).

Biological fertilizer can be a liquid or solid substance that comprises viable (living) microorganisms, increases the efficiency of nutrient intake (PGP) and is applied to seed, plant, soil or other forms (Raddadi et al. 2007; Vessey 2003). According to Azizoglu (2019), several commercial biopesticide *B. thuringiensis* based products, but there are no commercial *B. thuringiensis* based biofertilizers and PGP products on the market. Furthermore, until now, the ability of *B. thuringiensis* as a biofertilizer, biostimulator and PGP has been demonstrated in different researches (Armada et al. 2015, 2016; Bais et al. 2006; Cherif-Silinil et al. 2016; Delfim et al. 2018; Jouzani et al. 2017; Mishra et al. 2009; Raddadi et al. 2007, 2008; Wang et al. 2014).

Bacillus spp. is considered to be the supreme noteworthy PSB (Abdallah et al. 2018; Behera et al. 2014). Although P is unavailable in different soils, it is a major limiting element of plant establishment. The crops absorb P at less concentration although phosphate occurs in the soil and plants uptake phosphate in two soluble forms, i.e. monobasic or dibasic ions (Glass 1989; Raddadi et al. 2007). *B. thuringiensis* and *B. subtilis* strains taken from the wheat rhizosphere have high PGP action, including phosphate mobilization and biostimulation properties (Cherif-Silinil et al. 2016; Jouzani et al. 2017).

12.6 Plant Growth Promoter

B. thuringiensis impart good effects on plant development as a PGP, and by using biotechnological applications, it can offer valuable products (Jouzani et al. 2017; Mishra et al. 2009). *B. thuringiensis* is beneficial in promoting plant growth and improve mobilization of P, production of IAA (Indole-3-acetic acid), ACC deaminase, phosphate-solubilizing enzyme, siderophores and ethylene. These also possess antimicrobial activity to counter various plant pathogens, and *B. thuringiensis* have been verified in many crops, which are demonstrated in Table 12.3 (Cruz and Ishii 2012; Jouzani et al. 2017; Raddadi et al. 2007; Sharma and Saharan 2016). *Pseudomonas*, *Bradyrhizobium*, *Bacillus*, *Herbaspirillum*, *Rhizobium* and *Azospirillum* are outstanding bacteria as PGP, and they cooperate with plant roots (Ahmad et al. 2008; Halda-Alija 2003; Pindi et al. 2014). In addition, phytohormones have important functions in plant growth and development as regulators and signals connections for bacterias colonize the plant roots, key roles in plant pathology, and microorganisms interactions (Raddadi et al.

Table 12.3 Name of the crops which were inoculated with P-solubilizing *Bacillus thuringiensis*

Plant	References
Wheat	Selvakumar et al. (2008)
Peanut	Wang et al. (2014)
Soybean	Mishra et al. (2009)
Lavandula and *Salvia*	Armada et al. (2014)
Maize	Armada et al. (2015)
Wheat	Delfim et al. (2018)
Mustard	Vishwakarma et al. (2018)
Lettuce	Gomes et al. (2003)
Soybean	Bais et al. (2006)
Alnus firma	Babu et al. (2013)
Canola	Freitas et al. (1997)

2007; Sergeeva et al. 2002). Nevertheless, IAA (Indole-3-acetic acid) is a phytohormone and is physiologically, biochemically and genetically well-researched plant growth hormone (Chaabouni et al. 2012; Del Pozo et al. 2005; Raddadi et al. 2007). *Bacillus* strains are successful in promoting the growth of wheat and maize crops. This is because of the formation of IAA (Indole-3-acetic acid), ACC deaminase, siderophores and phosphate-solubilizing enzyme (Beneduzi et al. 2008; Pindi et al. 2014; Trivedi and Pandey 2008). Some *B. thuringiensis* strains with PGP abilities act on plant roots and prove beneficial for sustainable crop yield (Armada et al. 2016; Gomes et al. 2003; Jouzani et al. 2017; Mishra et al. 2009; Sharma and Saharan 2016). Gomes et al. (2003) reports that IAA (Indole-3-acetic acid) produced by *B. thuringiensis* strain C25 isolated from *Brassica oleracea* (cabbage) improves the development of *Lactuca sativa* in controlled conditions. Likewise, Mishra et al. (2009) reported that co-inoculation of *Rhizobium leguminosarum*-PR1 with *B. thuringiensis* strain KR1 (IAA-producing) considerably enhanced the growth of pea and lentil plants in comparison to inoculation of *R. leguminosarum*-PR1 only. Besides, the co-inoculation of *Bradyrhizobium japonicum* with *B. thuringiensis* as well stimulated the growth of soybean and incremented root volume, shoot root weight, total biomass and nodule number compared to the rhizobia inoculation and control (Jouzani et al. 2017; Mishra et al. 2009). ACC deaminase and other compounds are produced by *B. thuringiensis*, in this context (Cherif-Silinil et al. 2016).

Furthermore, Bais et al. (2006) observed that *B. thuringiensis* when co-inoculated with *B. japonicum* resulted in increased nodulation, growth and yield in soybean crop. ACC is a pioneer amino acid of the naturally occurring ethylene. It is a central hormone for growth and development plus stress tolerance. It controls numerous developmental courses (Raddadi et al. 2007). ACC deaminase activity is noted in various *Bacillus* spp. It is a good stimulant for root elongation during sprouting. ACC deaminase produced by *B. thuringiensis* strain acts as an efficient plant growth regulator. Praça et al. (2012) highlighted that actual colonization of *B. thuringiensis* on seedling root surface. This affects physiology of host plants plus this bacterium can function as a superior PGP. While Sharma and

Saharan (2016) observed that *B. thuringiensis* has the ability to mature in highly concentrated medium of heavy metals. It has also been stated that this strain displayed noteworthy ACC deaminase activity when 100% of *Vigna radiata* seeds germinated in the presence of *B. thuringiensis*. Also, Armada et al. (2016) states that mixture of arbuscular mycorrhizal fungal (AMF) strains plus native *B. thuringiensis* strains enhanced the growth of *Lavandula dentata* in dearth of water situations. Furthermore, the native *B. thuringiensis* strains isolated from the same soil expended in the testing created ACC deaminase. Additionally, *B. thuringiensis* can associate with AMF, favouring P solubilization, ethylene production and other characteristics which resulted in increasing nutrient bioavailability, primarily in P-bounded settings (Cruz and Ishii 2012). These are the benefits of the links between the AMF and bacteria. This can deliver additional benefits precisely in hostile circumstances like drought, diseases, pests and nutrient deficiencies or unavailability.

Wang et al. (2014) found that *B. thuringiensis* increase peanut biomass and yield. In fact, the inoculation increased the number of nodules per plant by 41.7%. Nodule endophytes act as a profound link between *B. thuringiensis* and the plant because they enhance the efficacy of the circulation of nutrients to the plant. In addition, investigators have witnessed that co-inoculation of phosphate-solubilizing bacteria and rhizobia can raise growth and production of legumes. This also amplifies the intake of N and P in plants (Rosas et al. 2006; Vishwakarma et al. 2018). However, Armada et al. (2015) demonstrated that inoculation treatments did not influence shoot and root biomass yield of maize when plants were grown under good water settings, although it considerably impacts the root length. Thus, dual arbuscular mycorrhizal plus *B. thuringiensis* inoculations improved root length by 20%. On the other hand, under drought settings the highest shoot growth was attained in plants inoculated with only *B. thuringiensis*, while in those dually inoculated, there was 30% increase in shoot dry weight.

Recently, Vishwakarma et al. (2018) worked in pot experiments and found that the co-inoculation of *Pseudomonas* and *B. thuringiensis*, respectively, incremented the growth of *Brassica juncea* (mustard) over to the controls. Together *Pseudomonas* sp. and *B. thuringiensis* cause plant growth promotion and increase in disease resistance (Aeron et al. 2011). *Bacillus* sp. boosts heavy metal tolerance in plants (Upadhyay et al. 2017). In this context, studies demonstrate the complex part of bacterial strains in plant growth promotion besides stress improvement. Similarly, plants inoculated with *B. thuringiensis* upsurge nutrient uptake under drought environments and enhance macro- and micronutrient intake and shoot dry weight of maize crop. Inoculation enhances the macro- and micronutrient content that shows the importance of this practice in modern agriculture (Armada et al. 2015). Moreover, Delfim et al. (2018) evaluated P concentrations in wheat plants that were grown in two dissimilar volcanic soils (andisol and ultisol). These plants were inoculated with *B. thuringiensis*, and the positive as well as negative effects of this strain were observed on plant growth and P nutrition for wheat, showing that it is principally dependent on the soil type. In addition, Freitas et al. (1997) studied more than hundred bacteria isolated from the rhizosphere of field plants and concluded that the utmost efficient inoculant was *B. thuringiensis*. It considerably stemmed in increase of the number plus weight of pods as well as seed yield deprived of P quantity. This displays the possible application of *B. thuringiensis* as inoculant for canola. In addition, the authors suggest that P solubilization is not the main process in charge of positive growth reaction. Although the positive outcome of this biological fertilizer (inoculation) is not to be restricted to solitary nutrient element like P, several nutrients can be solubilized by *B. thuringiensis*. In addition, the inoculation with *B. thuringiensis* has been tested on various crops and demonstrated their agronomical impacts, in different conditions and parts of the world.

12.7 Environmental Impact

Exist a debate amongst researches as well as politicians regarding the negative environmental influence of the excessive and wrong use of chemical fertilizers, and the alternatives or solutions to reduce the environmental impacts, although it is evident that *B. thuringiensis* as biofertilizer and PGP can provide sustainable crop production and immense environmental benefits. Countries like India, China, Argentina, Brazil and the United States are the greatest fervent users of *B. thuringiensis* in agriculture as pesticide, insecticides and disease control agent owing to its entomopathogenic abilities (Sanahuja et al. 2011; Stabb et al. 1994). In fact, in these countries they can easily encourage the study and use of *B. thuringiensis* as a fertilizer or biostimulator and PGP.

One of the principal impacts of *B. thuringiensis* use in agriculture has been the reduction of pesticide sprays plus an associated lessening in the occurrences of poisonings due to chemical exposure. In addition to it, mean yield increases of up to 10% have raised up net revenue for practically 40% of population (Mushtaq et al. 2018; Subramanian and Qaim 2010). In this regard, the usage of *B. thuringiensis* as biofertilizer is an environmental approach that permits for escalating the accessibility of P in soil and its uptake in plants and can diminish the application of mineral fertilizers in agriculture (Delfim et al. 2018).

Intrinsic stress-tolerant bacteria support the plant and soil health besides developing plant growth, nutrient acquisition, stress tolerance and pest control on the adverse environmental conditions. Bulk of the microorganisms form spores or resting stages, thus resisting more than the others (Armada et al. 2014, 2015; Dangar 2008).

In addition, Babu et al. (2013) reported that *B. thuringiensis* GDB-1 inoculated in *Alnus firma* crop and it increased the competence for phytoremediation of soil encompassing mine tailings tainted with diverse heavy metals such as arsenic, lead, zinc, cadmium, copper and nickel. It can reduce the metabolic disturbances and stress produced by high quantities of heavy metals. Additionally, reduction in CO_2 emissions and conservation of soil and water help in the bioremediation of high concentration of heavy metals plus additional contaminants, biosynthesis of metal nanoparticles and manufacture of diverse novel bio-products (Jouzani et al. 2017).

12.8 Conclusions

Phosphorus (P) is a non-renewable natural resource in soil and is present in mineral and organic form. It is an important nutrient for plant growth but its availability is lower in soil and for plant growth. It is unavailable to plants as it is typically existent as fixed or retained form in the soil. Therefore, it is necessary to find alternatives to increase its solubility. *Bacillus thuringiensis* possesses the capability to solubilize P plus produce different compounds such as siderophores, enzymes, ACC deaminase and IAA (Indole-3-acetic acid) which help crop growth and support negative environmental conditions. In addition, to become available in soil and for plant intake, both P forms should be possible to use, and *B. thuringiensis* play an important role in this process. In addition, multiple positive responses (i.e. P nutrition, tree improvement, biotic and abiotic stress tolerance and other beneficial effects) were associated to the application of *B. thuringiensis* in various crops. *B. thuringiensis* has a great potential to produce biofertilizer or biostimulator. In this case, researches must be done to optimizing and diffusing this biotechnology by commercial application, therefore improving productivity over low cost and aiding economic viability for farmers.

References

Abdallah DB, Frikha-Gargouri O, Tounsi S (2018) Rizhospheric competence, plant growth promotion and biocontrol efficacy of Bacillus amyloliquefaciens subsp. plantarum strain 32a. Biol Control 124:61–67

Aeron A, Dubey RC, Maheshwari DK, Pandey P, Bajpai VK, Kang SC (2011) Multifarious activity of bioformulated Pseudomonas fluorescens PS1 and biocontrol of Sclerotinia sclerotiorum in Indian rapeseed (Brassica campestris L.). Eur J Plant Pathol 131:81–93

Ahmad F, Ahmad I, Khan MS (2008) Screening of free-living rhizospheric bacteria for their multiple plant growth promoting activities. Microbiol Res 163:173–181

Armada E, Roldán A, Azcón R (2014) Differential activity of autochthonous bacteria in controlling drought stress in native Lavandula and Salvia plants species under drought conditions in natural arid soil. Microb Ecol 67:410–420

Armada A, Azcón R, López-Castillo OM, Calvo-Polanco M, Ruiz-Lozano JM (2015) Autochthonous arbuscular mycorrhizal fungi and Bacillus thuringiensis from a degraded Mediterranean area can be used to improve physiological traits and performance of a plant of agronomic interest under drought conditions. Plant Physiol Biochem 90:64–74

Armada E, Probanza A, Roldán A, Azcón R (2016) Native plant growth promoting bacteria Bacillus thuringiensis and mixed or individual mycorrhizal species improved drought tolerance and oxidative metabolism in Lavandula dentata plants. J Plant Physiol 192:1–12

Azizoglu U (2019) Bacillus thuringiensis as a biofertilizer and biostimulator: a mini-review of the little-known plant growth-promoting properties of Bt. Curr Microbiol 76(11):1379–1385

Babu AG, Kim JD, Oh BT (2013) Enhancement of heavy metal phytoremediation by Alnus firma with endophytic Bacillus thuringiensis GDB-1. J Hazard Mater 250:477–483

Bais HP, Weir TL, Perry LG, Gilroy S, Vivanco JM (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. Annu Rev Plant Biol 57:233–266

Behera BC, Singdevsachan SK, Mishra RR, Dutta SK, Thatoi HN (2014) Diversity, mechanism and biotechnology of phosphate solubilizing microorganism in mangrove-a review. Biocatal Agric Biotechnol 3:97–110

Beneduzi A, Peres D, Da Costa PB, Zanettini MH, Passaglia LM (2008) Genetic and phenotypic diversity of plant growth-promoting bacilli isolated from wheat fields in southern Brazil. Res Microbiol 159:244–250

Bhat RA, Shafiq-ur-Rehman MM, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Bowen GD, Rovira AD (1999) The rhizosphere and its management to improve plant growth. Adv Agron 66:1–102

Chaabouni I, Guesmi A, Cherif A (2012) Secondary metabolites of Bacillus: potentials in biotechnology. In: Sansinenea E (ed) Bacillus thuringiensis biotechnology chapter 18. Springer, Dordrecht, pp 347–366

Cherif A, Ouzari H, Daffonchio D, Cherif H, BenSlama K, Hassen A, Jaoua S, Boudabous A (2001) Thuricin 7: a novel bacteriocin produced by Bacillus thuringiensis BMG1AE7, a new strain isolated from soil. Lett Appl Microbiol 32:243–247

Cherif-Silinil H, Silini A, Yahiaoui B, Ouzari I, Boudabous A (2016) Phylogenetic and plant-growth-promoting characteristics of Bacillus isolated from the wheat rhizosphere. Ann Microbiol 66:1087–1097

Cruz AF, Ishii T (2012) Arbuscular mycorrhizal fungal spores host bacteria that affect nutrient biodynamics and biocontrol of soil borne plant pathogens. Biol Open 1:52–57

Dangar JTK (2008) Microbial population dynamics, especially stress tolerant Bacillus thuringiensis, in partially anaerobic rice field soils during postharvest period of the Himalayan, island, brackish water and coastal habitats of India. World J Microbiol Biotechnol 24:1403–1410

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish fauna. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 51–68

Del Pozo JC, Lopez-Matas MA, Ramirez-Parra E, Gutierrez C (2005) Hormonal control of the plant cell cycle. Physiol Plant 123:173–183

Delfim J, Schoebitz M, Leandro P, Hirzel J, Zagal E (2018) Phosphorus availability in wheat, in volcanic soils inoculated with phosphate-solubilizing bacillus thuringiensis. Sustainability 10:144

Delfim J, Gerding M, Zagal (2020) Phosphorus fractions in Andisol and Ultisol inoculated with Bacillus thuringiensis and phosphorus uptake by wheat. J Plant Nutr 43:2728–2739. https://doi.org/10.1080/01904167.2020.1793176

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Dodor DE, Tabatabai AM (2003) Effect of cropping systems on phosphatases in soils. J Plant Nutr Soil Sci 166:7–13

Freitas J, Banerjee MR, Germida JJ (1997) Phosphate-solubilizing rhizobacteria enhance the growth and yield but not phosphorus uptake of canola (Brassica napus L.). J. Biol. Fertil. Soil 24:358–364

Glass ADM (1989) Plant nutrition: an introduction to current concepts. Jones and Bartlett Publishers, Boston

Gomes AMA, Mariano RLR, Silveira EB, Mesquita JCP (2003) Isolamento, seleção de bactérias e efeito de Bacillus spp. na produção de mudas orgânicas de alface. Hort Brasileira 21:701–705

Gong S, Wang X, Zhang T, Li Q, Zhou J (2010) Release of inorganic phosphorus from red soils induced by low molecular weight organic acids. Acta Pedol Sin 47:692–697

Halda-Alija L (2003) Identification of indole-3-acetic acid producing freshwater wetland rhizosphere bacteria associated with Juncus effusus L. Can J Microbiol 49:781–787

Jones DL, Oburger E (2011) Solubilization of phosphorus by soil microorganisms. In: B€unemann EK et al (eds) Phosphorus in action, soil biology. Springer-Verlag, Berlin Heidelberg

Jorquera MA, Hernandez MT, Rengel Z, Marschner P, Mora MD (2008) Isolation of culturable phosphobacteria with both phytate-mineralization and phosphate-solubilization activity from the rhizosphere of plants grown in a volcanic soil. Biol Fertil Soils 44:1025–1034

Jouzani GS, Valijanian E, Sharafi R (2017) Bacillus thuringiensis: a successful insecticide with new environmental features and tidings. Appl Microbiol Biotechnol 101:2691

Khan MS, Zaidi A, Ahmad E (2014) Mechanism of phosphate solubilization and physiological functions of phosphate solubilizing microorganisms. In: Khan MS, Zaidi A, Musarrat J (eds) Phosphate solubilizing microorganisms: principles and application of microphos technology, 1st edn. Springer International Publishing, Cham, pp 31–62

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Lin QM, Wang H, Zhao XR, Zhao ZJ (2001) Capacity of some bacteria and fungi in dissolving phosphate rock. Microbiology 28:26–30

Lindsay WL (1979) Chemical equilibria in soil. John Wiley and Sons, New York

Lyngwi NA, Nongkhlaw M, Kalita D, Joshi SR (2016) Bioprospecting of plant growth promoting bacilli and related genera prevalent in soils of pristine sacred groves: biochemical and molecular approach. PLoS One 11:0152951

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mishra PK, Mishra S, Selvakumar G, Bisht JK, Kundu S, Gupta HS (2009) Coinoculation of Bacillus thuringiensis-KR1 with rhizobium leguminosarum enhances plant growth and nodulation of pea (Pisum sativum L.) and lentil (Lens culinaris L.). World J Microbiol Biotechnol 25:753–761

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, pp 152–178

Nannipieri P, Giagnoni L, Landi L, Renella G (2011) Role of phosphatase enzymes in soil. In: Bunemann E, Oberson A, Frossard E (eds) Phosphorus in action: biological processes in soil phosphorus cycling. Soil biology, vol 26. Springer, Berlin, Heidelberg, pp 215–243

Pindi PK, Sultana T, Vootla PK (2014) Plant growth regulation of Bt-cotton through Bacillus species. 3. Biotech 4:305–315

Praça LB, Gomes ACMM, Cabral G, Martins ÉS, Sujii ER, Monnerat RG (2012) Endophytic colonization by Brazilian strains of Bacillus thuringiensis on cabbage seedlings grown in vitro. Bt Res 3:11–19

Qiao JQ, Wu JH, Rong R, Huo XW, Gao R, Borriss R (2014) Stimulation of plant growth and biocontrol by Bacillus amyloliquefaciens subsp. plantarum FZB42 engineered for improved action. Chem Biol Technol Agric 12:702–708

Raddadi N, Cherif A, Ouzari H, Marzorati M, Brusetti L, Boudabous A, Daffonchio D (2007) Bacillus thuringiensis beyond insect biocontrol: plant growth promotion and biosafety of polyvalent strains. Ann Microbiol 57:481–494

Raddadi N, Cherif A, Boudabous A, Daffonchio D (2008) Screening of plant growth promoting traits of Bacillus thuringiensis. Ann Microbiol 58:47–52

Rashid A, Bhat RA, Qadri H, Mehmood MA (2019) Environmental and socioeconomic factors induced blood lead in children: an investigation from Kashmir, India. Environ Monit Assess 191(2):76. https://doi.org/10.1007/s10661-019-7220-y

Rodríguez H, Fraga R (1999) Phosphate solubilizing bacteria and their role in plant growth promotion. Biotech Adv 17:319–339

Rosas SB, Andres JA, Rovera M, Nestor SC (2006) Phosphate solubilizing Pseudomonas putida can influence the rhizobia legume symbiosis. Soil Biol Biochem 38:3502–3505

Sanahuja G, Banakar R, Twyman RM, Capell T, Christou P (2011) Bacillus thuringiensis: a century of research, development and commercial applications. Plant Biotechnol J 9:283–300

Selvakumar G, Kundu S, Gupta AD, Shouche YS, Gupta HS (2008) Isolation and characterization of Nonrhizobial plant growth promoting Bacteria from nodules of kudzu (Pueraria thunbergiana) and their effect on wheat seedling growth. Curr Microbiol 56:134–139

Sergeeva E, Liaimer A, Bergman B (2002) Evidence for production of the phytohormone indole-3-acetic acid by cyanobacteria. Planta 215:229–238

Sharma N, Saharan BS (2016) Bacterization effect of culture containing 1-aminocyclopropane-1-carboxylic acid deaminase activity implicated for plant development. Microbiol Res J Int 16:1–10

Siegel JP (2001) The mammalian safety of *Bacillus thuringiensis*-based insecticides. J Invertebr Pathol 77:13–21

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Stabb EV, Jacobson LM, Handelsman J (1994) Zwittermicin a producing strains of Bacillus cereus from diverse soils. Appl Environ Microbiol 60:4404–4412

Stevenson FJ, Cole MA (1999) Cycles of soil: carbon, nitrogen, phosphorus, sulfur, micronutrients, 2nd edn. Wiley, New York

Subramanian A, Qaim M (2010) The impact of Bt cotton on poor households in rural India. J Dev Stud 46:295–311

Trivedi P, Pandey A (2008) Plant growth promotion abilities and formulation of Bacillus megaterium strain B 388 (MTCC6521) isolated from a temperate Himalayan location. Indian J Microbiol 48:342–347

Upadhyay N, Vishwakarma K, Singh J, Mishra M, Kumar V, Rani R, Mishra RK, Chauhan DK, Tripathi DK, Sharma S (2017) Tolerance and reduction of chromium (VI) by Bacillus sp. MNU16 isolated from contaminated coal mining soil. Front Plant Sci 8:778

Van Vuuren DP, Bouwman A, Beusen A (2010) Phosphorus demand for the1970–2100 period: a scenario analysis of resource depletion. Glob Environ Change 20:428–439

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586

Vishwakarma K, Kumar V, Tripathi D, Sharma S (2018) Characterization of rhizobacterial isolates from Brassica juncea for multitrait plant growth promotion and their viability studies on carriers. Environ Sustainability 1:253–265

Wang T, Liu M, Li H (2014) Inoculation of phosphate solubilizing bacteria Bacillus thuringiensis B1 increases available phosphorus and growth of peanut in acidic soil. Acta Agric Scand BSP 64:252–259

Chapter 13
Cyanobacteria as Sustainable Microbiome for Agricultural Industries

Charu Gupta, Mir Sajad Rabani, Mahendra K. Gupta, Aukib Habib, Anjali Pathak, Shivani Tripathi, and Rachna Singh

13.1 Introduction

Cyanobacteria are a distinct group of prokaryotic organisms, performing oxygenic photosynthesis. Blue-green algae (BGA) comprise about 150 genera and 2000 species and are classified into 5 subsections, i.e., *Chroococcales*, *Nostocales*, *Oscillatoriales*, *Pleurocapsales*, and *Stigonematales* (Boone and Castenholz 2001). Blue-green algae are the most archaic organisms in the plant world and are not actually recognized as "true" algae. They are called as cyanobacteria, as their structure looks much more like bacteria and have a cell wall made up of peptidoglycan. Their body is formed from a single cell, often clustered cells as colonies of various shapes. Generally, cyanobacteria cells consist of distinct sizes, ranging from 1 μm for unicellular forms to over 30 μm for multicellular species. Moreover, it is larger than other bacteria (Singh and Montgomery 2011). They have contrast morphology with three basic morphological forms including unicellular, filamentous without heterocyst, and filamentous forms with heterocyst (Singh and Montgomery 2011). Heterocysts are specialized and differentiated cells that can fix atmospheric dinitrogen (N_2) that are important for their survival under nitrogen-limiting conditions (Kumar et al. 2010a).

The exponential increase in the global population and changing climate pose a significant challenge to crop production. With this increase in population, the demand for food production has also increased. Therefore, the industries have shifted their focus on input of synthetic fertilizers in order to meet the demand. Although these synthetic fertilizers are capable of enhancing the production, they

---

C. Gupta (✉) · R. Singh
School of Studies in Microbiology, Jiwaji University, Gwalior, Madhya Pradesh, India

M. S. Rabani · M. K. Gupta · A. Habib · A. Pathak · S. Tripathi
Microbiology Research Lab., School of Studies in Botany, Jiwaji University, Gwalior, Madhya Pradesh, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_13

exert severe effects on the quality of soil and water and produce negative effects on plants as well (Bhat et al. 2017a; Dervash et al. 2020). Hence, there is a dire need to intensify the agricultural production in a sustainable way and find solutions to this problem. We need to shift our focus on sustainable organic biofertilizers for better food quality and maintenance of soil health. Plants are associated with complex microbiomes, which have an ability to promote plant growth and tolerance to multiple stresses, regulate plant nutrition, and biocontrol phytopathogens. The combination of useful plant microbe and microbiome interactions may correspond to a promising sustainable solution to enhance agricultural production. Cyanobacterial species are well recognized for their positive contribution as sustainable microbiome in agriculture and can also play an active role in bioremediation. Features of cyanobacteria have drawn the attention of researchers, which is recognized as a prosperous source of different bioactive compounds with antiviral, antifungal, antibacterial, and anticancerous properties (Bhat et al. 2017a, b; Malik et al. 2001). They are one of the most extensively used organisms in farming as organic fertilizers. Nitrogen is considered as the second growth-limiting element after water, and competency of this element could be enhanced by using cyanobacterial biofertilizers. These organic biofertilizers provide organic carbon, phosphorous, and nitrogen which are beneficial for enhancing the soil fertility, growth, and development of plants. Certain cyanobacterial species also help in bioremediation of heavy metals and other toxic compounds that refrain soil and water pollution.

