

Microbial impact on climate-smart agricultural practices

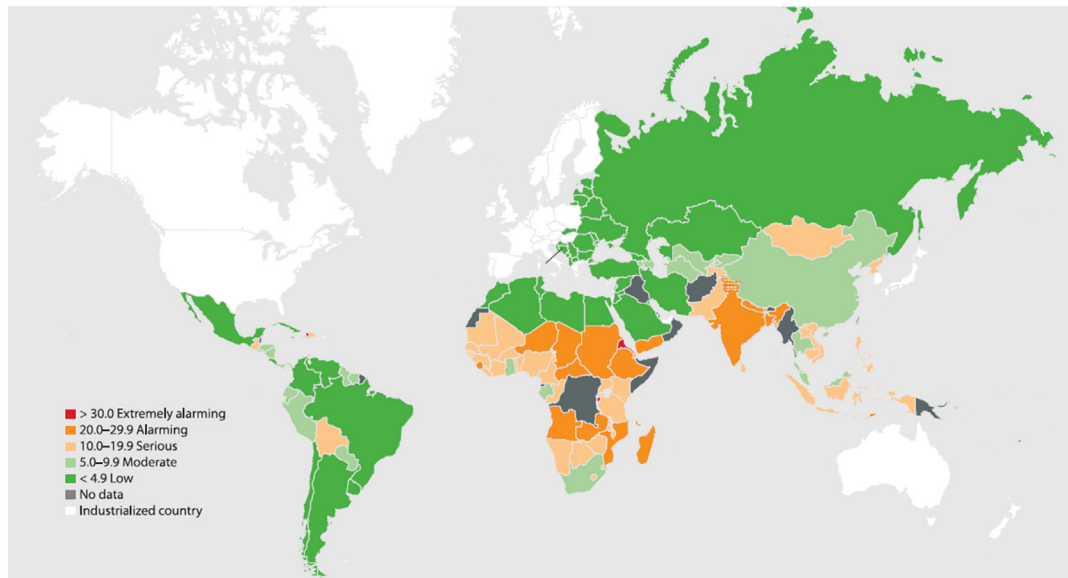
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9.1 Introduction

Climate change is expected to impact and shape the future of food production and agricultural systems across the world. This impact will be intense in most especially in economically underdeveloped countries due to rising climate uncertainties and risks projection difficulties in predicting the precise impact of climate change on agriculture in these regions (De Pinto, Cenacchi, Kwon, Koo, & Dunston, 2020). Over the past few decades, increasing temperatures have reduced crop yield (Lobell, Schlenker, & Costa-Roberts, 2011) and in the tropical and midlatitude countries, the results of modeling studies have predicted that climate change will further decrease the potentials of crop yield (Knox, Hess, Daccache, & Wheeler, 2012; Rosenzweig et al., 2014). Increasing atmospheric carbon dioxide (CO₂) is expected to threaten human nutrition causing deficiencies in macro- and micronutrients in food crops (Myers et al., 2014). Studies have also shown decreased concentrations of zinc, iron, and protein in grains of wheat, barley, rice soybean, sorghum, and grasses grown under elevated atmospheric CO₂ concentrations (Maurya et al., 2020; Soba et al., 2020; Tausz-Posch, Tausz, & Bourgault, 2020). Climate change is likely to impact global food security target, especially for the poor who may be affected by the prices of stable food (Wheeler & Von Braun, 2013). Currently, 20% of the world's population are food-insecure and majority of these population are found in developing regions (sub-Saharan Africa and South Asia) where additional population growth of 2.4 billion is projected by 2050 (Lipper et al., 2014). Countries in these regions are ranked in the most extreme “alarming” category of the Global Hunger Index (Fig. 9.1), and globally the projections that climate change will impact agricultural productivity are real (Alexandratos & Bruinsma, 2012).

**FIGURE 9.1**

Global distribution of hunger as quantified by the 2012 Global Hunger Index. The Welthungerhilfe, IFPRI, and Concern Worldwide Hunger map 2012 calculated a Global Hunger Index for 120 countries by using the proportion of people who are undernourished, the proportion of children under 5 who are underweight, and the mortality rate of children younger than age 5, weighted equally. [Reproduced with permission from Welthungerhilfe, IFPRI, and Concern Worldwide (von Grebmer et al., 2012)].

