Ravindra Soni
Deep Chandra Suyal
Prachi Bhargava
Reeta Goel *Editors*

# Microbiological Activity for Soil and Plant Health Management

Springer

# Microbiological Activity for Soil and Plant Health Management

Ravindra Soni • Deep Chandra Suyal •
Prachi Bhargava • Reeta Goel
Editors

# Microbiological Activity for Soil and Plant Health Management

Springer

*Editors*
Ravindra Soni
Department of Agricultural Microbiology, College of Agriculture
Indira Gandhi Krishi Vishwa Vidyalaya
Raipur, Chhattisgarh, India

Prachi Bhargava
Department of Bioscience & Technology
Shri Ramswaroop Memorial University
Barabanki, Uttar Pradesh, India

Deep Chandra Suyal
Department of Microbiology
Akal College of Basic Sciences, Eternal University
Sirmaur, Himachal Pradesh, India

Reeta Goel
Institute of Applied Sciences & Humanities
GLA University
Mathura, Uttar Pradesh, India

ISBN 978-981-16-2921-1 ISBN 978-981-16-2922-8 (eBook)
https://doi.org/10.1007/978-981-16-2922-8



This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

# Preface

Food is one out of the three basic necessities for any living form on this biosphere. Therefore, human race has strived hard to fulfil its demands mostly at the cost of nature. With the growing population on this planet, productivity enhancement with limited arable land resource has become the major challenge for the agriculture communities. Be it the Green revolution or blue revolution, current agricultural practices have resulted a huge amount of toxic effluents directly or indirectly into the soil, air, and water. Therefore, the need of the hour is to increase the arable land with sustainable agriculture practices and judiciously involve microorganisms as the major stakeholders. These microorganisms being indigenous can beautifully interact with their micro environment surroundings either synergistically or antagonistically making plant–microbe synergism as ecological sustainable. Being at the receiving end of agricultural products, man has tried to curtail the losses occurred due to biotic and abiotic stresses. It is, therefore, important to explore the dynamic microbe–plant–soil interactions going on at every fractions of second. Keeping this perspective in mind, this book is a brainchild to recapitulate the labyrinthine mechanisms involved in microbe abetted sustainable management of soil environment. It consists of chapters focusing on challenges and opportunities of microbes in sustainable agriculture, the various factors governing the soil ecosystem affecting the plant mineral nutrition, usage of microbes to deal with biotic and abiotic stress, etc. Innovations and recent trends in current agriculture have been highlighted with explicit reference to new strategies for commercialization of microbial technologies and futuristic approaches for indigenous microbial resource conservation and management.

While accomplishing higher goals, it is always WE and never ME. The editors nimbly acknowledge the overwhelming support and encouragement received from all the well-wishers. The editors express their heartfelt gratitude to all the authors who have contributed in shaping this book. It is their cooperation, understanding, patience, and timely response that have made this dream come true. Due to the

predefined page limitation, all the acknowledgement cannot be added here. Any suggestions to improvise the book is welcomed.

Raipur, Chhattisgarh, India — Ravindra Soni
Sirmaur, Himachal Pradesh, India — Deep Chandra Suyal
Barabanki, Uttar Pradesh, India — Prachi Bhargava
Mathura, Uttar Pradesh, India — Reeta Goel

# Contents

## About the Editors

**Ravindra Soni** is an Assistant Professor at the Department of Agricultural Microbiology, I.G.K.V., and Raipur, India. He has more than 12 years of teaching & research experience in the field of agricultural microbiology, microbial ecology, molecular biology & biotechnology. He is a recipient of the DST- Young Scientist award from SERB, Department of Science & technology, India. He was also selected for UGC-DS Kothari Postdoc Fellowship and Insa summer Fellowship. He has published edited books, lab manual, several research articles and chapters in reputed international journals and books.

**Deep Chandra Suyal** is an Assistant Professor at the Department of Microbiology, Akal College of Basic Sciences, Eternal University, Baru Sahib, Himachal Pradesh, India. He has been actively engaged in research for 11 years, and has experience in the fields of agricultural microbiology, molecular biology & biotechnology and metagenomics. He is currently investigating the genomics & proteomics of cold adapted microorganisms. He has published numerous articles and books with reputed international journals and publishers. He has three patents in his credit.

**Prachi Bhargava** has over 16 years of teaching and research experience in microbial molecular biology and is currently working as an Associate Professor at Shri Ramswaroop Memorial University, Lucknow. She has worked as Principal Investigator on various major Government of India sponsored projects, and was recently involved in a project sponsored by SERB, New Delhi. As an active researcher, Dr Bhargava has published numerous research and review articles in respected journals, along with several book chapters. She has also co-edited two books with renowned publishers.

**Reeta Goel** is a Professor and former Head of the Department of Microbiology, G. B. Pant University of Agriculture & Technology, Uttrakhand, India. She has also served as visiting scientist at various institutes in the USA and has more than 35 years of teaching and research experience in the area of plant-microbe interactions, microbial ecology, bio-degradation and metagenomics, especially with reference to higher altitudes. She has worked extensively in the field of genomics and proteomics of cold adapted microorganisms. She has published over 100 research articles, book chapters and edited books. She has six patents to her credit, including one U.S. Patent, and received numerous awards for her contributions to science & technology. Presently, serving as distinguished Professor at GLA UNIVERSITY, MATHURA, UP (India) after her retirement.

# Recent Trends in Organic Farming

# 20

Charles Oluwaseun Adetunji, Osikemekha Anthony Anani, Olugbemi T. Olaniyan, Abel Inobeme, Frances N. Olisaka, Eseosa Oluwadamilare Uwadiae, and Omoregbe Nosa Obayagbona

**Abstract**

It has been clarified that the whole globe will experience a rapid increase in population. Therefore, there is a need to identify a sustainable solution that could help to meet the demand of the ever-growing population. Some of the rising question from the majority of the globe is how to proffer solution of the challenges of foods insecurity, climates changes, high level of anthropogenic activities in the environment, and high level of unemployment among the youths, as well as a higher level of mortality rate as a result of the recent pandemic activity

C. O. Adetunji (✉)
Applied Microbiology, Biotechnology and Nanotechnology Laboratory, Department of Microbiology, Edo Stae University Uzairue, Iyamho, Edo State, Nigeria
e-mail: adetunji.charles@edouniversity.edu.ng

O. A. Anani
Laboratory of Ecotoxicology and Forensic Biology, Department of Biological Science, Faculty of Science, Edo Stae University Uzairue, Iyamho, Edo State, Nigeria

O. T. Olaniyan
Laboratory for Reproductive Biology and Developmental Programming, Department of Physiology, Edo Stae University Uzairue, Iyamho, Nigeria

A. Inobeme · E. O. Uwadiae
Department of Chemistry, Edo Stae University Uzairue, Iyamho, Nigeria

F. N. Olisaka
Environmental and Public Health Microbiology Laboratory, Department of Biological Sciences, Faculty of Science, Benson Idahosa University, Benin City, Edo State, Nigeria

O. N. Obayagbona
Department of Environmental and Animal Biology, Faculty of Life Sciences, University of Benin, Benin City, Edo State, Nigeria

Dept. of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City, Edo State, Nigeria



R. Soni et al. (eds.), *Microbiological Activity for Soil and Plant Health Management*,
https://doi.org/10.1007/978-981-16-2922-8_20

due to COVID-19. Furthermore, some other challenges include malnutrition and several nutrition challenges. Therefore, provides comprehensive details on the numerous microorganism that could influence soil health in promoting plant growth, and serves as potential bioremediation of polluted soil as well as provide detailed information on the application of plant growth-promoting rhizobacteria (PGPR) in sustainable agriculture and environment as well as provide detailed information on other beneficial microorganisms that could boost Agricultural production.

**Keywords**

Plant growth-promoting rhizobacteria · Sustainable agriculture · Agricultural production · Environment · Biological control agent · Biological fertilizers · Beneficial microorganisms

## 20.1 Introduction

The global farming practices have gradually been transformed with the emergence of organic farming. The rationale behind this approach to farming is the utilization of various kinds of organic-based fertilizers such as bone meal, compost manure, and green manure and replacement of chemical pesticides that are not environmentally friendly. Organic farming emerged with a view to promoting agricultural sustainability as an innovative technology for meeting the agricultural needs of the fast growing global population (Tsvetkov et al. 2018). This agricultural technique is remarkable for environmental friendliness. There are an increasing concern and demand for safe food which has resulted in the high demand for food and related products that are cultivated organically without the use of pesticides. Currently, the sale of such products is not quite accessible to farmers who cultivate on small scale and the sale of the excess production is usually done in local markets without certification (Nielsen 2019).

The advancement of organic farming is a result of the concerns about the negative consequences associated with industrialized farming practices of the twentieth century. The industrialized agricultural practices of the twentieth century were related to the utilization of agricultural chemicals which have a deleterious influence on the environment and reduction in soil fertility, decline in immunity of plants and overall biodiversity, which in all would affect the quality of food and human health.

According to the United Nations (2015), the human population is due to hit over 9.1 billion in 2050. This growth can be forecasted to tell negatively on the demand for food, land resources, and security of other agricultural products (Yanakittkul and Aungvaravong 2020).

Accelerated agriculture using chemicals like pesticides, insecticides, and fertilizers to boost plant products is an essential and critical sector that has assisted in the management of food products to meet the increasing request for food by the ever-evolving human population. It has been estimated that using this method of food production, the rate of meeting the global population food demand like meat 0.47 billion tonnes and grains 3 billion tonnes was billed to hit 70% (FAO 2015). However, this accelerated agriculture comes with a lot of economic toll resulting in the use of five million tonnes of farm chemicals annually Chakrabarty et al. (2014) and Fernando (2017), the yearly pollution and buildup of pesticides and heavy metals in the ecosystem, and possible health risk (Anani and Olomukoro 2019; Anani et al. 2020a, b; Adetunji and Anani 2020; Yanakittkul and Aungvaravong 2020).

The influence of farm chemicals on the soil, water, and air has greatly impacted human health via the accumulation and consumption of toxins in food which have caused several health diseases in humans like cancer, Alzheimer, Parkinson, diabetes, reproductive ailments, learning incapacities, autism, and asthma diseases (Katherine and Hendrik 2010; Owens et al. 2010; Onder et al. 2011; Costa et al. 2014; Sharma and Singhvi 2017). These problems can be averted by the practice of sustainable farming which will positively control the negative ecological influences on agriculture, thus ensuring good and quality food free from toxins. Such sustainable practice is organic farming (FAO 2013; Muller et al. 2017).

Organic farming is one of the existing forms of agriculture that refrains from the utilization of chemicals like pesticides such as fertilizers to promote nutrients, the fertility of the soil, pests, and diseases (Foley et al. 2011; Muller et al. 2017; Yanakittkul and Aungvaravong 2020). The benefits derived from organic farming as measured to the range of ecological indicators caused by the use of synthetic chemicals for farming have been recounted by various authors (Mäder et al. 2002; Schader et al. 2012; Seufert et al. 2012; Tuomisto et al. 2012; Meier et al. 2015; Reganold and Wachter 2016). So, organic farming is an appropriate answer to mitigate the utilization of artificial chemicals, thus avoiding environmental and health problems and food contamination (Sharma and Singhvi 2017; Sangkumchaliang and Huang 2012).

In recent times, organic food has gained popularity among farmers, consumers, and concerned stakeholders. In 2014, the revenue derived from the organic food hub market was estimated to be US$ 80 billion because of the economically driven policies set by the European Unions and the USA (FiBL and IFOAM 2016). Organic farming has been a novel area of agriculture that produces new products that are of great appeal in the food sector. These products have been estimated to cover an arable hectare of 43.7 million about 0.99% of the world's land (Yanakittkul and Aungvaravong 2020). The amalgamation of sustainable economic and environmental safety opportunities in agriculture using the organic method of farming has aided in soil-organic matter improvement via waste recycling, in turn, this will benefits humans because it assists in the reduction of noxious pollutants in the soil and the food (Ulm et al. 2019; Yanakittkul and Aungvaravong 2019).

The role of PGPR as a sustainable organic agriculture tool has been at the forefront of modern farming. Recent application of PGPR in organic farming has shown a positive influence on the soil structure and functions by way of the reduction of the impacts of herbicides, pesticides, and fertilizer chemicals (Vejan et al. 2016; Backer et al. 2018; dos Santos et al. 2020). The roots of the plant are colonized by beneficial bacterial that excite their growth via different mechanisms. The impacts and performances of these growth-stimulating microorganisms (fungal and bacterial) have been earlier reported by different studies (Vessey 2003; Perez-Montano et al. 2014; Meena et al. 2017; Backer et al. 2018; Alooa et al. 2019; Adetunji and Anani 2020; dos Santos et al. 2020).

PGPR is a perfect substitute for the agriculturist to combat serious social and ecological problems that stem up such as food shortages caused by epidemics, nutrient deficiencies, abiotic and biotic factors. The microbial consortia of PGPR (rhizomicrobiome) are linked to all parts of the plants like roots, leaves, stems, fruits, and flowers Berg et al. (2016) which assist these parts of plants to overcome these challenges (Smith et al. 2015). Though, these conditions differ across the various plant structures.

The rhizomicrobiome use two types of mode of actions (direct and indirect) in which they use to promote plant productivity and growth. The direct mode of action consists of phytohormones such as auxins, siderophores, phosphorus solubilization, and nitrogen fixing that are used for plant production (Riggs et al. 2001; Khalid et al. 2004; Cassán et al. 2009; Krey et al. 2013; Yu et al. 2019). The indirect mode of action is linked to biological control through the means of antagonistic action against pathogenic plant microorganisms by inducing resistance and systemic responses that interfere with the bacterial minimal sensing systems (Mahmood et al. 2016; dos Santos et al. 2020).

This chapter anticipates evaluating the application of plant growth-promoting rhizobacteria (PGPR) as sustainable agriculture and environmental tools. The authors highlighted the significance of PGPR in sustainable agriculture and in the bioremediation of polluted environments. Moreover, specific examples of beneficial attributes of some beneficial microorganisms such as *Rhizobium*, *Azospirillum*, *Bacillus*, *Pseudomonas*, *Serratia*, and *Stenotrophomonas* when applied as PGPR for boosting agricultural products were highlighted.

## 20.2 Roles of Microorganism as the Potential Rejuvenator of Polluted Soil, Soil Health Promoter, and Plant Growth Stimulator

Tahat et al. (2020) evaluated the sustainable application of microorganisms for the improvement of soil health. The authors stated that a fit soil behaves as an active biotic system that transports various ecological services like removal of GHGs (greenhouse gases) from the atmosphere, decomposition, regulation, and recycling of nutrients, the sustenance of plant productivity, and water quality. The health of the soil is closely linked to sustainable farming and the activities of microorganisms. Soil health sustainability is explicitly based on the ability of the plants to manufacture food products without the inference or influence of ecological factors. Nematodes, cyanobacteria, and AMF (arbuscular mycorrhizal fungi) play an essential role in the regulation of plant response to ecological stress, the cycling of soil nutrients, production of plant hormones, availability of nutrient to plants, and the efficient utilization of soil water. Agricultural activities have revealed that tillage and organic farming have efficiently improved soil health by increasing the numbers of soil microbes in activities, diversity, and abundance.