13.2 Evolutionary History

Cyanobacteria belong to kingdom *Monera* (Prokaryotes), division *Eubacteria*, and class *Cyanobacteria*. However, their taxonomic classification at higher levels about the order, family, genera, and species is still controversial (Ernst et al. 2006; Hitzfeld et al. 2000). Cyanobacteria exhibit a wide range of morphologies among all bacteria (Table 13.1). Moreover, the conventional taxonomic classifications of blue-green algae focused on morphology and development have been classified into five principal groups (Rippka et al. 1979):

Group I (*Chroococcales*) – Organisms that consist solitary and colonial unicellular forms, for example, *Gloeocapsa* and *Synechococcus*

Group II (*Pleurocapsales*) – Organisms that comprise thallus-forming cyanobacteria, unicellular to pseudo-filamentous with cells capable of both multiple and binary fission, for example, *Pleurocapsa* and *Dermocarpella*

Group III (*Oscillatoriales*) – Organisms that consist of filamentous cyanobacteria and cell differentiation is absent, for example, *Phormidium* and *Microcoleus*

Group IV (*Nostocales*) – Organisms that comprise filaments, marked by cell differentiation to develop akinetes and heterocysts, for example, *Anabaena* and *Nostoc*

Table 13.1 System of classification of cyanobacteria

Type of cell	Mode of reproduction	G+C %	Recognized genera	Other properties
Unicells or aggregates	Binary fission or budding	35–71	*Synechococcus*, *Synechocystis*, *Gloeobacter*, *Gloeothece*, *Gloeocapsa*, *Chamaesiphon*	Almost always non-motile
Unicells or aggregates	Multiple fission to baeocytes	38–47	*Dermocarpa*, *Xenococcus*, *Myxosarcina*, *Chroococcidiopsis*	Usually some baeocytes are motile
Filaments; unbranched trichomes with only vegetative cells	Binary fission in a single plane	40–67	*Spirulina*, *Lyngbya*, *Oscillatoria*, *Pseudanabaena*, *Phormidium*, *Plectonema*	Usually motile
Filaments can form heterocyst; no true branching	Hormogonia formed, binary fission in a single plane	38–47	*Anabaena*, *Nodularia*, *Nostoc*, *Cylindrospermum*, *Scytonema*, *Calothrix*, *Tolypothrix*, *Rivularia*	Often motile; may form akinetes
Filaments can form heterocyst; and true branches	Hormogonia, akinetes, hormocysts; binary fission in more than one plane	42–46	*Chlorogloeopsis*, *Fischerella*, *Mastigocladus*	Greatest morphological complexity and differentiation in cyanobacteria

Group V (*Stigonematales*) – Organisms that consist of cell-differentiating cyanobacteria with more complex multicellular organization, for example, *Stigonema* and *Mastigocladus*

Molecular phylogenies of the cyanobacteria favor few groups but not all these groupings (Giovannoni et al. 1988; Tomitani et al. 2006; Turner et al. 1999). Unsurprisingly, molecular analyses support the characters like cell differentiation or multiple fission of the phylogenetic affinities of taxa, while unicells and simple filaments do not constitute monophyletic groupings.

Phylogenies usually support in placing *Gloeobacter* as the sister group to all other existing cyanobacteria or as a paraphyletic basal grouping (Turner 1997). Other clades that exhibit consistency in molecular phylogenies comprises of unicellular taxa, where *Synechecoccus* and *Prochlorococcus* being the dominated strains; Group II, baeocyte forming cyanobacteria; and the sheath forming Group III filaments forms along with some unicellular lineages (e.g., Lyngbya/Phormidium/Plectonema) (Sánchez-Baracaldo et al. 2005; Turner et al. 1999). The phylogeny of Tomitani et al. (2006), based on sequence analysis of 16SrRNA, hetR, and rbcL genes and with spacious sampling of multicellular taxa, onward supports the monophyly of cyanobacteria that distinguishes akinetes and heterocysts: Group V lineages form a clade nested within a paraphyletic Group IV.

13.3 Cyanobacteria Under Extreme Conditions

Cyanobacteria are commonly known as blue-green algae and often called as false eukaryotic algae. They are usually Gram-negative prokaryotes, achieve photosynthesis, and can fix atmospheric nitrogen into usable forms. They are omnipresent in ponds, lakes, water streams, rivers, and wetlands. They can survive at low pH value of 4–5 (Pfennig 1969, 1974) with optimal pH of 7.5–10 (Fogg 1956), while can also survive at high temperatures of 45–70 °C (Castenholz 1978).

Cyanobacteria can also grow under extreme environmental conditions such as in hot springs, arid deserts, hypersaline water, and cold environments and are also exploited for the refinement of alkaline soils (Rashid et al. 2019; Singh 2014). Their ability to survive under extreme conditions can be utilized to diminish the salt content from affected soils and can also enhance carbon (C), nitrogen (N), and phosphorus (P) content of the soil. It is said that cyanobacteria stimulate water permeability and soil accumulation and are useful in enhancing soil quality and structure of arid or subarid regions. Rogers and Burns (1994) studied that cyanobacterial inoculation boosts the stability of soil aggregates that enhanced WHC (water holding capacity) and aeration of poor structured soils. Such organisms diminish the sodicity and compaction of soils by enhancing organic carbon, WHC, and soil aeration and favor the biodiversity of other useful microflora as well.

13.4 Cyanobacteria as Potential Biofertilizers

The increased demand for food production is achieved by the application of synthetic fertilizers. Excessive utilization of synthetic fertilizers deteriorates the soil and water quality (Dar et al. 2020; Mehmood et al. 2019), makes plants more prone to diseases, and also causes reduction in soil fertility (Aktar et al. 2009; Dong et al. 2012). These chemicals also lead to increase in salinity and improper content of nutrients and reduce water holding capacity of soils (Bhat et al. 2018a; Dar et al. 2013; Savci 2012; Sofi et al. 2017). Moreover, it has also been found that prolonged use of chemical fertilizers causes changes in soil pH and kills the beneficial soil microbes. Meanwhile, the production of synthetic and chemical fertilizers is an expensive process to produce as they need large energy resources (Mahanty et al. 2017). Therefore, to overcome all these adverse effects, organic biofertilizers seem to be considerable natural inducers for sustainable growth and development of plants (Du Jardin 2015).

Cyanobacteria play a vital role in maintaining and boosting soil fertility, thereby increasing growth and yield of crops as a biofertilizer (Bhat et al. 2018a, b; Song et al. 2005). They are a group of microbes, cosmopolitan in distribution that can fix atmospheric nitrogen and can adapt in various types of soil and environment. Cyanobacterial fertilizers are considered as better in comparison to manure from farmyards and chemical fertilizers due to high amount of organic content that maintains the moisture holding capacity and mineral availability in the soils (Aitken and Senn 1965; Kumar and Bawaja 2018). These fertilizers have longer shelf life, are cost-effective and convenient for use, and enhance aeration, humus formation, and moisture retaining capacity of soils along with increased nutrient uptake. They can also increase the rate of seed germination, growth, and yield of plants. It is also said that these fertilizers improve resistance to diseases, insects, nematodes, pests, and various stresses including drought, frost, salinity, etc. in plants (Dar and Bhat 2020; Kumar et al. 2012c).

Biological systems with the ability of nitrogen fixation offer an ecological and sustainable alternative to chemical fertilizers (Hegde et al. 1999; Vaishampayan et al. 2001). Several cyanobacterial species are bestowed with the specialized cells called heterocysts that are basically modified cells with thick walls. Heterocysts have been recognized as a site of (N_2) fixation, where a conglomerate enzyme nitrogenase catalyzes the process of nitrogen fixation (Singh et al. 2011b). The fixed N_2 may be released by secretion or microbial degradation in the form of free amino acids, polypeptides, ammonia, vitamins, and auxin-like substances after the cell death (Subramanian and Sundaram 1986). N_2-fixing ability has been reported in cyanobacteria containing heterocysts as well as in several unicellular and filamentous forms that lack heterocyst. About 2×10^2 metric tons (MT) of nitrogen is fixed annually by biological means (Guerrero et al. 1981), and the total N_2 fixation is ~90 kg N $ha^{-1}y^{-1}$ (Metting 1988). The nitrogen fixation is carried out by symbiotic and free-living eubacteria, including cyanobacteria where cyanobacteria can fix <10 kg of N $ha^{-1}y^{-1}$; however, dense mats of cyanobacteria can fix ~10–30 kg of N ha^{-1} annually (Aiyer et al. 1972). Therefore, blue-green algae account for essential naturally available organic fertilizers (Prasanna et al. 2013; Vaishampayan et al. 2001). Some BGA such as *Anabaena*, *Nostoc*, and *Trichodesmium* contribute to about 36% of nitrogen fixation globally and are reported to enhance soil fertility in fields used for cultivation of rice in different parts of the world. Rice cultivation in tropical areas depends mainly on biological N_2 fixation that is usually carried by cyanobacteria (Vaishampayan et al. 2001). In cultivated agriculture systems, ~32 Tg of nitrogen is fixed annually by biological means, and cyanobacteria can fix about 20–30 kg of nitrogen ha^{-1} along with organic components (Issa et al. 2014; Singh et al. 2016; Subramanian and Sundaram 1986). They form symbiotic associations with different organisms like fungi, algae, diatoms, bryophytes, pteridophytes, gymnosperms, and angiosperms (Khanday et al. 2016; Rai et al. 2000; Sarma et al. 2016). A list of N_2-fixing cyanobacteria is presented in Fig. 13.1.

Besides nitrogen fixation, cyanobacteria are also known to mineralize insoluble form of phosphate in soil. Phosphorus (P) is the second essential element for plants and microbes after nitrogen. There is approximately 0.05% phosphorus available in soil, and only a small proportion (0.1%) of this P is available for plant uptake. Most of the aquatic systems have often limited P and N content. Adjustments with algal biofertilizers can help in overcoming this problem that involves biochemical and physiological adaptations. Meanwhile, they can also excrete various substances that can enhance soil fertility and nutrient availability for plants. They excrete certain extracellular phosphatases immediately during P-limited conditions (Healy 1973).

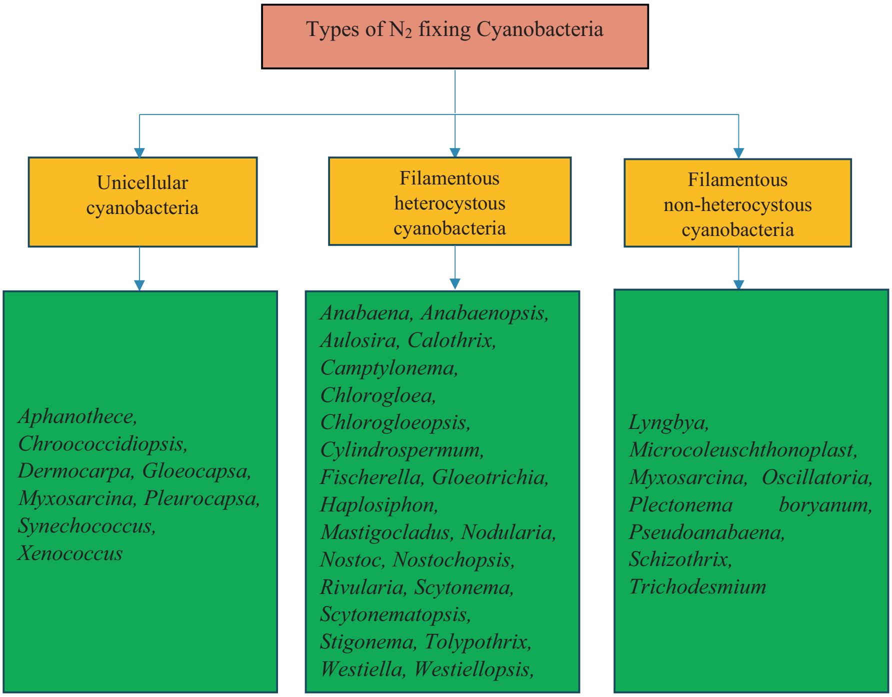


Fig. 13.1 Certain N_2-fixing cyanobacteria

Cyanobacterial biofertilizers can also excrete some other substance and change the pH of the surroundings, which in turn can make adsorbed P available (Grobbelaar 1983). Additionally, these biofertilizers can store sufficient P in excess to their basic needs.

Similarly, some cyanobacteria and other algae could produce and release iron-specific chelators, also called siderophores, which have the ability to make iron available to microorganisms and plants (Benderliev 1999). Moreover, they are also reported to enrich other microelements such as Cu, Co, Mn, Zn, etc. in plant parts (Das et al. 1991; Lange 1976).

13.4.1 Merits of Cyanobacterial Fertilizers

- Cyanobacteria enhance the diverse beneficial soil microorganisms, fertility of soil, plant-microbe associations.
- They can also inhibit or suppress several soilborne plant pathogens and parasites and protect the plant from diseases.
- Nutritional status is more balanced in these biofertilizers due to enhanced microbial activities.

- They improve and reclaim the soil nutrient status by increasing the organic matter content of these soils and regulate acidity, alkalinity, salinity, and fertility of soils.
- Enhances the diversity of soil methanotrophs and methane sink strength of these soils in the long term.

13.4.2 Demerits of Chemical Fertilizers

- Chemical fertilizers are nonrenewable, inhibit symbiotic N_2 fixation, and disturb plant-microbe associations by suppressing the useful soil microflora.
- Softening of plant tissues that result in increased susceptibility of plants to diseases and pathogens.
- Loss of nutrients from soil through fixation and leaching.
- Suppress the soil methanotroph number and methane sink potential.
- Soil and water deterioration, soil acidification or alkalization, reducing soil fertility, thereby causing damage to ecosystem and its stability.

13.5 Cyanobacteria: As Biocontrol Agents

The approach of sustainability in agriculture is not optimistic without admiring the methods used to suppress the infestation by insects or pests. The use of synthetic chemicals in agriculture systems for the control of insects, pests, fungi, and bacteria is connected with the severe effects on environment and human health. Thus, there is an increasing demand for biological-based alternative products where the role of microbes has been recognized in attaining long-term, durable, eco-friendly, and cost-effective food security. Cyanobacteria and other algae have been suggested as safe and efficient biocontrol agents (Bhatti et al. 2017; Gol'din 2012; Nassar et al. 1999; Schrader et al. 2002) that can be exploited for treating plant pathogens mainly associated with soilborne diseases. There are various species of cyanobacteria that have the ability to produce compounds that exhibit antifungal, insecticidal, nematocidal, cytotoxic, and herbicidal properties (Biondi et al. 2004). However, the role of secondary metabolites formed by these cyanobacteria in the management of phytopathogens and their execution in protection of agricultural yield is receiving a considerable attention (Kulik 1995; Singh et al. 2014). Several bioactive compounds that have the ability to kill or inhibit some useless microflora and fauna are alkaloids, amides, indoles, lipopeptides, and polyketides (Abarzua et al. 1999; Burja et al. 2001). These compounds inhibit the biochemical and physiological activities in the target species. Studies have shown that extracts of *Chlorococcum humicolum* inhibited the growth of *Botrytis cinerea* in strawberry and *Erysiphe polygoni* in tomato seedlings (Kulik 1995). A few cyanobacteria obtained from paddy fields have been reported to possess efficient antifungal activities against soilborne pathogens (Kim 2006) and also prevent vegetables and flowers from pathogenic fungi (Manjunath et al. 2010; Prasanna et al. 2013). A study revealed that inoculating rice fields with cyanobacterial biofertilizers can reduce the number of mosquitoes (Victor and Reuben 2000). Further, extracts from cyanobacteria have shown mosquito larvicidal properties (Singh et al. 2013). Some have been found useful in preventing root rot disease in cotton and also improve the plant rhizosphere (Babu et al. 2015). Microalgae extracts contain tocopherols, polyphenols, pigments, and oils that possess antimicrobial properties (Dewi et al. 2018).

Furthermore, formulations from cyanobacterial extracts are reported to suppress the growth of saprophytes like *Aspergillus oryzae*, *Chaetomium globosum*, and *Cunninghamella blakesleeana* and phytopathogens such as *Sclerotinia sclerotiorum* and *Rhizoctonia solani* (Kulik 1995). Certain researchers recorded that *Fischerella muscicola* produce a bioactive compound called fischerellin, with antifungal activities against phytopathogens like *Pyricularia oryzae* (rice blast), *Uromyces appendiculatus* (brown rust), *Erysiphe graminis* (powdery mildew), and *Phytophthora infestans*. However, it did not show any significant effect against *Monilinia fructigena* (brown rot) and *Pseudocercosporella herpotrichoides* (stem break) (Hagmann and Juttner 1996; Papke et al. 1997).

Extracts of toxins from cyanobacteria can be useful in fighting against leaf roller larvae and moth (Sathiyamoorthy and Shanmugasundaram 1996). Cyanobacterial species like *Nostoc muscorum* has been found effective against soil fungi, known to produce “damping off” disease (De Caire et al. 1990). *Sclerotinia sclerotiorum*, one of the deadly phytopathogens affecting members of family Compositae like lettuce (Lactuca sativa L.) and other species of rosette plants causing cottony rot of vegetables and flowers (Tassara et al. 2008), is suppressed by *N. muscorum*. Also, the extracts from *N. muscorum* inhibit the growth of the plant pathogen *Rhizoctonia solani* responsible for causing root and stem rots (Kulik 1995). *Nostoc* sp. is known as a potential producer of cryptophycin and a source of natural pesticides used against the insects, fungi, and nematodes (Biondi et al. 2004; Mushtaq et al. 2018). Furthermore, *N. muscorum* is also known to exhibit antagonistic effects against other fungi like *Aureobasidium*, *Alternaria*, and *Cladosporium* responsible for causing “wood blue stain” (grayish or bluish discoloration of sapwood). Thus, it is evident from the studies that several cyanobacterial strains and different formulations from them can be employed as biocontrol agents in the field of agriculture. However, current information about the biocontrol activities of cyanobacteria explains that only few experiments have been performed in the field conditions, while majority of experiments are performed under lab conditions. Therefore, a pervasive research is needed to determine the feasibility of cyanobacteria as a sustainable tool for biocontrol of several phytopathogens. Some cyanobacterial species exhibiting antagonistic effects against different plant pathogens are depicted in Fig. 13.2.

Extracts from certain cyanobacteria and other microalgae are reported to enhance plant defense enzyme activities, thereby increasing immunity of plants. Application of dry powder from microalgae and inoculation of cyanobacteria were found effec-

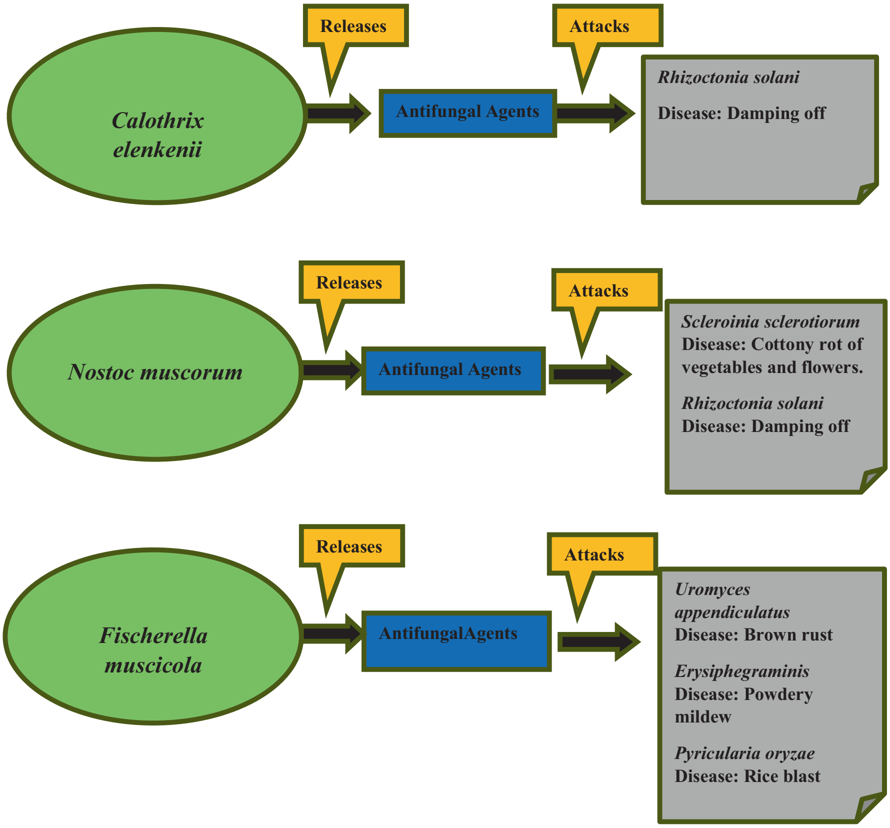


Fig. 13.2 Antagonistic effect of cyanobacterial species against plant pathogens

tive in reducing the gall formation and nematode infestation (Hamouda and El-Ansary 2017; Paracer 1987). In addition to their role as biocidal agents, certain cyanobacteria have been found to degrade organophosphorus and other chlorinated pesticides (Ibrahim et al. 2014; Kuritz 1998; Subramanian et al. 1994).

13.6 Cyanobacteria: As Plant Growth-Promoting Organisms

Besides contributing as biofertilizers, cyanobacteria play an important role in enhancing soil fertility in different ways by producing a combination of plant growth-promoting substances. They secrete extracellular plant growth-promoting chemicals, hormones such as auxin, abscisic acids, cytokinin, or gibberellins (Ahmad and Winter 1968; Marsalek et al. 1992; Rodgers et al. 1979; Singh and Trehan 1973). Studies have shown that some strains of cyanobacteria produce the growth regulators as intracellular metabolites, while others secrete these directly in the neighboring environment (Abdel-Raouf 2012). These hormones could serve as plant growth-promoting substances in agricultural systems which can activate certain cascades in plant metabolism that ultimately lead to improved growth, yield, and crop quality (Zhao et al. 2005). These hormones can also improve plant tolerance to different biotic and abiotic stresses (Marsalek et al. 1992). Inoculation of carious cyanobacterial strains in rice fields showed the presence of indole acetic acid (IAA) and indole butyric acid (IBA) (Li et al. 2018). It was observed that cyanobacterial extracts speed up the seed germination and seedling growth. Also, the crop yield and the quality of protein content were improved in these crops.

They are also reported to produce vitamins, particularly amino acids (Vorontsova et al. 1988), or vitamin B_{12} and biotin (Grieco and Desrochers 1978; Misra and Kaushik 1989a, b), antibiotics, and toxic substances. During the stressful environmental conditions, plants adjust the hormone production level to fight against various stresses (Peleg and Blumwald 2011).

13.6.1 Auxin (IAA/Indole-3-Acetic Acid)

Auxin is known to enhance plant rooting system, thus promoting the potential of roots to attain improved nutrients (Spaepen et al. 2007). *Anabaena*, *Calothrix*, *Chlorogloeopsis*, *Cylindrospermum*, *Glactothece*, *Nostoc*, *Plectonema*, *Synechocystis*, etc. are some of the cyanobacterial strains that produce auxin (Singh et al. 2016). Further, chromatography analysis of a substance obtained from *Nostoc muscorum* from rice fields exhibited auxinic activity and features like that of indole acetic acid. It has been observed that the synthesis of phytohormones in microalgae depends on the precursors, amino acids, from plants (Zhao 2012). For instance, auxin synthesis in cyanobacteria was observed only with the accumulation of tryptophan (Sergeeva et al. 2002).

13.6.2 Gibberellin

Anabaenopsis and *Cylindrospermum* are some of the gibberellin secreting cyanobacteria. Gibberellin plays a vital role in inhibiting and stimulating germination of seeds; it is needed to break dormancy of seeds. It has been reported that in the absence of exogenous gibberellin, gibberellin-deficient mutants fail to germinate (Gupta and Chakrabarty 2013). Gibberellin-like compound was found in *Phormidium foveolarum* which was active in GA bioassays (Gupta and Agarwal 1973). Increased protein content was observed in pea seeds when inoculated with cyanobacterial strains due to activation of certain metabolic processes caused by gibberellin (Osman et al. 2010).

13.6.3 Cytokinin

Cytokinin acts as a regulator for shoot development and a negative regulator for root development. Cytokinin also promotes cell division, enhances photosynthetic rate, as well as plays a vital role in the recognition of the shoot meristems. In roots, the rate of differentiation of meristematic cell is regulated by cytokinin (Werner et al. 2010). Meanwhile, cyanobacterial strains have been found to exude cytokinin-like substances (Strick et al. 1997). *Anabaena*, *Chlorogloeopsis*, and *Calothrix* are some of the cytokinin-secreting cyanobacteria (Singh et al. 2016). *Anabaena* sp., when inoculated in wheat fields, significantly stimulated shoot length, spike length, lateral root, and weight of grains.

13.6.4 ABA (Abscisic Acid)

It controls various aspects of plant development such as germination, cell division, elongation, embryo maturation, seed dormancy, and floral induction. It also confers the stress tolerance to crops under abiotic stresses (Finkelstein 2013). Blue-green algae have been found to produce abscisic-like substances that can improve growth and yield of crops. *Nostoc muscorum*, *Trichormus variabilis*, and *Synechococcus leopoliensis* are among the few ABA-producing cyanobacteria (Marsalek et al. 1992).

Nitrogen fixation by cyanobacteria is an important factor that maintains soil fertility. They can directly or indirectly benefit plants in one or other ways. Blue-green algae can bind soil particles due to the adhesive properties of mucilage exudates. Thus, they can reduce soil erosion and water loss from soils as well. There are reports which suggest that cyanobacteria may release biologically active compounds into the soil and may significantly enhance plant growth. Marine cyanobacterial species serve as an essential source of vitamin production on a large scale. *Spirulina* is an abundant source of thiamine, riboflavin, vitamin B12, and beta-carotene (Lau et al. 2015). Certain cyanobacteria such as *Nostoc calcicola*, *Anabaena oryzae*, and *Spirulina* reduced the galls in cowpea caused by *Meloidogyne* and enhanced the plant growth (Youssef and Ali 1998). Some reports emphasized that the inoculation of cyanobacteria in rice fields can improve seed germination and root and shoot growth (Misra and Kaushik 1989a, b). It has also been reported that cyanobacterial inoculation in wheat fields improved the dry weight and chlorophyll content of the plants (Obreht et al. 1993). Extracellular chemicals secreted by cyanobacteria and their colonization around wheat plant roots reveal profound effects on growth of plants, although the agronomic efficiency was not estimated (Gantar et al. 1995a, b). The rapid growth of cyanobacterial cells and essential nutritional requirements primarily CO_2, water, and sunlight furnish an extensive opportunity for the commercial application of cyanobacterial strains as plant growth regulators (Ruffng 2011).

Additionally, studies have shown that the treatment of paddy seedlings with the cyanobacterial filtrates of *Anabaena oryzae*, *N. calcicola*, *Microchaete tenera*, or *Cylindrospermum muscicola* had increased both shoot and root length (Mohamed 2001).

13.7 Sustainable Agriculture and Microbiome

The advanced fields of science have provided many sustainable agricultural practices for the improvement of crop productivity. The soil microbiome is responsible for various processes occurring in the environment that are related to the well-being of plants. Several functions are credited to soil microbiome in relation to plants, for example, their ability to provide nutrients (nitrogen fixation and phosphorus solubilization), their role in nutrient uptake, and their ability in plant protection by secreting various bioactive compounds. Microbes associated with plants offer a sustainable solution to overcome the problems connected with soil salinity, fertility, and land deterioration. Soil microbiomes are exceptional as they are directly involved in enhancing soil fertility, plant growth promotion, and lowering different biotic and abiotic stresses (Glick 2010). Cyanobacteria are important organisms that have a significant role in the maintaining soil fertility due to N_2 fixation, making them a suitable natural source for soil fertility enhancement (Song et al. 2005). Blue-green algae have a leading role in sustainable agriculture. Efficient N_2-fixing cyanobacteria like *Nostoc*, *Anabaena*, *Aulosira*, *Calothrix* sp., etc., have been applied to enhance rice cultivation across the different agroecological regions. The cyanobacterial applications have been practiced in paddy fields since ages, but now their use in various others crops is tested. Cyanobacteria also find its applications as in the production of phytohormones in free-living as well as in symbiotic associations. They perform a vital role in maintaining the structure and fertility of soils (Singh 2014; Singh et al. 2016; Vaishampayan et al. 2001) and in reusing the residues of crops and are involved in processing and preservation of crops (Hanson 1996; Saddler 1993). Activity of microbes in enhancing soil fertility, biocontrol, and bioremediation requires the influx of natural microbial or genetically engineered inoculants. Soil fertility maintenance with inexhaustible resources is the primary demand of sustainable agriculture by mitigating the requirement of chemical fertilizers. Among such resources, transgenic and natural N_2-fixing microorganisms are the important candidates. The N_2-fixing microbes can be used as coating on seeds or can be directly inoculated in soil. However, in both the cases, their acclimatization needs to be assured. Certain biosensors have been developed that can be used for manipulation, monitoring, and management of microbial consortia (Burlage and Kuo 1994).

The different metabolites produced by microorganisms have the competence to help in the establishment of sustainable agricultural practices, and biocompatible microbial polymers are the perfect example of it that must be used for coating of pesticides, fertilizers, and nutrients. This will aid in targeted delivery of pesticides, fertilizers, and nutrients in agriculture by hindering their application in certain industry or antisocial activities. Bioremediation of contaminated water and soil is a sustainable approach to convert wasteland into agricultural practices. Transgenic or natural N_2-fixing microorganisms in mixed cultures are used in different bioremediation practices and wasteland reclamation (Atlas 1995). Microbial interactions along with biogeochemical and ecological balances of affined ecosystems should be recognized for effective bioremediation of terrestrial and aquatic ecosystems (Anderson and Lovley 1997; Tiedje 1997). Among diverse valuable microorganisms, cyanobacteria can fix atmospheric N_2 and CO_2 and produce energy rich biomass containing various metabolites and other substances of economic importance. Therefore, they can be used in energy production, nutrition, and agricultural sectors. Also, advancements in cyanobacterial cultivation, screening, and genetic manipulations have facilitated new manners to use these photosynthetic microorganisms to combat various socioeconomic problems (Sarsekeyeva et al. 2015).