Adapted from von Grebmer, K., Ringler, C., Rosegrant, M.W., Olofinbiyi, T., Wiesmann, D., Fritschel, H., Badiane, O., Torero, M., Yohannes, Y., Thompson, J., von Oppeln, C., Rahall, J. 2012. *Global Hunger Index: The Challenge of Hunger: Ensuring Sustainable Food Security Under Land, Water, and Energy Stresses* (Welthungerhilfe, IFPRI, Concern Worldwide, 2012); www.ifpri.org/publication/2012-global-hunger-index-0. <http://dx.doi.org/10.2499/9780896298101>.

According to the Food and Agriculture Organization of the United Nations (FAO), agriculture is also the world's second largest emitters of greenhouse gases (GHGs) (FAO, 2016). This is largely due to the use of fossil fuel-based fertilizers, agricultural machinery, biomass burning, enteric fermentation, and animal husbandry (Liu, Zhang, & Bae, 2017). Biomass fires contribute to the interannual variability and rising of CO₂, methane (CH₄), and nitrous oxide (N₂O) and other trace gases in the atmosphere (Smith, Bustamante et al., 2014). Over the last decade, peat and forest fires have contributed 300 million tCO₂eq year⁻¹ of the anthropogenic emissions of non-CO₂ gases (Smith, Bustamante et al., 2014) and with savanna burning added 200 million tCO₂eq year⁻¹ (Tubiello et al., 2013). Deforestation associated with slash and burn practices have also contributed directly CO₂ emission of over 1.5 billion tCO₂eq year⁻¹ (Smith, Bustamante et al., 2014). Many researchers have also studied the carbon abatement in others sectors including transportation (Baloch & Suad, 2018; Li, Zhao, & Brand, 2018), building (Ma, Yan, & Cai, 2017), and tourism (Ben & Hadhri, 2018). On the other hand, agriculture contributes significantly to the storing CO₂, improve the overall ecosystem functions and services such as controlling rainfall runoff and soil

erosion, carbon sequestration even below the plow layer, and increasing water infiltration (Kay et al., 2019). Given that agriculture and climate change have multiple interrelated risks and uncertainties, it is in this scenario that the concept of climate-smart agriculture (CSA) emerged in 2009 (FAO, 2010) to increase food productivity and mitigate climate risks.

Microorganisms are one of the most important components of an ecosystem and virtually perform crucial functions in most of the agroecosystem services and operations. Ajibade, Adelodun, Lasisi et al. (2021) defined microorganisms as unicellular organisms that are categorized into four main groups such as bacteria, algae, protist, and fungi. Their abundance and activities can have a ripple effect on the fertility, productivity, and sustainability of a cropland, prevention of nutrient depletions, minimize GHG emissions, and the degradation of soil water and other essential resources (Wagg, Bender, Widmer, & van der Heijden, 2014). It is important to note that changes in the environment affects microbial processes and services. Hence, the main objective of this study is to review and compile the state of art in the knowledge of microbial impact on CSA, with special emphasis on the experimental data that prove or suggest the impact of soil microorganism on climate change adaptation, GHG mitigation, and nutrient cycling to improve food productivity.

9.2 Climate-smart agriculture: definition and concept

The term “climate-smart agriculture (CSA)” was first coined in 2009 and according to the FAO definition, it is a kind of new agricultural practice for increasing productivity, enhancing climate resilience and reducing GHGs emissions to increase food productivity for the world’s growing population under climate change (FAO, 2010). The International Fund for Agricultural Development (IFAD) defined CSA as a multiple-benefit approach for addressing climate change uncertainties on agriculture (IFAD, 2012). The World Bank also defined CSA as a holistic approach for developing sustainable and inclusive food value chains for climate-smart landscapes (World Bank, 2013). Lipper et al. (2014) presented CSA as a set of strategies for avoiding the “lose-lose” results in sustainable agriculture by the inclusion of climate adaptation and mitigation approaches to food production (Fig. 9.2). Therefore the coexistence and cooperation between food production, climate mitigation, and climate adaptation as foundational backbone towards achieving sustainable and equitable transitions in agricultural systems and livelihoods across different scales is contained as CSA. The CSA has a broad goal of achieving the “triple win” aims known as its objectives, namely (1) increasing agricultural productivity (food security), (2) building resilience to climate change (adaptation), and (3) reducing GHG emission from agriculture (mitigation) (FAO, 2010; Lipper et al., 2014), and with examples presented in Table 9.1. These objectives (pillars) of CSA are briefly enumerated in the following sections.