Li et al. (2017) evaluated the function of soil microorganisms in promoting flora growth. The ever-evolving growing population has elicited a great demand for more food. This has necessitated the need to employ modern farming to meet this demand. The need to cultivate novel crop assortments for an increase in the resistance against environmental stressors and insects as well as in the improvement of their yields is very important in the sustainable maintenance of the health of the soil and the plant at large. Though, crops are still requiring artificial nutrients like fertilizers and manure to boost their efficiencies and quality. Recent studies showed that microbes found in the soil provide more positive influence when compared to synthetic fertilizers. These microbes based on their great gene pool serve as a probable resource for the recycling of nutrients and biochemical actions for plant development. In conclusion, the authors recommend the modification of the microbiota in the soil to elicit the growth of the plants and improve the soil health.

Hayat et al. (2010) assessed the role of soil bacteria in promoting the health of the soil and the growth of plants. Soil microbes like bacteria are very significant in the biological, geographical, and chemical cycling of nutrients to plants. Bacterial and plant association in the root rhizoids as the rhizosphere are the major determining factors of soil and plant health as well as fertility. PGPR is usually known as beneficial bacteria to plant, commonly also referred to as plant growth-promoting organisms that have the efficiency to elicit plant development during the root colonizing process. They are important in the ecological sustenance of soil and plant health via symbiosis. Specific microbes that are significant in this process are *Mesorhizobium*, *Sinorhizobium*, *Allorhizobium*, *Azorhizobium*, *Bradyrhizobium*, and *Rhizobium*—a group of cyanobacteria that are nitrogen fixers. Typical examples of microorganisms that are nitrogen fixers include *Pseudomonas, Klebsiella, Enterobacter*, and *Azospirillum*. They have the capability to colonize and attach themselves to the root superficial region of plants thus promoting and facilitating indirectly and directly nutrients cycling and uptake, the reduction of and prevention of phytopathogens. This can be attained by the production of some metal-binding and small molecules called siderophores. PGPR can also produce HCN (hydrogen cyanide) which they can use to prevent the cell wall of plant pathogens with the aid of biodegradable enzymes like ß-1,3-glucanase and chitinase. PGPR can also affect the direct development of plants by the production of plant hormones like indole-3-acetic acid, abscisic acid, ethylene, gibberellins, cytokinins, and auxins which have been recounted for another genus of bacteria.

Some PGPR function as a reservoir for ammonia and ACC (1-aminocyclopropane-1-carboxylate) in higher flora, by resolving them into ammonia and α-ketobutyrate. This will enhance the development of the plants' roots, therefore decreasing the levels of ethylene in the microrhizome community. Moreover, the PGPR also aid in the solubilization of nutrients and phosphates, thus improving the organic matter constituents and stress resistance of the soil and plant to external and internal factors. They also retain enough organic soil nitrogen in the soil and plants, thereby releasing sufficient nutrients to them.

Sathya et al. (2016) evaluated in a review the function of soil microorganisms in the sustenance of soil health. The authors recounted that soil health is characterized by the persistent ability to carry significant biotic systems. The chief driver of soil health is to maintain all the factors controlling sustainable farming to preserve the natural contents therein. Microbes perform a crucial function in the health of the soil, thus influencing the various chemicals, geomaterials, and biological cycling of nutrients like phosphorus, sulfur, nitrogen, and carbon as well as other micro- and macronutrients that play an imperative role in the preservation of the biological and health of the soil. These microbes also have the ability to overpower directly or indirectly the soil-borne diseases and enhance their agricultural outputs. Their role in nutrient cycling also contributes directly or indirectly to the production and promotion of enzymes and phytohormones that aid in combating insects and plant diseases. The massive genetic assortment and role of different microbial consortia like actinomycetes, fungi, and bacteria are indelible assets in the functioning of the soil health and all the other biological entities that promote or contribute to as functional soil health pointers.

Most soil fertilities are usually tied with the effective role and actions of soil microbes. de Souza et al. (2015) evaluated the role of PGPB as special engineers in the restructuring of the health of agricultural soils. The authors reported that microbial and plant associations in the root nodules are the major driver of soil lushness, productivity, and heath of the plants. PGPB are organisms that can improve the protection and growth of plants towards ecological stressors, diseases, and other factors that have close links with plants like endophytes that could influence the development of the plants. Some significant characteristics of bacterial like the fabrication of siderophores, plant hormones, deaminase action of ACC, solubilization of phosphate, and biological fixation of nitrogen are special traits of the PGPB and solitary roles to improve the soil and flora fertility. PGPB inoculants also improve the agronomic efficacy by decreasing the rate of environmental contamination and economic cost via production on the ground that the utilization of fertilizer chemicals be phase out or reduced. For PGPB inoculants to attain success in eliciting the productivity and growth of the plant, there have to be several steps that can impact their efficacy of inoculation like the health of the soil, colonization of microbes in the root nodules, and plant root exudation.

Ojo et al. (2015) evaluated the impact of fertilizers on the population and growth of microbes in the soil. The putrefaction of organic matter and the accessibility of nutrients in the soil depend on the activities of microorganisms therein. Inorganic and organic fertilizers are important in the improvement of the needs of the soil microbes for the development of the floras. Ojo et al. (2015) opined that the low population of microbes is caused by the inefficiency of organic nutrients or matter to be readily remedied by altering the soil with organic nutrients and fertilizers, thus permitting more time for the microbial community to thrive reproductively. The microorganisms increase the soil components via the digestion of the organic matter and humus to aid in the fixating of nitrogen in the rhizosphere.

Seneviratne et al. (2011) evaluated the implications in the utilization of biofertilizer and compost in organic farming. The authors reported that compost and biofertilizers have been fingered as a promising substitute to the traditional induced chemical fertilizers because of their positive influence on the development of the plant as well as the improvement of the soil quality, health, and its functions. Compost and biofertilizers also have the ability to decrease the ecological and human risk or damages from pollutants by biodegradation. Biofertilizers derived from microorganisms have been known to date for their beneficial influence on the biological activities of plants such as economic and environmental viability, the structural buildup of soil richness, phytohormones production, manufacture of antibiotics, flora pathogen suppression, plant stimulation, and nitrogen fixation. Compost, however, is significant in the improvement of the chemical, biological, physical structure of the soil. The limitation of this influence depends on the derived source of the compost as well as the process it undergoes. However, one of the demerits of the utilization of compost includes the probable presence of heavy metals, the possible link of pathogens, high generation of ammonia, excessive production of leachate in bulky volumes, and inadequate result delivery. Therefore, there is a need to combine the compost and biofertilizers to achieve maximum soil health.

Javaid (2011) tested and evaluated in a rice plant pot assay the impact of biofertilizers (effective microorganisms and biopower) on the growth and development of various amendment of soils. The amendments were fertilizer-NPK, farmyard manure (FYM), and green manure (GM). The results from the biological experiment showed that the usage of the biopower negatively influenced the yield and growth of the plant in the fertilizer-NPK amendment. Conversely, the same biofertilizer sharply improved the yield and growth of the amended GM soil, whereas their influence on the FYM amendment was not significant. In the GM amendment, the application of effective microorganisms improved the yield of the rice by 46%. An amalgam of both biofertilizers markedly enhanced the shoot and root growth in the soil amended with the FYM. The findings from this study showed that effective microorganisms and biopower biofertilizers sharply improved the biomass of the shoot and roots as well as the yield of the grain in the amended GM soils.

Microorganisms in the soil perform significant roles in the control of the soil ecosystem. Alexander and Chong (2014) in a biological experiment tested and evaluated the influence of biological control messengers on the microbial consortia of soils in oil palm farmstead. The authors stated that the microbial consortia may play the role of a check-balance to different plant diseases. Besides, soil microorganisms are subtle to the vicissitude of soil factors.

Alexander and Chong (2014) recounted that the effects of these messengers on the diversity and population of soil microbes are still vague. The results from the study revealed that feasible microbes were seen scattered in the cultured media after counting using the CFU (colony forming unit). They were later recognized by employing molecular and Biolog techniques. The novel predominant species identified were *Trichoderma spp., Streptomyces spp., Yarrowia spp.*, *Burkholderia spp., Microbacterium spp.,* and *Enterobacter spp*. The colony forming unit for the yeast was $10^2$ to 10 $^6$CFU/g and that for bacteria was $10^3$ to $10^6$CFU/g. They remained unchanged after treatment of the soils. Though, the colony forming unit for fungi was later amplified to 10 4 cfu/g in the amended soil. The utilization of biological messengers to regulate the root and stem disease of oil palm has served as a sustainable promising tool for the management of these pathogens. The authors concluded that the usage of biofertilizers in the soil can potentially enhance the evenness and richness of the distribution of microorganisms in the soil as biomessengers.

Sachidanand et al. (2019) evaluated in a review of the influences of microbes on soil structure ex situ. The authors reported that soil microbes help to preserve the ecosystem via structural and functional engineering of the soil. The interaction of the microbes with the chemical, biological, and physical features of the soil brings about control of the soil negative impacts and possibly agricultural ecosystem management. The authors stated that in some cases, the soil is the main determinant factor that controls the complexity and diversity of soil microbes as well as their symbiotic relationships with the other abiotic and biotic entities. In conclusion, the authors proposed a theoretical framework founded on the relative forces and strengths exerted by the soil microbes on the soil.

Lehman et al. (2015) assessed the bio-health of the enhancement of soil via reverse soil breakdown of pollutants by microbes. The authors recounted that soil health relates to the biological processes, effects, and properties that manipulate high yield and qualities of crop production, improves the availability of nutrients, protects the plant against pathogens, and manages and regulates ecological stressors like high temperature and drought. The authors opined that microbes serve as an engineering tool in addressing these factors with a perception of sustainable management, repair, and regulation of all abiotic and biotic constituents in the soil environment. In conclusion, the authors recommended novel researches that will project the sustainable productivity and utilization of soil microorganisms for soil health rejuvenation.

Globally, the degradation of land by the activities of humans and natural occurrences has become a bane to soil animals and the ecosystem at large. The drive for ecosystem sustainability is geared towards the conservation, management, and improvement of the agricultural land for the present and future generations. Singh et al. (2016) assessed the role of microbes as soil engineers in the ecorestoration of polluted land. The authors reported that to ensure total restoration of degraded soil or land, a systematic approach towards the establishment of set goals should be considered. This will enable timely reverse degradation, structural and aggregate growth, balanced micro-ecosystem, nutrient formation and cycling, and the degradation of litters by the activities of microbes. The sustainable enhancement of the agricultural soil relies on the biodiversity and bioprocess that are buildup in the ecosystem, which allow crop productivity and soil fruitfulness. This will enable the restoration of land that has already be degraded.

Nunes et al. (2012) tested and evaluated the activities of soil microbes in the degradation of impacted soil. The authors stated that soil degradation results in severe biological changes. This process can reduce the biomass of soil microbes. The result from the biological experiment showed that the enzyme and biomass activities of the soil microbes were reduced by the impacted land to about 8–10 times more than the natural vegetation. Besides, after the restoration of the land, the soil microbial biomass and the natural biomass improved by two- and five-fold correspondingly when compared to the highly impacted land. The findings showed that impacted land produced a low microbial consortium but the restored land may elicit both short- and long-run increases in the biomass and the soil consortia of microbes.

Masciandaro et al. (2013) in a synergic method evaluated the bioremediation of soil impacted with organic matter using microorganisms. The authors recounted that bioremediation which is a natural process depends on plants, fungi, and bacteria to remove, transform, and breakdown pollutants, thus ensuring ecosystem conservation of the biological and physical properties. The application of sludge and compost (organic matter) on soil has been seen to activators or messengers of microorganisms to improve on the degradation potentials of pollutants. Their presence in the soil aids in swift degradation, organic matter, and nutrient cycling via the processes of bioaugmentation, bio-enhancement, and biotransformation which are considered as possible accelerators of pollutants breakdown. Besides, during these processes, the activities of the microorganisms provide the platform for soil health, water retention ability of the soil, the porosity of the soil, and the exchange capacity of a cation. Masciandaro et al. (2013) also opined that plant species also serve as tools for the reclamation of impacted land by using the strategy of bioabsorption and biotransformation of pollutants as well as the promotion of the breakdown of organic matter by the activities of the microorganisms at the rhizosphere. The plants also provide a good microenvironment that is palatable for eliciting the activity and proliferation of the microorganisms.

Ajao et al. (2011) tested and evaluated the bioremediation potentials of microbial consortia on soils sourced from automobile mechanic workshops. The authors reported that the activities of microorganisms in the significant restoration of impacted hydrocarbons soils defined their ecological role in the mineralization and biotransformation of crude oil products into less toxic forms. Eighty-six polluted soil samples from 15 stations were collected and assayed for the bioremediation study. The isolation techniques carried on the samples resulted in the identification of five bacterial species which are *Bacillus sp*., *Serratia sp*., *Pseudomonas sp*., *Flavobacterium sp*., and *Acinetobacter sp*. The bioremediation setup was set for 2 months by employing amalgam isolates culture of lipase, dehydrogenase, protein, and TVC as bioindicators. The outcome from the experiment showed increased activity of the dehydrogenase, protein, and TVC recorded in the first month were 5.53 mg/g, $6.3 \times 107$, and 163.15μgTPF$g^{-1}$ soil correspondingly at 7.17 pH concentration. However, a gradual reduction (4.72 unit/g) was observed in the activities of the lipase with a percentage increase (65.41%) of the crude oil at the sixth week. The findings from this study showed a possible ecological implication for designing a bioremediation procedure for the decontamination of crude oil polluted or impacted soil sites.

## 20.3 Features of Organic Farming

There are areas of differences between traditional farming and organic farming practices and this lies in most cases in the approaches utilized during the crop production processes. The environmental impact of agricultural activities is vital when looking at the organic farming approach. This, therefore, implies that one of the major focuses of organic farming is the preservation, conservation, and management of the ecosystem and concern on minimization of various synthetic materials that are not of organic origin (Skoufogianni et al. 2015).

This approach to farming also aids the improvement of soil health as the combined agricultural practices utilized in organic farming are known to bring about an increase in the carbon reservoir, most especially during mixed farming and crop rotational practices. In organic farming, there is efficient carbon friendly monitoring in terms of reduction of overall emissions with respect to sequestration (Smith et al. 2019).

The practice of organic farming brings about a reduction in the emission of nitrogen oxide since elementary nitrogen is not utilized as fertilizer and the content of nitrate ions in the soil is lower with greater aeration of the soil. This, therefore, implies that the rate of emission of nitrogen gas is lower when related to the traditional farming system as a result of the lower availability of nitrogen. The nitrogen obtained from the green manure during organic farming does not contribute to the overall emission of $N_2O$. There is an enhancement in the structure of the soil and a reduction in the emission of $N_2O$. Replacement of urea with other materials of organic sources is a unique management plan for the reduction of $N_2O$ in the soil (Jalota et al. 2018).

Another factor that catalyzed the advancement of organic farming lies in intensive animal rearing that brought about an increase in medicaments, the poor health state of animals, and a decline in lifespan. At first, organic farming was developed primarily by the farmers, this was then fully supported by scientific findings. At present, there are national laws and government-approved trademarks for the consumption of organic-based food materials. There are government programs at present that boost organic farming.

The major advancement in the area of organic farming is related to the improvement in the quality of soil, enhancing efficient management of pests, the introduction of agencies with the major concern of certifying, and provision of labels so as to ensure the safety of such foods for human consumption. The sector of organic farming basically has developed to a US$60 billion sector of the global food production as of 2012 (Francis 2013).