13.8 Cyanobacteria: A Sustainable Tool for Sustainable Agriculture

A serious focus in the last few decades has been put on the safe and eco-friendly approaches by exploiting the beneficial soil microbes in sustainable crop production. Cyanobacteria are known for their significant contribution in regulating the biogeochemical cycles of nitrogen, carbon, and oxygen (De Ruyter and Fromme 2008; Karl et al. 2002). They can fix atmospheric nitrogen in soil and root nodules, solubilize phosphate into usable forms, produce phytohormones and metabolites to uphold root growth, and decompose organic matter for soil mineralization. These features can increase the crop yields, enhance soil structure by aggregation of the soil particles, help in retaining water sources, and induce tolerance to various stresses in plants. They have undergone an array of structural and functional alterations during the evolution that allows their cosmopolitan distribution (Olson 2006). Cyanobacteria enhance the plant growth by improving nutrient uptake, form complex soil matrices, and help in plant defense response against various pathogens and diseases by secreting various metabolites and bioactive compounds. Additionally, they can improve the stress tolerance of plants against salt stress, drought stress, nutrient deficiency, weed infestation, and heavy metal contamination. Cyanobacteria can also help in soil formation processes, as they secrete certain biomolecules and other bioactive compounds. They have gained the attention of agriculturalists not only for their plant growth-promoting characters but also for their role in decomposing organic waste and detoxifying several toxic substances like pesticides and heavy metals (Aislabie and Deslippe 2013; Ma et al. 2016). For example, *Spirulina maxima* is known to acclimatize under high salinity and alkaline conditions (pH 11) that facilitate an advantage of protection from other competitors and grazers (Habib et al. 2008). The cyanobacterial ability of fixing nitrogen aids their survival and growth in the nitrogen-limiting habitats. This cyanobacterial trait makes them economically and agronomically vital as biofertilizers (Singh 2014; Vaishampayan et al. 2001).

Certain cyanobacterial species are known to create symbiotic associations with plants and other organisms. This ability of cyanobacteria could be exploited to develop suitable consortia of microbes for bioremediation of soil and water (Rai et al. 2000; Hamouda et al. 2016). Cyanobacterial exopolysaccharides (EPS) contribute to about 25 percent of the total biomass (Nisha et al. 2007). Cyanobacteria perform the activities in the upper crust of soil and the exopolysaccharide acts as a sticky agent for adhering to soil particles. The EPS can bind soil particles that lead to aggregation of soil particles, accumulation of organic content, and increase in water holding capacity of soil (Malamlssa et al. 2001). Therefore, it supports the growth and survival of other plant growth-promoting microbes. Also, the cyanobacterial growth rectifies the physical and chemical properties of soils. Cyanobacterial EPS and PGPRs may contribute to a positive alteration and reclamation of poor soils (Flaibani et al. 1989; Paul and Nair 2008).

The traditional agriculture practices rely on the input of chemical pesticides and fertilizers and methods like excessive irrigation and intensive tillage. This may lead to overexploitation of natural resources like water and soil, rise on the cost of agricultural production, and environmental pollution (Dar et al. 2016; Kumar et al. 2012a, b, c, d, e). Thus, there is a necessity to accept sustainable agricultural approaches that are eco-friendly and cost-effective and help us to attain long-term food security. An eco-friendly management practice for complex agroecosystems without interrupting the interactions among ecological components such as water, climatic, and edaphic factors including the living components supports the long-term increment for sustainable increase in crop productivity.

Cyanobacterial application (Fig. 13.3) contributes in economic benefits by reducing input costs, N_2-fixation, phosphorus mineralization, nutrient cycling, water storage, refrain pollution, and land deterioration especially through mitigating the utilization of agro-chemicals, nutrient recycling, and restoration of soil fertility (Shukia et al. 2008). Some of the benefits facilitated to the agroecosystem, by utilizing cyanobacteria, are presented below:

- Improved solubilization and motility of nutrients of limited supply
- Biocontrol of plant pathogens and diseases
- Detoxification of xenobiotics and heavy metals; restrict their motility and transport in plants
- Plant growth stimulation with the help of plant growth-promoting attributes
- Reclaiming the chemical and physical conditions of soils

13.9 Role of Cyanobacteria in Bioremediation

Industrial revolution has possibly brought growth in economy and social change globally. These changes have caused a number of environmental issues. Certain types of toxic industrial effluents released from fertilizer factories, oil refineries, dye industries, and other chemical industries may badly affect the environment

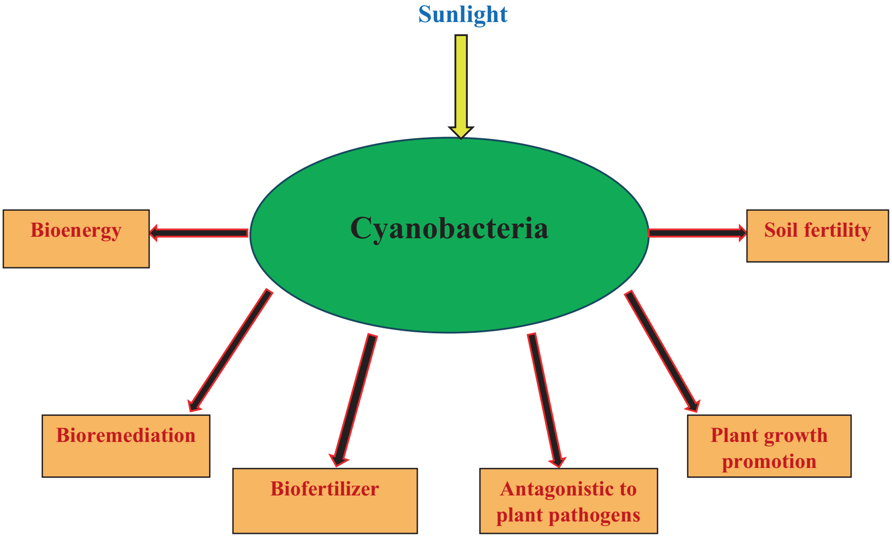


Fig. 13.3 Applications of cyanobacteria

and human health. However, traditional physical and chemical methods are extensively applied for removal of toxic pollutants, but these methods are not found effective and eco-friendly (Mallick 2002; Ruffng 2011). Cyanobacteria can be used as an effective tool for wasteland reclamation and combating various types of noxious pollutants like heavy metals (Rai et al. 1998; Singh et al. 2011b), pesticides (Megharaj et al. 1994), polycyclic aromatic hydrocarbons (Cerniglia et al. 1980a, b; Narro et al. 1992), xenobiotics (Megharaj et al. 1987), crude oil (Al-Hasan et al. 1998, 2001), phenol and catechol (Shashirekha et al. 1997), and radioactive compounds (Acharya et al. 2012) either through their agglomeration or degradation. They play a crucial role in the biodegradation of various industrial discharges including brewery and distilleries, paper and sugar mill, oil refinery, dye, and pharmaceutical industries because of their high potential of metal sorption and multiplication rate. They can be useful also in the treatment of wastewater and agro-industrial effluents (Singh et al. 2016; Vilchez et al. 1997). Certain cyanobacterial species have been observed to show biosorption of various heavy metals including *Spirulina platensis* for Ni, Cu, Cd, Pb, and Zn (Greene et al. 1987); *Nostoc calcicola* against Cu (Verma and Singh 1990); *Oscillatoria angustissima* for Zn and Cu (Ahuja et al. 1999); *Synechococcus* sp. for Ni, Cu, Cd, and Pb (Yee et al. 2004); and *Microcystis* for Cd and Ni (Pradhan and Rai 2000; Rai et al. 1998). *Phormidium bigranulatum*-dominated mats were found efficient in the removal of Cd(II), Pb(II), and Cu(II) from aqueous solutions (Kumar et al. 2012a, c; Kumar and Gaur 2014). Cyanobacteria exhibit a great range of tolerance against pesticides by accumulating them or via degradation mechanism (Ahmad and Venkatraman 1973; Pabbi and Vaishya 1992). Several cyanobacterial genera such as *Anabaena*, *Nodularia*, *Oscillatoria*, *Nostoc*, *Microcystis*, *Synechococcus*, and

Cyanothece possess a great potential for the elimination or biodegradation of lindane residues (i.e., g-hexachlorocyclohexane) (El-Bestawy et al. 2007; Kuritz and Wolk 1995). Kumar et al. (2010a, b) reported two pesticides 2,4-dichlorophenoxyacetic acid (2,4-D) and paraquat (PQ) have a potent sorbent known as *Oscillatoria* sp.-dominated cyanobacterial mat. Cyanobacterial microflora also increased transformation and biodegradation of some polycyclic aromatic hydrocarbons, organophosphorus compounds, and organic compounds. *Aulosira fertilissima* and *Nostoc* sp. have been found efficient for the biodegradation of organic compounds, and an extensive range of organochlorine and organophosphorus pesticides were biodegraded by *Anabaena* sp., *Nostoc* sp., *Lyngbya* sp., *Synechococcus elongates*, and *Microcystis* sp. (Forlani et al. 2008; Semple et al. 1999). *Synechocystis* sp. has been reported as an efficient tool for the mineralization of anilofos herbicide. Synthetic dyes are not readily degraded; they are mutagenic, toxic, and carcinogenic in nature and cause serious harmful effects to the environment. Several cyanobacterial species like *Oscillatoria rubescens*, *N. linckia*, and *L. lagerteimii* were demonstrated for the elimination of synthetic dyes. *Phormidium* sp. has been reported to biodegrade the extensive range of dyes like Ff sky blue, indigo, and acid red 119 (Dellamatrice et al. 2017). It is reported that certain cyanobacterial species like *Synechococcus* sp., *Oscillatoria salina*, *Aphanocapsa* sp., and *Plectonema terebrans* are helpful in biodegrading crude oil and other surfactants through forming mats in aquatic environments (Cohen 2002; Radwan and Al-Hasan 2000). Cyanobacterial species like *Agmenellum* sp. and *Oscillatoria* sp. were able to oxidize naphthalene into 1-naphthol and n-alkanes (Cerniglia et al. 1979; Cerniglia et al. 1980a). Besides this, the role of cyanobacterial mats in the elimination of several harmful dyes has been also recorded. Kumar et al. (2012b) have investigated that through the batch contact method, an *Oscillatoria* sp.-dominated cyanobacterial mat has efficiency for sorbing methylene blue (MB).

Studies have shown that several cyanobacteria such as *Spirulina laxissima*, *Oscillatoria geminata*, *Nostoc carneum*, and *Nostoc insulare* eliminated radioactive contaminants such as Ra, Cs, Am, and Sr (Pohl and Schimmack 2006), and uranium was also removed by *Anabaena torulosa* (Acharya et al. 2012) from radioactive pollutant contaminated sites. Table 13.2 shows the list of some cyanobacterial species in the elimination of heavy metals in various ecosystems.

The cyanobacterial species have a competence of biodegradation and can be raised through an emergent technology probably known as genetic engineering (Kuritz and Wolk 1995). This can be explored as a maintenance-free and eco-friendly bioremediation tool for befouled ecosystems. Many researches on remediation by genetically modified cyanobacterial species emphasize that it will provide a better future prospectus in the field of bioremediation of various environmental pollutants. The genetically engineered strains of *Anabaena* sp. became paramount in biodegrading both 4-chlorobenzoate and lindane pesticides. These modified *Anabaena* sp. strains were obtained by inserting *Arthrobacter globiformis* operon fcb ABC from plasmid pCH1 (known for biodegradation of halobenzoate) via triparental mating recombinant tool (Kaplan et al. 1994).

Table 13.2 Removal of heavy metals by some cyanobacterial species

Heavy metals	Cyanobacteria
Chromium	*N. calcicola*, *Chroococcus* sp.
Cobalt	*N. muscorum*, *Anabaena subcylindrica*
Cadmium	*Nostoc linckia*, *N. rivularis*, *Tolypothrix tenuis*
Copper	*N. muscorum*, *A. subcylindrica*
Zinc	*N. linckia*, *N. rivularis*
Lead	*N. muscorum*, *A. subcylindrica*, *Gloeocapsa* sp.
Manganese	*N. muscorum*, *A. subcylindrica*
Mercury	*Spirulina platensis*, *Aphanothece flocculosa*

13.10 Conclusion

Due to exponential rise in population, production of food in large quantities has become a problem for agricultural industries. To overcome this problem, industries have become dependent on chemical fertilizers and pesticides that are not only harmful for human consumption but affecting the soil fertility, reducing organic components, affecting the quality of crops, and causing soil and water pollution. Also, the excessive use of chemical fertilizers has caused several environmental problems such as greenhouse effect, ozone layer depletion, and acidification of water. Thus, there is an urgent need to adapt feasible and sustainable agricultural practices for sufficient cost-effective food production for the rising human population on a global scale that will use lesser energy and are eco-friendly. Thus, biofertilizers containing microbes like bacteria, fungi, and cyanobacteria are recommended as possible and sustainable solution for the large-scale agricultural practices which are natural, eco-friendly, and cost-effective and also maintain soil structure as well as biodiversity. In the last few decades, much attention has been paid toward the possibility of using algae as biological tool that can reduce the resultant soil pollution and in addition can also improve both soil structure and plant health. Cyanobacterial biofertilizers could be the perfect substitute to inorganic chemical fertilizers that can play an important role in maintaining the soil integrity and fertility, improving crop production, controlling plant pathogens, and stimulating plant growth. The reason to select cyanobacteria is that it can be maintained at low cost and under simple growth requirements. Plant growth-promoting substances produced by cyanobacteria can improve growth and development of plants, thereby production. They also produce bioactive compounds with anti-algal, antifungal, antibacterial, and antiviral properties and can suppress or inhibit the growth and activity of different plant pathogens. Blue-green algae have photosynthetic ability which when integrated with the other crop plants through genetic engineering can lead to the production of beneficial transgenic varieties. Cyanobacterial exopolysaccharide secretions improve the efficiency of soil by holding the soil particles together, adding carbon, phosphorus, and nitrogen to soil, refraining soil erosion as well. The present chapter emphasized on the role of cyanobacteria in soil fertility, enhancing soil nutritional status and reclamation of soils. All these unprecedented applications of cyanobacterial species suggest their use as a sustainable microbiome in agriculture.

Despite the fact that considerable amount of information has been gathered on the beneficial effects of several strains of cyanobacteria, very little is known about their abundance, periodicity, and succession in the rice field.

References

Abarzua S, Jakubowski S, Eckert S, Fuchs P (1999) Biotechnological investigation for the prevention of marine biofouling II. Blue-green algae as potential producers of biogenic agents for the growth inhibition of microfouling organisms. Bot Mar 42:459–465

Abdel-Raouf N (2012) Agricultural importance of algae. Afr J Biotechnol 11:11648–11658. https://doi.org/10.5897/AJB11.3983

Acharya C, Chandwadkar P, Apte SK (2012) Interaction of uranium with a filamentous, heterocystous, nitrogen-fixing cyanobacterium, Anabaena torulosa. Bioresour Technol 116: 290–294

Ahmad MH, Venkatraman GS (1973) Tolerance of Aulosira fertilissima to pesticides. Curr Sci 42:108

Ahmad MR, Winter A (1968) Studies on the hormonal relationships of algae in pure culture. I. the effect of indole-3-acetic acid on the growth of blue-green and green algae. Planta 78: 277–286

Ahuja P, Gupta R, Saxena RK (1999) Zn^{2+} biosorption by Oscillatoria anguistissima. Process Biochem 34(1):77–85

Aislabie J, Deslippe JR (2013) Soil microbes and their contribution to soil services. In: Dymond JR (ed) Ecosystem services in New Zealand-conditions and trends. Manaaki Whenua Press, Lincoln, pp 143–161

Aitken JB, Senn TL (1965) Seaweed products as a fertilizer and soil conditioner for horticultural crops. Bot Mar 8(1):144–147

Aiyer RS, Sulahudean S, Venkataraman GS (1972) Long-term algalization field trial with high yielding rice varieties. Indian J Agric Sci 42:380–383

Aktar W, Sengupta D, Chowdhury A (2009) Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip Toxicol 2(1):1–12

Al-Hasan RH, Al-Bader DA, Sorkhoh NA, Radwan SS (1998) Evidence for n-alkane consumption and oxidation by filamentous cyanobacteria from oil-contaminated coasts of the Arabian Gulf. Mar Biol 130:521–527

Al-Hasan RH, Khanafer M, Eliyas M, Radwan SS (2001) Hydrocarbon accumulation by picocyanobacteria from the Arabian Gulf. J Appl Microbiol 91(3):533–540

Anderson RT, Lovley JR (1997) Ecology and biogeochemistry of in situ ground water bioremediation. Adv Microbial Ecol 15:289–350

Atlas RM (1995) Bioremediation. Chem Eng News 3:32–42. p 032

Babu S, Bidyarani N, Chopra P, Monga D, Kumar R, Prasanna R, Kranthi S, Saxena AK (2015) Evaluating microbe-plant interactions and varietal differences for enhancing biocontrol efficacy in root rot disease challenged cotton crop. Eur J Plant Pathol 142:345–362. https://doi.org/10.1007/s10658-015-0619-6

Benderliev K (1999) Algae and cyanobacteria release organic chelators in the presence of inorganic Fe(III) thus keeping iron dissolved. Bulgarian J Plant Physiol 25:65–75

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds)

Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman MM, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide Techniques To Remediate Pesticides In Polluted Ecosystems. In: Wani KA (ed) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Mamta, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Biondi N, Piccardi R, Margheri MC, Rodolfi L, Smith GD, Tredici MR (2004) Evaluation of Nostoc strain ATCC 53789 as a potential source of natural pesticides. Appl Environ Microbiol 70:3313–3320

Boone DR, Castenholz RW (2001) The Archaea and the deeply branching and phototrophic bacteria. In: Garrity GM (ed) Bergey's manual of systematic bacteriology, 2nd edn. Springer-Verlag, New York, pp 33–38

Burja AM, Banaigs B, Abou-Mansour E, Burgess JG, Wright PC (2001) Marine cyanobacteria – a prolific source of natural products. Tetrahedron 57:9347–9377

Burlage RS, Kuo CT (1994) Living biosensors for the management and manipulation of microbial consortia. Ann Rev Microbiol 48:291–301

Castenholz RW (1978) The biogeography of hot spring algal through enrichment cultures. Mitt Int Ver Limnol 21:296–315

Cerniglia CE, Gibson DT, Van Baalen C (1979) Algal oxidation of aromatic hydrocarbons: formation of 1-naphthol from naphthalene by Agmenellum quadruplicatum, strain PR-6. Biochem Biophys Res Commun 88(1):50–58

Cerniglia CE, Gibson DT, Baalen CV (1980a) Oxidation of naphthalene by cyanobacteria and microalgae. J Gen Microbiol 116:495–500

Cerniglia CE, Van Baalen C, Gibson DT (1980b) Oxidation of biphenyl by the cyanobacterium, Oscillatoria sp., strain JCM. Arch Microbiol 125(3):203–207

Cohen Y (2002) Bioremediation of oil by marine microbial mats. Int Microbiol 5(4):189–193

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecologia Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dar GH, Bhat RA, Kamili AN, Chishti MZ, Qadri H, Dar R, Mehmood MA (2020) Correlation between pollution trends of fresh water bodies and bacterial disease of fish fuana. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 51–68

Das SC, Mandal B, Mandal LN (1991) Effect of growth and subsequent decomposition of bluegreen algae on the transformation of iron and manganese in submerged soils. Plant Soil 138:75–84. https://doi.org/10.1007/BF00011810

De Caire GZ, De Cano MS, De Mule MCZ, De Halperin DR (1990) Antimycotic products from the cyanobacterium Nostoc muscorum against Rhizoctonia solani. Phyton 51:1–4

De Ruyter YS, Fromme P (2008) Molecular structure of the photosynthetic apparatus. In: Herrero A, Flores E (eds) The cyanobacteria, molecular biology, genomics and evolution. Caister Academic Press, Norfolk, pp 217–269

Dellamatrice PM, Silva-Stenico ME, de Moraes LAB, Fiore MF, Monteiro RTR (2017) Degradation of textile dyes by cyanobacteria. Braz J Microbiol 48(1):25–31

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Dewi IC, Falaise C, Hellio C, Bourgougnon N, Mouget J-L (2018) Chapter 12 – anticancer, antiviral, antibacterial, and antifungal properties in microalgae. In: Levine IA, Fleurence J (eds) Microalgae in health and disease prevention. Academic Press, London, pp 235–261

Dong W, Zhang X, Wang H, Dai X, Sun X, Qiu W, Yang F (2012) Effect of different fertilizer application on the soil fertility of paddy soils in red soil region of southern China. PLoS One 7(9):e44504

Du Jardin P (2015) Plant biostimulants: definition, concept, main categories and regulation. Sci Hort 196:3–14

El-Bestawy EA, Abd El-Salam AZ, Mansy AERH (2007) Potential use of environmental cyanobacterial species in bioremediation on lindane-contaminated effluents. Int Biodeterior Biodegrad 59:180–192

Ernst B, Neser S, O'Brien E, Hoeger SJ, Dietrich DR (2006) Determination of the filamentous Cyanobacteria Planktothrix rubescens in environmental water samples using an image processing system. Harmful Algae 5(3):281–289

Finkelstein R (2013) Abscisic acid synthesis and response. Arabidopsis Book/American Society of Plant Biologists 11:e0166

Flaibani A, Olsen Y, Painter TJ (1989) Polysaccharides in desert reclamation: composition of exocellular proteoglycan complexes produced by filamentous blue-green and unicellular green edaphic algae. Carbohydr Res 190:235–248

Fogg GE (1956) The comparative physiology and biochemistry of the blue-green algae. Bacteriol Rev 20:148–165

Forlani G, Pavan M, Gramek M, Kafarski P, Lipok J (2008) Biochemical bases for a widespread tolerance of cyanobacteria to the phosphonate herbicide glyphosate. Plant Cell Physiol 49(3):443–456

Gantar M, Kerby NW, Rowell P, Obreht Z, Scrimgeour R (1995a) Colonization of wheat (Triticum vulgare L.) by N2-fixing cyanobacteria. IV. Dark nitrogenase activity and effects of cyanobacteria on natural 15N abundance on plants. New Phytol 129:337–343

Gantar M, Rowell P, Kerby NW, Sutherland IW (1995b) Role of extracellular polysaccharide in the colonization of wheat (Triticum vulgare L.) roots by N2- fixing cyanobacteria. Biol Fertil Soils 19:41–48

Giovannoni SJ, Turner S, Olsen GJ, Barnes S, Lane DJ, Pace NR (1988) Evolutionary relationships among cyanobacteria and green chloroplast. J Bacteriol 170:3584–3592

Glick BR (2010) Using soil bacteria to facilitate phytoremediation. Biotechnol Adv 28: 367–374

Gol'din E (2012) Biologically active microalgae and cyanobacteria in nature and marine biotechnology. Turk J Fish Aquat Sci 12:423–427

Greene B, McPherson R, Darnall D (1987) Algal sorbents for selective metal ion recovery. In: Metals speciation, separation, and recovery. Lewis Publishers, Chelsea, pp 315–332, 12 fig, 1 tab, 13 ref.

Grieco E, Desrochers R (1978) Production de vitamine B12 par une algae blue. Can J Microbiol 24:1562–1566

Grobbelaar JU (1983) Availability to algae of N and P adsorbed on suspended solids in turbid waters of the Amazon River. Arch Hydrobiol 96:302–316

Guerrero MG, Vega JM, Losada M (1981) The assimilatory nitrate reducing system and its regulation. Annu Rev Plant Physiol 32:168–204

Gupta AB, Agarwal PR (1973) Extraction, isolation and bioassay of a gibberellin-like substance from *Phormidium foveolaru*m. Ann Bot 37(152):737–741

Gupta R, Chakrabarty SK (2013) Gibberellic acid in plant: still a mystery unresolved. Plant Signal Behav 8(9):e25504

Habib MAB, Parvin M, Huntington TC, Hasan MR (2008) A review on culture, production and use of Spirulina as food for humans and feeds for domestic animals and fish. Food and Agriculture Organization of the United Nations, Rome

Hagmann L, Juttner F (1996) Fischerellin A, a novel photosystem-II inhibiting allelochemical of the cyanobacterium Fischerella muscicola with antifungal and herbicidal activity. Tetrahedron Lett 37:6539–6542

Hamouda RA, El-Ansary MSM (2017) Potential of plant-parasitic nematode control in banana plants by microalgae as a new approach towards resistance. Egypt J Biol Pest Control 27:165–172

Hamouda RAEF, Sorour NM, Yeheia DS (2016) Biodegradation of crude oil by Anabaena oryzae, Chlorella kessleri and its consortium under mixotrophic conditions. Int Biodeterior Biodegrad 112:128–134

Hanson D (1996) Biotechnology is future path for crop protection. Chem Eng News 74(20): 22–22

Healy FP (1973) Characteristics of phosphorus deficiency in *Anabaena*. J Phycol 9:383–394

Hegde DM, Dwiwedi BS, Babu SNS (1999) Biofertilizers for cereal production in India: a review. Indian J Agric Sci 69:73–83

Hitzfeld BC, Höger SJ, Dietrich DR (2000) Cyanobacterial toxins: removal during drinking water treatment, and human risk assessment. Environ Health Perspect 108:113–122

Ibrahim W, Karam M, El-Shahat RM, Adway AA (2014) Biodegradation and utilization of organophosphorus pesticide malathion by Cyanobacteria. Biomed Res Int 2014:392682

Issa AA, Abd-Alla MH, Ohyama T (2014) Nitrogen fixing cyanobacteria: future prospect. Adv Biol Ecol Nitrogen Fixation 2:23

Kaplan A, Schwarz R, Lieman-Herwitz J, Reinhold L (1994) Physiological and molecular studies on the response of cyanobacteria to changes in the ambient inorganic carbon concentration. In: Bryant DA (ed) The molecular biology of cyanobacteria. Advances in photosynthesis, vol 1. Springer, Dordrecht, pp 469–485

Karl D, Michaels A, Bergman B, Capone D, Carpenter E, Letelier R, Stal L (2002) Dinitrogen fixation in the world's oceans. In: The nitrogen cycle at regional to global scales. Springer, Dordrecht, pp 47–98

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kim J-D (2006) Screening of Cyanobacteria (Blue-Green algae) from rice paddy soil for antifungal activity against plant pathogenic fungi. Mycobiology 34:138–142. https://doi.org/10.4489/MYCO.2006.34.3.138

Kulik MM (1995) The potential for using cyanobacteria (blue-green algae) and algae in the biological control of plant pathogenic bacteria and fungi. Eur J Plant Path 101:585–599

Kumar G, Bawaja P (2018) Biofertilizer: a tool for sustainable agriculture in changing environment. In: Ansari MW, Kumar S, Kaula BC, Wattal RK (eds) Introduction to challenges and strategies to improve crop productivity in changing environment. R.K. Enriched Public Pvt. Ltd, Dwarka, pp 83–92

Kumar D, Gaur JP (2014) Growth and metal removal potential of a Phormidium bigranulatum-dominated mat following long-term exposure to elevated levels of copper. Environ Sci Pollut Res 21:10279–10285

Kumar D, Prakash B, Pandey LK, Gaur JP (2010a) Sorption of paraquat and 2,4-D by Oscillatoria sp.-dominated cyanobacterial mat. Appl Biochem Biotechnol 160:2475–2485

Kumar K, Mella-Herrera RA, Golden JW (2010b) Cyanobacterial heterocyst. Cold Spring Harb Perspect Biol 2(4):a000315

Kumar G, Baweja P, Sahoo D (2012a) Seaweeds: a potential source of biofertilizer. In: Sahoo DB, Kaushik BD (eds) Algal biotechnology and environment. I.K. International, New Delhi, pp 43–52

Kumar M, Bauddh K, Sainger M, Sainger PA, Singh JS, Singh RP (2012b) Increase in growth, productivity and nutritional status of rice (Oryza sativa L. cv. Basmati) and enrichment in soil fertility applied with an organic matrix entrapped urea. J Crop Sci Biotechnol 15:137–144

Kumar D, Rai J, Gaur JP (2012c) Removal of metal ions by Phormidium bigranulatum (Cyanobacteria)-dominated mat in batch and continuous flow systems. Bioresour Technol 104:202–207

Kumar D, Singh A, Pandey LK, Gaur JP (2012d) Sorption of methylene blue by an Oscillatoria sp.-dominated cyanobacterial mat. Biorem J 16(1):48–56