The rapid advancement in organic farming has a strong impact on the emission of $N_2O$. Though some countries are likely to seriously depend on synthetic fertilizer, some others would have the capacity of reducing the use of mineral fertilizers. In organic farming, food is grown with the environmental constraints of the release of $N_2O$. There are also many organic materials that are produced as by-products which can be utilized in the production of biofertilizer such as animal manures, plant residues, biosolids, among others. The use of organic amendments gives remarkable trade-offs that can result in the emission of greenhouse gases (Lal 2016).

There have also been reports that the emission of greenhouse gases, as well as the use of energy in organic farming practices, are more pronounced when compared to the traditional production of crops. This is as a result of the greater intensity of highly demanded cash crops, frequent cultivation of farms, and higher fertilizer usage in organic farming. Storage methods and manure applications have a serious effect on the emission of greenhouse gases. The use of anaerobic digestion could be useful in the reduction of emission and storage. The spreading out of manures during the coolest times of the day also helps in the reduction of emissions.

The method used in the application of manure, whether as solid or slurry, incorporation or broadcasting among others also affects the emission of greenhouse gases. The use of grass residues during organic rotations can also increase the emissions of $N_2O$ (Lal 2016).

Badgley et al. emphasized that organic farming practice would be relevant in feeding the rapidly growing population using the currently available landmass while ensuring total conservation of the fertility and structure of the soil. Farming practices that ensure conservation are currently being encouraged for the recovery of soils that have degraded. There is also an overall increase in productivity and food security.

## 20.4 Benefits of Organic Farming

Several agricultural benefits on the ecosystem have been attributed to conservation agriculture some of which include reduction of soil erosion, enhancement of water use, efficient cycling of nutrients, and reduction of soil organic carbon loss. There is also an enhancement of the organic matter content of the soil during organic farming, brought about by the activities of microorganisms on the organic materials. A proper comprehension of the processes involves requires researchers to focus more on and promote researches on soil structure, humus content, and microorganisms' profile.

### 20.4.1 Environment

The use of organic farming has been documented to be generally more beneficial to the ecosystem when compared to traditional farming practices. This is so because there is no form of contamination of soil, water, and other immediate environments during this type of farming practice. This also implies that there is no fear of leaching agrochemicals from topsoil into underground water bodies and rivers which could be taken into the bodies of aquatic organisms and passed across the food chain. In addition, the organic farming practice also ensures the preservation of wildlife, retreat for natural wildlife, rather than destruction of their natural habitats, avoidance of toxic chemicals, and maintenance of field margin.

Agricultural diversity of organisms is a vital component of the ecosystem that is affected by the particular method of farming adopted. Organic farming is known to enhance the level of agro diversity. The relegation of chemical pesticides and the use of other green substituent make it possible for different groups of plants and animals to flourish in the farmlands. This also helps in ensuring natural balance in the ecosystem. There are varying methods that have been used for the comparison of the impact of farming practices on the environment. Most researchers have used the assessment of biodiversity of organisms, nutrient emission, land use, and soil properties for comparing organic and conventional farming practices.

In a study conducted by Mondelaers et al. (2009) they carried out a comparison of the traditional farming and the organic farming system through the use of a meta-analysis approach with a focus on the impact on the environment, efficiency of land use, soil carbon content, leaching of materials into surround environment and water bodies, production of greenhouse gas as well as the general biodiversity.

Hole et al. (2005) in their review made a comparison on biodiversity in traditional and organic farming. They observed that organic practice generally brought about an improvement in biodiversity. In a related study carried out Hole et al. (2005), there was no negative environmental and population impact associated with organic agriculture especially in terms of biodiversity. Rather it was confirmed that this technique led to an increase in biodiversity especially the varieties of herbaceous plants when compared to conventional farming. It was also reported when used alone, organic farming is not sufficient for the preservation of species of animals (Bengtsson et al. 2005).

## 20.5 Production Requirements in Organic Farming

Organic farming is unique in that it utilizes the functional integrity of the system, unlike other traditional farming practices that require an abundance of various materials that are synthetic in nature and other man-made substances (Boelling et al. 2003). Another major advantage of organic farming is its dependence on water and soil which are localized materials that are readily available in the farming environment with less concern for heavy tools and equipment. Though there is variation in the actual production method, there are some general principles that are basically the same such as the soil management by addition of organic substances, avoidance of the use of chemical pesticides and fertilizers that are synthetic in nature, and utilization of crop rotation system.

## 20.6 Crop Requirements

Prior to the harvesting of organic crops, no prohibited substance must be applied to the farmland 3 years to the period of harvest (Escoba and Hue 2007). Genetic engineering, sludges from sewage, and ionizing radiation must not be used for farming. Preservation of the soil nutrients will be achieved through the use of permissible practices such as cover crops, crop rotation alongside animals, and plant materials that are not allowed. There will be preferential usage of organic stock and seeds, while farmers could only use nonorganic under certain permissible conditions. Agricultural weeds, pests, and disease could be managed through biological, physical, and mechanical approaches.

## 20.7 Effects on Soil Quality

The role of soil quality in sustainable farming cannot be overemphasized hence more recently, various researchers have carried out studies in this regard. It has also been reported that organic farming helps in the improvement of the quality of soil (Otutumi et al. 2004).

## 20.8 Advantages of Organic Farming

### 20.8.1 Sustainability

One of the major concerns of organic farming practice is the future implications of any agricultural practice on the ecosystem and environment at large. Food production is associated with the setting up of ecological balance so as to prevent problems of pests and soil fertility (Tsvetkov et al. 2018).

### 20.8.2 Ecological Services

There are more favorable interactions and balances between the agroecosystem and the variables within the environment during organic farming. Some of the associated phenomena include waste recycling, soil conditioning and forming, nutrient cycling, and sequestration of carbon.

### 20.8.3 Biodiversity

Organic farming promotes agricultural diversity as well as the preservation of the environment. There is an enhancement of various species of macro and micro fauna and flora in the environment since chemical pesticides and other toxic materials are not used during the farming practice. Various studies have documented that there is an increase in the level of biodiversity during organic farming when compared to other known farming practices.

## 20.9 Challenges Faced in Organic Farming

1. It demands much labor.
2. Organic materials commonly required may not be available in the appropriate quantity.
3. Poor adherence to standard practices in organic farming (Garg and Balodi 2014).

## 20.10 Role of PGPR as Biotechnological Tool for the Achievement of Sustainable Agriculture and Environment

It has been well reported that the utilization of beneficial microorganisms to boost agricultural production has expanded in the last few years due to population explosion, food shortage, and increased pest pathogenic attack. Qessaoui et al. (2019) showed that many biomolecules are extracted from beneficial microbes that act as plant growth-promoting rhizobacteria. The authors utilized soil inoculated by *Pseudomonas sp*. bacterial isolates to enhance the production of *Solanum lycopersicum*, thus it was revealed that there was a substantial upsurge in seed germination, which enlarged the collar diameter and increased leaf number. It was concluded that this isolate facilitated the growth of the plant. Gupta et al. (2015) demonstrated that soil health is an integral part of agricultural resources that demands critical attention. Pathogenic microbes affect the physicochemical status of soil, plants, and threaten the entire sustainable agricultural sector if not quickly reviewed. Over the years, chemical fertilizers have rendered soil integrity poor, wrecking serious havoc on the ecosystem. Recently, renewed interest in the use of biological fertilizers has increased. Many biological agents are emanating for promoting plant growth in an eco-friendly sustainable agricultural process. Tan et al. (2015) highlighted the significance of biofertilizers in enhancing growth plus the yield of agricultural crops. They stimulate phytohormone production, biological nitrogen fixation, mineralizing organic phosphate, suppress pathogens.

Vejan et al. (2016) reported that PGPR is capable of increasing agricultural production through regulation of hormone, nutrition, stress resistance factors. Previously, it has been revealed that due to a reduction in the quality of soil health and impact on the environment caused by synthetic chemical fertilizers, many are now beginning to adopt the utilization of biofertilizers as alternatives to promote plant growth in sustainable farming. *Azotobacter chroococcum, Klebsiella variicola, Rhizobium larrymoorei, Klebsiella pneumonia* are known to stimulate plant development and act as biofertilizers in organic farming practice. Beg and Singh (2009) revealed that across the globe, increased productivity has been witnessed in the agricultural sector due to the adoption and utilization of biofertilizers. Raimi et al. (2017) suggested that many parts of the developing countries suffer from food shortage and low productivity due to soil pollution, consistent use of synthetic fertilizers, thus recent approach in the maintenance of sustainable agriculture incorporates the use of microbial fertilizers such as Azotobacter and many others. These microbes produce metabolites that protect the crop from pathogenic attack and boost the soil nutrients. Katiyar et al. (2015) showed that PGPR promotes systemic resistance, biofertilization, biocontrol of plant pathogens. Gupta et al. (2015) showed that PGPR increases soil fertility, suppresses phytopathogens, and enhances plant growth promotion, for the development of an eco-friendly approach in sustainable agriculture.

Paul and Nair (2008) reported that sol salinity is regulated by microbes and agricultural crops. The authors studied the mode of activity explored by PGPR in regulating salt tolerance utilizing proteome analysis. They discovered that many of the salt regulatory proteins are upregulated, thereby alleviating the high osmolarity and generating inhibitory metabolites when plant growth-promoting rhizosphere inoculant *P. fluorescens* MSP-393 is applied. Kaur et al. (2016) revealed that PGPR improves crop productivity by colonizing the plant rhizosphere or endophyte, and production of beneficial biomolecules such as organic acids, phytohormones, siderophores, antibiotics, and growth regulators utilized for plant defense system against pathogenic attack. Mishra (2018) showed that crop productivity amid harsh environmental conditions such as drought, pest attack, global warming can be enhanced through the utilization of PGPR, thereby generating exopolysaccharides as biocontrol agents. Jiménez-Gómez et al. (2017) suggested that bacterial inoculants portends the capability to produce positive results on crop yields without any adverse effects. The utilization of PGPR has increased over the years due to the huge demand placed on agricultural products across the globe. Di Benedetto et al. (2017) highlighted a few modes of action by which PGPR could induce plant growth such as nutrient uptake, production of hormones, inhibition of pathogens. Sharma et al. (2019) suggested that in the developing countries where huge monies are spent on procuring synthetic chemicals to improve agricultural productivity resulting in increased negative environmental and health impact, environment friendly plant growth-promoting rhizobia should be adopted as a substitute to synthetic fertilizers for sustainable agriculture.

Dago et al. (2018) reported that improving soybean and maize crops, rhizobacteria such as *Pseudomonas fluorescence* was utilized as biofertilizer, thus a significant difference in terms of crops development was noticed compared to those that were not treated with biofertilizer. Osman and Yin (2018) reported that PGPR could influence plant growth through a number of mechanisms like nitrogen fixation, enzyme synthesis, bioremediation of contaminants, production of volatile organic compounds. Khan et al. (2020) revealed that plant growth regulators like putrescine and salicylic acid are important components of plant development. The authors thus investigated the role of the regulators on chickpea grown in sandy soil. It was observed that chickpea plants integrated with plant growth regulators showed increased capacity for drought tolerance and they recommended that its utilization increases agricultural productivity. Zuluaga et al. (2020) highlighted the relationship between plants and their microbiome for growth-promoting agricultural productivity through alleviating stress by utilizing bacterial inoculants. Kuan et al. (2016) showed that in maize plants, plant growth-promoting rhizobacteria bacterial strains isolated from maize roots at two different locations in Malaysia provided an alternative to increasing crop yield. The strains evaluated in this study are *Klebsiella sp*. Br1, *Acinetobacter sp*. S3r2, and *Bacillus pumilus* S1r1. The authors revealed that all the strains showed positive results for phosphate solubilization, auxin production, and increased N2 fixation. Lengai and Muthomi (2018) suggested that many important biopesticides are derived from plants, microorganisms, and insects utilized in the management of pest and disease conditions. The authors disclosed that biopesticides are now being considered as potential alternatives to synthetic chemical pesticides due to the huge negative impact on the environment and human-caused by these synthetic chemicals. Thus the physiochemical characteristics of the biopesticides like biodegradability, low toxicity, less expensive, eco-friendly nature give them a greater advantage over synthetic chemicals.

Yadav and Yadav (2019) revealed that actinobacteria can be developed and used as biofertilizers for sustainable agriculture to improve plant growth and soil physiology. This class of bacteria (*Acidimicrobiia, Coriobacteriia, Actinobacteria, Nitriliruptoria, Thermoleophilia, and Rubrobacteria*) possesses huge biological characteristics with multifarious plant growth-promoting attributes. Today, actinobacteria are significantly explored for bio-inoculants for different crop growth-promoting effects. Kawalekar (2013) reported that biofertilizers are utilized for proper plant growth while minimizing the use of synthetic fertilizers and also to promote soil health in a cost-effective way. Srivastava and Singh (2017) revealed that PGPR is now a widely recognized approach in agriculture due to the green revolution as an alternative strategy to synthetic chemicals. PGPR such as *Achromobacter, Azospirillum, Azotobacter, Acetobacter, Chryseobacterium, Bacillus, Flavobacterium, Klebsiella, Enterococcus, Pseudomonas, Serratia, Paenibacillus*, and *Rhizobium* act as bioremediation, biodegradation, biocatalyst, biofertilizers, biocontrol/biopesticide agents in sustainable agricultural practice. Garg and Chandel (2010) predicted change in environmental conditions caused by anthropogenic activities, thereby affecting soil, air, and water agro-ecosystems. Thus reversing this trend will demand the incorporation of natural beneficial microbes in maintaining plant productivity and soil fertility like crop plants with arbuscular mycorrhizal. Different genes, chemical structures, and signal transduction pathways are activated to facilitate water/nutrients uptake, alleviation of abiotic soil stresses, disease protection, and increasing crop production/yield. Goswami et al. (2016) showed that the population explosion has placed a huge demand for food and other agricultural produce. Thus, today PGPR offers a promising approach in sustainable agriculture to enhance soil microbial flora and promote plant growth. Gopalakrishnan et al. (2015) revealed that many challenges are witnessed with modern agricultural practices such as climate change, soil fertility impairment, increased pests, and insect attacks. Thus the use of biofertilizers, biopesticides as plant growth promoters is gathering massive attention among different stakeholders to provide a sustainable approach for agricultural practice.

Jacoby et al. (2017) reported that a plant-rich ecosystem is made up of diverse microorganisms providing support for mineral nutrition, metabolic activities, plant shape, and defense mechanism. Mahmood et al. (2016) showed that through seed inoculation, beneficial microbes perform a significant function in the growth of the plant, soil fertility, and environmental health. Tuhuteru et al. (2016) carried out a study to obtain the most effective isolate in PGPR as biological fertilizers. They observed that the isolates were able to stimulate increase seed growth, increase the chlorophyll content with other physiochemical properties. Singh (2018) and Rifat et al. (2012) reported that PGPR like *Azospirillum brasilense, Azospirillum amazonense, Azospirillum lipoferum, Bacillus tropicalis, Acetobacter diazotrophicus, Bacillus borstelensis, Herbaspirillum seropedicae, Herbaspirillum rubrisubalbicans, Klebsiella sp., Rahnella aquatilis, Enterobacter sp., Herbaspirillum seropedicae, Paenibacillus azotofixans,* and *Bacillus circulans* enhanced crop growth through nitrogen fixation, production of hormones, production of enzymes and cytokinins, increased resistance to stress, solubilization, and mineralization of other nutrients. Zerihun et al. (2019) revealed that PGPR stimulates plant growth and protects plants stress factors. Thus the authors carried out a study to identify and characterize plant growth promoter bacteria colonizing the rhizosphere during the flowering phase for generating bioinoculant. The observed that the PGPR can be utilized as biofertilizers, biocontrol, and biopesticides to improve crop yield and productivity.

Kour et al. (2020) showed that beneficial microbes utilized as biofertilizers bring important nutrients from the soil to the plants to improve the quality and yield. Utilizing microbial bioinoculants represents an important part of sustainable agriculture. These microbes are known to colonize the plant epiphytic, rhizospheric, and endophytic system, thus regulating nutrients uptake, production of plant growth hormones and enzymes, and fixation of nitrogen. Bechtaoui et al. (2019) reported that over the years, greater attention has been placed on the role of PGPR as biofertilizer, thus the authors evaluated the application of biofertilizer bacteria plus rhizobial strains on the production of plant crops in Morocco. Their ability to solubilize complex mineral phosphorus was also investigated together with the ability to generate different biomolecules. They discovered that the combined strains displayed the most beneficial effects which significantly stimulate plant growth, hence they suggested that rhizobacterial inoculation could be utilized as potential biofertilizers.

Backer et al. (2018) stated that phytomicrobiome microbes are linked with plant tissues, thus providing a wide range of benefits to plants such as nutrients acquisition, improving soil texture, regulating extracellular molecules, activating different signals, and ultimately facilitating plant growth. The authors established that inoculating plants with PGPR could stimulate crop growth which can also improve plant tolerance for stresses by stimulation of systemic resistance. Bhat et al. (2019) highlighted the importance of plant growth-promoting rhizosphere as a capable tool for eco-friendly and ecological crop production. Amaya-Gómez et al. (2020) showed that rhizobacteria are capable of improving plant nutrients, regulate phytohormones, suppress diseases, and enhance plant survival.

Deepmala et al. (2016) demonstrated that the current soil management strategy involves the use of biofertilizers like phyla actinobacteria, firmicutes, proteobacteria, and bacteroidetes to facilitate growth and improve the biomass improvement of seedling germination, plant health, vigor, height, nutrient content of shoot tissues, shoot weight, early bloom, increase nodulation in legumes, improve chlorophyll content. Yadav et al. (2017) and Kenneth et al. (2019) suggested that rhizobacteria colonize extracellular and intracellular rhizoenvironment as biocontrol, biostimulation, and biofertilization. They revealed that to achieve self-sufficiency in agriculture, the utilization of genetically modified microbes must be deployed to enhance soil–plant–microbial interaction and develop soil flora and fauna. Orhan et al. (2006) studied the effects of two Bacillus strains on organically grown primocane fruiting raspberry. They discovered that the application of bacteria significantly enhanced the affected soil pH and nutritional contents, promoted growth, increased the yield, of the raspberry plant under organic farming conditions.

Adedeji et al. (2020) revealed the African continent is the worst hit in terms of global food insecurity due to poor economy, land degradation which is threatening the productivity in agriculture. They suggested that sustainable eco-friendly strategies like plant growth-promoting bacteria should be adopted to increase agricultural productivity, reduce environmental pollution, and improve the economy. García-Fraile et al. (2015) and Kalayu (2019) demonstrated that several rhizospheric bacterial strains like Bacillus, Rhizobium, Pseudomonas, Aspergillus, Penicillium, possess plant growth-promoting properties like phytohormones, stress resistance, and improve nutrients uptake through phosphate-solubilizing microbes. Agbodjato et al. (2015) discovered that maize rhizospheres contain a huge amount of diverse microorganisms like *B. polymyxa, B. anthracis, B. pantothenticus, B. circulans, B. thuringiensis, P. cichorii, P. syringae, P. putida,* and *Serratia marcescens* with a high rate of ammonium and hydrogen cyanide production, thus suggesting that these rhizobacteria could be utilized as biological fertilizers in promoting maize production.

Noumavo et al. (2016) highlighted the benefits of PGPR in promoting plant growth and development such as exopolysaccharides production, siderophores production, phosphate solubilization, phytostimulation, systemic resistance, production of antibiotics, enzymes, and nutrients uptake. Paul and Lade (2014) revealed that the arid and semi-arid regions are salt-stressed agricultural unproductive areas. Therefore, PGPR is one of the alternative solutions to enhance agricultural productivity through rhizobacteria counteracting the osmotic stress and enhancing plant growth. This approach will enhance resistance to diseases, nutrient uptake, stress tolerance, hydration, biocontrol of phytopathogens, chlorophyll content, increasing K+ concentration, solubilization of mineral phosphate, osmolyte accumulation, salinity tolerance, and synthesis of antioxidative enzymes. Bhardwaj et al. (2014) and Pahari et al. (2017) recommended that due to the consistent application of synthetic chemicals over the years, the soil has been contaminated, thus the authors investigated the role of eleven bacteria isolate on some contaminated soil in promoting plant growth activities. Vibha and Madhu (2015) highlighted the role of various regulatory chemicals secreted within the vicinity of the rhizosphere such as biofertilizers, biocontrol, and biostimulants. They revealed that through genetic engineering, many of the biomolecules are incorporated into field practices in agriculture to enhance productivity. Mishra and Dash (2014) revealed that the economy of India thrives on agricultural practices, and fertilizer is a major contributing factor. Over the years, the application of synthetic fertilizers has endangered the ecosystems, plants, humans, animals, and soil, hence naturally grown biofertilizers are beginning to receive attention for sustainable agriculture economic development.

Several scientists have investigated plant growth-promoting rhizobacteria as biocontrol agents through local antagonism to soil-borne pathogens, nitrogen fixation, production of phytohormones, phosphate solubilization, nutrient mobilization, or by induction of systemic resistance against pathogens for improved cropping systems. They suggested that many bacteria inoculants displayed significant plant growth-promoting properties (Romero-Perdomo et al. 2019; Beneduzi et al. 2012; Ramprasad et al. 2014). Sinha et al. (2014) and Ahirwar et al. (2019) applied bacterial inoculants such as Azotobacter, phosphorus solubilizing bacteria, Clostridium pasteurianum, Azospirillum, vesicular arbuscular mycorrhiza to stimulate microbial activity as biofertilizers in organic farming. Many of the biomolecules are converted into powerful biofertilizers, bio-herbicides, biopesticides, bio-insecticides, viral-based bio-insecticides, and fungal based bio-insecticides utilizing microbial biotechnology.

Bashan et al. (2014) and Khatoon et al. (2020) discovered that one of the important components of soil health is PGPR with multiple ecological functions in the rhizosphere soil producing phytohormones, innate immunity, and other metabolites. Cummings (2009) showed that PGPR could improve the yield of graminaceous crops through genetically engineered strains. They revealed in their study that the physicochemical and biological features of the soils are also a major contributing factor through the direct relationship between plant–microbial organism to facilitate, phosphate solubilization, phytohormones, hydrogen cyanide production, biological nitrogen fixation, stress and biocontrol activity, antibiotic fabrication, siderophore production, synthesis of antifungal metabolites.

## 20.11 Specific Samples of Beneficial Microorganisms that Could Lead to Sustainable Agriculture and the Environment

### 20.11.1 *Rhizobium spp*

Tiwari et al. (2017) recounted the role of *Azotobacter* sp. and Rhizobium on plant growth, chlorophyll contents, nodule appearance, and carbohydrate content. The authors revealed that *Rhizobium sp.* and *Azotobacter* have friendly associations for field application most especially for sustainable agriculture. Poonia (2011) demonstrated that most Rhizobium can provide nitrogen for plant physiological needs essential for growth and development and act as a biofertilizer, thereby decreasing the use of synthetic agrochemicals. Today, agricultural production is challenged by diverse environmental and climatic factors affecting soil health and fertility. PGPR act with legumes resulting in enhanced nutrients through nitrogen fixation, systemic resistance, tolerance to stress, production of phytohormones, and solubilizing phosphates in the plant root exudates. Zeffa et al. (2019) investigated the role of *Azospirillum brasilense* as PGPR in promoting nitrogen use efficiency in maize. They suggested that rhizobia form root nodules that fix nitrogen in symbiotic legumes, thus performing the experiment in nonlegumes would be a useful way of increasing productivity in agricultural practice particularly among the resource-poor countries. From their finding, it was revealed that biomolecules like auxins, abscisic acids, cytokinins, lumichrome, lipo-chitooligosaccharides, vitamins, and riboflavin produced by rhizobia may be responsible for the plant growth property, phosphorus uptake in maize, millet, and sorghum.

Environmental factors like heat, salinity, and drought are known to alter crop growth and other soil physiological processes. In order to mitigate these effects, PGPR has been suggested to constantly minimize the negative impact of environmental stresses. Rhizobacteria have been reported to significantly improve grain yield (Bashan and de-Bashan 2010). Azospirillum–plant interaction has been shown to cause single phytohormone activity, nitrogen fixation, collections of small-sized molecules or enzymes, multiple phytohormones, increased membrane activity, the proliferation of the root system, mobilization of minerals, increased water plus mineral uptake, elimination of environmental stressors in plants, biocontrol of phytopathogens. Fukami et al. (2018) highlighted and attributed the plant growth-promoting bacteria role of genus Azospirillum towards tolerance of biotic and abiotic stresses, mediated by phytohormones through ethylene/jasmonic acid signaling pathway (Foyer et al. 2019) revealed that symbiotic nitrogen fixation is a major mechanism of legume–rhizobia relationship which may further be enhanced by arbuscular mycorrhiza.

Naveed et al. (2015) and Patel et al. (2017) revealed that rhizobia–legume and nonlegumes symbiosis for biological nitrogen fixation is changing agricultural practices. Through the development of root nodules, rhizobia fix nitrogen from the atmosphere. Bankole et al. (2019) and Borges et al. (2019) suggested that symbiotic relationship with plant roots such as rhizobia, actinomycetes, mycorrhizal fungi, diazotrophic bacteria provides an opportunity for biofertilizer, biostimulation, and biocontrol mechanism. Datta et al. (2015) and Mabrouk and Belhadj (2012) showed that rhizobium is a gram negative bacterium linked with a symbiotic relationship with the roots of leguminous/nonleguminous plants containing granules of β-hydroxybutyrate. There are different classes of rhizobium such as Rhizobium, Mesorhizobium, Bradyrhizobium, Sinorhizobium, and Azorhizobium with efficient plant growth-promoting ability like phytohormones, phosphate solubilization, siderophores production, and hydrogen cyanide production. A symbiotic process exists in rhizobia with leguminous plants with energy in the form of nutrients, then fixing dinitrogen from the atmosphere for plant uptake and subsequent reduction of dinitrogen into ammonia making use of 16 molecules of ATP with a complex set of enzymes and releasing various chemicals by the root cells into the soil (Abhinav et al. 2015).

The application of *Rhizobium leguminosarum* and *Pseudomonas* jesseni P10 as a PGPR to support the growth and nodulation abilities of *Lens culinaris* Medik has been documented (Iqbal et al. 2012). These bacteria are also known for producing a plant growth enzyme, 1-aminocyclopropane-1-carboxylate deaminase (ACC deaminase) and these PGPR bacteria have also been isolated from plastic enriched compost (PEC) (Iqbal et al. 2012).

Yadegari and Rahmani (2010) reported that two bacteria, *Pseudomonas fluorescens* P-93 and *Azospirillum lipoferum* S-21 elicited appreciable plant promoting activities on the seeds of the bean plant (*Phaseolus vulgaris*) especially when co-cultured with two *Rhizobium* strains either individually or in combination. In an in vitro study, Flores-félix et al. (2013) sequestered *Rhizobium leguminosarum* strain PEPV 16 from the nodules of *Phaseolus vulgaris*. The authors revealed that the root nodule bacteria displayed some PGPR properties and was able to add a significant upsurge of N and K uptake in Carrot and Lettuce plants. Co-inoculation of *Rhizobium* spp. and *Enterobacter cloacae and Pseudomonas* spp PGPR strains were recorded to have reduced Cu. stress in *Vicia faba* than when compared to the non-inoculated plants (Fatnassi et al. 2015). Aamir et al. (2013) reported that the co-treatment of Mung Bean using Rhizobium and PGPRs containing ACC deaminase significantly enhanced the nodulation and growth of the plant. They observed that this was done by reducing the stress associated with salinity. Afzal and Bano (2008) also compared the outcome of inoculating together and singly, Rhizobium, and a phosphate-solubilizing bacterium with or without phosphate fertilizer, on *Triticum aestivum* plant (Wheat). The authors discovered that there was a 29% increase in growth and a significant improvement in plant morphology when a dual combination with P fertilizer was used when compared to those treated without fertilizers. This study revealed that dual treatment with a phosphate fertilizer is very important for plant growth and subsequent wheat plant yield.

### 20.11.2 *Azospirillum spp*

Saikia et al. (2010) and Sahu et al. (2017) reported that the growing human population across the globe demands a novel strategy to increase agricultural productivity so as to meet the growing demand. The authors pointed attention to the utilization of microbes like *Azospirillum spp*, micro-aerophillic microorganisms as biofertilizers to enhance the development. *Azospirillum spp* act as nitrogen-fixing bacteria, enhance seed germination, increase proton flux, facilitate seedling growth, phosphorus solubilization, generation of phytohormones like indole-3-acetic acid, sequestration of iron, enhance photosynthetic pigments, increase dry matter partitioning, plant growth promoters, restoration of vegetation in a harsh environment, alleviate stresses, and increase seed quality (Fukami et al. 2018).

Cassan and Diaz-Zorita (2016) reported that *Azospirillum sp*. is a PGPR that can colonize several plant species to fix nitrogen, produce metabolite, and several phytohormones like siderophore, nitric oxide, abscisic acid, ethylene biocontrol of phytopathogens, gibberellins, phosphate solubilization indole-3-acetic acid. Mehnaz et al. (2007) and Fukami et al. (2018) exhibited that genus *Azospirillum spp* confer to plants stresses tolerance, signaling molecules activation such as jasmonic acid/ethylene pathway, osmotic adjustment, mediate antioxidants, and detoxification of oxidative stress. Pereyra et al. (2007) showed that Azospirillum spp portends the potential to improve plant development as well as secretion of antimicrobial activity and other secondary metabolites that help in stimulating phytohormones, and in production of biofertilizers (Barassi et al. 2007).