Kumar D, Yadav A, Gaur JP (2012e) Growth, composition and metal removal potential of a Phormidium bigranulatum dominated mat at elevated levels of cadmium. Aquat Toxicol 116:24–33

Kuritz T (1998) Cyanobacteria as agents for the control of pollution by pesticides and chlorinated organic compounds. J Appl Microbiol 85:186S–192S. https://doi.org/10.1111/j.1365-2672.1998.tb05298.x

Kuritz T, Wolk CP (1995) Use of filamentous cyanobacteria for biodegradation of organic pollutants. Appl Environ Microbiol 61(3):1169

Lange W (1976) Speculations on a possible essential function of the gelatinous sheath of blue-green algae. Can J Microbiol 22:1181–1185

Lau NS, Matsui M, Abdullah AAA (2015) Cyanobacteria: photoautotrophic microbial factories for the sustainable synthesis of industrial products. BioMed Res Int 2015:1–9

Li SW, Zeng XY, Leng Y, Feng L, Kang XH (2018) Indole-3-butyric acid mediates antioxidative defense systems to promote adventitious rooting in mung bean seedlings under cadmium and drought stresses. Ecotoxicol Environ Saf 161:332–341. https://doi.org/10.1016/j.ecoenv.2018.06.003

Ma Y, Oliveira RS, Freitas H, Zhang C (2016) Biochemical and molecular mechanisms of plant-microbe-metal interactions: relevance for phytoremediation. Front Plant Sci 10(3389):00918

Mahanty T, Bhattacharjee S, Goswami M, Bhattacharyya P, Das B, Ghosh A, Tribedi P (2017) Biofertilizers: a potential approach for sustainable agriculture development. Environ Sci Pollut Res 24(4):3315–3335

Malamlssa OL, Bissonnais Y, Defarge C, Trichet J (2001) Role of a cyanobacterial cover on structural stability of sandy soils in the Sahelian part of western Niger. Geoderma 101:15–30

Malik FR, Ahmed S, Rizki YM (2001) Utilization of lignocellulosic waste for the preparation of nitrogenous biofertilizer. Pak J Biol Sci 4(4):1217–1220

Mallick N (2002) Biotechnological potential of immobilized algae for wastewater N, P and metal removal: a review. Biometals 15:377–390

Manjunath M, Prasanna R, Nain L, Dureja P, Singh R, Kumar A, Jaggi S, Kaushik BD (2010) Biocontrol potential of cyanobacterial metabolites against damping off disease caused by *Pythium aphanidermatum* in solanaceous vegetables. Arch Phytopathol Plant Prot 43:666–677. https://doi.org/10.1080/03235400802075815

Marsalek B, Zahradnickova H, Hronkova M (1992) Extracellular abscisic acid produced by cyanobacteria under salt stress. J Plant Physiol 139:506–508

Megharaj M, Venkateswarlu K, Rao AS (1987) Metabolism of monocrotophos and quinalphos by algae isolated from soil. Bull Environ Contam Toxicol 39(2):251–256

Megharaj M, Madhavi DR, Sreenivasulu C, Umamaheswari A, Venkateswarlu K (1994) Biodegradation of methyl parathion by soil isolates of microalgae and cyanobacteria. Bull Environ Contam Toxicol 53(2):292–297

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Metting B (1988) Microalgae in agriculture. In: Borowitzka MA, Borowitzka LJ (eds) Micro-Algal biotechnology. Cambridge University Press, Cambridge, pp 288–304

Misra S, Kaushik BD (1989a) Growth promoting substances of cyanobacteria. I. Vitamins and their influence on rice plant. Proc Indian Sci Acad 55:295–300

Misra S, Kaushik BD (1989b) Growth promoting substances of cyanobacteria II: detection of amino acids, sugars and auxins. Proc Ind Natl Sci Acad 6:499–504

Mohamed AMA (2001) Studies on some factors affecting production of algal biofertilizers. MSc thesis, Faculty of Agriculture Engineering, Al-Azhar University, Cairo, Egypt

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, pp 152–178

Narro ML, Cerniglia CE, Van BC, Gibson DT (1992) Metabolism of phenanthrene by the marine cyanobacterium Agmenellum quadruplicate PR-6. Appl Environ Microbiol 58:1351–1359

Nassar MM, Hafez ST, Nagaty IM, Khalaf SA (1999) The insecticidal activity of cyanobacteria against four insects, two of medical importance and two agricultural pests with reference to the action on albino mice. J Egypt Soc Parasitol 29:939–949

Nisha R, Kaushik A, Kaushik CP (2007) Effect of indigenous cyanobacterial application on structural stability and productivity of an organically poor semi-arid soil. Geoderma 138:49–56

Obreht Z, Kerby NW, Gantar M, Rowell P (1993) Effects of root associated N2-fixing cyanobacteria on the growth and nitrogen content of wheat (Triticum vulgare L.) seedlings. Biol Fertil Soils 15:68–72

Olson JM (2006) Photosynthesis in the Archean era. Photosynth Res 88:109–117

Osman MEH, El-Sheekh MM, El-Naggar AH, Gheda SF (2010) Effect of two species of cyanobacteria as biofertilizers on some metabolic activities, growth, and yield of pea plant. Biol Fertil Soils 46:861–875. https://doi.org/10.1007/s00374-010-0491-7

Pabbi S, Vaishya AK (1992) Effect of insecticides on cyanobacterial growth and nitrogen fixation. In: Kaushik BD (ed) Proceeding of the 1992 National Symposium on cyanobacterial nitrogen fixation. Indian Agriculture Research Institute, New Delhi, pp 389–493

Papke U, Gross EM, Francke W (1997) Isolation, identification and determination of the absolute configuration of Fischerellin B. a new algicide from the freshwater cyanobacterium Fischerellin muscicola (Thuret). Tetrahedron Lett 38:379–382

Paracer S (1987) Effective use of marine algal products in the management of plant-parasitic nematodes. J Nematol 19:194

Paul D, Nair S (2008) Stress adaptations in a plant growth promoting rhizobacterium (PGPR) with increasing salinity in the coastal agricultural soils. J Basic Microbiol 48:378–384

Peleg Z, Blumwald E (2011) Hormone balance and abiotic stress tolerance in crop plants. Curr Opin Plant Biol 14(3):290–295

Pfennig N (1969) Rhodopseudomonas acidophila, sp. n., a new species of the budding purple non sulfur bacteria. J Bacteriol 99:597–602

Pfennig N (1974) Rhodopseudomonas globformis, sp. n., a new species of the Rhodospirillaceae. Arch Microbiol 100:197–206

Pohl P, Schimmack W (2006) Adsorption of radionuclides (134Cs, 85Sr, 226Ra, 241Am) by extracted biomasses of cyanobacteria (Nostoc carneum, N. insulare, Oscillatoria geminata and Spirulina laxissima) and Phaeophyceae (Laminaria digitata and L. japonica; waste products from alginate production) at different pH. J Appl Phycol 18:135–143

Pradhan S, Rai LC (2000) Optimization of flow rate, initial metal ion concentration and biomass density for maximum removal of Cu^{2+} by immobilized Microcystis. World J Microbiol Biotechnol 16:579–584

Prasanna R, Sharma E, Sharma P, Kumar A, Kumar R, Gupta V, Pal RK, Shivay YS, Nain L (2013) Soil fertility and establishment potential of inoculated cyanobacteria in rice crop grown under non flooded conditions. Paddy Water Environ 11(1–4):175–183

Radwan SS, Al-Hasan RH (2000) Oil pollution and cyanobacteria. In: The ecology of cyanobacteria. Kluwer Academic Publishers, New York, pp 307–319

Rai LC, Singh S, Pradhan S (1998) Biotechnological potential of naturally occurring and laboratory grown Microcystis in biosorption of Ni^{2+} and Cd^{2+}. Curr Sci 74:461–463

Rai AN, Söderbäck E, Bergman B (2000) Cyanobacterium-plant symbioses. New Phytol 147:449–481

Rashid A, Bhat RA, Qadri H, Mehmood MA (2019) Environmental and socioeconomic factors induced blood lead in children: an investigation from Kashmir, India. Environ Monit Assess 191(2):76. https://doi.org/10.1007/s10661-019-7220-y

Rippka R, Deruelles J, Waterbury JB, Herdman M, Stanier RY (1979) Generic assignments, strain histories and properties of pure cultures of cyanobacteria. J Gen Microbiol 111:1–61

Rodgers GA, Bergman B, Henriksson E, Udris M (1979) Utilization of blue-green algae as biofertilizers. Plant Soil 52:99–107

Rogers SL, Burns RG (1994) Changes in aggregate stability, nutrient status, indigenous microbial populations and seedling emergence following inoculation of soil with Nostoc muscorum. Biol Fertil Soils 18:209–215

Ruffng AM (2011) Engineered cyanobacteria: teaching an old bug new tricks. Bioeng Bugs 2(3):136–149

Saddler JN (1993) Bioconversion of forest and agricultural plant residues. CAB International, Wallingford, p 394

Sánchez-Baracaldo P, Hayes PK, Blank CE (2005) Morphological and habitat evolution in the Cyanobacteria using a compartmentalization approach. Geobiology 3:145–166

Sarma MK, Kaushik S, Goswami P (2016) Cyanobacteria: a metabolic power house for harvesting solar energy to produce bio-electricity and biofuels. Biomass Bioenergy 90: 187–201

Sarsekeyeva F, Zayadan BK, Usserbaeva A, Bedbenov VS, Sinetova MA, Los DA (2015) Cyanofuels: biofuels from cyanobacteria. Reality and perspectives. Photosynth Res 125: 329–340

Sathiyamoorthy P, Shanmugasundaram S (1996) Preparation of cyanobacterial peptide toxin as a biopesticide against cotton pests. Appl Microbiol Biotechnol 46:511–513. https://doi.org/10.1007/s002530050852

Savci S (2012) An agricultural pollutant: chemical fertilizer. Int J Environ Sci Dev 3(1):73

Schrader KK, Nagle DG, Wedge DE (2002) Algal and cyanobacterial metabolites as agents for pest management. In: Upadhyay RK (ed) Advances in microbial toxin research and its biotechnological exploitation. Springer, Boston, pp 171–195

Semple KT, Cain RB, Schmidt S (1999) Biodegradation of aromatic compounds by microalgae. FEMS Microbiol Lett 170(2):291–300

Sergeeva E, Liaimer A, Bergman B (2002) Evidence for production of the phytohormone indole-3-acetic acid by cyanobacteria. Planta 215:229–238

Shashirekha S, Uma L, Subramanian G (1997) Phenol degradation by the marine cyanobacterium Phormidium valderianum BDU-30501. J Ind Microbiol Biotechnol 19:130–133

Shukia SP, Singh JS, Kashyap S, Giri DD, Kashyap AK (2008) Antarctic cyanobacteria as a source of phycocyanin: an assessment. Ind J Marine Sci 37:446–449

Singh JS (2014) Cyanobacteria: a vital bio-agent in eco-restoration of degraded lands and sustainable agriculture. Clim Change Environ Sustain 2:133–137

Singh SP, Montgomery BL (2011) Determining cell shape: adaptive regulation of cyanobacterial cellular differentiation and morphology. Trends Microbiol 19(6):278–285

Singh VP, Trehan T (1973) Effects of extracellular products of Aulosira fertilissuna on the growth of rice seedlings. Plant Soil 38:457–464

Singh JS, Pandey VC, Singh DP (2011a) Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. Agric Ecol Environ 140:339–353

Singh RP, Bauddh K, Sainger M, Singh JS, Jaiwal PK (2011b) Nitrogen use efficiency in higher plants under drought, high temperature, salinity and heavy metal contaminations. In: Jain V, Kumar AP (eds) Nitrogen use efficiency in higher plants. New Delhi Publishing Agency, New Delhi, pp 99–123

Singh H, Ahluwalia AS, Khattar JS (2013) Induction of sporulation by different nitrogen sources in Anabaena naviculoides, a Diazotrophic strain capable of colonizing paddy field soil of Punjab (India). Vegetos 26(1):283–292

Singh N, Dhar DW, Tabassum R (2014) Review: role of cyanobacteria in crop protection. Proc Natl Acad Sci U S A. https://doi.org/10.1007/s40011-014-0445-1

Singh JS, Kumar A, Rai AN, Singh DP (2016) Cyanobacteria: a precious bio-resource in agriculture, ecosystem, and environmental sustainability. Front Microbiol 7:529

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Song T, Martensson L, Eriksson T, Zheng W, Rasmussen U (2005) Biodiversity and seasonal variation of the cyanobacterial assemblage in a rice paddy field in Fujian, China. FEMS Microbiol Ecol 54:131–140

Spaepen S, Vanderkyden J, Remans R (2007) Indole-3- acetic acid in microbial and microorganism – plant signaling. FEMS Microbiol Rev 31:425–448

Strick WA, Staden JV, Van-Staden J (1997) Screening of some South African seaweeds for cytokinin-like activity. South Afr J Bot 63(3):161–164

Subramanian G, Sundaram SS (1986) Induced ammonia release by the nitrogen fixing cyanobacterium Anabaena. FEMS Microbiol Lett 37:151–154

Subramanian G, Sekar S, Sampoornam S (1994) Biodegradation and utilization of organophosphorus pesticides by cyanobacteria. Int Biodeterior Biodegradation 33:129–143. https://doi.org/10.1016/0964-8305(94)90032-9

Tassara C, Zaccaro MC, Storni MM, Palma M, Zulpa G (2008) Biological control of lettuce white mold with cyanobacteria. Int J Agric Biol 10:487–492

Tiedje JM (1997) Environmental biotechnology. Curr Opin Biotechnol 8:267

Tomitani A, Knoll AH, Cavanaugh CM, Ohno T (2006) The evolutionary diversification of cyanobacteria: molecular phylogenetic and paleontological perspectives. Proc Natl Acad Sci U S A 103:5442–5447

Turner S (1997) Molecular systematics of oxygenic photosynthetic bacteria. Plant Systemat Evol 11:13–52

Turner S, Pryer KM, Miao VPW, Palmer JD (1999) Investigating deep phylogenetic relationships among cyanobacteria and plastids by small submit rRNA sequence analysis. J Euk Microbiol 46:327–338

Vaishampayan A, Sinha RP, Hader DP, Dey T, Gupta AK, Bhan U, Rao AL (2001) Cyanobacterial biofertilizers in rice agriculture. Bot Rev 67(4):453–516

Verma SK, Singh SP (1990) Factors regulating copper uptake in cyanobacteria. Curr Microbiol 21:33–37

Victor TJ, Reuben R (2000) Effects of organic and inorganic fertilisers on mosquito populations in rice fields of southern India. Med Vet Entomol 14:361–368

Vilchez C, Garbayo I, Lobato MV, Vega J (1997) Microalgae-mediated chemicals production and wastes removal. Enzym Microb Technol 20(8):562–572

Vorontsova GV, Romansova NI, Postnova TI, Selykh IO, Gusev MV (1988) Bio-stimulating effect of cyanobacteria and ways to increase it. I. Use of nutrients – super products of amino acids. Moscow Univer Bio. Sci Bull 43:14–19

Werner T, Nehnevajova E, Kollmer I, Novak O, Strnd M, Kramer U, Schmulling T (2010) Root-specific reduction of cytokinin causes enhanced root growth, drought tolerance, and leaf mineral enrichment in Arabidopsis and Tobacco. Plant Cell 22:3905–3920

Yee N, Benning LG, Phoenix VR, Ferris FG (2004) Characterization of metal-cyanobacteria sorption reactions: a combined macroscopic and infrared spectroscopic investigation. Environ Sci Technol 38:775–782

Youssef MMA, Ali MS (1998) Management of Meloidogyne incognita infecting cowpea by using some native blue-green algae. Anz Schädlingskunde, Pflanzenschutz, Umweltschutz 71(1):15–16

Zhao Y (2012) Auxin biosynthesis: a simple two-step pathway converts tryptophan to indole-3-acetic acid in plants. Mol Plant 5:334–338

Zhao J, Davis LC, Verpoorte R (2005) Elicitor signal transduction leading to production of plant secondary metabolites. Biotechnol Adv 23:283–333

Chapter 14
Intercropping: A Substitute but Identical of Biofertilizers

Muhammad Khashi u Rahman, Zahoor Hussain, Xingang Zhou, Irfan Ali, and Fengzhi Wu

14.1 Introduction

The growing human population is expected to reach around nine billion by the mid of the twenty-first century (Gerland et al. 2014). To successfully meet the need of fast-growing population, it is predicted to double the crop production figure of 2005 (Tilman et al. 2011). Although this goal seems pretty unachievable with limited environmental impacts, this challenge can be met through intensification of agriculture. By proper land management practices and increasing yield per capita of some cereal and vegetable crops, researchers have granted human to cope with growing population and reduced the number of unnourished people as compared to the nineteenth century (Pingali 2012). However, current infrastructure of agriculture sector and poor land management practices in underdeveloped and many developing countries are proving quite challenging to ensure the future global food security. The gluttonous desire of increasing yield per capita in short period of time has tremendously increased the continuous cropping and use of chemical fertilizers and pesticides (Gouda et al. 2018; Mushtaq et al. 2018). The use of extensive chemical fertilizers and continuous cropping have caused degradation of agricultural land;

M. Khashi u Rahman (✉) · X. Zhou · F. Wu (✉)
Key Laboratory of Biology and Genetic Improvement of Horticultural Crops
(Northeast Region), Ministry of Agriculture and Rural Development,
Northeast Agricultural University, Harbin, China

College of Horticulture and Landscape Architecture, Northeast Agricultural University,
Harbin, China

Z. Hussain
Department of Horticulture, University College of Agriculture, University of Sargodha,
Sargodha, Pakistan

I. Ali
Department of Horticulture, PMAS-Arid Agriculture University, Rawalpindi, Pakistan

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_14

hence the researchers are now mainly focusing on safer agricultural practices, i.e., biocontrol or diversification of crop species.

Selection of proper cropping system is a key element of good land management practices in sustainable agriculture. Intercropping, which is growing two or more crops simultaneously on same land, has been found effectively curbing crop diseases, increasing nutrient use efficiency, improving soil health, and enhancing overall crop yield (Zhou et al. 2011; Jin et al. 2020; Bhatti et al. 2017). Basically, intercropping is an interspecific interaction in which plants of two or more species interact with each other either to facilitate (positive interaction) or to compete for survival (negative interaction). Some examples of positive interactions are facilitation of neighboring crop plant through nutrient availability, i.e., legume/cereal system (Duchene et al. 2017), nutrient acquisition (Zou et al. 2018; Bhat et al. 2017a, b; Sofi et al. 2017; Shafi et al. 2018), suppression of plant-specific pathogenic microbiota and eventually the diseases (Zhu and Morel 2019), modulation of composition of root exudates (Lv et al. 2020), and warning of possible future danger via release of volatile organic compounds (VOCs) (Khashi u Rahman et al. 2019). On the other hand, the main example of negative interactions in intercropping is allelopathy that can be utilized in sustainable agriculture, i.e., weed management (Bhadoria 2011; Arif et al. 2015; Dervash et al. 2020). In sustainable agriculture, these both kinds of interactions can be used as safer ways to get higher yield per capita.

The mechanism underlying interaction between crop species during intercropping is complex, and its understanding is important for practical development of any sustainable agroecosystem (Fig. 14.1). In aboveground interactions, plants interact with each other in competition or facilitation through physical means and via communication through VOCs. In belowground interactions, plants interact with each other through root exudates, common mycorrhizal network (CMNs), and chemical signals. This chapter will improve our understandings about how intercropping can facilitate sustainable agriculture and the mechanism involved in aboveground and belowground facilitative interspecific interactions during intercropping.

14.2 A Successful Intercropping System

Several factors are considered for a productive and successful intercropping system because the features of intercropping vary with climatic condition, soil type, recourse availability, and economic value (Maitra et al. 2020). To assure the proper utilization of available resources and minimize the competition between crops, selection of species is the key as intercropping may not be beneficial or might be harmful if proper species are not chosen. For example, the combination of legumes and cereals is considered for N_2 fixation, and growing maize (*Zea mays* L.) with legume crops, i.e., groundnut (*Arachis hypogaea*), black gram (*Vigna mungo*), and green gram (*Vigna radiata*), assures shade for legume species that are tolerant to shad and for management of cereal components in maize (Manasa et al. 2018). Another important consideration for a successful intercropping system is the matu-

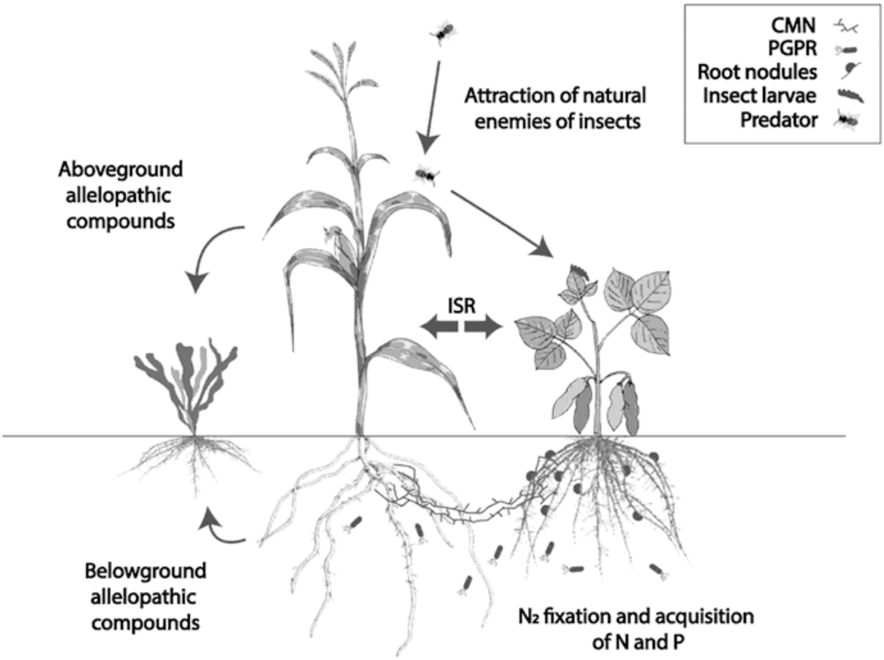


Fig. 14.1 A diagram illustrating possible mechanisms involved in facilitative interspecific interaction between different species during intercropping. Some species such as legumes have natural ability of fixing environmental N_2 and facilitate neighboring species in acquisition of N. Some species interact with each other via common mycorrhizal networks (CMN) and enhance P acquisition as well as induce systematic resistance against disease through recruiting plant growth-promoting bacteria (PGPR). Moreover, volatile compounds secreted from certain species attract natural enemies and facilitate neighboring species to combat insect pests. Similarly, some species possess allelopathic potential which can be manipulated in controlling weeds

rity time of crop species. To minimize the resource competition, crop species selected for intercropping system are usually of different maturity time. When intercropped species have different growing periods, the competition for major resources decreases, and their complementary effects benefit the system in the form of higher yield of both crops. For example, the maize as a base crop is usually planted with legume species as intercrop because most of the legumes are of short duration of life span. In maize/green gram system, green grams reach its reproductive stage after 56–60 days after plantation, while by that time maize only reach its knee-height stage (Maitra et al. 2020). In this way, the demand of stage-based nutrients and water is managed with minimum competition between species. Lithourgidis et al. (2011) suggested that being a long-duration crop, maize can potentially manage its need of major resources after harvest of leguminous crops when intercropped together.

Generally, crop yield depends on crop density and maturity parameters. However, because intercropping is accommodation of two or more crops at same period of time, several compromises are made during intercropping system. Intercropping is classified into replacement series and additive series (Kour et al. 2014; Singh et al. 2020). In replacement series, all crops are termed as component crops instead of base or intercrop and are sown with equal distribution, without 100% density of particular specie as in sole cropping. For example, the spacing between maize rows is about 60–80 cm in sole cropping, which can be used for other component crop without reducing recommended plant density. However, in additive series, intercrop is accommodated with base crop which is sown in 100% density as monocropping; however, compromises in planting geometry and spacing are made. Overall, it is obvious that some part of population of crops are scarified for another crop in intercropping; however, it is recommended to increase the density of crops to maximize the yield advantages. Time of planting is also crucial to get higher yield and utilization of available resources (Addo-Quaye et al. 2011). In this regard, one crop of long duration is planted as base crop, while short-term duration crops are sown as intercrop so that intercrop can be harvested before the need of resources for base crop tend to increase. In this way, not only the resources are utilized in efficient way, but the higher yield of both crops can be promised.

14.3 Intercropping Facilitating Plant Nutrients

The crop yield is closely related to nutrient acquisition by crop plants. The major role that intercropping plays in a facilitative interspecific interaction is the mobilization of unavailable nutrients and their uptake by plants (Vandermeer 1992; Dar and Bhat 2020). Nitrogen (N) and phosphorus (P) are the main nutrients that are quite essential for plant vegetative growth and productivity. It is now well understood that intercropping can mitigate the stressful condition of plant belowground environment and make N and P available for plant acquisition.

14.3.1 N_2 Fixation and N Availability

Although N is abundant on earth, its deficiency in plants due to unavailability causes huge losses in crop production all around the world. Synthetic fertilizers are being used to fulfill plant N requirement; however excess use of fertilizers is also degrading soil stability by unbalancing the N cycle and eutrophication, and the loss of gaseous N_2O has contributed in global warming. To assure long-term solution for this, researchers have been trying to find some biological means, and intercropping leguminous crops is one of them. Addition of legumes in intercropping has been widely practiced due to their natural ability of utilizing atmospheric N_2. In this system the competition between plants for acquisition of N decreases, and it also provides substantial amount of N to base crop after harvest of intercropped legume crop (Bedoussac et al. 2015; Bhat et al. 2018a, b). It has been shown that intercropped legume can store around 40–100 kg/hec N in plants, and the yield of base crop can be increased up to 30–40% if intercropped with legume (Amossé et al. 2013). It is now widely understood that leguminous crops fix more environmental N_2 when intercropped with a crop with no ability to fix N_2 or have more requirement of N for growth and production. This is because of the natural trait of legumes that absorb unavailable N_2 and transform it to plant-available form only when there is competition between plants for acquisition of N in low N available environment. The main legumes cultivated for the purpose of N_2 fixation are clovers (*Trifolium* spp.), lupin (*Lupinus angustifolius* L.), soybean, pea (*Pisum sativum* L.), pigeon pea (*Cajanus cajan* L.), cowpea (*Vigna unguiculata* L.), faba bean (*Vicia faba* spp. minor L.), *Crotalaria spectabilis* Roth., alfalfa (*Medicago sativa*), and fenugreek (*Trigonella foenum-graecum* L.) (Xue et al. 2016).

The process of N_2 fixation is governed by diazotrophic prokaryotic microorganisms belonging to archaebacteria and eubacteria. A well-organized mutualistic relationship is formed between host and species for N_2 fixation process (Garg 2009). Generally, these bacteria are free-living and fix N in symbiotic process with plants; however, there are some cyanobacteria with the ability to fix N independently. The process of symbiotic N fixation takes place in specialized structures on legume roots, called nodules, where species from many genera of *Rhizobiaceae* fix inorganic N to available form. In addition to root surface, *Azorhizobium caulinodans* can form nodules on stem of legume crops (Xue et al. 2016). The N_2 fixation is catalyzed by nitrogenase which is an anaerobic enzyme carrying complex metalloclusters on its active sites. The metallocluster usually contains iron as the main element along with molybdenum or vanadium or alone (Curatti et al. 2006). The nodules contain a specific oxygen diffusion barrier and synthases oxygen carrier protein to protect the catalyzing enzyme, because nitrogenase is inhibited if exposed to oxygen. Moreover, the nif genes associated with N_2 fixation process have been well categorized now because of ecological and economic importance of this process.

14.4 P Availability and Acquisition

P is an important element in plant life cycle and is being consumed so quickly. The deficiency of P is the major limiting factor in crop growth and yield as P availability controls the process of N_2 fixation (Isaac et al. 2012). The natural P already available in the soil is already insufficient for plants, and its demand is rising nearly twice as the human population growth. To fulfill the basic requirement of P to plant, P is applied in the form of fertilizers, which are being excessively used in order to maximize the crop yield. According to Syers et al. (2008), only 15–30% of applied P fertilizer is taken up by crop plants in the year of its application because of its slow diffusion and high fixation in soil. P limitation is usually overcome by the application of Pi fertilizers, but such P is basically from a nonrenewable resource (Vaccari 2009), which is expected to become scarce in the near future.