*Azospirillum* spp. has been recorded to resist stress conditions and has been a good PGPR in agriculture (Diaz-Zorita and Fernandez-Canigia, 2009; Bashan and de-Bashan 2010). Couillerot et al. (2010) monitored the inoculant presence and quantity of the PGPR *Azospirillum lipoferum* CRT1 in the rhizosphere of maize seedlings using real-time polymerase chain reaction (PCR) method. García-Fraile et al. (2015) compared the in vitro drought tolerance and PGPR qualities of 36 different strains of *Azospirillum* including a strain Az39 which was regularly used in Argentina for inoculating and planting of Maize. It was discovered that strain Az19 had the highest drought, salt stress resistant, and PGPR qualities out of all isolated strains. The co-inoculation of *Azospirillum* strains with other PGPR has been a plus in the field of agriculture. This synergistic combination greatly improves nutrient availability and stimulates each other's physiological and biochemical systems, leading to an improved plant growth rate. Previously, it was observed that at inoculation of $10^7$ in its stationary phase, there was effective coaggregation of *Azospirillum* with other PGPR. The authors also recorded that other factors like pH and temperature also enhanced coaggregation at 5 and 35 to 40 ° C, respectively. In an experiment performed by previously, researchers had inoculated the PGPRs, *Azospirillum brasilense*, and *Bacillus sphaericus* with 33% nitrogen fertilizer to determine the growth yield and productivity of banana plantlets. It was recorded that nutrients were significantly increased and an early flowering at 3 weeks was observed. It was also discovered that the physical features of the banana fruits, when compared to the control of the experiment were considerably improved. The amount of nitrogen (N) and phosphorus (P) nutrients required by plants for their growth cannot be overemphasized. The use of NP fertilizers and their effects on the environment is of great concern. Nitrate serves as a pollutant of groundwater and the gradual loss of phosphorus from the soil through runoff finds its way to surface waters. Alternate eco-friendly methods in improving plant growth should be made available to help in the preservation of the environment. Ejaz et al. (2020) performed an experiment to determine the effectiveness of PGPRs in enhancing the development, produce, and quality of plants. They co-inoculated the pea plant (*Pisum sativum* L.) with nitrogen-fixing *Azospirillum* strain and a phosphorus solubilizing *Agrobacterium tumefaciens* strain at a different percentage of reduced nitrogen and phosphorus fertilizer (60, 65, 70, 75, 80%, and the proposed dose 100%) and compared it with a nitrogen–phosphorus (100%) fertilizer without any inoculum. It was discovered that the PGPR co-inoculation with 75% NP treated pea plant presented a 55% plant growth and development when compared to the 100% NP which was not inoculated with both rhizobacterium. They concluded that the co-inoculation of important NP rhizobacterium strains can be beneficial to the environment and also a cost-effective choice.

Scientists have identified *Azospirillum* strains as effective stimulators in the rhizosphere aiding root exudation and development. Baudoin et al. (2009) in an experiment investigated the genotypic construction of the rhizobacterial population present on maize seedlings grown in the field after its inoculation with *Azospirillum lipoferum* CRT1. They revealed that there was an alteration in the native bacteria present in the rhizosphere at days 7 and 35 and they concluded that treatment of seed with *Azospirillum lipoferum* CRT1 increased the presence of different bacteria in the field soil.

### 20.11.3 *Bacillus spp*

Metin et al. (2014) reported that *Bacillus megaterium* strain, *B. subtilis* strain, and *Pantoea agglomerans* strain can act as PGPR to improve seedling quality and growth in cabbages. Radhakrishnan et al. (2017) revealed that genetic and environmental factors greatly affect crop productivity and yield, thus *Bacillus* and *Pseudomonas spp* are now being utilized to facilitate plant growth by inducing physiological changes such as exopolysaccharides and siderophores secretion, pathogenic microbial control, water transport, nutrient uptake, and production of other several active metabolites like chitosanase, cellulase, protease, glucanase, hydrogen cyanide, and lipopeptides. Bacillus spp. release ammonia from nitrogenous organic matter through nifH gene, thus produce nitrogenase, fix atmospheric nitrogen, enhance plant growth plus yield by delaying senescence, iron-chelating properties generated through siderophore production which help to solubilize iron from minerals plus organic compounds in rhizospheres.

Raaijmakers and Mazzola (2012) and Malviya et al. (2012) reported that Bacillus species have been proposed to increase crop yield and quality, root colonization, chlorophyll content. Barea (2015) demonstrated that exploiting the agroecosystem of soil microbial host seems to be a promising approach. Thus the authors investigated the role of sustainable and organic agricultural production through the utilization and management of soil microorganisms such as *Bacillus spp*. The plant-linked microbiome has been revealed to ameliorate the negative impacts of stress factors, increase crop productivity. Villarreal-Delgado et al. (2017) showed that the genus Bacillus is widely distributed in the agro-ecosystems. The authors further analyzed and discovered that the microbe's mechanism of action involves secretion of toxins, phytopathogens suppression, antibiotics, siderophores, induced systemic resistance, and lytic enzymes. Jamal et al. (2018) revealed that *Bacillus amyloliquefaciens* Y1 strain was studied to identify its role on soil properties, rhizosphere bacterial flora, pepper seedling growth, plus soil enzyme activities.

From their results, it was observed that *B. amyloliquefaciens* Y1 displayed a positive role on soil fertility and recommended for biofertilizer application.

Hashem et al. (2019) reported that many microbes can stimulate plant growth and replace chemical fertilizers or pesticides. PGPR has been revealed to induction of systemic resistance, competitive omission, and antibiosis. The authors discovered that *Bacillus subtilis* exhibits these characteristics by secreting secondary metabolites, cell-wall degrading enzymes, enhances nitrogen fixation, hormones, antioxidants defense enzymes secretion, and solubilizes soil phosphorus, production of siderophores and exopolysaccharides. The authors suggested that multidisciplinary approaches such as molecular biology, physiology, biotechnology should be adopted to harness the beneficial properties of many of these plant growth-promoting rhizosphere.

Alooa et al. (2019) revealed that rhizospheric bacteria improve soil fertility and promote plant growth by producing enzymes like glucanases, chitosanases, and chitinases, siderophores, and antibiotics like pyoluteorin, zwittermicin A, and oomycin. *Bacilli rhizobacteria* are known to offer unique functions and properties such as biofertilization, bioprotection, and phytostimulation. The authors inoculated tomato seedlings with cell suspensions of B. subtilis and discovered that shoot and root growth are enhanced, increased seedling vigor was noticeable in the leaf area of the plants and higher levels of phytohormones are secreted.

It has been discovered that the genus *Bacillus* has been documented to be highly effective for phosphate-solubilizing capability. *Bacillus amyloliquefaciens* having PGPR traits and able to induce resistance to *Rhizoctonia solani* and *Fusarium solani in* in vitro has been detected in the potato rhizosphere. The restoration of the effects of salinity stress in the root system of the soybean plant (*Glycine max* L.) has been known to be carried out by the PGPR *Bacillus firmus* SW5. As a consequence, this bacterium significantly improved plant quality, yield, and antioxidant defense systems. The size and texture of tomato plants (*Lycopersicon esculentum* Mill, cv Rio Fuego) cultivated under greenhouse conditions and exposed to inoculated cultures of the PGPR *B. subtilis* BEB-13bs strain introduced at the plant root were investigated. The control system showed no effect on the plant yield but there was a considerable increase in the yield after inoculation with the PGPR *B. subtilis* strain. The authors opined that the PGPR *Bacillus subtilis* BEB-13bs strain had a positive impact on the fruit quality and yield of the cultivated tomatoes.

Lim and Kim (2013) investigated the effect of multi-functional PGPR *Bacillus licheniformis* K11 on the drought resistance attribute of the pepper plant (*Capsicum annuum* L.). The authors observed that in using a control, after a 15 day period, the pepper plants exposed to drought stress did not survive, while those inoculated with the PGPR *B. licheniformis* K11 strain survived. They reported the presence of pathogenesis-related protein 10 (*CaPR-10*), dehydrin-like protein (*Cadhn)* (cytoplasmic small heat shock protein class I) *sHSP*, and (vacuolar H+-ATPase) *VA* stress proteins genes in *C. annuum* L. inoculated with *B. licheniformis* K11. They concluded that *B. licheniformis* K11 was a good agent that could be applied as biofertilizer for the better productivity of the plant. Probanza et al. (2002) studied the effect of two different species of PGPR *Bacillus*; *B. licheniformis* CECT 5106 and *B. pumilus* CECT 5105, respectively, when used individually or in combination to treat *Pinus pinea* plant seedlings. The authors observed an improved growth and modification in microbial populations present in the rhizosphere when used individually than when used as a consortium. They concluded that the respective PGPR *Bacillus* species could not function effectively as a consortium due to competition in the rhizosphere of the affected plant.

### 20.11.4 *Serratia spp*

Rhizospheric borne *Serratia* strains isolated from the plant; *Nothofagus alpine* was reported to exhibit the ability to promote growth in the diameter of the plant (Martínez et al. 2018). The authors also observed the growth promoting ability of the bacteria with respect to the root collar, biomass, its height, nitrogen, and chlorophyll content of *N. alpine* plantlets. They discovered that all the isolated strains also caused increased production of plant metabolites such as 1-aminocyclopropane-1-carboxylic acid deaminase and indole acetic acid, and also increased nitrogen fixing capacity of the plant. They concluded that *Serratia* strains are PGPR which can be utilized as biofertilizers when applied in plant nurseries.

Earlier experiments have demonstrated that an appreciable decline in the oxidative stress markers with an increment in salinity stress tolerance in maize (*Zea mays* L.) by rhizospheric *Serratia liquefaciens* KM4, thereby impacting positively on the overall phenotypic and genotypic receptiveness of the plant. The genome of PGPR *Serratia marcescens* CDP-13 cultured from a plant, *Capparis decidua* was sequenced and the bacterium was known for its ability to reduce the impact of physical and biological stress on the host plant. The sequenced *Serratia marcescens* CDP-13 was discovered to have significant traits of PGPRs which include considerable growth in the saline concentration of up to 6%, aiding the improvement of wheat grown under high salt concentration. The study concluded that *Serratia marcescens* CDP-13 has the probability to enhance salt stress and act as a substitute for pesticides. Researchers have conducted a study on the usage of rhizospheric borne plant growth-promoting bacterium; *S. nematodiphila* PEJ1011 to establish the growth-promoting effect of gibberellin (GA) on pepper (*Capsicum annuum L*). It was detected that *S. nematodiphila* PEJ1011 improved the low-temperature effect on *Capsicum annuum L,* helping the plant adapt to low-temperature stress. The combined effect of the PGPR *Pseudomonas fluorescens* and *Serratia marcescens* to protect and prevent the symptoms of the cucumber mosaic cucumovirus on the cotyledon of *Cucumis sativus* and *Lycopersicum esculentum* was studied by Raupach et al. (1996). Using the enzyme-linked immunoabsorbent assay to detect the presence of the viral antigen, the authors discovered that the symptoms on plants were significantly reduced after treatment with PGPR on the seedlings and did not develop any noticeable symptoms till the end of the experiment. They concluded that the use of different genus of PGPR possesses the capability to control viral diseases of plants.

However, the mutual effect of two different concentrations of genistein (0 and 20μM) and either of *Serratia proteamaculans* or *Serratia liquefaciens* was used to determine the growth yield, fixation of nitrogen, and nodulation of soybean types (*Bradyrhizobium japonicum).* There was no significant difference recorded in using both of the PGPR with genistein but a difference was recorded when genistein was used separately.

### 20.11.5 *Pseudomonas spp*

Genus *Pseudomonas*is an important rhizobacterium involved in the growth and proper development of plants and known for its phosphate soulibilizing capability. A comparative study of the effectiveness of two different methods (microcapsules and liquid) utilized in the inoculation of different strains of PGPR *Pseudomonas putida*; FA-8, FA-56, and FA-60 in Tomato (*Lycopersicon esculentum)* was performed and the study was also aimed at evaluating the growth enhancing effect of the bacterium on the tomato plant. The authors observed that using the microcapsule inoculation method, *Pseudomonas putida* FA-56 produced the highest indole acetic acid (IAA) at 23.02μg $mL^{-1}$ revealing a significant increment in all physiological characteristics and bacterial population in the plant rhizosphere. It was confirmed that the inoculation method of PGPR using microcapsules was a good substitute to chemical fertilizers, thereby promoting biofertilizers.

Bakker et al. (1986) studied the potential application of *P. putida* WCS358 for the treatment of potato seed tubers (*Solanum tuberosum* L.cv Bintje) at long and short term crop rotation. The *P. putida* WCS358 had siderophores and were also known nonproducing Tn5 transposon mutants. The authors observed that potato seed treatment with siderophore producing Tn5 transposon mutant in long crop rotations yielded no significant yield, but a significant yield of 13% after 86 days of short crop rotation was recorded when the siderophore producing Tn5 wildtype was used in the experiment. They reported that the presence of siderophores in PGPR was a necessary requirement for a good potato tuber yield.

Audenaert et al. (2002) demonstrated that salicylic acid (SA) a known siderophore metabolite elicited by the PGPR *P. aeuriginosa*7NSK2 was not a sufficient determinant of induced resistance in *Pseudomonas aeuriginosa* 7NSK2 exposed to *Botrytis cinerea*, but rather additional metaboliteswhich included Pyochelin and pyocyanin. An evaluation of the growth increment of Sorghum was done using some Arbscular mycorrhizal fungi; *Glomus fasciculatum* and *Glomus aggregatum* together with forty (40) known different fluorescent *Pseudomonas* spp., individually and together. Criteria employed for selection of the different fluorescent *Pseudomonas* spp., was their position of a single and/or numerous PGPR quality known to aid plant growth. It was documented that *Pseudomonas* spp. P10 and P13 which exhibited PGPR attributes such as exopolysaccharide, IAA, gibberellic acid, siderophore, and phosphate solubilization had a better outcome with Abscular mycorrhizae. Whereas *Pseudomonas* spp. P38 that posses the ability to produce hydrogen cyanide (HCN) and also an effective solubilizer of phosphate showed no significant effect. They concluded that the various PGPR features of different *Pseudomonas* strains may not be sufficient to present them as PGPR. It has been reported that the PGPR *Pseudomonas aurantiaca* SR1 was found to colonize the root of two (2) cereal crops: wheat (*Triticum aestivum* L) and maize (*Zea mays*). The researchers observed that when the PGPR *P. aurantiaca* SR1 was inoculated during propagation, plant growth was enhanced even when used with or without fertilizers. The biological fertilizer has in turn aided the alleviation of inorganic nitrogen pollution.

Previously, scientists have demonstrated that different strains of *Pseudomonas* sp. assisted in phosphorus fertilization and uptake of nutrients in *T. aestivum* L. under both field and greenhouse conditions. Mirza et al. (2006) reported that the growth of rice was positively aided by nitrogen-fixing *Pseudomonas* strains that have been known to be a potential PGPR inoculant. Previously, it has been observed that the presence of heavy metals in soil negatively affected the expression of PGPR traits of the respective *Pseudomonas* strains which were previously reported to have good growth-promoting traits.

### 20.11.6 *Stenotrophomonas spp*

Stenotrophomonas is one of the PGPR, known for its multiple traits and adaptability. Stenotrophomonas is known for its ability to be a good PGPR and is also isolated and characterized from the rhizosphere of different crops (Kumar and Audipudi 2015; Patel and Saraf 2017). This PGPR is also extensively involved in nitrogen and sulfur biogeochemical cycles. In the delivery of PGPR as bioinoculants into the rhizosphere and on seedlings for plant growth and improvement, the form in which it is added is very important. Kumar et al. (2019) isolated six strains of PGPR, known to be of the genus Stenotrophomonas from five various plants (*Solanum tuberosum, Triticum aestivum, Bacopa monnieri, Zea mays,* and *Aloe barbadensis*). They discovered that they had the ability to reduce nitrogen to ammonia when compared to *Azotobacter chroococum*. *S. rhizophilia* was recorded to have survived in various liquid carriers and was concluded that these PGPRs can be used in the production of liquid biofertilizer. In a recent study, researchers have investigated the reductive ability of Stenotrophomonas on Cr (IV). The authors revealed that the PGPR was extremely resistant to chromium and had a 92.5% reduction in Cr(IV) to Cr(III) within 28 h. They concluded that the rhizobacterium would serve in bioremediation of chromium polluted soils.

Alavi et al. (2013) studied the process linked with stress in the rhizosphere. The improvement of cucumber resistance to cucumber green mottle mosaic virus has been recorded by the PGPR *Stenotrophomonas maltophilia* HW2 (Li et al. 2016). It was also discovered that in 3 days *S. maltophilia* repressed the phenotypic expression of the viral protein on the leaf of the cucumber, making a good biological control agent in sustainable agriculture.

## 20.12 Specific Examples of Beneficial Microorganism Involved in the Maintainaece of Soil Health

Tahat et al. (2020) reported that soil health is linked with sustainable agriculture providing abundant nutrients for plant development. Recently, organic farming utilizing PGPR has been accepted as an alternative to synthetic chemicals due to its adverse effects on soil fertility and plant physiology. The authors revealed that these plant promoters could affect the level of plant composition, productivity, soil integrity, soil nutrient cycling, and its sustainability. They showed that organic farming systems are known to increase soil nutrient mineralization and microorganism large quantity and diversity as well as soil physical features. Conservation tillage, enhanced soil fungi abundance, earthworm diversity, environmental factors like physical, chemical, biological facilitate dynamic soil–rhizosphere–plant systems and stability for agricultural sustainability.

Rafiquea et al. (2017) reported that microbial application for plant growth facilitates soil health and fertility compared to chemical fertilizer. An adequate supply of phosphorus to plant is a significant indication for soil health to satisfy crop nutritional requirements. Phosphate-solubilizing microorganisms in the soil microbial communities such as *Clostridium pasteurianum, Rhodobacter, cyanobacteria, Methanogens, Bacillus mucilaginous, Bacillus circulans, Bacillus megaterium, Pseudomonas striata, Bacillus subtilis* facilitate soil management strategies for eco-friendly soil fertility enhancement, controlled soil pH.

Medina and Azcón (2010) reported that enhancing the capability of soil microorganisms for the inhibition of pathogens is an important strategy for sustainable agriculture such as regulation of plant defense activity, plant hormone signaling crosstalk, development of soil microbe–plant insect relationship. Hirsch et al. (2013) highlighted the importance of soil microorganisms in alleviating the negative impacts of osmotic stressors like salinity and drought. Many land areas across the globe are increasingly being polluted with many contaminants, thus raising the level of salinity and pH. Therefore, for the plant to cope with this osmotic stress, an appropriate mechanism must be developed such as water uptake capacity, activation of the antioxidant system, transpiration rates, maintenance of ionic homeostasis, and lowered reactive oxygen species generation.

### 20.12.1 Mycorrhizal Associations

Steffen et al. (2020) reported that crop production in agricultural practice is constantly being influenced by many environmental and climatic factors, thus scientists are always searching for ways to improve crop production through organic farming. The associations between arbuscular mycorrhizal fungi and plants have been evaluated for many years. The role of mycorrhizal on plant growth under stressful conditions was studied on the quality plus performance of crops. The rhizosphere characteristic feature is a major determinant of plant performance, thus arbuscular mycorrhizae are one of the common types of symbiotic relationships between rhizosphere microorganisms and plant roots. The mycorrhizal inoculants have been revealed to stimulate plant growth and development through advanced biotechnology integrated with multidisciplinary knowledge of biochemistry, microbiology, molecular biology, immunology, cell biology, enzymology, genetics, bioengineering, physiology, biophysics, chemical engineering, mathematics, to continually utilize microorganisms and their components to stimulate plant metabolism with maximum efficiency. Recent advances in the field of arbuscular mycorrhiza and their impact on plant quality, environmental protection, and biodiversity conservation need further evaluation.

Meena et al. (2017) revealed that exploring the symbiotic relationship of arbuscular mycorrhiza and crop tolerance to an unfavored environment is a sustainable approach in organic farming that needs further elucidation. The present agricultural practice is no longer sustainable due to the high cost of fertilizers, global warming due to synthetic agrochemical use, poor soil fertility as a result of constant tillage, and application of chemicals. It has been documented that Mycorrhiza fungal could exhibit a symbiotic relationship with plant roots such as *Chenopodiaceae, Caryophyllaceae, Amaranthaceae, Polygonaceae, Commelinaceae, Brassicaceae, Cyperaceae, Juncaceae* in the rhizosphere with the ability to supplied different amounts of phosphorus. Arbuscular mycorrhizas are now seen to influence plant community development, water relations, nutrient uptake and above-ground productivity, tolerant of adverse conditions, microbial biofertilizers, optimized microbiomes, biocontrol microbes, soil matching microbe-crops for different soil types.

Jakhar et al. (2017) reported that mycorrhizae display essential functions in plant growth, soil fertility, and plant protection, also their filamentous networks promote bi-directional nutrient movement. Oruru and Njeru (2016) reported that Arbuscular mycorrhizal fungi display a vital function in biological soil fertility, plant protection, and nutrition. Barea et al. (2011) and Surendirakumar et al. (2019) showed that mycorrhizal facilitate resilience of plant host against environmental stresses like nutrient deficiency, soil disturbance, and drought as biofertilizers, biostimulants, and bioprotectors.

## 20.13 Conclusion and Future Recommendation

Therefore, this chapter intends to provide detailed information on comprehensive information on sustainable biotechnology tools that could boost an increase in agricultural and food production. The application of genetic engineering and advanced biotechnology tool such as synthetic biology could help in the identification of a novel consortium that could help in the achievement of sustainable organics agriculture. Detailed facts on microorganisms that could influence soil health in promoting plant growth, as biological fertilizers, biological control agent, wastelands restoration, and bioremediations were also highlighted. The application of metabolomics could help to identify beneficial metabolites that could lead to the management of pests and diseases which are biotic factors that mitigate the increase in agricultural production as well as those that could help in regulating abiotic stress like salinity and drought that affect increased in agricultural production.

## References

Aamir M et al (2013) Co-inoculation with rhizobium and plant growth promoting rhizobacteria (PGPR) for inducing salinity tolerance in mung bean under field condition of semi-arid climate. Asian J Agric Biol 1(1):7–12

Adedeji AA, Häggblom MM, Babalola OO (2020) Sustainable agriculture in Africa: plant growth-promoting rhizobacteria (PGPR) to the rescue. Sci Afr 9:e00492. https://doi.org/10.1016/j.sciaf.2020.e00492

Adetunji CO, Anani OA (2020) Bio-fertilizer from trichoderma: boom for agriculture production and management of soil- and root-borne plant pathogens. In: Mishra P, Mishra RR, Adetunji CO (eds) Innovations in food technology. Springer, Singapore, pp 245–256

Afzal A, Bano A (2008) Rhizobium and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (Triticum aestivum). Int J Agric Biol 10(1):85–88

Agbodjato NA, Noumavo PA, Baba-Moussa F, Salami HA, Sina H, Sèzan A, Bankolé H, Adjanohoun A, Baba-Moussa L (2015) Characterization of potential plant growth promoting rhizobacteria isolated from maize (Zea mays L.) in central and northern Benin (West Africa). Hindawi Publishing Corporation Appl Environ Soil Sci 2015:901656, 9 pages. https://doi.org/10.1155/2015/901656

Ahirwar NK, Singh R, Chaurasia S, Chandra R, Prajapati S, Ramana S (2019) Effective role of beneficial microbes in achieving the sustainable agriculture and eco-friendly environment development goals: a review. Front Environ Microbiol 5(6):111–123. http://www.sciencepublishinggroup.com/j/fem. https://doi.org/10.11648/j.fem.20190506.12

Ajao AT, Oluwajobi AO, Olatayo VS (2011) Bioremediation of soil microcosms from auto-mechanic workshops. J Appl Sci Environ Manag 15(3):473–477

Alavi P et al (2013) Root-microbe systems: the effect and mode of interaction of stress protecting agent (SPA) Stenotrophomonas rhizophila DSM14405T. Front Plant Sci 4:1–10. https://doi.org/10.3389/fpls.2013.00141

Alexander A, Chong KP (2014) The impact of biological control agents on soil microbial communities in oil palm plantation soils. Am-Eurasian J Sustain Agric 8:8–17

Alooa BN, Makumba BA, Mbega ER (2019) The potential of bacilli rhizobacteria for sustainable crop production and environmental sustainability. Microbiol Res 219:26–39

Amaya-Gómez CV, Porcel M, MesaGarriga L, Gómez-Álvarez MI (2020) A framework for the selection of plant growth promoting rhizobacteria based on bacterial competence mechanisms. Appl Environ Microbiol 86:e00760–e00720. https://doi.org/10.1128/AEM.00760-20

Anani OA, Olomukoro JO (2019) Assessment of metal accumulation and bioaccumulation factor of some trace and heavy metals in freshwater prawn and crab. IntechOpen. https://doi.org/10.5772/intechopen.88103

Anani OA, Olomukoro JO, Ezenwa IM (2020a) Limnological evaluation in terms of water quality of Ossiomo River, Southern Nigeria. Int J Conserv Sci 11(2):571–588

Anani OA, Olomukoro JO, Enuneku AA (2020b) Geospatial mapping, environmetrics and indexing approach for a tropical river sediment in Southern Nigeria. Pak J Sci Ind Res Ser A Phys Sci 63A(3):176–187

Audenaert K, De Meyer G, Höfte M (2002) Abscisic acid determines basal susceptibility of tomato to Botrytis cinerea and suppresses salicylic acid dependent signaling mechanisms. Plant Physiol 128:491–501

Barassi CA, Sueldo RJ, Creus CM, Carrozzi LE, Casanovas EM, Pereyra MA (2007) Dynamic soil, dynamic plant. Global science books Azospirillum spp., a dynamic soil bacterium favourable to vegetable crop production. Dyn Soil Dyn Plant 1(2):68–82

Beneduzi A, Ambrosini A, Passaglia LMP (2012) Plant growth-promoting rhizobacteria (PGPR): their potential as antagonists and biocontrol agents. Genet Mol Biol 35:41044–41051

Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, Subramanian S, Smith DL (2018) Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Front Plant Sci 9:1473. https://doi.org/10.3389/fpls.2018.01473

Bakker PAHM, Lamers JG, Bakker AW, Marugg JD, Weisbeek PJ, Schippers B (1986) The role of siderophores in potato tuber yield increase by Pseudomonas putida in a short rotation of potato. Neth J Plant Pathol 92:249–256

Bankole SO et al (2019) Potential significance of beneficial microbes for sustainable soil management and plant utilization. Acta Sci Microbiol 2(6):88–95

Barea JM (2015) Future challenges and perspectives for applying microbial biotechnology in sustainable agriculture based on a better understanding of plant-microbiome interactions. J Soil Sci Plant Nutr 15(2):261–282

Barea JM, Palenzuela J, Cornejo P, Sánchez-Castro I, Navarro-Fernández C, Lopéz-García A, Estrada B, Azcón R, Ferrol N, Azcón-Aguilar C (2011) Ecological and functional roles of mycorrhizas in semi-arid ecosystems of Southeast Spain. J Arid Environ 75:1292–1301

Bashan Y, de-Bashan LE (2010) How the plant growth-promoting bacterium azospirillum promotes plant growth—a critical assessment. Adv Agron 108(2):77–136. https://doi.org/10.1016/S0065-2113(10)08002-8

Bashan Y, de-Bashan LE, Prabhu SR, Hernandez J-P (2014) Advances in plant growth-promoting bacterial inoculant technology: formulations and practical perspectives (1998–2013). Plant Soil 378:1–33. https://doi.org/10.1007/s11104-013-1956-x

Baudoin E et al (2009) Impact of inoculation with the phytostimulatory PGPR Azospirillum lipoferum CRT1 on the genetic structure of the rhizobacterial community of field-grown maize. Soil Biol Biochem 41(2):409–413. https://doi.org/10.1016/j.soilbio.2008.10.015

Bechtaoui N, Raklami A, Tahiri A-I, Benidire L, El Alaoui A, Meddich A, Göttfert M, Oufdou K (2019) Characterization of plant growth promoting rhizobacteria and their benefits on growth and phosphate nutrition of faba bean and wheat. 2019. Published by The Company of Biologists Ltd. Biol Open 8:bio043968. https://doi.org/10.1242/bio.043968

Beg MA, Singh JK (2009) Effects of biofertilizers and fertility levels on growth, yield and nutrient removal of green gram (Vigna radiata) under Kashmir conditions. Indian J Agric Sci 79 (5):388–390

Bengtsson J, Ahnstrom J, Weibull AC (2005) The effects of organic agriculture on biodiversity and abundance: a meta-analysis. J Appl Ecol 42:261–269. https://doi.org/10.1111/j.1365-2664.2005.01005.x

Berg G, Rybakova D, Grube M, Koberl M (2016) The plant microbiome explored: implications for experimental botany. J Exp Bot 67:995–1002. https://doi.org/10.1093/jxb/erv466

Bhardwaj D, Ansari MW, Sahoo RK, Tuteja N (2014) Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microb Cell Factories 13:66. http://www.microbialcellfactories.com/content/13/1/66

Bhat MA et al (2019) Plant growth promoting rhizobacteria (PGPR) for sustainable and eco-friendly agriculture. Acta Sci Agric 3(1):23–25

Boelling D, Groen AF, Sørensen P, Madsen P, Jensen J (2003) Genetic improvement of livestock for organic farming systems. Livest Prod Sci 80:79–88

Borges CS, de Sá EL, Muniz AW, Filho O (2019) Potential use of rhizobium for vegetable crops growth promotion. Afr J Agric Res 14(8):477–483. https://doi.org/10.5897/AJAR2017.12885

Cassan F, Diaz-Zorita M (2016) Azospirillum sp. in current agriculture: from the laboratory to the field. Soil Biol Biochem 103:117–130

Cassán F, Perrig D, Sgroy V, Masciarelli O, Penna C, Luna V (2009) Azospirillum brasilense Az39 and Bradyrhizobium japonicum E109, inoculated singly or in combination, promote seed germination and early seedling growth in corn (Zea mays L.) and soybean (Glycine max L.). Eur J Soil Biol 45:28–35. https://doi.org/10.1016/j.ejsobi.2008.08.005

Chakrabarty T, Akter A, Saifullah ASM, Sheikh MS, Bhowmick AC (2014) Use of fertilizer and pesticide for crop production in agrarian area of Tangail district, Bangladesh. Environ Ecol Res 2(6):253–261. https://doi.org/10.13189/eer.2014.020605

Costa C, Garcia-Lestion J, Costa S, Coelho P, Silva S, Pingqarilho M, Valdiqlesias V, Mattei F, Dali Armi V, Bonassi S, Laffon B, Snawder J, Teixeira JP (2014) Is organic farming safer to farmers' health? A comparison between organic and traditional farming. Toxicol Lett 230:166–176

Couillerot O et al (2010) Development of a real-time PCR method to quantify the PGPR strain Azospirillum lipoferum CRT1 on maize seedlings. Soil Biol Biochem 42(12):2298–2305. https://doi.org/10.1016/j.soilbio.2010.09.003

Cummings SP (2009) The application of plant growth promoting rhizobacteria (PGPR) in low input and organic cultivation of graminaceous crops; potential and problems. Environ Biotechnol 5 (2):43–50

Dago ND, Diarrassouba N, Saraka MDY, Moroh J-LA, Fofana IJ, Baba-Moussa L, Coulibaly A (2018) Predicting maize and soybean crops dry biomass through rhizobacteria microorganisms activity on foliar bio-fertilizer in an arid agro-climate: a multiple linear regression analysis. Afr J Microbiol Res 12(34):835–848. https://doi.org/10.5897/AJMR2018.8899