The availability of P in the soil can be increased by different biological processes and land management practices such as intercropping. To the date, many intercropping systems have been reported that can be practiced for utilization of unavailable P in the soil and to improve the P uptake by plant. Among those, intercropping of cereals with legumes have been studied the most because legume crops fix more N_2 when intercropped with those species that are unable to fix N_2 or sole cropping (Dar et al. 2013; Jensen et al. 2020; Bhat et al. 2018a, b). During nodulation/N_2 fixation, leguminous plants release H^+ and take more cations than anions. The released H^+ ions are specifically important in dissolving soil unavailable P (Tang et al. 1997). In addition, increased N_2 fixation by legumes also increases rate of proton excretion that also plays an important role in P mobilization in rhizosphere (Li et al. 2003). In legume/cereal intercropping system, maize with faba bean (*Vicia faba*), white lupin (*Lupinus albus*), and soybean (*Glycine max*); wheat with faba bean and soybean; and in other combinations, wheat/maize and Alfred stonecrop (*Sedum alfredii* Hance)/upland kangkong (*Ipomoea aquatica* Forsk.) are widely practiced in different parts of the world.

In alkaline soils where pH is the main limiting factor of crop production, P availability can be increased by introducing legumes with cereals via the effects of change in pH and release of organic compounds through root exudation (Zhang et al. 2016). Researchers have found two main processes controlling the process of P availability in rhizosphere that both are regulated by acidification and Ca uptake by plant. These processes are (i) the desorption of P from metal oxyhydroxides and clay minerals which is endorsed by synergetic effects of Ca^{2+} desorption of PO_4^{3-} desorption and (ii) P sorbing on surfaces and dissolution of Ca-P minerals (Messaoudi et al. 2020). In intercropping, the roots of the plants interact exclusively with the soil microbiota which further affect plant nutrition uptake efficiency either directly by mobilizing plant-unavailable nutrients and uptake or indirectly through root growth promotion (Richardson et al. 2009). Studies have shown that many microorganisms can effectively dissolve insoluble inorganic P and mineralized organic P during intercropping. For example, the intercropped wheat increases abundance of *Pseudomonas* and *Bacillus* spp. community in cucumber (*Cucumis sativus*) rhizosphere (Jin et al. 2020), and most of the species of these microbes have the ability to solubilize and mineralize phosphate and also enhance the absorption of P by plant roots (Wang et al. 2007). *Trichoderma* spp. is another microbial community which is greatly affected by intercropping and also has the ability to dissolve the fixed phosphate existing in the soil, so as to improve the soil fertility and plant growth (Kapri and Tewari 2010).

14.5 Pest Management

14.5.1 Weed Management

Intercropping play an important role in controlling weeds through utilization of land space, resource-based competition, canopy development, root growth, and allelopathy (Joyful and Pieterse 2019). For example, the intercropping oats (*Avena sativa* L.) and some varieties of ryegrass and rye (*Secale cereale* L.) with maize has determinantal effects on emergence of weed (Bezuidenhout et al. 2012). Several intercrops secret allelochemicals through root exudation which suppress germination and early seedling growth of some weeds. The biomass canopy or remaining crop residues of intercrop may also affect germination of photoblastic weed seeds by interfering with phytochrome-mediated germination. Another effect of intercrop biomass on weed germination is through conserving soil water moisture or creating a waterlogged environment to suppress weed germination. According to Teasdale et al. (2007), when intercrop of short duration is harvested, the remaining residues lower the soil temperature and eventually suppress weed germination. Although, intercropping legume crops with cereals or other crops facilitates base crops through availability and acquisition of nutrients, the mechanism of weed suppressiveness via allelopathy in legume/cereal system is still poorly understood. However, the weed suppressiveness effects of legumes in greenhouse and laboratory tests have been reported (Rueda-Ayala et al. 2015).

Allelopathy, a phenomenon of suppressing growth of neighboring plant through belowground or aboveground secretion of allelochemicals, is a potential biological way of controlling weeds. Moreover, the herbicidal effects on weeds decrease gradually when herbicides are frequently used; hence intercropping allelopathic crops not only controls the weeds as biological measure but also maintains herbicidal effects (Jabran et al. 2010). Many crops have been reported with efficiency of allelopathy that can be used in intercropping combating weeds. Rye is the most effective allelopathic crop which releases more than 15 important allelochemicals such as benzoxazinones [2(3H)-benzoxazolinone (BOA) and 2,4-(dihydroxy-1,4(2H)-benzoxazin-3-one (DIBOA)] (Schulz et al. 2013). Sorghum (*Sorghum bicolor* L.) is also an important allelopathic crop that can be used in curbing weed; however its efficiency varies with environmental conditions, growth stage, and cultivar. The most important allelochemicals screened from sorghum are cyanogenic glycoside (dhurrin), *p*-benzoquinone (sorgoleone), and phenolics (Weston et al. 2013). Among those, sorgoleone is the allelochemical of high potential released in root exudates of sorghum. Other examples of potential allelopathic crops that may be cultivated as component crop in intercropping include Brassicaceae family and sunflower (*Helianthus annuus* L.). The phenolic compounds and benzoxazinoids secreted from maize plants can effectively reduce germination of weeds especially at early maize growth stage (Jabran 2017). Glucosinolate is an allelochemical of Brassicaceae family which, after release, decomposes into several biological compounds. These compounds inhibit growth of neighboring plants/weed when they are taken up from rhizosphere (Patersen et al. 2001). Several other crops with allelopathic efficiency have been recently reviewed by Pannacci et al. (2017) and can be manipulated in intercropping against weeds.

14.6 Insect Management

Insects trace their host plant through the emission of specific volatiles by plants. However, if the diversity of plant species increases, the simultaneous emission of volatiles from more than two plants may hinder the location of host plant. In this regard, intercropping is the best biological way to minimize loss in crop production due to insect attack. Moreover, the non-host plant can emit certain volatile organic compounds (VOCs) that are repellent to some insects. For example, the treatment of extracts of garlic (*Allium sativum* L), tansy (*Tanacetum vulgare*) L., and patchouli (*Pogostemon cablin* Blance) was found to be potential repellents to moth (Landolt et al. 1999). Onion (*Allium cepa* L.) can also be intercropped with base crops as it releases some sulfur containing organic compounds (thiols) that can repel several insects. Garlic has been widely accepted as an intercrop because of the ability of release of certain volatiles. Intercropping garlic with cabbage or other vegetable crops can significantly reduce the insect attack incidence and improve crop yield (Debra and Misheck 2014). Apart from vegetables, when garlic was intercropped with a cereal (i.e., wheat), the incidence of grain aphid (*Sitobion avenae*) significantly reduced, and wheat yield was increased (Zhou et al. 2011). Moreover, citrus-emitted volatiles disulfide and trisulfides (dimethyl trisulfide) inhibit the attack of Asian citrus psyllid (*Diaphorina citri*) (Mann et al. 2011).

Another mechanism involved in intercropping controlling insect incidence is that the VOCs released by non-host plant attract natural enemies of the pest insect. For example, the intercropping wheat with a non-host plant molasses grass corn has significantly increased the abundance of parasite *Cotesia sesamiae* and decreased the infestation of stem borer (Khan et al. 1997). In this study, molasses grass (*Melinis minutiflora*) emitted VOCs to attract the natural enemy of stem borer that reduced the level of its infestation. Similarly, intercropping some aromatic flowering plants like basil (*Ocimum basilicum* L.), French marigold (*Tagetes patula* L.), and ageratum (*Ageratum houstonianum*) in apple orchards hindered the *Aphis citricola* attack by shifting predator-prey abundances (Song et al. 2013). Similarly, Xu et al. (2018) found that releasing of E-β-farnesene and methyl salicylate in wheat/pea system significantly reduced the attack of aphids and promoted the abundance of its predators, i.e., ladybeetle (*Coccinella septempunctata*) and lacewings (*Chrysoperla carnea*). Flowering species are mostly intercropped with base crop because aromatic and colorful plants attract several insects foraging for nectar and pollen, while the architecture of flower provides the support in the form of shelter to combat insect pests (Walton and Isaac 2011). For example, the wasps and ladybeetle are attracted to colors and are the predators of several insect pests. Accordingly, results were found in kale (*Brassica oleracea*)/Apiaceae intercropping system where the abundance of natural predator *Lipaphis erysimi* increased in intercropping as compared to monocropped kale (Silva et al. 2016).

14.7 Soilborne Pathogen and Other Diseases

Intercropping provides diverse exosystemic effects and disease control is one of them. Different field experiments have proved that crop yield of intercropped species was mostly higher as compared to monocropping which was closely related to reduction in disease incidence (Bouws and Finckh 2008; Fajinmi and Odebode

2010; Lv et al. 2020). It was observed that intercropping oat with barley (*Hordeum vulgare*) significantly reduced the overall leaf spot caused by *Drechslera avenae* and rye with wheat reduced the leaf spot damage caused by *Rhynchosporium secalis* (Boudreau 2013). Similarly, wheat leaf rust caused by *Puccinia triticina* and strip rust caused by *Puccinia striiformis* were reduced by intercropping rye (Peng et al. 2006). Cereal/legume is a widely adopted system in many parts of the world due to diverse characteristics of leguminous crops such as N_2 fixation and pathogen management. A 5-year continuous experiment revealed that intercropped faba bean can decline powdery mildew of wheat by 26–49% (Chen et al. 2007). In addition, when barley was intercropped with lupin, the brown spot of lupin caused by *Pleiochaeta setosa* decreased extensively by 78–87% (Hauggaard-Nielsen et al. 2008). Similarly, the disease severity of *Ascochyta* blight in oats reduced up to 70% when intercropped with triticale and 82% when intercropped with faba bean (Fernández-Aparicio et al. 2010). In Nigeria, a series of different combinations of rows of sesame (*Sesamum indicum*) with maize revealed that the *Cercospora* leaf spot and *Alternaria* leaf blight of sesame was significantly reduced (Enikuomehin et al. 2011). Moreover, reduction in maize bushy stunt mycoplasma, maize rayado fino virus, and corn stunt spiroplasma in intercropping system with beans has been reported (Castro et al. 1992; Shiu and Wu 2010).

Cassava mosaic disease (CMD) has caused severe economic loss and devastating famine mostly in African continents (Legg and Fauquet 2004). Intercropping cassava with different agronomic crops such as maize, beans, sweet potato (*Ipomoea batatas*), and sorghum has been proved to curb CMD and reduce its incidence to 29.5% as compared to monocropping (39.5%) (Night et al. 2011). Potato (*Solanum tuberosum*), another important agronomic crop, reduced the incidence of late blight caused by *Phytophthora infestans* during mixed cropping with faba bean or with cereal or grass-clover as boarder crops (Bouws and Finckh 2008). As compared to agronomic crop, less intension has been given to horticultural crops in terms of disease control by increasing species diversity. However, there are some dominant examples that some lethal soilborne diseases can be arrested efficiently in intercropping of fruits or vegetables. Tomato is usually intercropped with onion and cucumber to reduce the disease incidence of *Verticillium dahliae* (Li et al. 2018) and tomato leaf curl, respectively, which was reduced up to 80% in intercropping as compared to monocropping (Mabvakure et al. 2016). In addition, interplanting marigold in tomato (*Lycopersicon esculentum* L.) rows has been found effective in controlling nematode infestations such as root-knot nematode (*Meloidogyne incognita*) (Tibugari et al. 2012). In chili pepper, reduction of *Phytophthora* blight (Zu et al. 2008) and *Pepper veinal mottle virus* (Fajinmi and Odebode 2010) has been reported when intercropped with maize as compared to sole cropping. Other prominent examples of potential intercropping system may include watermelon (*Citrullus lanatus*)/rice (*Oryza sativa*) to curb *Fusarium* wilt (Su et al. 2008), cucumber/chili pepper (*Capsicum annuum*) to control cucumber root-knot nematode *M. incognita* (Dong et al. 2012), plantains/cassava (*Manihot esculenta*) to reduce black sigatoka of plantains caused by *Mycosphaerella fijiensis* (Emebiri and Obiefuna 1992), banana/marigold to sustain two nematode species *Radopholus similis* and

Helicotylenchus multicinctus (Mclntyre et al. 2001), and grapes (*Vitis vinifera* L.)/ alfalfa (*Medicago sativa*) or white clover to control downy mildew (Ji et al. 2011).

The reduction of disease in intercropping could be because of inhibition of pathogen due to allelopathic effects, induction of plant systematic resistance against pathogen, or by control of insect attack due to non-host plants of component crop. Several plants secrete allelochemical with strong antimicrobial potential through root exudation or volatilization (Massalha et al. 2017; Li et al. 2020a, b; Tan et al. 2020). These allelochemicals play a critical role in depressing some deadly diseases of neighboring species. For example, release of some phenolic compounds in root exudates of non-host plant can inhibit spore germination of *Verticillium dahliae*, *Fusarium* spp., and *Cylindrocladium parasiticum* (Gao et al. 2014; Zhu and Morel 2019). Furthermore, some compounds with nematocidal potential, i.e., thiopurines and thiophenes in root exudates of *Asteraceae* spp., can reduce population of pathogenic nematodes of neighboring plants (Tsay et al. 2004). Similarly, crown daisy (*Chrysanthemum coronarium*) secrets lauric acid that first attracts nematode *Meloidogyne incognita* through chemotaxis which is carried out because of the presence of a neuromodulator peptide in nematode genes and then induces nematode death (Dong et al. 2014). In maize/pepper (*Piper nigrum*) intercropping system, the non-host plant maize attracts *Phytophthora capsici*, a soilborne pathogen of pepper, and then releases antimicrobial compounds [(2,4-dihydroxy-7-methoxy-2H-1,4-benzoxazin-3(4H)] to kill the pathogen, thus protecting pepper plant (Yang et al. 2014; Bhat et al. 2017a, b). The strategy is called "attract and kill," which is well-studied in the recent decade. Another mechanism underlying intercropping control plant diseases is activation of immune system of neighboring plant either through release of some chemical compounds to affect the expression of markers of immune systems or by perturbation of the environment (Zhu and Morel 2019). For example, the activity of phenylalanine ammonia lyase (PAL), a key biosynthetic catalyst, in watermelon was significantly higher upon infection when intercropped with wheat as compared to sole cropping (Xu et al. 2015; Dar et al. 2016; Mehmood et al. 2019).

14.8 Intercropping and Soil Sickness

Soil sickness is the rise of unfavorable and negative conditions in the soil for plant growth and development induced by the plant itself. It is a negative plant-soil feedback dates to the start of agriculture (Huang et al. 2013). However, persistent works started in the early twentieth century when researchers first studied phytotoxins in root exudates and plant litter and their effects of ion imbalance in the soil (Schreiner and Reed 1907). Since then, many soilborne pathogens in different agronomic and horticultural crops have been screened out in result of soil sickness.

When same crop is continuously cultivated on same piece of land, it starts degrading soil properties with every passing cropping season. The level of crop-specific phenolic compounds released from root exudates and crop residues increases, and, after a specific period of time, it starts affecting crop plant growth through imbalance in soil nutrition, shift in microbial communities, and increase in disease incidence; the whole phenomenon is called "autotoxicity" (Khasi u Rahman et al. 2019). According to Ogweno and Yu (2006), the three main reasons of soil sickness are increase in soilborne pests, degradation in soil physiochemical properties, and autotoxicity. Several studies conducted on exogenously applied phenolic compounds have found that these phenolic compounds, at higher concentration, reduce abundance of plant beneficial microbiota, induce soilborne disease and negatively affect plant growth (Liu et al. 2017; Zhou et al. 2018; Wang et al. 2018; u Rahman et al. 2020). The main autotoxic compounds released through root exudations include phenols, naphthoquinones, aliphatic aldehydes, simple organic acids, coumarins, alkaloids, cinnamic and benzoic acids, long-chain fatty acids, lactones, cyanohydrins, purines, steroids, terpenoids, tannins, and others (Huang et al. 2013).

Soil microbial communities are important element of any agroecosystem, and shift in their composition may lead to strong changes in soil biochemical processes. Some microorganisms facilitate crop plant growth by mineral availability or by inhibiting pathogenic organisms. For example, the common mycorrhizal networks (CMN) formed by arbuscular mycorrhizal fungi (AMF) link plants for signal transport and also stimulate P acquisition. Similarly, some microbial species are producers of plant growth-promoting substances, i.e., cytokinin and indole-3-acetic acid (Khara and Arora 2010; Khanday et al. 2016). Studies have found that increase in plant-specific diversity tend to increase in plant beneficial bacterial and overall microbial abundance and diversity, while continuous sole cropping results in decrease in soil microbial diversity because of accumulation of autotoxins (Larkin 2003).

Intercropping is a practical way of increasing plant species diversity on same land that could decrease level of accumulated autotoxin and alter soil microbial community composition to facilitate crop plants. In maize/sorghum system, benzoxazinoids and strigolactones secreted by sorghum facilitate AMF and attract competitive colonizer *Pseudomonas putida* with plant beneficial characteristics (Neal et al. 2012). Intercropping marigold with Brassicaceae could be an efficient way to reclaim soil sickness by controlling some soilborne diseases and soil nematodes (Cohen et al. 2005). Similarly, Chinese chive (*Allium tuberosum*)-released compounds can inhibit bacterial wilt in many crop species. Overall, intercropping is an efficient and recommended method to recover soil sickness because increase in diversity of crop species does not allow autotoxins to accumulate, facilitates nutrient acquisition, alters soil microbial community composition, and lowers the soilborne disease incidence.

14.9 Conclusion

Intercropping is a cropping system with diverse features that can be utilized to increase crop yield in an eco-friendly way. Among several intercropping systems, cereal/legume is a prominent crop combination to increase soil N and P availability and acquisition by plants. Moreover, selection of allelopathic species could be used to control weeds without use of chemical-based herbicides. The insect pests and several soilborne diseases can also be combat with intercropping by choosing certain agronomic or horticultural crops with respective potentials. In addition, soil sickness is a major issue because of the trend of continuous monocropping in different parts of the world, which can be solved by introduction of different crop species on same area of land. With so many features, we recommend intercropping to be adopted for the development of sustainable agriculture and eco-friendly agroecosystem especially in soil sickness areas.

References

Addo-Quaye AA, Darkwa AA, Ocloo GK (2011) Yield and productivity of component crops in a maize-soybean intercropping system as affected by time of planting and spatial arrangement. ARPN J Agric Biol Sci 6(9):50–57

Amossé C, Jeuffroy MH, Celette F, David C (2013) Relay-intercropped forage legumes help to control weeds in organic grain production. Eur J Agron 49:158–167

Arif M, Cheema ZA, Khaliq A, Hassan A (2015) Organic weed management in wheat through allelopathy. Int J Agric Biol 17(1):127–134

Bedoussac L, Journet EP, Hauggaard-Nielsen H, Naudin C, Corre-Hellou G, Jensen ES, Prieur L, Justes E (2015) Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron Sustain Dev 35(3):911–935

Bezuidenhout SR, Reinhardt CF, Whitwell MI (2012) Cover crops of oats, stooling rye and three annual ryegrass cultivars influence maize and *Cyperus esculentus* growth. Weed Res 52(2):153–160

Bhadoria PBS (2011) Allelopathy: a natural way towards weed management. J Exp Agric Int 1:7–20

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacog Phytochem 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of Toxic Heavy Metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 189–209

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Boudreau MA (2013) Diseases in intercropping systems. Annu Rev Phytopathol 51:499–519

Bouws H, Finckh MR (2008) Effects of strip intercropping of potatoes with non-hosts on late blight severity and tuber yield in organic production. Plant Pathol 57(5):916–927

Castro V, Rivera C, Isard SA, Gámez R, Fletcher J, Irwin ME (1992) The influence of weather and microclimate on *Dalbulus maidis* (Homoptera: Cicadellidae) flight activity and the incidence of diseases within maize and bean monocultures and bicultures in tropical America. Ann Appl Biol 121(3):469–482

Chen Y, Zhang F, Tang L, Zheng Y, Li Y, Christie P, Li L (2007) Wheat powdery mildew and foliar N concentrations as influenced by N fertilization and belowground interactions with intercropped faba bean. Plant Soil 291(1–2):1–13

Cohen MF, Yamasaki H, Mazzola M (2005) Brassica napus seed meal soil amendment modifies microbial community structure, nitric oxide production and incidence of Rhizoctonia root rot. Soil Biol Biochem 37(7):1215–1227

Curatti L, Ludden PW, Rubio LM (2006) NifB-dependent in vitro synthesis of the iron–molybdenum cofactor of nitrogenase. Proc Natl Acad Sci 103(14):5297–5301.x

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecologia Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Debra KR, Misheck D (2014) Onion (*Allium cepa*) and garlic (*Allium sativum*) as pest control intercrops in cabbage based intercrop systems in Zimbabwe. IOSR J Agric Veterin Sci 7(2):13–17

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 183–196

Dong L, Huang C, Huang L, Li X, Zuo Y (2012) Screening plants resistant against *Meloidogyne incognita* and integrated management of plant resources for nematode control. Crop Prot 33:34–39

Dong L, Li X, Huang L, Gao Y, Zhong L, Zheng Y, Zuo Y (2014) Lauric acid in crown daisy root exudate potently regulates root-knot nematode chemotaxis and disrupts Mi-flp-18 expression to block infection. J Exp Bot 65(1):131–141

Duchene O, Vian JF, Celette F (2017) Intercropping with legume for agroecological cropping systems: complementarity and facilitation processes and the importance of soil microorganisms. A review. Agric Ecosyst Environ 240:148–161

Emebiri LC, Obiefuna JC (1992) Effects of leaf removal and intercropping on the incidence and severity of black Sigatoka disease at the establishment phase of plantains (*Musa* spp. AAB). Agric Ecosyst Environ 39(3–4):213–219

Enikuomehin OA, Jimoh M, Olowe VIO, Ayo-John EI, Akintokun PO (2011) Effect of sesame (*Sesamum indicum* L.) population density in a sesame/maize (*Zea mays* L.) intercrop on the incidence and severity of foliar diseases of sesame. Arch Phytopathol Plant Protect 44(2):168–178

Fajinmi AA, Odebode CA (2010) Evaluation of maize/pepper intercropping model in the management of pepper veinal mottle virus, genus potyvirus, family potyviridae on cultivated pepper (*Capsicum annuum* L.) in Nigeria. Arch Phytopathol Plant Protect 43(15):1524–1533

Fernández-Aparicio M, Amri M, Kharrat M, Rubiales D (2010) Intercropping reduces *Mycosphaerella pinodes* severity and delays upward progress on the pea plant. Crop Prot 29(7):744–750

Gao X, Wu M, Xu R, Wang X, Pan R, Kim HJ, Liao H (2014) Root interactions in a maize/soybean intercropping system control soybean soil-borne disease, red crown rot. PLoS One 9:e95031

Garg N (2009) Symbiotic nitrogen fixation in legume nodules: process and signaling: a review. In: Sustainable Agriculture. Springer, Dordrecht, pp 519–531

Gerland P, Raftery AE, Ševčíková H, Li N, Gu D, Spoorenberg T, Alkema L, Fosdick BK, Chunn J, Lalic N, Bay G (2014) World population stabilization unlikely this century. Science 346(6206):234–237

Gouda S, Kerry RG, Das G, Paramithiotis S, Shin HS, Patra JK (2018) Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. Microbiol Res 206:131–140

Hauggaard-Nielsen H, Jørnsgaard B, Kinane J, Jensen ES (2008) Grain legume–cereal intercropping: the practical application of diversity, competition and facilitation in arable and organic cropping systems. Renew Agric Food Syst 23(1):3–12

Huang LF, Song LX, Xia XJ, Mao WH, Shi K, Zhou YH, Yu JQ (2013) Plant-soil feedbacks and soil sickness: from mechanisms to application in agriculture. J Chem Ecol 39(2):232–242

Isaac ME, Hinsinger P, Harmand JM (2012) Nitrogen and phosphorus economy of a legume tree-cereal intercropping system under controlled conditions. Sci Total Environ 434:71–78

Jabran K (2017) Maize allelopathy for weed control. In: Manipulation of allelopathic crops for weed control. Springer, Cham, pp 29–34

Jabran K, Cheema ZA, Farooq M, Hussain M (2010) Lower doses of pendimethalin mixed with allelopathic crop water extracts for weed management in canola (*Brassica napus*). Int J Agric Biol 12(3):335–340

Jensen ES, Carlsson G, Hauggaard-Nielsen H (2020) Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron Sustain Dev 40(1):5

Ji H, Chen Y, Qin Y, Pan P, Ma Y (2011) The control effect of the main grape diseases by intercropping forage grass in organic viticulture in Ili Valley of Xinjiang Uyghur Autonomous Region. Xinjiang Agric Sci 48(6):1089–1097

Jin X, Shi Y, Wu F, Pan K, Zhou X (2020) Intercropping of wheat changed cucumber rhizosphere bacterial community composition and inhibited cucumber *Fusarium* wilt disease. Sci Agric 77(5):e20190005

Joyful RT, Pieterse PJ (2019) Biochemical and morphological roles of allelopathic crops in integrated weed management: a review. Afr J Rural Dev 3(3):869–882

Kapri A, Tewari L (2010) Phosphate solubilization potential and phosphatase activity of rhizospheric *Trichoderma* spp. Braz J Microbiol 41(3):787–795

Khan ZR, Chiliswa P, Ampong-Nyarko K, Smart LE, Polaszek A, Wandera J, Mulaa MA (1997) Utilisation of wild gramineous plants for management of cereal stemborers in Africa. Int J Tropic Insect Sci 17(1):143–150

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Khare E, Arora NK (2010) Effect of indole-3-acetic acid (IAA) produced by *Pseudomonas aeruginosa* in suppression of charcoal rot disease of chickpea. Curr Microbiol 61(1):64–68

Khashi u Rahman M, Zhou X, Wu F (2019) The role of root exudates, CMNs, and VOCs in plant–plant interaction. J Plant Interact 14(1):630–636

Kour P, Kumar A, Sharma BC, Kour R, Sharma N (2014) Nutrient uptake as influenced by weed management in winter maize+ potato intercropping system. Indian J Weed Sci 46(4):336–341

Landolt PJ, Hofstetter RW, Biddick LL (1999) Plant essential oils as arrestants and repellents for neonate larvae of the codling moth (Lepidoptera: Tortricidae). Environ Entomol 28(6):954–960

Larkin RP (2003) Characterization of soil microbial communities under different potato cropping systems by microbial population dynamics, substrate utilization, and fatty acid profiles. Soil Biol Biochem 35(11):1451–1466

Legg JP, Fauquet CM (2004) Cassava mosaic geminiviruses in Africa. Plant Mol Biol 56(4):585–599

Li C, Tian Q, Khashi u Rahman M, Wu S (2020a) Effect of anti-fungal compound phytosphingosine in wheat root exudates on the rhizosphere soil microbial community of watermelon. Plant Soil 456:(1-2):223–240

Li PY, Rahman M, Zhou XG, Wu FZ, Sun LD, Guo PX, Dong H, Liu SW (2020b) Effects of wheat intercropping on the senescence of cucumber leaves. Allelopathy J 50(1):49–62

Li L, Zhang F, Li X, Christie P, Sun J, Yang S, Tang C (2003) Interspecific facilitation of nutrient uptake by intercropped maize and faba bean. Nutr Cycl Agroecosyst 65(1):61–71

Li HY, Zhou XG, Wu FZ (2018) Effects of root exudates from potato onion on *Verticillium dahliae*. Allelopath J 43(2):217–222

Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios D (2011) Annual intercrops: an alternative pathway for sustainable agriculture. Aust J Crop Sci 5(4):396

Liu J, Li X, Jia Z, Zhang T, Wang X (2017) Effect of benzoic acid on soil microbial communities associated with soilborne peanut diseases. Appl Soil Ecol 110:34–42

Lv J, Dong Y, Dong K, Zhao Q, Yang Z, Chen L (2020) Intercropping with wheat suppressed *Fusarium* wilt in faba bean and modulated the composition of root exudates. Plant Soil 448:153–164

Mabvakure B, Martin DP, Kraberger S, Cloete L, van Brunschot S, Geering AD, Thomas JE, Bananej K, Lett JM, Lefeuvre P, Varsani A (2016) Ongoing geographical spread of Tomato yellow leaf curl virus. Virology 498:257–264

Maitra S, Shankar T, Banerjee P (2020) Potential and advantages of maize-legume intercropping system. In: Maize-production and use. IntechOpen, London, pp 103–114

Manasa P, Maitra S, Reddy MD (2018) Effect of summer maize-legume intercropping system on growth, productivity and competitive ability of crops. Int J Manag Technol Eng 8(12):2871–2875

Mann RS, Rouseff RL, Smoot JM, Castle WS, Stelinski LL (2011) Sulfur volatiles from *Allium* spp. affect Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae), response to citrus volatiles. Bull Entomol Res 101(1):89–97

Massalha H, Korenblum E, Tholl D, Aharoni A (2017) Small molecules below-ground: the role of specialized metabolites in the rhizosphere. Plant J 90(4):788–807

McIntyre B, Gold C, Kashaija I, Ssali H, Night G, Bwamiki D (2001) Effects of legume intercrops on soil-borne pests, biomass, nutrients and soil water in banana. Biol Fertil Soils 34(5):342–348

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess Environ 191:104. https://doi.org/10.1007/s10661-019-7245-2

Messaoudi H, Gérard F, Dokukin P, Djamai H, Rebouh NY, Latati M (2020) Effects of intercropping on field-scale phosphorus acquisition processes in a calcareous soil. Plant Soil 449:331–341

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, UK, pp 152–178

Neal AL, Ahmad S, Gordon-Weeks R, Ton J (2012) Benzoxazinoids in root exudates of maize attract *Pseudomonas putida* to the rhizosphere. PLoS One 7:e35498

Night G, Asiimwe P, Gashaka G, Nkezabahizi D, Legg JP, Okao-Okuja G, Obonyo R, Nyirahorana C, Mukakanyana C, Mukase F, Munyabarenzi I (2011) Occurrence and distribution of cassava pests and diseases in Rwanda. Agriculture, Ecosystems &Environment 140(3–4):492–497

Ogweno J, Yu J (2006) Autotoxic potential in soil sickness: a re-examination. Allelopath J 18(1):93

Pannacci E, Lattanzi B, Tei F (2017) Non-chemical weed management strategies in minor crops: a review. Crop Prot 96:44–58

Peng H, Liu B, Luo L, Xi Y (2006) The studies on control crop diseases by using intercrop and mixture of variety in the fields. Southwest China J Agric Sci 19(6):1058–1062

Petersen J, Belz R, Walker F, Hurle K (2001) Weed suppression by release of isothiocyanates from turnip-rape mulch. Agron J 93(1):37–43

Pingali PL (2012) Green revolution: impacts, limits, and the path ahead. Proc Natl Acad Sci 109(31):12302–12308

Richardson AE, Barea JM, McNeill AM, Prigent-Combaret C et al (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. Plant Soil 321(1–2):305–339

Rueda-Ayala V, Jaeck O, Gerhards R (2015) Investigation of biochemical and competitive effects of cover crops on crops and weeds. Crop Prot 71:79–87

Schreiner O, Reed HS (1907) The production of deleterious excretions by roots. Bull Torrey Bot Club 34(6):279–303

Schulz M, Marocco A, Tabaglio V, Macias FA, Molinillo JM (2013) Benzoxazinoids in rye allelopathy-from discovery to application in sustainable weed control and organic farming. J Chem Ecol 39(2):154–174

Shafi S, Bhat RA, Bandh SA, Shameem N, Nisa H (2018) Microbes: key agents in the sustainable environment and cycling of nutrients. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Cambridge, U.K, p 152-179-188

Shiu T, Wu C (2010) Beneficial intercropping in the organic production of green onions (*Allium fistulosum* L.). J Taiwan Soc Hortic Sci 56(2):105–112

Silva V, Silveira L, Santos A, Santos A, Tomazella VB (2016) Companion plants associated with kale increase the abundance and species richness of the natural-enemies of *Lipaphis erysimi* (Kaltenbach) (Hemiptera: Aphididae). Afr J Agric Res 11(29):2630–2639

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) Freshwater pollution dynamics and remediation. Springer Nature, Singapore, pp 319–339

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Song B, Tang G, Sang X, Zhang J, Yao Y, Wiggins N (2013) Intercropping with aromatic plants hindered the occurrence of *Aphis citricola* in an apple orchard system by shifting predator–prey abundances. Biocontrol Sci Tech 23(4):381–395

Su SM, Ren LX, Huo ZH, Yang XM, Huang QW, Xu YC, Zhou J, Shen QR (2008) Effects of intercropping watermelon with rain fed rice on *Fusarium* wilt and the microflora in the rhizosphere soil [J]. Sci Agric Sin 41:704–712

Syers JK, Johnston AA, Curtin D (2008) Efficiency of soil and fertilizer phosphorous use. Reconciling changing concepts of soil phosphorous behaviour with agronomic information. Food and Agriculture Organization of the United Nations, Rome, p 110

Tan SC, Liu JY, Rahman M, Ma CL, Wu FZ, Zhou XG (2020) Effects of selected root exudates components on soil *Pseudomonas* spp. community structures and abundances. Allelopathy J 50(1):85–93

Tang C, Barton L, McLay CDA (1997) A comparison of proton excretion of twelve pasture legumes grown in nutrient solution. Aust J Exp Agric 37(5):563–570

Teasdale JR, Brandsaeter LO, Calegari A, Neto FS, Upadhyaya MK, Blackshaw RE (2007) Cover crops and weed management. Non chemical weed management principles. Concepts and technology. CABI, Wallingford, pp 49–64

Tibugari H, Mombeshora D, Mandumbu R, Karavina C, Parwada C (2012) A comparison of the effectiveness of the aqueous extracts of garlic, castor beans and marigold in the biocontrol of root-knot nematode in tomato. J Agric Technol 8(2):479–492

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci 108(50):20260–20264

Tsay TT, Wu ST, Lin YY (2004) Evaluation of Asteraceae plants for control of *Meloidogyne incognita*. J Nematol 36(1):36

U Rahman MK, Tan S, Ma C, Wu F, Zhou X (2020) Exogenously applied ferulic acid and p-coumaric acid differentially affect cucumber rhizosphere *Trichoderma* spp. community structure and abundance. Plant Soil Environ 66(9):461–467

Vaccari DA (2009) Phosphorus: a looming crisis. Sci Am 300(6):54–59

Vandermeer JH (1992) The ecology of intercropping. Cambridge University Press, Cambridge, UK

Walton NJ, Isaacs R (2011) Survival of three commercially available natural enemies exposed to *Michigan wildflowers*. Environ Entomol 40(5):1177–1182

Wang DW, Marschner P, Solaiman Z, Rengel Z et al (2007) Belowground interactions between intercropped wheat and *Brassicas* in acidic and alkaline soils. Soil Biol Biochem 39:961e971

Wang Z, Zhang J, Wu F, Zhou X (2018) Changes in rhizosphere microbial communities in potted cucumber seedlings treated with syringic acid. PLoS One 13:e0200007

Weston LA, Alsaadawi IS, Baerson SR (2013) Sorghum allelopathy—from ecosystem to molecule. J Chem Ecol 39(2):142–153

Xu W, Wang Z, Wu F (2015) Companion cropping with wheat increases resistance to *Fusarium* wilt in watermelon and the roles of root exudates in watermelon root growth. Physiol Mol Plant Pathol 90:12–20

Xu Q, Hatt S, Han Z, Francis F, Chen J (2018) Combining E-β-farnesene and methyl salicylate release with wheat-pea intercropping enhances biological control of aphids in North China. Biocontrol Sci Tech 28(9):883–894

Xue Y, Xia H, Christie P, Zhang Z, Li L, Tang C (2016) Crop acquisition of phosphorus, iron and zinc from soil in cereal/legume intercropping systems: a critical review. Ann Bot 117(3):363–377

Yang M, Zhang Y, Qi L, Mei X, Liao J, Ding X, Deng W, Fan L, He X, Vivanco JM, Li C (2014) Plant-plant-microbe mechanisms involved in soil-borne disease suppression on a maize and pepper intercropping system. PLoS One 9(12):e115052

Zhang D, Zhang C, Tang X, Li H, Zhang F, Rengel Z, Whalley WR, Davies WJ, Shen J (2016) Increased soil phosphorus availability induced by faba bean root exudation stimulates root growth and phosphorus uptake in neighbouring maize. New Phytol 209(2):823–831

Zhou X, Yu G, Wu F (2011) Effects of intercropping cucumber with onion or garlic on soil enzyme activities, microbial communities and cucumber yield. Eur J Soil Biol 47(5):279–287

Zhou X, Zhang J, Pan D, Ge X, Jin X, Chen S, Wu F (2018) *p*-Coumaric can alter the composition of cucumber rhizosphere microbial communities and induce negative plant-microbial interactions. Biol Fertil Soils 54(3):363–372

Zhu S, Morel JB (2019) Molecular mechanisms underlying microbial disease control in intercropping. Mol Plant-Microbe Interact 32(1):20–24

Zou X, Liu Z, Niu S, Yang N, Feng L (2018) Interspecific root interactions enhance biomass and nutrient acquisition of millet (*Setaria italica*) and mungbean (*Vigna radiata*) in intercropping system. Int J Agric Biol 20(5):1181–1187

Zu YQ, Hu WY, Wu BZ, Zhan FD, Li Y (2008) Effect of chilli pepper intercropping system on nutrient utilization, main diseases and pests and yield of chilli pepper. J Wuhan Bot Res 26:412–416

Chapter 15
Application of Phyllosphere Microbiota as Biofertilizers

Iqra Bashir, Rezwana Assad, Aadil Farooq War, Iflah Rafiq, Irshad Ahmad Sofi, Zafar Ahmad Reshi, and Irfan Rashid

15.1 Introduction

In the current scenario of rapid population growth, agriculture plays a critical role to meet the food demands of human population. Time-to-time revolutions in agriculture, particularly the third revolution commonly referred to as the "Green Revolution", resulted in significant crop production throughout the world. However, it encouraged the increased use of synthetic fertilizers that proved disastrous for our environment. In this regard, efforts have been made to produce fertilizers that ensure nutrient-rich foods along with maintenance of high-quality environment. In this course, the use of biofertilizers seems to be attractive, environmental-friendly, promising, and productive to fulfil the ever increasing demand of valuable natural products.

Biofertilizers are natural fertilizers consisting of living microbial inoculants of different species of bacteria, fungi, and algae, either alone or in combination, with the potential to mobilize essential nutrients in their most usable form through various bio-physiological processes. Plants harbour millions of the microbes, colonizing different plant parts and microbial load in each part having ample specific metabolic activities and physiological tasks linked to plant growth and fitness.

Phyllosphere being the set of photosynthetic leaves represents a most prevalent microbial niche influencing the plant survival and growth through the astonishing microbial interactions with their host plant (Vorholt 2012; Mendes et al. 2013; Bai et al. 2015; Peay et al. 2016; Khanday et al. 2016). The interaction between phyllosphere and its associated microbiota is not unidirectional. The host plant provides hospitable niche to microbial associates, and these microbes in turn alter plant's well-being in favourable or detrimental ways. There is growing evidence that microbes present in phyllosphere contribute to plant health by not only lifting host

---

I. Bashir · R. Assad (✉) · A. F. War · I. Rafiq · I. A. Sofi · Z. A. Reshi · I. Rashid
Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_15

plant's nutritional status but also providing pathogen defence and resistance to many against abiotic stresses (Arnold et al. 2003; Mendes et al. 2011; Vandenkoornhuyse et al. 2015; Busby et al. 2017; Bhat et al. 2018a, b; Mushtaq et al. 2018; Dar and Bhat 2020). Amidst current climate change, population explosion, as well as challenges in sustainable agriculture, these potential agricultural capabilities of phyllosphere microbiota could be utilized for development of biofertilizers to improve agricultural production.

15.2 An Overview of Plant Microbiota in Agriculture

Plant microbiota are the microbial component of the plant holobiont, associated with different plant surfaces and internal tissues of specific plant organs, viz. rhizosphere (Philippot et al. 2013), endosphere (Hardoim et al. 2008; Andreote et al. 2014; Berg et al. 2014), and phyllosphere (Vorholt 2012). As human microbiome is essential for well-being of every person (Quiza et al. 2015; Bhatti et al. 2017), likewise plant microbiome is critical for plant phenotype and health. From past more than a century now, microbial communities residing in various plant modules have shown the ability to contribute to indispensable plant-specific functions such as seed germination (Bragina et al. 2012; Truyens et al. 2015), nutrient supply (Tkacz and Poole 2015), protection of host from pathogens (Berendsen et al. 2012; Bulgarelli et al. 2013; Bhat et al. 2018a, b; Dervash et al. 2020), adaptation to various environmental challenges (Vandenkoornhuyse et al. 2015), and production of phytohormones and other bioactive metabolites (Zabetakis et al. 1999; Verginer et al. 2010; Shigenaga and Argueso 2016; Sofi et al. 2017). In regard to their agricultural importance, many beneficial plant-microbe interactions are well examined and explored. For example, numerous studies have reported that inoculation of rhizobia having potential to fix atmospheric nitrogen significantly increased the grain yields in several crop plants like lentil (Rashid et al. 2012), alfalfa and sugar beet (Ramachandran et al. 2011), groundnut (Sharma et al. 2011), and soybean (Grossman et al. 2011). Identically, *Pseudomonas putida* has been shown to enhance the rate of germination and promote growth of seedlings of cotton plants under alkaline and saline conditions (Yao et al. 2010). Weller et al. (2012) reported induction of systemic resistance against *Pseudomonas syringae* by *Pseudomonas fluorescens* in *Arabidopsis thaliana*. Similarly, *Piriformospora indica* (root endophyte) have also been shown to enhance plant growth, resistance against pathogens, and tolerance to various stresses (Delgado-Baquerizo et al. 2016). Likewise, there are ample studies showing the enormous agronomic impacts of plant-associated microorganisms.

Most of research has focused on use of single microbial inoculum with specific function. However, microbial consortia have more plant growth-promoting capability in comparison to a single microbe. For instance, the combined strains of *Rhizobium* and *Bacillus* were shown to improve root architecture and augment nodule formation in leguminous plants like bean, pigeon pea, and soybean (Checcucci et al. 2018). Berendsen et al. (2018) also showed microbial consortia containing

Xanthomonas sp., *Stenotrophomonas* sp., and *Microbacterium* sp. conferred better plant growth as compared to single inoculants in *Arabidopsis thaliana*. Similar results of different microbial combinations were also shown in grape vine, potato, tomato, and maize (Rolli et al. 2015; Molina-Romero et al. 2017; Berg and Koskella 2018; De Vrieze et al. 2018).

Moreover, different plant genotypes under varied environmental conditions behave differently with regard to microbial interaction (Da Costa et al. 2014; Thijs et al. 2014; Syranidou et al. 2016; Santos-Medellín et al. 2017; Bhat et al. 2017a, b). Therefore, it is highly crucial to consider the source, type, and habitat of microbial candidate chosen for inoculation under field conditions.

15.3 A Brief Outlook into Phyllosphere Microbial Diversity

The phyllosphere that is often defined as the aerial or the aboveground floral or vegetative parts, with leaves as the dominant part representing about 109 km^2 (Vorholt 2012), is recognized as a hospitable environment for colonization and continuity of microorganisms. Phyllosphere harbours diverse taxonomic groups of algae, bacteria, filamentous fungi, virus, and, less frequently, nematodes and protozoa (Andrews and Harris 2000; Hirano and Upper 2000; Lindow and Brandl 2003). Of the microbial load, bacteria are found to be most dominant colonizers, often found on an average of 10^6 to 10^7 cells/cm^2 of leaf tissue (Beattie and Lindow 1995; Hirano and Upper 2000; Andrews and Harris 2000; Lindow and Brandl 2003; Singh et al. 2020). The overall microbial richness of phyllosphere is quite high (Jumpponen and Jones 2009), but compared to rhizospheric bacterial communities, phyllosphere-associated communities are less diverse (Delmotte et al. 2009). Research conducted so far has shown proteobacteria, bacteroidetes, firmicutes, and actinobacteria as most prime bacterial lineages of phyllosphere (Ruinen 1965; Corpe and Rheem 1989; Furnkranz et al. 2008; Redford et al. 2010; Innerebner et al. 2011; Atamna-Ismaeel et al. 2012; Vorholt 2012; Watanabe et al. 2016). As far as fungi are concerned, the population of filamentous fungi can average between 10^2 and 10^8 CFU/g of leaf, whereas population of yeast can range between 10 and 10^{10} CFU/g of leaf (Thompson et al. 1993; Inacio et al. 2002). Mostly, fungal taxa belonging to the phylum Ascomycota and Basidiomycota are found as major groups among the other important fungi on the leaf surfaces (Last 1955; Dickinson 1976; Shafi et al. 2018). However, distribution and functions of other microbial communities of phyllosphere have not been yet fully investigated.

The phyllosphere microbiota primarily colonize through air, soil, water, or from seeds (Vorholt 2012; Dar et al. 2013, 2016; Mehmood et al. 2019). Representing plant-environment interface, this microbial habitat is dynamic in nature, due to rapid fluctuations in environmental variables like radiation levels, daily temperature, humidity, and nutrient availability (Lindow and Brandl 2003; Vorholt 2012; Bhat et al. 2017a, b). Besides these oscillating factors, the microbial community composition is also structured by constant factors like geography and type of plant species (Whipps et al. 2008; Redford and Fierer 2009; Redford et al. 2010). Consistent with this, Ding and Melcher (2016) demonstrated change in the composition, diversity, and dynamics of endophytic bacteria of tall grass, in accordance with change in collection time and location. Similar, variation in temperate tree leaf bacterial community structure on temporal and spatial scales was also shown by Laforest-Lapointe et al. (2016). Despite differences in such factors, individual plants in the same habitat have been shown to share some prevalent taxa known as "core" microbiome. Kembel and Mueller (2014) showed phyllosphere microbial community on leaves of Neotropical forest trees varies as a function of host plant traits. However, some bacterial clades including α, β, and γ proteobacteria, actinobacteria, and sphingobacteria were consistent in the samples, suggesting that these bacteria act as "core" of phyllosphere microbiota on these Neotropical trees. Similar constant bacterial "core" consisting of *Arthrobacter*, *Bacillus*, *Massilia*, *Pantoea*, and *Pseudomonas* was also distinct in laboratory- and field-grown Roman lettuce plants irrespective of variation in time, space, and environment (Rastogi et al. 2012).

15.4 Role of Phyllospheric Microbiota

The use of advanced culture-independent molecular techniques has defined phyllosphere as the earth's largest environmental surface area of microbial habitation (Lindow and Brandl 2003; Vorholt 2012; Peñuelas and Terradas 2014). The inhabitant complex microbial consortia can have positive (mutualistic), neutral (commensal), or negative (pathogenic) influences on their host plant, and through their complex plant-microbial interactions can contribute greatly to plant growth and robustness (Vorholt 2012; Bulgarelli et al. 2013; Brader et al. 2017) and consequently to ecosystem productivity. Recent studies have shown phyllosphere-associated microorganisms as important characters in multiple ecophysiological processes such as plant signalling (Shiojiri et al. 2006), bioremediation of environmental pollutants (Sguros 1955; Sandhu et al. 2007; Nakamiya et al. 2009; Yutthammo et al. 2010; Nadalig et al. 2014), carbon sequestration (Bringel and Couee 2015), climate regulation (Otte et al. 2004; Peñuelas and Staudt 2009; Schäfer et al. 2010), and in global carbon, nitrogen, and other nutrient cycles (Furnkranz et al. 2008; Knief et al. 2012). Besides, it has also proved as best suited model for theoretical ecological studies (Finkel et al. 2012; Meyer and Leveau 2012).

15.4.1 Agro-based Functions

The current omic techniques (metagenomics, proteomics, metabolomics) helped not only in revealing the enormous microbial diversity residing in the phyllosphere but also in identifying and understanding the mechanisms and behaviour of microbe-microbe and plant-microbe interactions that helped in recognition of the expected benefits of phyllosphere microbiome in plant science in general and agriculture in particular. There are immense evidences for phyllosphere microflora interaction in crop plants affecting fitness, quality, and output (Fig. 15.1). Among the multitude of functions performed by microbes in phyllosphere, one of the key roles is plant nutrition acquisition through various processes like fixation of atmospheric nitrogen (Bentley and Carpenter 1984; Giri and Pati 2004), solubilization of phosphorous (P) (Mwajita et al. 2013; Batool et al. 2016; Thapa et al. 2017), and siderophore production (biofortification of Fe mediated by microbes in different crops) (Scavino and Pedraza 2013; Fu et al. 2016; Thapa et al. 2018). The other important phyllosphere microbe-mediated functions include enhanced plant growth through production of plant growth regulators [like IAA (Spaepe et al. 2007), cytokines (Holland 2011), abscisic acid (Cao et al. 2011)], biological control of phytopathogens (Elad 1996; Zipfel et al. 2004; Innerebner et al. 2011) through many ways like non-pathogenic microbe-mediated induction of immune response of plant, competitive exclusion of pathogen by non-pathogenic microorganisms, or antibiotic production. Besides this, phyllosphere microorganisms have been also found to promote desiccation tolerance to host plants against environmental stressors (Lindow et al. 1982a, b;

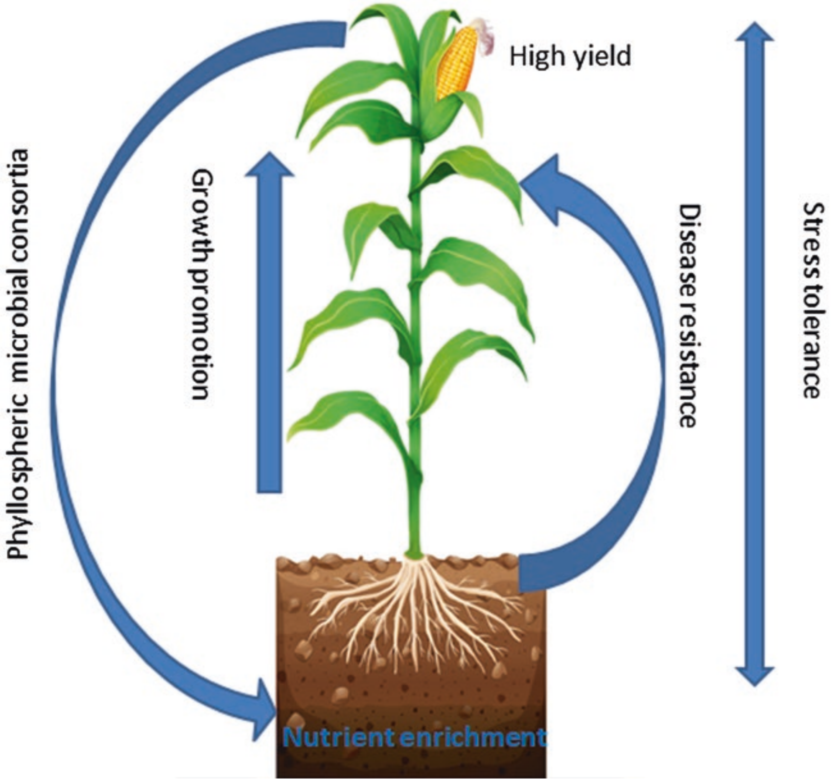


Fig. 15.1 Agro-based roles of phyllosphere microbiota

Wisniewski et al. 1997; Attard et al. 2012; Hubbard et al. 2014; del Rocío Mora-Ruiz et al. 2015), through production of various active metabolites and through bioremediation of harmful chemical compounds (Moulas et al. 2013; Sandhu et al. 2007; Waight et al. 2007; Yang et al. 2011; Ning et al. 2012; Xie et al. 2014).

Rice (*Oryza sativa* L.) is a major staple food crop in many developing countries, nourishing about half of the world's human population with 20% of direct intake of calories (Zeigler and Barclay 2008). Although many new cultivars of rice have been developed, it is facing decrease in yield due to several biotic and abiotic factors. Thus, for achieving sustainable rice yield, the amalgamation of beneficial plant microbes into agricultural productions is trending over the past few years. In this concern, a large number of studies have confirmed the influence of isolated colonizers of rice phyllosphere on yield, growth promotion, and pathogen inhibition (Maliti et al. 2005; Pedraza et al. 2009; Shamima Akter 2015, Thapa et al. 2017). Similarly, in other widely grown economical crop corn (*Zea mays* L.), the yield is limited by leaf disease called southern corn leaf blight (SCLB), caused by fungus *Bipolaris maydis*. Recent studies have shown the correlation between the increased severity of disease and decreased epiphytes of corn leaf (Manching et al. 2014). In other study, Marques et al. (2010) determined growth-promoting ability of six bacterial isolates on maize plant, and all of them have been reported to produce indole acetic acid (IAA), ammonia, and hydrogen cyanide (HCN), in both in vitro and greenhouse experiments.

Similarly, in a wide range of important crops like sugarcane, tomato, pigeon pea, mustard, potato, radish, etc., the beneficial phyllosphere microbes with multifold functional traits related to plant growth promotion and development have been documented, characterized, and well tested in laboratory. However, their field application is still lacking.

Various potential agro-based functions of the different microbial types isolated from phyllosphere of different plant sources are discussed in Table 15.1. This information can be used for development of useful bioproducts for agricultural purposes.

15.5 Conclusions and Future Prospects

Universal organic food production must be increased to meet the demand of rising consumers globally. Many countries have developed policies to reduce dependency on conventional chemical fertilizers owing to their hazardous effects on environmental health. In this context, phyllosphere microorganisms with multifunctional properties assume special significance. The phyllosphere represents the rich biohome of diverse molecular and chemical compounds in nature and often influences broad aspects of plant biology. The exploration of microbial diversity and their likely key roles on phyllosphere are acknowledged widely. There is a plethora of studies showing almost all the important crop functions including growth, production, utilization of essential nutrients, and immunity against various diseases are contributed by these microbial communities through many diverse

Table 15.1 Potential agro-based functions of phyllosphere microbiota associated with diverse host plants

S. No.	Plant source	Microorganism	Function	Reference
1.	Alfalfa (*Medicago sativa*)	*Methylobacterium* sp.	Increased IAA production	Omer et al. (2004)
2.	Apple (*Malus pumila*)	*Pseudomonas fluorescens*	Competitive exclusion of *Pseudomonas syringae* in apple and pear	Lindow et al. (1996), Stockwell and Stack (2007)
3.	Aquatic plants	*Pseudomonas aeruginosa*	Stress tolerance	Costerton et al. (1994)
		Bacteria	Arsenite oxidation	Xie et al. (2014)
4.	Bean (*Phaseolus vulgaris*)	*Methylobacterium* sp.	Enhanced plant growth promotion by increased activities of antioxidant enzymes – catalase (CAT) and superoxide dismutase (SOD)	El-Gawad et al. (2015)
5.	Chaparral (*Larrea divaricata*)	Ammonifiers Nitrifiers	Nitrogen fixation	Abril et al. (2005)
6.	Cotton (*Gossypium herbaceum*)	*Methylobacterium* sp.	Enhanced plant growth promotion by increased activities of antioxidant enzymes – catalase (CAT) and superoxide dismutase (SOD)	El-Gawad et al. (2015)
7.	Datura (*Datura inoxia*)	*Methylobacterium* sp.	Enhanced plant growth promotion by increased activities of antioxidant enzymes – catalase (CAT) and superoxide dismutase (SOD)	El-Gawad et al. (2015)
8.	Grape vine (*Vitis vinifera*)	*Bacillus* sp. *Staphylococcus* sp.	Antagonistic activity against pathogen *Botrytis cinerea*	Vionnet et al. (2018)
9.	Groundnut (*Arachis hypogaea*)	*Methylobacterium* sp.	Enhanced growth, seedling vigour and yield and induced immunity against rot pathogens *Aspergillus niger* and *Sclerotium rolfsii*	Madhaiyan et al. (2006)

(continued)

Table 15.1 (continued)

S. No.	Plant source	Microorganism	Function	Reference
10.	Mesquite (*Prosopis flexuosa*)	Ammonifiers Nitrifiers	Nitrogen fixation	Abril et al. (2005)
11.	Mistol (*Ziziphus mistol*)	Ammonifiers Nitrifiers	Nitrogen fixation	Abril et al. (2005)
12.	Mouse-ear cress (*Arabidopsis thaliana*)	*Burkholderia phytofirmans*	Enhanced photosynthetic rate, sugar uptake, root enlargement, and induced cold stress tolerance through production of proline and phenolics	Barka et al. (2006)
		Sphingomonas strains	Exclusion of pathogen *Pseudomonas syringae*	Innerebner et al. (2011)
13.	Mustard (*Brassica nigra*)	*Methylobacterium* sp.	Increased germination percentage and enhanced seedling growth	Meena et al. (2012)
		Methylobacterium extorquens	Promoted plant growth via production of indole acetic acid (IAA) and also enhanced seed germination and SVI	Pattnaik et al. (2017a)
14.	Peach (*Prunus persica*)	*Methylobacterium extorquens*	Promoted plant growth via production of indole acetic acid (IAA) and also enhanced seed germination and SVI	Pattnaik et al. (2017b)
15.	Pigeon pea (*Cajanus cajan*)	*Methylobacterium* sp.	Increased germination percentage and enhanced seedling growth	Meena et al. (2012)
16.	Potato (*Solanum tuberosum*)	*Methylobacterium* sp.	Increased germination percentage and enhanced seedling growth	Meena et al. (2012)
17.	Quebracho blanco (*Aspidosperma quebracho-blanco*)	Ammonifiers Nitrifiers	Nitrogen fixation	Abril et al. (2005)

(continued)

Table 15.1 (continued)

S. No.	Plant source	Microorganism	Function	Reference
18.	Radish (*Raphanus sativus*)	*Methylobacterium* sp.	Increased germination percentage and enhanced seedling growth	Meena et al. (2012)
19.	Rice (*Oryza sativa*)	Methylotrophic bacteria	Growth promotion	Maliti et al. (2005)
		Azospirillum brasilense	Improved yield	Pedraza et al. (2009)
		Fungal antagonists	Controlled sheath blight incidence by inhibiting the growth of *Rhizoctonia solani*	Shamima Akter (2015)
20.	Red clover (*Trifolium pratense*)	*Methylobacterium* sp.	Growth promotion via increased production of IAA	Omer et al. (2004)
21.	Snap broad bean (*Vicia faba*)	*Methylobacterium* spp.	Enhanced plant growth promotion by increased activities of antioxidant enzymes – catalase (CAT) and superoxide dismutase (SOD)	El-Gawad et al. (2015)
22.	Spruce trees	Chemolithoautotrophic ammonia oxidizing (CAO) and nitrite oxidizing (CNO) bacteria	Nitrogen fixation	Papen et al. (2002)
23.	Spinach (*Spinacia oleracea*)	*Bacillus* sp. *Pseudomonas* sp.	Inhibition of pathogen *Escherichia coli*	Lopez-Velasco et al. (2012)
24.	Strawberry (*Fragaria ananassa*)	*Methylobacterium zatmanii*	Promoted plant growth via production of indole acetic acid (IAA) and also enhanced seed germination and SVI	Pattnaik et al. (2017b)
25.	Sugarcane (*Saccharum officinarum*)	*Methylobacterium extorquens*	Accelerate germination, growth, and yield	Madhaiyan et al. (2005)
		Methylobacterium sp.	Increased germination percentage and enhanced seedling growth	Meena et al. (2012)
		Pantoea genus	Nitrogen fixation	Loiret et al. (2004)
26.	Tiny duckweed (*Wolffia australiana*)	Bacteria	Arsenic oxidation	Xie et al. (2014)

(continued)

Table 15.1 (continued)

S. No.	Plant source	Microorganism	Function	Reference
27.	Tobacco (*Nicotiana tabacum*)	*Achromobacter* sp. *Achromobacter* sp. *Alcaligenes* sp. *Bacillus* sp. *Enterobacter* sp. *Ochrobactrum* sp. *Pseudochrobactrum* sp. *Pseudomonas* sp. *Stenotrophomonas* sp.	Pathogen exclusion of *Pseudomonas syringae* pv. *tabaci*	Qin et al. (2019)
28.	Tomato (*Lycopersicon esculentum*)	*Sphingomonas* sp.	Growth promotion	Enya et al. (2007)
		Stenotrophomonas sp. *Pseudomonas* sp.	Promoted defence response and accelerated systemic resistance	Bringel and Couee (2015)
		Bacillus sp.	Suppression of *Botrytis cinerea* plant pathogen	Kefi et al. (2015)
		Methylobacterium sp.	Promoted plant growth nutrient uptake, seed germination, and SVI	Senthilkumar and Krishnamoorthy (2017)
29.	Spiny hackberry (*Celtis pallida*)	Ammonifiers, nitrifiers	Nitrogen fixation	Abril et al. (2005)
30	White clover (*Trifolium repens*)	*Methylobacterium* sp.	Increased production of growth hormone IAA	Omer et al. (2004)

mechanisms. Still, their utilization as biofertilizers in field conditions has not been wholly harnessed until now. The possible reasons could be the knowledge gap among the ecologists and agriculturalists regarding protocols of biofertilizer application, nonavailability of biofertilizers in markets, lack of awareness at cultivator level regarding usage and profitability, and absence of a supportive regulatory and policy framework. Thus, the success related to application of phyllosphere microbiota as biofertilizers requires integrated approach of microbiologists, agricultural advisors, manufacturers, farmers, and law-makers, to accustom plant growers regarding these innovative and eco-friendly products and promote their widespread usage.