Di Benedetto A, Corbo MR, Campaniello D, Cataldi MP, Bevilacqua A, Sinigaglia M, Flagella Z (2017) The role of plant growth promoting bacteria in improving nitrogen use efficiency for sustainable crop production: a focus on wheat Nilde. AIMS Microbiol 3(3):413–434. https://doi.org/10.3934/microbiol.2017.3.413

Datta A, Singh RK, Kumar S, Kumar S (2015) An effective and beneficial plant growth promoting soil bacterium "Rhizobium": a review. Ann Plant Sci 4(1):933–942

de Souza R, Ambrosini A, Passaglia L (2015) Plant growth-promoting bacteria as inoculants in agricultural soils. Genet Mol Biol 38(4):401–419. https://doi.org/10.1590/S1415-475738420150053

dos Santos RM, Diaz PAE, Lobo LLB, Rigobelo EC (2020) Use of plant growth-promoting rhizobacteria in maize and sugarcane: characteristics and applications. Front Sustain Food Syst 4:136. https://doi.org/10.3389/fsufs.2020.00136

Ejaz S et al (2020) Effects of inoculation of root-associative azospirillum and agrobacterium strains on growth, yield and quality of pea (Pisum sativum L.) grown under different nitrogen and phosphorus regimes. Sci Hortic 270:109401. https://doi.org/10.1016/j.scienta.2020.109401

Escoba O, Hue NV (2007) Current developments in organic farming. Recent Res Dev Soilsci 2:29–62

Fatnassi IC et al (2015) Comptes Rendus Biologies impact of dual inoculation with rhizobium and PGPR on growth and antioxidant status of Vicia faba L. under copper stress. C R Biol 338:241–254

Fernando PC (2017) Pesticides, environment, and food safety. Food Energy Secur 6(2):48–60

FiBL & IFOAM (2016) The world of organic agriculture statistics & emerging trends. Research Institute of Organic Agriculture FiBL & IFOAM Organics International. https://shop.fibl.org

Flores-félix JD et al (2013) Use of rhizobium leguminosarum as a potential biofertilizer for Lactuca sativa and Daucus carota crops. J Plant Nutr Soil Sci 176(6):876–882. https://doi.org/10.1002/jpln.201300116

Foley JA et al (2011) Solutions for a cultivated planet. Nature 478:337–342

Food and Agriculture Organization of the United Nations (2013) Food wastage footprint: impacts on natural resources: summary reports. FAO, Rome

Food and Agriculture Organization of the United Nations (2015) How to feed the world in 2050. https://www.fao.org

Foyer CH, Nguyen H, Lam H-M (2019) Legumes—the art and science of environmentally sustainable agriculture. Plant Cell Environ 42:1–5

Francis CA (2013) Reference module in earth systems and environmental sciences, organic farming

Fukami J, Cerezini P, Hungria M (2018) Azospirillum: benefits that go far beyond biological nitrogen fixation. AMB Expr 8:73. https://doi.org/10.1186/s13568-018-0608-1

García-Fraile P, Menéndez E, Rivas R (2015) Role of bacterial biofertilizers in agriculture and forestry. 2(3):183–205. https://doi.org/10.3934/bioeng.2015.3.183
Garg A, Balodi R (2014) Recent trends in agriculture: vertical farming and organic farming. Adv Plants Agric Res 1(4):142–144
Garg N, Chandel S (2010) Arbuscular mycorrhizal networks: process and functions. A review. Agron Sustain Dev 30(3). https://doi.org/10.1051/agro/2009054. Springer Verlag/EDP Sciences/INRA. hal-00886481
Gopalakrishnan S, Sathya A, Vijayabharathi R, Varshney RK, Laxmipathi Gowda CL, Krishnamurthy L (2015) Plant growth promoting rhizobia: challenges and opportunities. Biotech 5:355–377. https://doi.org/10.1007/s13205-014-0241-x
Goswami D, Thakker JN, Dhandhukia PC (2016) Portraying mechanics of plant growth promoting rhizobacteria (PGPR): a review. Cogent Food Agric 2:1127500. https://doi.org/10.1080/23311932.2015.1127500. Soil and Crop Sciences, Review Article
Gupta G, Parihar SS, Ahirwar NK, Snehi SK, Singh V (2015) Plant growth promoting rhizobacteria (PGPR): current and future prospects for development of sustainable agriculture. J Microb Biochem Technol 7:2. https://doi.org/10.4172/1948-5948.1000188
Hashem A, Tabassum B, Abd_Allah EF (2019) Bacillus subtilis: a plant-growth promoting rhizobacterium that also impacts biotic stress. Saudi J Biol Sci 26:1291–1297
Hayat R, Ali S, Amara U, Khalid R, Ahmed I (2010) Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol 60(4):579–598. https://doi.org/10.1007/s13213-010-0117-1
Hole DG, Perkins AJ, Wilson JD, Alexander IH, Grice PV, Evans AD (2005) Does organic farming benefit biodiversity? Biol Conserv 122:113–130. https://doi.org/10.1016/j.biocon.2004.07.018
Hirsch PR, Mauchline TH, Clark IM (2013) Culture-independent molecular approaches to microbial ecology in soil and the rhizosphere. In: de Bruijn FJ (ed) Molecular microbial ecology of the rhizosphere, vol 1. Wiley Blackwell, Hoboken, NJ, pp 45–55. https://doi.org/10.1186/s13568-018-0608-1
Iqbal MA, Khalid M, Shahzad SM, Ahmad M, Soleman N, Akhtar N (2012) Integrated use of rhizobium leguminosarum, plant growth promoting Rhizobacteria and enriched compost for improving growth, nodulation and yield of lentil (Lens culinaris Medik.). Chil J Agric Res 72: 104–110
Jacoby R, Peukert M, Succurro A, Koprivova A, Kopriva S (2017) The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. Front Plant Sci 8:1617. https://doi.org/10.3389/fpls.2017.01617
Jakhar SR, Kumar S, Jangir CK, Meena RS (2017) The role of mycorrhizal relationship in sustainable manner towards plant growth and soil fertility. Indian J Agric Allied Sci 3(4):19–24
Jalota SK et al (2018) Understanding climate change impacts on crop productivity and water balance. Elsevier, Amsterdam
Jamal Q, Lee YS, Jeon HD, Kim KY (2018) Effect of plant growth-promoting bacteria Bacillus amyloliquefaciens Y1 on soil properties, pepper seedling growth, rhizosphere bacterial flora and soil enzymes. Plant Protect Sci 54:129–137
Javaid A (2011) Effects of biofertilizers combined with different soil amendments on potted rice plants. Chil J Agric Res 71(1):157–163
Jiménez-Gómez A, Celador-Lera L, Fradejas-Bayón M, Rivas R (2017) Plant probiotic bacteria enhance the quality of fruit and horticultural crops. AIMS Microbiol 3(3):483–501. https://doi.org/10.3934/microbiol.2017.3.483
Kawalekar JS (2013) Role of biofertilizers and biopesticides for sustainable agriculture. J Biol Innov 2(3):73–78
Kalayu G (2019) Phosphate solubilizing microorganisms: promising approach as biofertilizers. Hindawi Int J Agron 2019:4917256, 7 pages. https://doi.org/10.1155/2019/4917256
Katherine K, Hendrik W (2010) Environmental impacts of agricultural technologies. Evans School Policy Analysis & Research (EPAR). EPAR Brief No. 65

Katiyar D, Hemantaranjan A, Singh B (2015) Chitosan as a promising natural compound to enhance potential physiological responses in plant: a review. Indian J Plant Physiol 20(1):1–9

Kaur H, Kaur J, Gera R (2016) Plant growth promoting Rhizobacteria: a boon to agriculture. Int J Cell Sci Biotechnol 5:17–22

Kenneth OC, Nwadibe EC, Kalu AU, Unah UV (2019) Plant growth promoting rhizobacteria (PGPR): a novel agent for sustainable food production. Am J Agric Biol Sci 14:35–54. https://doi.org/10.3844/ajabssp.2019.35.54

Khalid A, Tahir S, Arshad M, Zahir ZA (2004) Relative efficiency of rhizobacteria for auxin biosynthesis in rhizosphere and non-rhizosphere soils. Aust J Soil Res 42:921–926. https://doi.org/10.1071/SR04019

Khan N, Bano AMD, Babar A (2020) Impacts of plant growth promoters and plant growth regulators on rainfed agriculture. PLoS One 15(4):e0231426. https://doi.org/10.1371/journal.pone.0231426

Khatoon Z, Huang S, Rafique M, Fakhar A, Kamran MA, Santoyo G (2020) Unlocking the potential of plant growth-promoting rhizobacteria on soil health and the sustainability of agricultural systems. J Environ Manag 273:111118

Kour D, Rana KL, Yadav AN, Yadav N, Kumar M, Kumar V, Vyas P, Dhaliwal HS, Saxena AK (2020) Microbial biofertilizers: bioresources and eco-friendly technologies for agricultural and environmental sustainability. Biocatal Agric Biotechnol 23:101487. https://doi.org/10.1016/j.bcab.2019.101487

Krey T, Vassilev N, Baum C, Eichler-Löbermann B (2013) Effects of long-term phosphorus application and plant-growth promoting rhizobacteria on maize phosphorus nutrition under field conditions. Eur J Soil Biol 55:124–130. https://doi.org/10.1016/j.ejsobi.2012.12.007

Kuan KB, Othman R, Abdul Rahim K, Shamsuddin ZH (2016) Plant growth-promoting rhizobacteria inoculation to enhance vegetative growth, nitrogen fixation and nitrogen remobilisation of maize under greenhouse conditions. PLoS One 11(3):e0152478. https://doi.org/10.1371/journal.pone.0152478

Kumar N, Audipudi V (2015) Exploration of a novel plant growth promoting bacteria Stenotrophomonas maltophilia AVP27 isolated from the chilli rhizosphere soil. Int J Eng Res Gen Sci 3(1):265–276

Kumar A et al (2019) Stenotrophomonas: a versatile diazotrophic bacteria from the rhizospheric soils of Western Himalayas and development of its liquid biofertilizer formulation. Vegetos 32 (1):103–109. https://doi.org/10.1007/s42535-019-00013-8

Lal R (2016) Climate change and agriculture, 2nd edn

Lehman RM, Cambardella CA, Stott DE, Acosta-Martinez V, Manter DK, Buyer JS, Maul J, Smith J, Collins H, Halvorson J, Kremer R, Lundgren J, Ducey TF, Jin VL, Karlen DL (2015) Understanding and enhancing soil biological health: the solution for reversing soil degradation. Sustainability 7:988–1027. https://doi.org/10.3390/su7010988

Lengai GMW, Muthomi JW (2018) Biopesticides and their role in sustainable agricultural production. J Biosci Med 6:7–41. https://doi.org/10.4236/jbm.2018.66002

Li H et al (2016) Stenotrophomonas maltophilia HW2 enhanced cucumber resistance against cucumber green mottle mosaic virus. J Plant Biol 59:488–495. https://doi.org/10.1007/s12374-016-0246-6

Li S, Peng M, Liu Z, Shah S (2017) The role of soil microbes in promoting plant growth. Mol Microbiol Res 7(4):30–37

Lim J, Kim S (2013) Induction of drought stress resistance by multi-functional PGPR bacillus licheniformis K11 in pepper. Plant Pathol J 29(2):201–208

Mabrouk Y, Belhadj O (2012) Enhancing the biological nitrogen fixation of leguminous crops grown under stressed environments. Afr J Biotechnol 11(48):10809–10815. https://doi.org/10.5897/AJB10.2170

Mäder P et al (2002) Soil fertility and biodiversity in organic farming. Science 296:1694–1697

Mahmood A, Turgay OC, Farooq M, Hayat R (2016) Seed biopriming with plant growth promoting rhizobacteria: a review. FEMS Microbiol Ecol 92(8):fiw112

Malviya MK, Sharma A, Pandey A, Rinu K, Sati P, Palni LMS (2012) Bacillus subtilis NRRL B-30408: a potential inoculant for crops grown under rainfed conditions in the mountains. J Soil Sci Plant Nutr 12(4):811–824
Martínez OA, Encina C, Tomckowiack C, Droppelmann F, Jara R, Maldonado C, Muñoz O, García-Fraile P, Rivas R (2018) Serratia strains isolated from the rhizosphere of raulí (Nothofagus alpina) in volcanic soils harbour PGPR mechanisms and promote raulí plantlet growth. J Soil Sci Plant Nutr 18:804–819
Masciandaro G, Macci C, Peruzzi E, Ceccanti B, Doni S (2013) Organic matter-microorganism-plant in soil bioremediation: a synergic approach. Rev Environ Sci Biotechnol 12(4):399–419. https://doi.org/10.1007/s11157-013-9313-3
Medina A, Azcón R (2010) Effectiveness of the application of arbuscular mycorrhiza fungi and organic amendments to improve soil quality and plant performance under stress conditions. J Soil Sci Plant Nutr 10:354–372
Meena KK, Sorty AM, Bitla UM, Choudhary K, Gupta P, Pareek A et al (2017) Abiotic stress responses and microbe-mediated mitigation in plants: the omics strategies. Front Plant Sci 8: 172. https://doi.org/10.3389/fpls.2017.00172
Mehnaz S, Weselowski B, Lazarovits G (2007) Azospirillum canadense sp. nov., a nitrogen-fixing bacterium isolated from corn rhizosphere. Int J Syst Evol Microbiol 57:620–624
Meier MS et al (2015) Environmental impacts of organic and conventional agricultural products–are the differences captured by life cycle assessment? J Environ Manag 149:193–208
Metin T, Melek E, Ertan Y, Adem G, Kenan K, Recep K, Dursun A (2014) Plant growth-promoting rhizobacteria improved growth, nutrient, and hormone content of cabbage (Brassica oleracea) seedlings. Turk J Agric For 38:327–333. https://doi.org/10.3906/tar-1308-62. © TÜBİTAK
Mirza MS et al (2006) Molecular characterization and PCR detection of a nitrogen-fixing Pseudomonas strain promoting rice growth. Biol Fertil Soils 43(2):163–170. https://doi.org/10.1007/s00374-006-0074-9
Mishra VK (2018) Plant growth promoting rhizobacteria (PGPR) mediated temperature, drought and pesticide stress tolerance of crop plants through multidisciplinary approach. Am J Res Commun 6(3):1–9
Mishra P, Dash D (2014) Rejuvenation of biofertilizer for sustainable agriculture and economic development. Cons J Sustain Dev 11(1):41–61
Mondelaers K, Aertsens J, Van Huylenbroeck G (2009) A meta-analysis of the differences in environmental impacts between organic and conventional farming. Br Food J 111:1098–1119. https://doi.org/10.1108/00070700910992925
Muller A, Schader C, Scialabba NE, Brüggemann J, Isensee A, Erb K, Smith P, Klocke P, Leiber F, Tolze MS, Niggli U (2017) Strategies for feeding the world more sustainably with organic agriculture. Nat Commun 8:1290. https://doi.org/10.1038/s41467-017-01410-w
Naveed M, Mehboob I, Hussain MB, Zahir ZA (2015) Perspectives of rhizobial inoculation for sustainable crop production. In: Plant microbes symbiosis: applied facets. Springer, India, pp 209–239. https://doi.org/10.1007/978-81-322-2068-8_11
Nehra V, Choudhary M (2015) A review on plant growth promoting rhizobacteria acting as bioinoculants and their biological approach towards the production of sustainable agriculture. J Appl Nat Sci 7(1):540–556
Nielsen KM (2019) Organic farming. In: Encyclopedia of ecology (second edition). Elsevier, Amsterdam
Noumavo PA, Agbodjato NA, Baba-Moussa F, Adjanohoun A, Baba-Moussa L (2016) Plant growth promoting rhizobacteria: beneficial effects for healthy and sustainable agriculture. Afr J Biotechnol 15(27):1452–1463. https://doi.org/10.5897/AJB2016.15397
Nunes J, Araujola SF, Nunesal M, Carneiroaa A, Tsaib M (2012) Impact of land degradation on soil microbial biomass and activity in northeast Brazil. Pedosphere 22(1):88–95
Ojo OI, Olajire-Ajayi BL, Dada OV, Wahab OM (2015) Effects of fertilizers on soil's microbial growth and populations: a review. Am J Eng Res 4(7):52–61

Onder M, Ceyhan E, Kahraman A (2011) Effects of agricultural practices on environment. international conference on biology. In: International conference on biology, environment and chemistry, vol 24. IPCBEE, pp 28–32. http://ipcbee.com/vol24/6-ICBEC2011-C00015
Orhan E, Esitken A, Ercisli S, Turan M, Sahin F (2006) Effects of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient contents in organically growing raspberry. Sci Hortic 111:38–43
Oruru MB, Njeru EM (2016) Upscaling arbuscular mycorrhizal symbiosis and related agroecosystems services in smallholder farming systems. Hindawi Publishing Corporation BioMed Res Int 2016:4376240, 12 pages. https://doi.org/10.1155/2016/4376240
Osman NI, Yin S (2018) Isolation and characterization of pea plant (Pisum sativum L.) growth-promoting rhizobacteria. Afr J Microbiol Res 12(34):820–828. https://doi.org/10.5897/AJMR2018.8859
Otutumi AT, Oliveira TS, Mendoça ES, Lima JBF (2004) Qualidade do solo em sistemas de cultivo agroecológicos no município de Tauá-CE. In: Oliveira TS et al (eds) Solo e água: aspectos de uso e manejo com ênfase no semi-árido nordestino. Departamento de ciências do solo, UFC, Fortaleza, CE, ix, 31 pp
Owens K, Feldman J, Kepner J (2010) Wide range of diseases linked to pesticides. Pestic You 30: 13–21
Pahari A, Pradhan A, Priyadarshini S, Nayak SK, Mishra BB (2017) Isolation and characterization of plant growth promoting rhizobacteria from coastal region and their effect on different vegetables. Int J Sci Environ Technol 6(5):3002–3010
Patel T, Saraf M (2017) Exploration of novel plant growth promoting bacteria stenotrophomonas maltophilia MTP42 isolated from the rhizospheric soil of Coleus forskohlii. Int J Curr Microbiol App Sci 6(11):944–955
Patel R, Rathor G, Bhargav BH, Singh K, Bharti D (2017) Study and effect of rhizobium bacteria and culture suspension isolated from root nodules at Nimad area. Pharma Innov J 6(9):368–371
Paul D, Lade H (2014) Plant-growth-promoting rhizobacteria to improve crop growth in saline soils: a review. Agron Sustain Dev 34(4):737–752. https://doi.org/10.1007/s13593-014-0233-6. Springer Verlag/EDP Sciences/INRA. hal-01234840
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
Pereyra MA, González RL, Creus CM, Barassi CA (2007) Root colonization vs. seedling growth, in two Azospirillum-inoculated wheat species. Cereal Res Commun 35:1621–1629
Perez-Montano F, Alias-Villegas C, Bellogin RA, del Cerro P, Espuny MR, Jimenez-Guerrero I et al (2014) Plant growth promotion in cereal and leguminous agricultural important plants: from microorganism capacities to crop production. Microbiol Res 169:325–336. https://doi.org/10.1016/j.micres.2013.09.011
Poonia S (2011) Rhizobium: a natural biofertilizer. Int J Eng Manag Res 1(1):36–38. ISSN No.: 2250-0758
Probanza A et al (2002) Pinus pinea L. seedling growth and bacterial rhizosphere structure after inoculation with PGPR Bacillus (B. licheniformis CECT 5106 and B. pumilus CECT 5105). Appl Soil Ecol 20:75–84
Qessaoui R, Bouharroud R, Furze JN, El Aalaoui M, Akroud H, Amarraque A, VanVaerenbergh J, Tahzima R, Mayad EH, Chebli B (2019) Applications of new rhizobacteria pseudomonas isolates in agroecology via fundamental processes complementing plant growth. Sci Rep 9: 12832. https://doi.org/10.1038/s41598-019-49216-8
Raaijmakers JM, Mazzola M (2012) Diversity and natural functions of antibiotics produced by beneficial and plant pathogenic bacteria. Annu Rev Phytopathol 50:403–424
Radhakrishnan R, Hashem A, Abd_Allah EF (2017) Bacillus: a biological tool for crop improvement through bio-molecular changes in adverse environments. Front Physiol 8:667. https://doi.org/10.3389/fphys.2017.00667

Rafiquea M, Sultanc T, Ortasb I, Chaudharya HJ (2017) Enhancement of maize plant growth with inoculation of phosphate-solubilizing bacteria and biochar amendment in soil. Soil Sci Plant Nutr 63(5):460–469. https://doi.org/10.1080/00380768.2017.1373599
Raimi A, Adeleke R, Roopnarain A (2017) Soil fertility challenges and biofertiliser as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. Cogent Food Agric 3:1400933. https://doi.org/10.1080/23311932.2017.1400933
Ramprasad D, Debasish SD, Bhattar SB (2014) Plant growth promoting Rhizobacteria – an overview. Eur J Biotechnol Biosci 2(2):30–34
Raupach GS, Liu L, Murphy JF, Tuzun S, Kloepper JW (1996) Induced systemic resistance in cucumber and tomato against cucumber mosaic virus using plant growth-promoting rhizobacteria. Plant Dis 80:891–894
Reganold JP, Wachter JM (2016) Organic agriculture in the twenty-first century. Nat Plants 2:1–8
Riggs PJ, Chelius MK, Iniguez AL, Kaeppler SM, Triplett EW (2001) Enhanced maize productivity by inoculation with diazotrophic bacteria. Funct Plant Biol 28:829–836. https://doi.org/10.1071/PP01045
Romero-Perdomo F, Ocampo-Gallego J, Camelo-Rusinque M, Bonilla R (2019) Plant growth promoting rhizobacteria and their potential as bioinoculants on Pennisetum clandestinum (Poaceae). Rev Biol Trop 67(4):825–832
Sachidanand B, Mitra N, Kumar V, Roy R, Mishra B (2019) Soil as a huge laboratory for microorganisms. Agric Res Tech Open Access J 22(4):ARTOAJ.MS.ID.556205
Sahu PK, Gupta A, Sharma L, Bakade R (2017) Mechanisms of Azospirillum in plant growth promotion. Sch J Agric Vet Sci 4(9):338–343
Saikia SP, Dutta SP, Goswami A, Bhau BS, Kanjilal PB (2010) Chapter 16: Role of Azospirillum in the improvement of legumes. In: Microbes for legume improvement. Springer-Verlag, Wien, pp 389–408. https://doi.org/10.1007/978-3-211-99753-6_16
Sangkumchaliang P, Huang WC (2012) Consumers' perceptions and attitudes of organic food products in northern Thailand. Int Food Agribus Manag Rev 15:87–102
Sathya A, Vijayabharathi R, Gopalakrishnan S (2016) Soil microbes: the invisible managers of soil fertility. In: Singh DP et al (eds) Microbial inoculants in sustainable agricultural productivity. Springer, New Delhi, pp 1–16. https://doi.org/10.1007/978-81-322-2644-4_1
Schader C, Stolze M, Gattinger A (2012) Environmental performance of organic farming. In: Boye JI, Arcand Y (eds) Green technologies in food production and processing. Springer, New York, pp 183–210
Seneviratne G, Jayakody K, Weerasekara M, Someya T, Ryuda N (2011) Microbial biofertilizer application versus compost use in agriculture: soil health implications. In: Miransari M (ed) Soil microbes and environmental health. Nova Science Publishers, pp 81–117
Seufert V, Ramankutty N, Foley JA (2012) Comparing the yields of organic and conventional agriculture. Nature 485:229–232
Sharma N, Singhvi R (2017) Effects of chemical fertilizers and pesticides on human health and environment: a review. Int J Agric Environ Biotechnol 10(6):675–679
Sharma K, Sharma S, Rajendra Prasad S (2019) PGPR: renewable tool for sustainable agriculture. Int J Curr Microbiol App Sci 8(1):525–530
Singh I (2018) Plant growth promoting rhizobacteria (PGPR) and their various mechanisms for plant growth enhancement in stressful conditions: a review. Eur J Biol Res 8(4):191–213. https://doi.org/10.5281/zenodo.1455995
Singh A, Vaish B, Singh RP (2016) Eco-restoration of degraded lands through microbial biomass: an ecological engineer. Acta Biomedica Scientia 3(1):133–135
Sinha RK, Valani D, Chauhan K, Agarwal S (2014) Embarking on a second green revolution for sustainable agriculture by vermiculture biotechnology using earthworms: reviving the dreams of Sir Charles Darwin. Int J Agric Health Saf 1:50–64
Skoufogianni E, Solomou A, Molla A, Martinos K (2015) Organic farming as an essential tool of the multifunctional agriculture. IntechOpen, London. https://doi.org/10.5772/61630

Smith LG, Kirk GJD, Jones PJ et al (2019) The greenhouse gas impacts of converting food production in England and Wales to organic methods. Nat Commun 10:4641. https://doi.org/10.1038/s41467-019-12622-7

Smith DL, Praslickova D, Ilangumaran G (2015) Inter-organismal signaling and management of the phytomicrobiome. Front Plant Sci 6:722. https://doi.org/10.3389/fpls.2015.00722

Srivastava R, Singh A (2017) Plant growth promoting rhizobacteria (PGPR) for sustainable agriculture. Int J Agric Sci Res (IJASR) 7(4):505–510. ISSN (P): 2250-0057; ISSN (E): 2321-0087

Steffen RB, Steffen GPK, Saldanha CW (2020) Importance of mycorrhization under heat stress conditions: technological tools to stimulate mycorrhizal colonization. J Agric Environ Sci 9 (1):8–14. https://doi.org/10.15640/jaes.v9n1a2

Surendirakumar K, Pandey RR, Muthukumar T (2019) Influence of indigenous arbuscular mycorrhizal fungus and bacterial bioinoculants on growth and yield of Capsicum chinense cultivated in non-sterilized soil. J Agric Sci 157(1):31–44. https://doi.org/10.1017/S0021859619000261

Tahat MM, Alananbeh KM, Othman YA, Leskovar DI (2020) Soil health and sustainable agriculture. Sustainability 12:4859. https://doi.org/10.3390/su12124859

Tan KZ, Radziah O, Halimi MS, Khairuddin AR, Shamsuddin ZH (2015) Assessment of plant growth-promoting rhizobacteria (PGPR) and rhizobia as multi-strain biofertilizer on growth and N2 fixation of rice plant. AJCS 9(12):1257–1264

Tiwari S, Chauhan RK, Singh R, Shukla R, Gaur R (2017) Integrated effect of rhizobium and azotobacter cultures on the leguminous crop black gram (Vigna mungo). Adv Crop Sci Tech 5 (3):1–9. https://doi.org/10.4172/2329-8863.1000289

Tsvetkov I, Atanassov A, Vlahova M, Carlier L, Christov N, Lefort F, Rusanov K, Badjakov I, Dincheva I, Tchamitchian M, Rakleova G (2018) Plant organic farming research–current status and opportunities for future development. Biotechnol Biotechnol Equip 32(2):241–260

Tuhuteru S, Sulistyaningsih E, Wibowo A (2016) Effects of plant growth promoting rhizobacteria (PGPR) on growth and yield of shallot in Sandy coastal land. Ilmu Pertanian (Agric Sci) 1 (3):105–110. Available online at http://journal.ugm.ac.id/jip.doi.org/10.22146/ipas.16349

Tuomisto H, Hodge I, Riordan P, Macdonald D (2012) Does organic farming reduce environmental impacts?–a meta-analysis of European research. J Environ Manag 112:309–320

Ulm F, Avelar D, Hobson P, Penha-Lopes G, Dias T, Maguas C, Cruz C (2019) Sustainable urban agriculture using compost and an open-pollinated maize variety. J Clean Prod 212:622–629

United Nations (2015) Population pyramids of the world from 1950 to 2100. World population prospects. https://un.org

Vejan P, Abdullah R, Khadiran T, Ismail S, Boyce AN (2016) Role of plant growth promoting rhizobacteria in agricultural sustainability—a review. Molecules 21:573. https://doi.org/10.3390/molecules21050573

Vessey JK (2003) Plant growth promoting rhizobacteria as biofertilizers. Plant Soil 255:571–586. https://doi.org/10.1023/A:1026037216893

Villarreal-Delgado MF, Villa-Rodríguez ED, CiraChávez LA, Estrada-Alvarado MI, Parra-Cota FI, De los Santos-Villalobos S (2017) The genus Bacillus as a biological control agent and its implications in the agricultural biosecurity. Rev Mex Fitopatol 36(1):95–130. https://doi.org/10.18781/R.MEX.FIT.1706-5

Yadav N, Yadav AN (2019) Actinobacteria for sustainable agriculture. J Appl Biotechnol Bioeng 6 (1):38–41

Yadav AN, Verma P, Singh B, Chauahan VS, Suman A, Saxena AK (2017) Plant growth promoting bacteria: biodiversity and multifunctional attributes for sustainable agriculture. Adv Biotechnol Microbiol 5(5):AIBM.MS.ID.555671. https://doi.org/10.19080/AIBM.2017.05.5556671

Yadegari M, Rahmani HA (2010) Evaluation of bean (Phaseolus vulgaris) seeds' inoculation with rhizobium phaseoli and plant growth promoting rhizobacteria (PGPR) on yield and yield components. Afr J Agric Res 5(9):792–799

Yanakittkul P, Aungvaravong C (2019) Proposed conceptual framework for studying the organic farmer behaviors. Kasetsart J Soc Sci 40:491–498

Yanakittkul P, Aungvaravong C (2020) A model of farmers intentions towards organic farming: a case study on rice farming in Thailand. Heliyon 6(2020):e03039

Yu H, Ling N, Wang T, Zhu C, Wang Y, Wang S et al (2019) Responses of soil biological traits and bacterial communities to nitrogen fertilization mediate maize yields across three soil types. Soil Till Res 185:61–69. https://doi.org/10.1016/j.still.2018.08.017

Zeffa DM, Perini LJ, Silva MB, de Sousa NV, Scapim CA, Oliveira ALM et al (2019) Azospirillum brasilense promotes increases in growth and nitrogen use efficiency of maize genotypes. PLoS One 14(4):e0215332. https://doi.org/10.1371/journal.pone.0215332

Zerihun T, Birhanu G, Genene T, Adey F, Solomon C, Tesfaye A, Fasil A (2019) Isolation and biochemical characterization of plant growth promoting (PGP) bacteria colonizing the rhizosphere of Tef crop during the seedling stage. Biomed J Sci Tech Res 14(2):MS.ID.002534

Zuluaga MYA, Lima Milani KM, Azeredo Gonçalves LS, Martinez de Oliveira AL (2020) Diversity and plant growth-promoting functions of diazotrophic/N-scavenging bacteria isolated from the soils and rhizospheres of two species of Solanum. PLoS One 15(1):e0227422. https://doi.org/10.1371/journal.pone.0227422