References

Abril AB, Torres PA, Bucher EH (2005) The importance of phyllosphere microbial populations in nitrogen cycling in the Chaco semi-arid woodland. J Trop Ecol 21(1):103–107

Akter S (2015) Application of phyllosphere bacterial antagonist against rice sheath blight. Doctoral thesis, Universiti Putra Malaysia

Andreote FD, Gumiere T, Durrer A (2014) Exploring interactions of plant microbiomes. Sci Agric 71:528–539

Andrews JH, Harris RF (2000) The ecology and biogeography of microorganisms on plant surfaces. Annu Rev Phytopathol 38:145–180

Arnold AE et al (2003) Fungal endophytes limit pathogen damage in a tropical tree. Proc Natl Acad Sci U S A 100:15649–15654

Atamna-Ismaeel N, Finkel OM, Glaser F et al (2012) Bacterial anoxygenic photosynthesis on plant leaf surfaces. Environ Microbiol Rep 4:209–216

Attard E, Yang H, Delort AM et al (2012) Effects of atmospheric conditions on ice nucleation activity of *Pseudomonas*. Atmos Chem Phys 12:10667–10677

Bai Y et al (2015) Functional overlap of the Arabidopsis leaf and root microbiota. Nature 528:364–369

Barka EA, Nowak J, Clément C (2006) Enhancement of chilling resistance of inoculated grapevine plantlets with a plant growth-promoting rhizobacterium, *Burkholderia phytofirmans* strain PsJN. Appl Environ Microbiol 72:7246–7252

Batool F, Rehman Y, Hasnain S (2016) Phylloplane associated plant bacteria of commercially superior wheat varieties exhibit superior plant growth promoting abilities. Front Life Sci 9:313–322

Beattie GA, Lindow SE (1995) The secret life of foliar bacterial pathogens on leaves. Annu Rev Phytopathol 33:145–172

Bentley BL, Carpenter EJ (1984) Direct transfer of newly-fixed nitrogen from free-living epiphyllous microorganisms to their host plant. Oecologia 63:52–55

Berendsen RL, Pieterse CMJ, Bakker PAHM (2012) The rhizosphere microbiome and plant health. Trends Plant Sci 17:478–486

Berendsen RL, Vismans G, Yu K, Song Y, de Jonge R, Burgman WP et al (2018) Disease-induced assemblage of a plant-beneficial bacterial consortium. ISME J 12:1496–1507

Berg M, Koskella B (2018) Nutrient- and dose-dependent microbiome-mediated protection against a plant pathogen. Curr Biol 28:2487–2492

Berg G, Grube M, Schloter M, Smalla K (2014) Unraveling the plant microbiome: looking back and future perspectives. Front Microbiol 5:148

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017a) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 189–209

Bhatti AA, Haq S, Bhat (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Brader G, Compant S, Vescio K, Mitter B, Trognitz F, Ma LJ, Sessitsch A (2017) Ecology and genomic insights into plant-pathogenic and plant-nonpathogenic endophytes. Annu Rev Phytopathol 55:61–83

Bragina A, Berg C, Cardinale M et al (2012) *Sphagnum* mosses harbour highly specific bacterial diversity during their whole lifecycle. ISME J 6:802–813

Bringel F, Couee I (2015) Pivotal roles of phyllosphere microorganisms at the interface between plant functioning and atmospheric trace gas dynamics. Front Microbiol 6:486

Bulgarelli D, Schlaeppi K, Spaepen S, Ver Loren van Themaat E, Schulze-Lefert P (2013) Structure and functions of the bacterial microbiota of plants. Annu Rev Plant Biol 64:807–838

Busby PE et al (2017) Research priorities for harnessing plant microbiomes in sustainable agriculture. PLoS Biol 15:e2001793

Cao FY, Yoshioka K, Desveau D (2011) The roles of ABA in plant–pathogen interactions. J Plant Res 124:489–499

Checcucci A, DiCenzo GC, Ghini V, Bazzicalupo M, Beker A, Decorosi F, Dohlemann J, Fagorzi C, Finan TM, Fondi M et al (2018) Creation and characterization of a genomically hybrid strain in the nitrogen-fixing symbiotic bacterium Sinorhizobium meliloti. ACS Synth Biol 7:296483

Corpe WA, Rheem S (1989) Ecology of the methylotrophic bacteria on living leaf surfaces. FEMS Microbiol Ecol 62:243–249

Costerton JW, Lewandowski Z, DeBeer D et al (1994) Biofilms, the customized microniche. J Bacteriol 176:2137–2142

Da Costa PB, Granada CE, Ambrosini A, Moreira F, de Souza R, dos Passos JFM, Arruda L, Passaglia LM (2014) A model to explain plant growth promotion traits: a multivariate analysis of 2,211 bacterial isolates. PLoS One 9(12):116020

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from Fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

De Vrieze M, Germanier F, Vuille N, Weisskopf L (2018) Combining different potato-associated *Pseudomonas* strains for improved biocontrol of *Phytophthora infestans*. Front Microbiol 9:2573

del Rocío Mora-Ruiz M, Font-Verdera F, Díaz-Gil C et al (2015) Moderate halophilic bacteria colonizing the phylloplane of halophytes of the subfamily Salicornioideae (Amaranthaceae). Syst Appl Microbiol 38:406–441

Delgado-Baquerizo M, Maestre FT, Reich PB, Jeffries TC, Gaitan JJ, Encinar D et al (2016) Microbial diversity drives multifunctionality in terrestrial ecosystems. Nat Commun 7:10541–10548

Delmotte N, Knief C, Chaffron S, Innerebner G, Roschitzki B, Schlapbach R, von Mering C, Vorholt JA (2009) Community proteogenomics reveals insights into the physiology of phyllosphere bacteria. Proc Natl Acad Sci 106:16428–16433

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 183–196

Dickinson CH (1976) Fungi on the aerial surfaces of higher plants. In: Microbiology of aerial plant surfaces. Academic Press, New York, pp 293–325

Ding T, Melcher U (2016) Influences of plant species, season and location on leaf endophytic bacterial communities of non-cultivated plants. PLoS One 11:e0150895

Elad Y (1996) Mechanisms involved in the biological control of *Botrytis cinerea* incited diseases. Eur J Plant Pathol 102:719–732

El-Gawad HGA, Ibrahim MFM, El-Hafez AAA, El-Yazied AA (2015) Contribution of pink pigmented facultative methylotrophic bacteria in promoting antioxidant enzymes, growth and yield of snap bean. Am Eurasian J Agric Environ Sci 15:1331–1345

Enya J, Shinohara H, Yoshida S, Negishi TTH, Suyama K, Tsushima S (2007) Culturable leaf-associated bacteria on tomato plants and their potential as biological control agents. Microb Ecol 53:524–536

Finkel OM, Burch AY, Elad T, Huse SM, Lindow SE, Post AF et al (2012) Distance-decay relationship partially determine diversity patterns of phyllosphere bacteria on Tamarix trees across the Sonoran desert. Appl Environ Microbiol 78:6187–6193

Fu SF, Sun PF, Lu HY, Wei JY, Xiao HS, Fang WT, Cheng BY, Chou JY (2016) Plant growth-promoting traits of yeasts isolated from the phyllosphere and rhizosphere of *Drosera spatulata lab*. Fungal Biol Rev 120:433–448

Furnkranz M, Wanek W, Richter A, Abell G, Rasche F, Sessitsch A (2008) Nitrogen fixation by phyllosphere bacteria associated with higher plants and their colonizing epiphytes of a tropical lowland rainforest of Costa Rica. ISME J 2:561–570

Giri S, Pati BR (2004) A comparative study on phyllosphere nitrogen fixation by newly isolated *Corynebacterium* sp. and *Flavobacterium* sp. and their potentialities as biofertilizer. Acta Microbiol Immunol Hung 51:47–56

Grossman JM, Schipanski ME, Sooksanguan T, Drinkwater LE (2011) Diversity of rhizobia nodulating soybean [Glycine max (Vinton)] varies under organic and conventional management. Appl Soil Ecol 50:14–20

Hardoim PR, van Overbeek LS, van Elsas JD (2008) Properties of bacterial endophytes and their proposed role in plant growth. Trends Microbiol 16:463–471

Hirano SS, Upper CD (2000) Bacteria in the leaf ecosystem with emphasis on *Pseudomonas syringae*—a pathogen, ice nucleus, and epiphyte. Microbiol Mol Biol Rev 64:624–653

Holland MA (2011) Nitrogen: give and take from phylloplane microbes. In: Ecological aspects of nitrogen metabolism in plants. Wiley-Blackwell, London, pp 217–230

Hubbard M, Germida JJ, Vujanovic V (2014) Fungal endophytes enhance wheat heat and drought tolerance in terms of grain yield and second-generation seed viability. J Appl Microbiol 116:109–122

Inacio J, Pereira P, de Carvalho M, Fonseca A, Amaral-Collaco MT, Spencer-Martins I (2002) Estimation and diversity of phylloplane mycobiota on selected plants in a Mediterranean-type ecosystem in Portugal. Microb Ecol 44:344–353

Innerebner G, Knief C, Vorholt JA (2011) Protection of Arabidopsis thaliana against leaf-pathogenic *Pseudomonas syringae* by *Sphingomonas* strains in a controlled model system. Appl Environ Microbiol 77:3202–3210

Jumpponen A, Jones KL (2009) Massively parallel 454 sequencing indicates hyperdiverse fungal communities in temperate *Quercus macrocarpa* phyllosphere. New Phytol 184(2):438–448

Kefi A, Slimene IB, Karkouch I, Rihouey C, Azaeiz S, Bejaoui M, Belaid R, Cosette P, Jouenne T, Limam F (2015) Characterization of endophytic *Bacillus* strains from tomato plants (*Lycopersicon esculentum*) displaying antifungal activity against *Botrytis cinerea* Pers. World J Microbiol Biotechnol 31:1967–1976

Kembel SW, Mueller RC (2014) Plant traits and taxonomy drive host associations in tropical phyllosphere fungal communities. Botany 92:303–311

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Knief C, Delmotte N, Chaffron S, Stark M, Innerebner G, Wassmann R, von Mering C, Vorholt JA (2012) Metaproteogenomic analysis of microbial communities in the phyllosphere and rhizosphere of rice. ISME J 6:1378–1390

Laforest-Lapointe I, Messier C, Kembel SW (2016) Host species identity, site and time drive temperate tree phyllosphere bacterial community structure. Microbiome 4:27

Last FT (1955) Seasonal incidence of Sporobolomyces on cereal leaves. Trans Br Mycol Soc 38:221–239

Lindow SE, Brandl MT (2003) Microbiology of the phyllosphere. Appl Environ Microbiol 69:1875–1883

Lindow SE, Arny DC, Upper CD (1982a) Bacterial ice nucleation: a factor in frost injury to plants. Plant Physiol 70:1084–1089

Lindow SE, Hirano SS, Barchet WR et al (1982b) Relationship between ice nucleation frequency of bacteria and frost injury. Plant Physiol 70:1090–1093

Lindow S, McGourty G, Elkins R (1996) Interactions of antibiotics with *Pseudomonas fluorescens* strain A506 in the control of fire blight and frost injury to pear. Phytopathology 86:841–848

Loiret FG, Ortega E, Kleiner D, Ortega-Rodes P, Rodes R, Dong Z (2004) A putative new endophytic nitrogen-fixing bacterium Pantoea sp. from sugarcane. J Appl Microbiol 97:504–511

Lopez-Velasco G, Tydings HA, Boyer RR, Falkinham JO, Ponder MA (2012) Characterization of interactions between *Escherichia coli* O157: H7 with epiphytic bacteria in vitro and on spinach leaf surfaces. Int J Food Microbiol 153(3):351–357

Madhaiyan M, Poonguzhali S, Lee HS, Hari K, Sundaram SP, Sa TM (2005) Pink-pigmented facultative methylotrophic bacteria accelerate germination, growth and yield of sugarcane clone Co86032 Saccharum officinarum L. Biol Fertil Soils 41:350–358

Madhaiyan M, Suresh Reddy BV, Anandham R, Senthilkumar M, Poonguzhali S, Sundaram SP, Sa TM (2006) Plant growth–promoting methylobacterium induces defense responses in groundnut Arachis hypogaea L. compared with rot pathogens. Curr Microbiol 53:270–276

Maliti CM, Basile DV, Corpe WA (2005) Effects of *Methylobacterium* spp. strains on rice *Oryza sativa* L. callus induction, plantlet regeneration, and seedlings growth in vitro 1. J Torrey Bot Soc 132:355–367

Manching HC, Balint-Kurti PJ, Stapleton AE (2014) Southern leaf blight disease severity is correlated with decreased maize leaf epiphytic bacterial species richness and the phyllosphere bacterial diversity decline is enhanced by nitrogen fertilization. Front Plant Sci 5:403

Marques AP, Pires C, Moreira H, Rangel AO, Castro PM (2010) Assessment of the plant growth promotion abilities of six bacterial isolates using Zea mays as indicator plant. Soil Biol Biochem 42(8):1229–1235

Meena KK, Kumar M, Kalyuzhnaya MG, Yandigeri MS, Singh DP, Saxena AK, Arora DK (2012) Epiphytic pink-pigmented methylotrophic bacteria enhance germination and seedling growth of wheat (*Triticum aestivum*) by producing phytohormone. Anton Leeuw 101:777–786

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mendes R et al (2011) Deciphering the rhizosphere microbiome for disease-suppressive bacteria. Science 332:1097–1100

Mendes R, Garbeva P, Raaijmakers JM (2013) The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS Microbiol Rev 37:634–663

Meyer KM, Leveau JH (2012) Microbiology of the phyllosphere: a playground for testing ecological concepts. Oecologia 168:621–629

Molina-Romero D, Baez A, Quintero-Hernández V, Castañeda-Lucio M, Fuentes-Ramírez LE, Bustillos-Cristales MDR et al (2017) Compatible bacterial mixture, tolerant to desiccation, improves maize plant growth. PLoS One 12:e0187913

Moulas C, Petsoulas C, Rousidou K, Perruchon C, Karas P, Karpouzas DG (2013) Effects of systemic pesticides imidacloprid and metalaxyl on the phyllosphere of pepper plants. Biomed Res Int 2013:969750

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–178

Mwajita MR, Murage H, Tani A, Kahangi EM (2013) Evaluation of rhizosphere, rhizoplane and phyllosphere bacteria and fungi isolated from rice in Kenya for plant growth promoters. Springerplus 2:606

Nadalig T, Greule M, Bringel F, Keppler F, Vuilleumier S (2014) Probing the diversity of chloromethane-degrading bacteria by comparative genomics and isotopic fractionation. Front Microbiol 5:523

Nakamiya K, Nakayama T, Ito H, Shibata Y, Morita M (2009) Isolation and properties of a 2-chlorovinylarsonic acid-degrading microorganism. J Hazard Mater 165:388–393

Ning J, Gang G, Bai Z et al. (2012) In situ enhanced bioremediation of dichlorvos by a phyllosphere Flavobacterium strain. Front Environ Sci Eng 6:231–237

Omer ZS, Tombolini R, Broberg A, Gerhardson B (2004) Indole-3-acetic acid production by pink-pigmented facultative methylotrophic bacteria. Plant Growth Regul 43:93–96

Otte ML, Wilson G, Morris JT, Moran BM (2004) Dimethylsulphoniopropionate (DMSP) and related compounds in higher plants. J Exp Bot 55:1919–1925

Papen H, Geβler A, Zumbusch E, Rennenberg H (2002) Chemolithoautotrophic nitrifiers in the phyllosphere of a spruce ecosystem receiving high atmospheric nitrogen input. Curr Microbiol 44:56–60

Pattnaik S, Rajkumari J, Parasuraman P, Siddhardha B (2017a) Plant growth promoting activity of pink pigmented facultative Methylotroph–Methylobacterium extorquens MM2 on Lycopersicon esculentum L. J Appl Biol Biotechnol 5:042–046

Pattnaik S, Rajkumari J, Paramanandham P, Busi S (2017b) Indole acetic acid production and growth promoting activity of *Methylobacterium extorquens* MP_1 and *Methylobacterium zatmanii* MS_4 in tomato. Int J Veg Sci 23:321–330

Peay KG, Kennedy PG, Talbot JM (2016) Dimensions of biodiversity in the Earth mycobiome. Nat Rev Microbiol 14:434–447

Pedraza RO, Bellone CH, de Bellone SC et al (2009) *Azospirillum* inoculation and nitrogen fertilization effect on grain yield and on the diversity of endophytic bacteria in the phyllosphere of rice rainfed crop. Eur J Soil Biol 45:36–43

Peñuelas J, Staudt M (2009) BVOCs and global change. Trends Plant Sci 15:133–144

Peñuelas J, Terradas J (2014) The foliar microbiome. Trends Plant Sci 19:278–280

Philippot L, Raaijmakers JM, Lemanceau P et al (2013) Going back to the roots: the microbial ecology of the rhizosphere. Nat Rev Microbiol 11:789–799

Qin C, Tao J, Liu T, Liu Y, Xiao N, Li T, Gu Y, Yin H, Meng D (2019) Responses of phyllosphere microbiota and plant health to application of two different biocontrol agents. AMB Express 9:42

Quiza L, St-Arnaud M, Yergeau E (2015) Harnessing phytomicrobiome signaling for rhizosphere microbiome engineering. Front Plant Sci 6:507

Ramachandran VK, East AK, Karunakaran R, Downie JA, Poole SP (2011) Adaptation of *Rhizobium leguminosarum* to pea, alfalfa and sugar beet rhizosphere investigated by comparative transcriptomics. Genome Biol 12:106–109

Rashid MH, Schafer H, Gonzalez J, Wink M (2012) Genetic diversity of rhizobia nodulating lentil (*Lens culinaris*) in Bangladesh. Syst Appl Microbiol 35:98–109

Rastogi G, Sbodio A, Tech JJ, Suslow TV, Coaker GL, Leveau JHJ (2012) Leaf microbiota in an agroecosystem: spatiotemporal variation in bacterial community composition on field-grown lettuce. ISME J 6:1812–1822

Redford AJ, Fierer N (2009) Bacteria succession on the leaf surface: a novel system for studying successional dynamics. Microb Ecol 58:189–198

Redford AJ, Bowers RM, Knight R, Linhart Y, Fierer N (2010) The ecology of the phyllosphere: geographic and phylogenetic variability in the distribution of bacteria on tree leaves. Environ Microbiol 12:2885–2893

Rolli E, Marasco R, Vigani G, Ettoumi B, Mapelli F, Deangelis ML et al (2015) Improved plant resistance to drought is promoted by the root-associated microbiome as a water stress-dependent trait. Environ Microbiol 17:316–331

Ruinen J (1965) The phyllosphere – III. Nitrogen fixation in the phyllosphere. Plant Soil 22:375–394

Sandhu A, Halverson L J, Beattie GA (2007) Bacterial degradation of airborne phenol in the phyllosphere. Environ Microbiol 9:383–392

Santos-Medellín C, Edwards J, Liechty Z, Nguyen B, Sundaresan V (2017) Drought stress results in a compartment-specific restructuring of the rice root-associated microbiomes. MBio 8:e00764–e00817

Scavino AF, Pedraza RO (2013) The role of siderophores in plant growth-promoting bacteria. In: Bacteria in agrobiology: crop productivity. Springer, Berlin, Heidelberg, pp 265–285

Schäfer H, Myronova N, Boden R (2010) Microbial degradation of dimethylsulphide and related C1-sulphur compounds: organisms and pathways controlling fluxes of sulphur in the biosphere. J Exp Bot 61:315–334

Senthilkumar M, Krishnamoorthy R (2017) Isolation and characterization of tomato leaf phyllosphere Methylobacterium and their effect on plant growth. Int J Curr Microbiol App Sci 6:2121–2136

Sguros PL (1955) Microbial transformations of the tobacco alkaloids. I. Cultural and morphological characteristics of a nicotinophile. J Bacteriol 69:28–37

Shafi S, Bhat RA, Bandh SA, Shameem N, Nisa H (2018) Microbes: key agents in the sustainable environment and cycling of nutrients. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–179–188

Sharma P, Sardana V, Kandola SS (2011) Response of groundnut (*Arachis hypogaea* L.) to Rhizobium inoculation. Libyan Agric Res Centre J Int 2:101–104

Shigenaga AM, Argueso CT (2016) No hormone to rule them all: interactions of plant hormones during the responses of plants to pathogens. Semin Cell Dev Biol 56:174–189

Shiojiri K, Kishimoto K, Ozawa R, Kugimiya S, Urashimo S, Arimura G et al (2006) Changing green leaf volatile biosynthesis in plants: an approach for improving plant resistance against both herbivores and pathogens. Proc Natl Acad Sci U S A 103:16672–16676

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 319–339

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Spaepen S, Vanderleyden J, Remans R (2007) Indole-3-aceticacidinmicrobial and microorganism-plant signaling. FEMS Microbiol Rev 31:475–448

Stockwell VO, Stack JP (2007) Using *Pseudomonas* spp. for integrated biological control. Phytopathology 97:244–249

Syranidou E, Christofilopoulos S, Gkavrou G, Thijs S, Weyens N, Vangronsveld J et al (2016) Exploitation of endophytic bacteria to enhance the phytoremediation potential of the wetland helophyte *Juncus acutus*. Front Microbiol 7:1016

Thapa S, Prasanna R, Ranjan K, Velmourougane K, Ramakrishnan B (2017) Nutrients and host attributes modulate the abundance and functional traits of phyllosphere microbiome in rice. Microbiol Res 204:55–64

Thapa S, Ranjan K, Ramakrishnan B, Velmourougane K, Prasanna R (2018) Influence of fertilizers and rice cultivation methods on the abundance and diversity of phyllosphere microbiome. J Basic Microbiol 58:172–186

Thijs S, van Dillewijn P, Sillen W, Truyens S, Holtappels M, Ďhaen J et al (2014) Exploring the rhizospheric and endophytic bacterial communities of *Acer pseudoplatanus* growing on a TNT-contaminated soil: towards the development of a rhizocompetent TNT-detoxifying plant growth promoting consortium. Plant Soil 385:15–36

Thompson IP, Bailey MJ, Fenlon JS, Fermor TR, Lilley AK, Lynch JM, Mccormack PJ, Mcquilken MP, Purdy KJ, Rainey PB, Whipps JM (1993) Quantitative and qualitative seasonal-changes in the microbial community from the phyllosphere of sugar-beet (*Beta vulgaris*). Plant Soil 150:177–191

Tkacz A, Poole P (2015) Role of root microbiota in plant productivity. J Exp Bot 66:2167–2175

Truyens S, Weyens N, Cuypers A et al (2015) Bacterial seed endophytes: genera, vertical transmission and interaction with plants. Environ Microbiol Rep 7:40–50

Vandenkoornhuyse P, Quaiser A, Duhamel M, Le Van A, Dufresne A (2015) The importance of the microbiome of the plant holobiont. New Phytol 206:1196–1206

Verginer M, Siegmund B, Cardinale M et al (2010) Monitoring the plant epiphyte *Methylobacterium extorquens* DSM 21961 by real-time PCR and its influence on the strawberry flavor. FEMS Microbiol Ecol 74:136–145

Vionnet L, Vrieze MD, Dutartre A, Gfeller A, Lüthi A, L'Haridon F, Weisskopf L (2018) Microbial life in the grapevine: what can we expect from the leaf microbiome. OENO One 52:219–224

Vorholt JA (2012) Microbial life in the phyllosphere. Nat Rev Microbiol 10:828–840

Waight K, Pinyakong O, Luepromchai E (2007) Degradation of phenanthrene on plant leaves by phyllosphere bacteria. J Gen Appl Microbiol 53:265–272

Watanabe K, Kohzu A, Suda W et al (2016) Microbial nitrification in through fall of a Japanese cedar associated with archaea from the tree canopy. Springerplus 5:1596

Weller DM, Mavrodi DV, van Pelt JA, Pieterse CM, van Loon LC, Bakker PA (2012) Induced systemic resistance in *Arabidopsis thaliana* against *Pseudomonas syringae* pv. tomato by 2,4-diacetylphloroglucinol-producing *Pseudomonas fluorescens*. Phytopathology 102:403–412

Whipps JM, Hand P, Pink D, Bending GD (2008) Phyllosphere microbiology with special reference to diversity and plant genotype. J Appl Microbiol 105:1744–1755

Wisniewski M, Lindow SE, Ashworth EN (1997) Observations of ice nucleation and propagation in plants using infrared video thermography. Plant Physiol 113:327–334

Xie WY, Su JQ, Zhu YG (2014) Arsenite oxidation by the phyllosphere bacterial community associated with *Wolffia australiana*. Environ Sci Technol 48:9668–9674

Yang L, Wang Y, Song J et al. (2011) Promotion of plant growth and in situ degradation of phenol by an engineered Pseudomonas fluorescens strain in different contaminated environments. Soil Biol Biochem 43:915–922

Yao L, Wu Z, Zheng Y, Kaleem I, Li C (2010) Growth promotion and protection against salt stress by *Pseudomonas putida* Rs-198 on cotton. Eur J Soil Biol 46:49–54

Yutthammo C, Thongthammachat N, Pinphanichakarn P, Luepromchai E (2010) Diversity and activity of PAH-degrading bacteria in the phyllosphere of ornamental plants. Microb Ecol 59:357–368

Zabetakis I, Moutevelis-Minakakis P, Gramshaw JW (1999) The role of 2-hydroxypropanal in the biosynthesis of 2,5-dimethyl-4-hydroxy-2H-furan-3-one in strawberry (*Fragaria ananassa* cv *Elsanta*) callus cultures. Food Chem 64:311–314

Zeigler R, Barclay A (2008) The relevance of rice. Rice 1:3–10

Zipfel C, Robatzek S, Navarro L, Oakeley EJ (2004) Bacterial disease resistance in *Arabidopsis* through flagellin perception. Nature 428:764–767

Chapter 16
Biofertilizers: A Viable Tool for Future Organic Agriculture

Umair Riaz, Ghulam Murtaza, Ayesha Abdul Qadir, Faizan Rafi, Muhammad Akram Qazi, Shahid Javid, Muhammad Tuseef, and Muhammad Shakir

16.1 Introduction

The substances that have living microbes and reside in the area surrounding roots, i.e. rhizosphere, and are involved in enhancing the supply of nutrients to plants are known as biofertilizers. They include everything ranging from manures to those of plant extracts. The species of bacteria living in the rhizosphere of plant roots are together known as plant growth-promoting bacteria abbreviated as PGPR. This PGPR serves as the source of many biofertilizers. The biofertilizers are mainly derived from phosphate solubilizers, mycorrhizae, and nitrogen fixer groups of PGPR. Biofertilizers are one of the best ways to provide nutrients to plants without damaging the environment or health of soils and humans. As the biofertilizers are living formulations of beneficial microbes, they can be used to amend soil, root, or seed equally by making the availability of these microbes. This improves the health of the soil. The biofertilizers have living cells that make nutrients available, which

---

U. Riaz (✉)
Soil and Water Testing Laboratory for Research, Agriculture Department,
Government of Punjab, Bahawalpur, Punjab, Pakistan

G. Murtaza (✉) · A. A. Qadir · F. Rafi
Institute of Soil and Environmental Sciences, University of Agriculture,
Faisalabad, Punjab, Pakistan
e-mail: gmurtaza@uaf.edu.pk

M. A. Qazi · M. Shakir
Rapid Soil Fertility Survey and Soil Testing Institute, Lahore, Punjab, Pakistan

S. Javid
Provincial Reference Fertilizer Testing Laboratory, Raiwind, Lahore, Punjab, Pakistan

M. Tuseef
National Institute of Food Science and Technology, University of Agriculture,
Faisalabad, Punjab, Pakistan

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4_16

are not available generally to the plant (Ismail et al. 2013). Many microbes that increase plant growth are involved in regulating many processes of soil. These processes include decomposition of the OM and the availability of different plant nutrients like potassium, iron, phosphorus, magnesium, and nitrogen, enhancing the growth of plants (Dar et al. 2013; Lalitha 2017). The steps involving the production of biofertilizers are the following:

- The first step is the separation of microbes from the soil.
- Screening of microorganisms in the lab for plant growth.
- Greenhouse screening of microorganisms in pots filled with soils to enhance growth in them.
- The screening in the field of those the most effective microorganisms in cropped soil.
- Inoculum refining.
- Production of biofertilizers.

The biofertilizers are prepared by selection of most efficient bacterial strains that are passed by various steps as mentioned above (Bhattacharjee and Dey 2014). Organic farming has gained much attention throughout the world because it is environment-friendly and enables the growth of healthy and safe food free from agrochemicals. It is tough to grow crops without synthetic chemicals for the growing population of the world. But there exist many opportunities where organic agriculture can be promoted. Biofertilizers play a crucial role in organic farming. The microbes have a basic role in fixation of the atmospheric N, which is very crucial in enhancing the fertility of the soil. These microbes also convert insoluble phosphates to soluble, making them available for plants. Biofertilizers have shown a great impact on the mobilization of nutrients in the soil (Venkatashwarlu 2008).

16.2 Biofertilizer Scope

The use of synthetic fertilizers has caused a lot of problems. Pesticides and fertilizers have contaminated water, air, and soil. Their misuse has killed crop-friendly worms and destroyed a beneficial population of microbes in the soil. The prices of fertilizers are increasing day by day because of the depletion of fossil fuels. This is affecting the input costs. The fertility and productivity of the soil are also decreasing due to the increasing gap between the supply and removal of nutrients. Biofertilizers have great potential to cope with this situation. The selection of P-solubilizing and nitrogen-fixing strains according to the environment of the soil is critical to understand. The symbiotic relation between microbes and plants in different agroclimatic conditions is also a great interest for many researchers. Biofertilizers, in combination with fertilizers, are the best option for achieving the goal of maximum yield. A lot of work is being done on formulating new types of biofertilizers. The powdered and liquid formulations are its best examples (Mahdi et al. 2010; Mushtaq et al. 2018; Shafi et al. 2018).

16.3 Organic Agriculture History

Sir Albert Howard is considered the first known person who gave the concept of organic agriculture. He published a book *An Agricultural Testament* in 1943 in which he gave the basic idea of organic farming. He stated that organic waste can be recycled and gave the process like present-day composting. The first person to use term organic for farming was Walter Northbourne. He explained his concept of making a farm a whole organic system in his book *Look to the Land*. Howard may be called a polarizing personality. The era from 1940 to 1978 might be known as the era of polarization of agriculture into organic and non-organic. The farmers of the inorganic approach ignored organic farming, but all the universities and research institutes continued to conduct researches on organic farming. Organic farming was recognized at the national level in the USA from 1979 to 1990. The USDA and universities did a lot of work during this period on organic farming. In the beginning, the standards proposed by the USDA allowed the usage of food irradiation, sewage sludge, and GMOs. But due to the public pressure, they were taken back. The USDA gave the certification of organic foods in 2002 (Heckman 2006).

16.4 Why Organic Farming?

Apart from the adverse impacts of chemical fertilizers on soil and environment, the fertilizer factories are one of the primary sources of air, water, and land pollution. The groundwater of the areas where these factories are situated is reported to be contaminated (Zakharova et al. 2002; Mehmood et al. 2019).

16.4.1 Environmental Benefits

The pesticides being used by farmers across the world are damaging environment in many ways. These pesticides are one of the significant threats to the environment. Their misuse or overuse is very dangerous to the environment as well as the plant population of that area (Kumar and Puri 2012; Dar et al. 2016; Dar and Bhat 2020; Dervash et al. 2020). It is very crucial in this decade of the twenty-first century to put forward environment-friendly alternatives to control the pests. The microbes can be used for degrading these pesticides. There are some bacteria that can reduce the toxicity caused by pesticides. These bacteria are from genera *Klebsiella*, *Azospirillum*, *Pseudomonas*, *Bacillus*, *Gordonia*, *Azotobacter*, *Serratia*, and *Enterobacter* (Shaheen and Sundari 2013). The enzymes have a key role in lysis. These are mostly produced by the microorganisms. Hydrolyses and esterase are one of the most vital among them. The glutathione S-transferases and oxidases have a mixed function in the degradation of the pesticides (Ortiz-Hernández et al. 2013; Sofi et al. 2017; Bhat et al. 2018a; Singh et al. 2020).

Tuomisto et al. (2012) state that organic farming had far less negative influence on the environment in comparison to conventional farming. The way farmers manage their farms is also significant in finding the impacts of conventional and organic farming on the environment. No single farming system can achieve the target yield. An optimal farming system involves the combination of both farming systems. The adoption of this optimal system depends upon the prices of that area. Some systems are designed to meet the specific targets, while others aim to work under sensitive environments. A policy is needed to design the optimal farming system.

16.4.2 Economic Benefit and Profitability

Organic farming systems are more cost-effective than traditional farming systems. Four factors are involved in improved income. The first factor involves the direct links of the farmers with consumers. Many farmers growing their commodities organically provide home delivery for their customers. This eliminates the role of a middleman. Second is that operational expenses of organic farming are one third less in terms of pesticides, chemicals, and energy. There are low input costs in growing cereals organically as low as 50–60%. The input expenses of horticultural and dairy products are 10–20% and 20–25%, respectively. The third factor is the premium price for organic foods in the market. Farmers get an excellent price of their organic produce. The fourth one is that organic farms are very resilient to the changing weather conditions in comparison to conventional farms. The adoption of organic farming improves the financial condition of the rural community as a whole. The on-farm sales of organic farmers are also higher as compared to conventional farmers. Their dependence on off-farm sales is low, and they mostly make money through direct marketing. The wages at the organic farms are much higher as compared to traditional farms that improve the economic condition of local tenants. Some disruptions are faced in the beginning when a farm shifts from conventional to organic farming. These disruptions require extensive research (MacRae et al. 2007).

16.4.3 Health Benefits

Over the last few decades, organic farming and organic foods have gained much popularity all over the world. The key difference between organic and traditional food products lies in its technique of growth. The certifications of organic foods vary among different regions of the world. The organic foods are featured by their strict constraint against synthetic fertilizers and pesticides. The phenolic compounds are produced in the plants by not using pesticides on them (Simonne et al. 2016; Bhatti et al. 2017).

The concentration of vitamin C is found much higher in foods obtained from organic plants as compared to inorganic foods. The organically produced yellow plums, carrots, sweet peppers, and tomatoes have more carotenoids than conventionally grown vegetables. More essential amino acids are present in organic foods (Popa et al. 2019; Bhat et al. 2017; Khanday et al. 2016). The milk produced organically has more amounts of long-chain fatty acids, conjugated linoleic acid, long-chain fatty acids, and alpha-linolenic acid. The organic bovine milk also has more desired fatty acids having higher levels of iron and alpha-tocopherol (Średnicka-Tober et al. 2016).

16.4.4 Organic Foods and Market

The demand for organic food is increasing around the globe. The revenues of organic drinks and food have increased in all regions of the world, but the significant growth in revenues is seen in North America and Europe. A shortage of supply is also seen in many sectors of organic products. These mostly include organic milk and yoghurt, organic meat, organic fruits, and some beverages. The demand for organic foods comes from the most developed countries. G7 countries account for a major import of organic foods. The Asian countries must develop internal markets and must have a check on exports of organic foods (Organic Monitor).

16.4.5 Organic Food for Sustainable Agriculture and Soil Fertility Management

Sustainable agriculture is not a specific methodology. It is a broad term. It includes many technologies and practices. Its recognition all over the world shows that traditional agriculture is not enough to meet the challenges of food security of the world. Traditional farming is facing the issue of low yield and high expenses of inputs. Monoculture farming has led to decreased soil fertility, destruction of beneficial microbes and insect populations, and vitality of the soil. The extra utilization of pesticides and fertilizers, the high energy consumption for tillage, and high costs of irrigation are one of the major concerns for agriculture.

Organic farming has a key role in sustainable agriculture. The traditional agriculture is exhausting natural resources at a very rapid pace. It is crucial that farmers must understand the ways of conserving their lands by using biofertilizers and other amendments. It is observed that the soil's beneficial microbes are not damaged in any agroecological zones when no pesticide is used. The low agricultural yields are linked to many biological, environmental, and physiological factors. These factors are improved by organic farming. The crops grown organically have shown good resistance against diseases. The selection of agricultural practices and technologies must be selected by keeping the concept of sustainable agriculture in mind. Organic foods are vital for food security and sustainable agriculture. Sustainable agriculture has a close link with improved soil fertility and productivity. Microbes have a crucial role in it. The plants can get nutrients efficiently from the soils having PGPR. The nutrient cycles become more efficient as microorganisms are involved in mineralization, decomposition, and accessibility of nutrients. The microbes are involved in the degradation of SOM. That is why they directly influence the WHC of the soil, soil acidity and toxicity, CEC, and P, N, and S reserves (Singh et al. 2011).

The farm either organic or traditional may be called sustainable when it produces high-quality food in adequate amounts, is economically viable, and participates in the welfare of the farmer community. The yield of organic foods is low than traditional foods. The most closing yield of organic farming with traditional farming is of soybean, rice, and corn. But the quality of organic foods is much higher (Reganold and Wachter 2016).

16.5 Causes of Low Adoption of Organic Farming

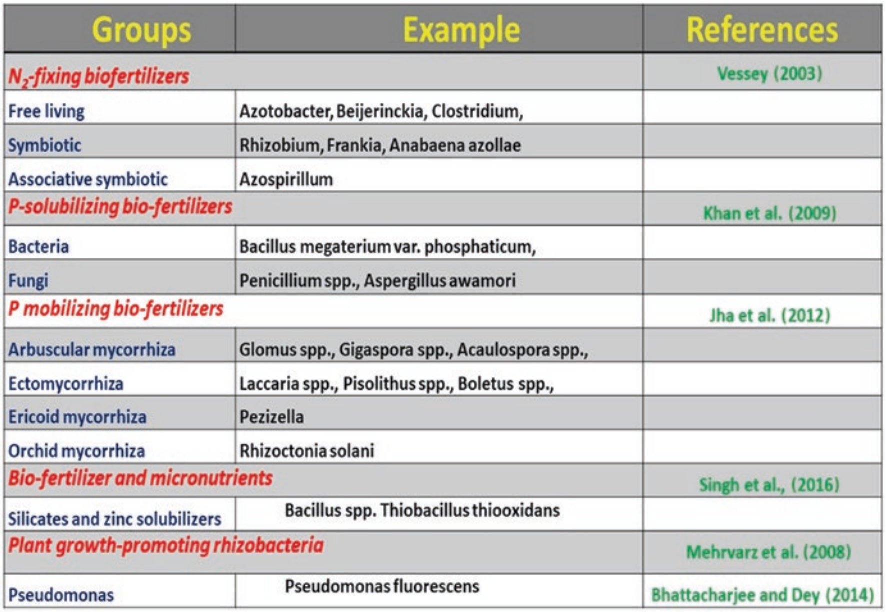
The importance of organic agriculture is being realized by farmers, policymakers, intellectuals, practitioners, academicians, and sensitive citizens. Despite the realization of the environmental, health, social, financial, or personal benefits linked with organic agriculture, the adoption of organic agriculture is restricted due to many challenges. The understanding of the factors that stand as barriers in the adoption of organic farming is important. In this section, all the possible difficulties faced by the organic respondents which hamper the extent of adoption of organic farming practices were grouped into five major categories, viz. infrastructural, economic, technological, socio-psychological, and educational constraints (Jangid et al. 2012; Bhat et al. 2018a). There are certain factors responsible for the adoption of organic agriculture in this era and are shown in Fig. 16.1 with respect to region.

16.6 Organic Agriculture and Biofertilizers

Natural farming/agriculture is characterized as “a creation framework that supports the strength of soils, biological systems and individuals. It depends on natural procedures, biodiversity and cycles adjusted to neighbourhood conditions, as opposed to the utilization of contributions with unfriendly impacts. Natural Horticulture joins convention, advancement, and science to profit the common condition and advance reasonable connections and a decent personal satisfaction for all included” (IFOAM). The Global Alliance for Natural Farming Development’s (IFOAM) meaning of natural agribusiness depends on the standard of well-being, the rule of biology, the guideline of decency, and the rule of care. Natural cultivating is one of the manageable horticultural frameworks and depends less on costly imports, for example, concoction manures and pesticides (Ramesh et al. 2005). Scofield (1986)

Fig. 16.1 Factors with respect to area that hinder in organic agriculture adoption

underscored that natural cultivating does not just confine to the usage of living materials yet weights on the concept of completeness, inferring the precise co-appointment of parts in a single entirety. The point of natural cultivating is to make incorporated, others conscious, earth and financially practical creation frameworks, which amplify dependence on ranch determined sustainable assets and the



Groups	Example	References
N_2-fixing biofertilizers		Vessey (2003)
Free living	Azotobacter, Beijerinckia, Clostridium,	
Symbiotic	Rhizobium, Frankia, Anabaena azollae	
Associative symbiotic	Azospirillum	
P-solubilizing bio-fertilizers		Khan et al. (2009)
Bacteria	Bacillus megaterium var. phosphaticum,	
Fungi	Penicillium spp., Aspergillus awamori	
P mobilizing bio-fertilizers		Jha et al. (2012)
Arbuscular mycorrhiza	Glomus spp., Gigaspora spp., Acaulospora spp.,	
Ectomycorrhiza	Laccaria spp., Pisolithus spp., Boletus spp.,	
Ericoid mycorrhiza	Pezizella	
Orchid mycorrhiza	Rhizoctonia solani	
Bio-fertilizer and micronutrients		Singh et al., (2016)
Silicates and zinc solubilizers	Bacillus spp. Thiobacillus thiooxidans	
Plant growth-promoting rhizobacteria		Mehrvarz et al. (2008)
Pseudomonas	Pseudomonas fluorescens	Bhattacharjee and Dey (2014)

Fig. 16.2 Groups of biofertilizers based on their nature and function

administration of environmental and organic procedures and connections, in order to give adequate degrees of yield, animals and human sustenance, insurance from irritations and infection, and a proper come back to the human and different assets (Lampkin 1994; Bhat et al. 2017).

Bio-composts are being basic segment of natural cultivating. Biofertilizers are generally used to quicken those microbial procedures which expand the accessibility of supplements that can be handily acclimatized by the plants. They enhance soil richness by fixation of the environmental N and solubilizing insoluble phosphates (Mazid and Khan 2015). These biofertilizers have been raised for the collection of the normally available natural arrangement of supplement assembly which colossally forms soil richness and crop yield (Pandey and Singh 2012). These days biofertilizers are more by and by for crop creation; different sorts of biofertilizers are accessible in the market (Fig. 16.2).

16.7 Potential Role of Biofertilizers in Agriculture

The consolidation of biofertilizers (N fixers) assumes a significant job in enhancing soil ripeness and yield crediting characters, and in this manner, the last yield has been accounted for by numerous labourers. Furthermore, their implementation in soil enhances soil biota and limits the exclusive utilization of concoction composts. Under calm conditions, immunization of Rhizobium improved number of cases plant-1, number of seed case 1 and 1000-seed weight (g) and in this way yield over the control. In rice under swamp conditions, the use of BGA+ *Azospirillum* is fundamentally helpful in improving LAI and all yield ascribing angles. The effectiveness of phosphate manures is low (15–20%) because of its obsession in acidic and antacid soils, and shockingly both soil types are prevailing in India bookkeeping over 34% causticity influenced and in excess of 7,000,000 hectares of profitable land saltiness/basic influenced. Hence, the vaccinations with PSB and other valuable microbial inoculants in these soils become obligatory to re-establish and keep up the compelling microbial populaces for solubilization of synthetically fixed phosphorus and accessibility of other large scale and micronutrients to reap great practical yield of different harvests (Mishra et al. 2013).

16.8 Advantages of Biofertilizers

Biofertilizers are an inexhaustible wellspring of supplements, support soil well-being, and increment the grain yields by 10–40%. Use as supplement concoction composts and supplant 25–30% substance manures, break down plant build-ups, and balance out C:N proportion of soil, improve surface, structure and water holding limit of the dirt, animates plant development by emitting development hormones and has no unfavourable impact on plant development and soil richness, solubilize and prepare supplements. Biofertilizers are an eco-accommodating, non-toxic, and financially savvy technique (Kawalekar 2013).

16.9 Limitations of Biofertilizers

Non-accessibility of proper and proficient strains of microbes. Absence of appropriate transporter, because of which timeframe of realistic usability is short, is another limitation. Showcasing of bio-manure is not simple as the item contains living beings, regular interest and creation of bio-composts, shortage and feasibility of VAM inoculum during capacity, and transportation is the serious issue. Absence of consciousness of ranchers and insufficient and unpractised staff are the other limitations (Kawalekar 2013).

References

Bhat RA, Dervash MA, Mehmood MA, Bhat MS, Rashid A, Bhat JIA, Singh DV, Lone R (2017) Mycorrhizae: a sustainable industry for plant and soil environment. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 473–502

Bhat RA, Shafiq-ur-Rehman, Mehmood MA, Dervash MA, Mushtaq N, Bhat JIA, Dar GH (2017b) Current status of nutrient load in Dal Lake of Kashmir Himalaya. J Pharmacogn Phytochem 6(6):165–169

Bhat RA, Beigh BA, Mir SA, Dar SA, Dervash MA, Rashid A, Lone R (2018a) Biopesticide techniques to remediate pesticides in polluted ecosystems. In: Wani KA, Mamta (eds) Handbook of research on the adverse effects of pesticide pollution in aquatic ecosystems. IGI Global, Hershey, pp 387–407

Bhat RA, Dervash MA, Qadri H, Mushtaq N, Dar GH (2018b) Macrophytes, the natural cleaners of toxic heavy metal (THM) pollution from aquatic ecosystems. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 189–209

Bhattacharjee R, Dey U (2014) Biofertilizer, a way toward organic agriculture: a review. Afr J Microbiol Res 8(24):2332–2343

Bhatti AA, Haq S, Bhat RA (2017) Actinomycetes benefaction role in soil and plant health. Microb Pathog 111:458–467

Dar S, Bhat RA (2020) Aquatic pollution stress and role of biofilms as environment cleanup technology. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 293–318

Dar GH, Bandh SA, Kamili AN, Nazir R, Bhat RA (2013) Comparative analysis of different types of bacterial colonies from the soils of Yusmarg Forest, Kashmir valley India. Ecol Balkanica 5(1):31–35

Dar GH, Kamili AN, Chishti MZ, Dar SA, Tantry TA, Ahmad F (2016) Characterization of *Aeromonas sobria* isolated from Fish Rohu (*Labeo rohita*) collected from polluted pond. J Bacteriol Parasitol 7(3):1–5. https://doi.org/10.4172/2155-9597.1000273

Dervash MA, Bhat RA, Shafiq S, Singh DV, Mushtaq N (2020) Biotechnological intervention as an aquatic clean up tool. In: Qadri H, Bhat RA, Mehmood MA, Dar GH (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 183–196

Heckman J (2006) A history of organic farming: transitions from sir Albert Howard's war in the soil to USDA national organic program. Renewable Agric Food Syst 21(3):143–150

Ismail E, Mohamed WW, Khattab S, Sherif FE (2013) Effect of manure and bio-fertilizers on growth, yield, silymarin content, and protein expression profile of Silybum marianum. Int J Med Arom Plants 3(4):430–438

Jangid MK, Khan IM, Singh S (2012) Constraints faced by the organic and conventional farmers in adoption of organic farming practices. Indian Res J Ext Educ 2:28–32

Jha MN, Kumar P, Chourasia SK (2012) Hope, hype and reality of biofertilizer. Fertil Technol 121:448–480

Kawalekar JS (2013) Role of biofertilizers and biopesticides for sustainable agriculture. J Bio Innov 2:73–78

Khan MZ, Zaidi A, Wani PA, Oves M (2009) Role of plant growth promoting rhizobacteria in the remediation of meta contaminated soils. Environ Chem Lett 7:1–19

Khanday M, Bhat RA, Haq S, Dervash MA, Bhatti AA, Nissa M, Mir MR (2016) Arbuscular mycorrhizal fungi boon for plant nutrition and soil health. In: Hakeem KR, Akhtar J, Sabir M (eds) Soil science: agricultural and environmental prospectives. Springer International Publishing, Cham, pp 317–332

Kumar M, Puri A (2012) A review of permissible limits of drinking water. Indian J Occup Environ Med 16(1):40

Lalitha S (2017) Plant growth–promoting microbes: a boon for sustainable agriculture. In: Sustainable agriculture towards food security. Springer, Singapore, pp 125–158

Lampkin NH (1994) Changes in physical and financial performance during conversion to organic farming: case studies of two English dairy farms. In: Lampkin NH, Padel S (eds) The economics of organic farming: an international perspective. CAB International, Oxon, pp 223–241

MacRae RJ, Frick B, Martin RC (2007) Economic and social impacts of organic production systems. Can J Plant Sci 87(5):1037–1044

Mahdi SS, Hassan G, Samoon S, Rather H, Dar SA, Zehra B (2010) Bio-fertilizers in organic agriculture. J Phytol 2:42–54

Mazid M, Khan TA (2015) Future of bio-fertilizers in Indian agriculture: an overview. Int J Agric Food Res 3:10–23

Mehmood MA, Qadri H, Bhat RA, Rashid A, Ganie SA, Dar GH, Shafiq-ur-Rehman (2019) Heavy metal contamination in two commercial fish species of a trans-Himalayan freshwater ecosystem. Environ Monit Assess 191:104. https://doi.org/10.1007/s10661-019-7245-2

Mehrvarz S, Chaichi MR, Alikhani HA (2008) Effects of phosphate solubilizing microorganisms and phosphorus chemical fertilizer on yield and yield components of barley (Hordeum vulgare L.). Am Eurasian J Agric Environ Sci 3:822–828

Mishra D, Rajvir S, Mishra U et al (2013) Role of bio-fertilizer in organic agriculture: a review. Res J Recent Sci 2(ISC-2012):39–41. ISSN 2277-2502

Mushtaq N, Bhat RA, Dervash MA, Qadri H, Dar GH (2018) Biopesticides: the key component to remediate pesticide contamination in an ecosystem. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–178

Organic Monitor. The global market for organic food and drink: business opportunities and future outlook. [cited 2007 Jun 27]

Ortiz-Hernández ML, Sánchez-Salinas E, Dantán-González E, Castrejón-Godínez ML (2013) Pesticide biodegradation: mechanisms, genetics and strategies to enhance the process. In: Biodegradation-life of science. Intech, Rijkea, Croatia, pp 251–287

Pandey J, Singh A (2012) Opportunities and constraints in organic farming: an Indian perspective. J Sci Res 56:47–72

Popa ME, Mitelut AC, Popa EE, Stan A, Popa VI (2019) Organic foods contribution to nutritional quality and value. Trends Food Sci Technol 84:15–18

Ramesh P, Singh M, Rao AS (2005) Organic farming its relevance to the Indian context. Curr Sci 88:561–568

Reganold JP, Wachter JM (2016) Organic agriculture in the twenty-first century. Nat Plant 2(2):1–8

Scofield A (1986) Organic farming: the origin of the name. Biol Agric Hortic 4:1–5

Shafi S, Bhat RA, Bandh SA, Shameem N, Nisa H (2018) Microbes: key agents in the sustainable environment and cycling of nutrients. In: Environmental contamination and remediation. Cambridge Scholars Publishing, Newcastle upon Tyne, pp 152–179–188

Shaheen S, Sundari K (2013) Exploring the applicability of PGPR to remediate residual organophosphate and carbamate pesticides used in agriculture fields. Int J Agric Food Sci Technol 4(10):947–954

Simonne A, Ozores-Hampton M, Treadwell D, House L (2016) Organic and conventional produce in the US: examining safety and quality, economic values, and consumer attitudes. Horticulturae 2(2):5

Singh JS, Pandey VC, Singh D (2011) Efficient soil microorganisms: a new dimension for sustainable agriculture and environmental development. Agric Ecosyst Environ 140(3–4):339–353

Singh M, Dotaniya ML, Mishra A et al (2016) Role of biofertilizers in conservation agriculture. In: Conservation agriculture. Springer, Singapore, pp 113–134

Singh DV, Bhat RA, Dervash MA, Qadri H, Mehmood MA, Dar GH, Hameed M, Rashid N (2020) Wonders of nanotechnology for remediation of polluted aquatic environs. In: Qadri H, Bhat RA, Dar GH, Mehmood MA (eds) *Freshwater pollution dynamics and remediation*. Springer Nature, Singapore, pp 319–339

Sofi NA, Bhat RA, Rashid A, Mir NA, Mir SA, Lone R (2017) Rhizosphere mycorrhizae communities an input for organic agriculture. In: Varma A et al (eds) Mycorrhiza-nutrient uptake, biocontrol, ecorestoration. Springer International Publishing, Cham, pp 387–413

Średnicka-Tober D, Barański M, Seal CJ, Sanderson R, Benbrook C, Steinshamn H, Gromadzka-Ostrowska J, Rembiałkowska E, Skwarło-Sońta K, Eyre M (2016) Higher PUFA and n-3 PUFA, conjugated linoleic acid, α-tocopherol and iron, but lower iodine and selenium concentrations in organic milk: a systematic literature review and meta-and redundancy analyses. Br J Nutr 115(6):1043–1060

Tuomisto HL, Hodge I, Riordan P, Macdonald DW (2012) Does organic farming reduce environmental impacts?–a meta-analysis of European research. J Environ Manag 112:309–320

Venkatashwarlu B (2008) Role of bio-fertilizers in organic farming: organic farming in rain fed agriculture: central institute for dry land agriculture. Hyderabad, Pakistan, pp 85–95

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255: 571–586

Zakharova T, Tatano F, Menshikov V (2002) Health cancer risk assessment for arsenic exposure in potentially contaminated areas by fertilizer plants: a possible regulatory approach applied to a case study in Moscow region–Russia. Regul Toxicol Pharmacol 36(1):22–33

Index

G. H. Dar et al. (eds.), *Microbiota and Biofertilizers, Vol 2*,
https://doi.org/10.1007/978-3-030-61010-4