9.2.1 Food security

Food security is constantly linked to nutrition, and according to the FAO (FAO, 2001), it is defined as an event when all people at all times have physical, social, and economic access to adequate, safe, and nutritious food to meet their nutritional needs and desire for productive and healthy life. The phrase “all people at all time” stresses the need for food security. Considering the present food system, the FAO predicted an increase in global food productivity (50%) by 2050 to meet the

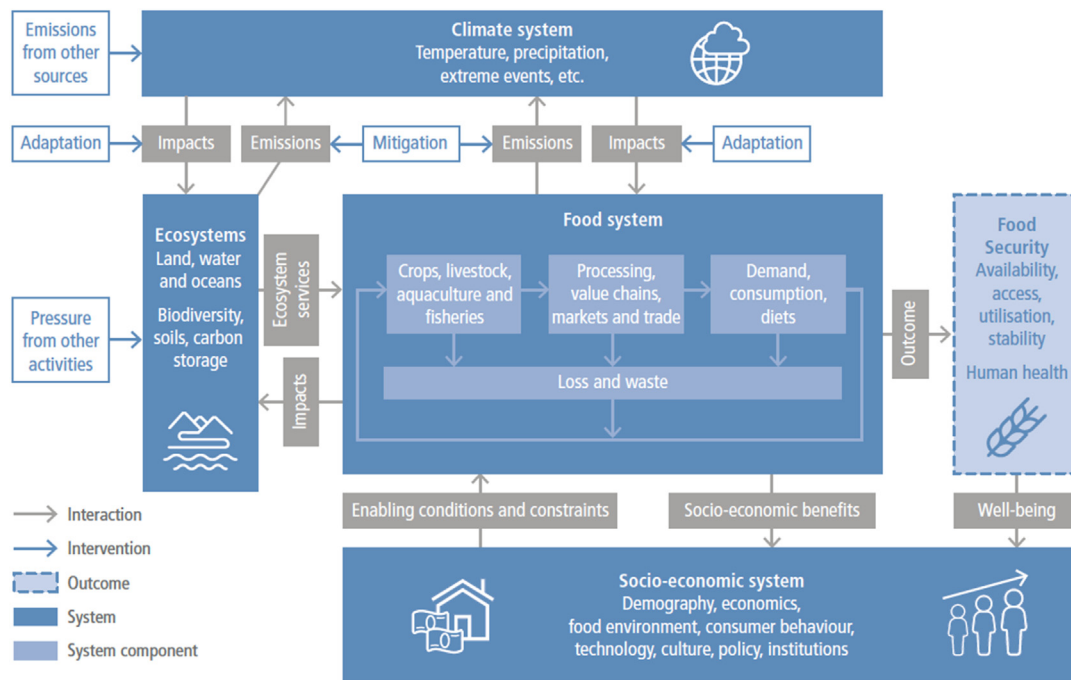
**FIGURE 9.2**

Diagram showing the interlinkages between climate variability, food systems, environment and socio-economic. This framework cut across all scales from local to regional and global levels. As such achieving food security in food system foster human sound health and somehow impact climate system and ecosystem which is largely driven by socio-economic system. Reducing GHG emissions in food systems can be achieved through mitigation approaches while adaption provides means to resilience against climate change.

Adapted from Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, Y. Xu, 2019: Food Security. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley, (eds.) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In press. https://www.ipcc.ch/site/assets/uploads/2019/11/08_Chapter-5.pdf.

worldwide demand (FAO, 2018). However, climate change is expected to negatively affect the food security by reducing food availability, accessibility, utility, and stability (FAO, IFAD, UNICEF, WFP, & WHO, 2018).

9.2.2 Adaptation

With the current food system, several climate risks can occur, cooccur, or reinforce each other, hence the need for adaptation in the system is necessary. Adaptation could be seen as the increasing

Table 9.1 Examples of climate-smart agricultural practices that offers productivity, adaptation, and/or mitigation benefits at farm level.

CSA practices	Description	Farm system	Region	Benefit	Reference
No tillage, zero tillage, or direct seeding	An agricultural practice where crops are established with minimal or no soil disturbance coupled with residue mulch retention and rational use of crop rotations	Rice—wheat systems	South Asia	It typically saves energy (e.g., tractor fuel, animal tillage, human labor), stop or revert soil and land degradation (soil organic matter decline, soil structural breakdown, soil erosion) and lead to more efficient use of water and other inputs	Erenstein and Laxmi (2008) , Erenstein, Sayre, Wall, Hellin, and Dixon (2012) , Hobbs, Sayre, and Gupta (2008) , Pittelkow et al. (2015) , Powlson et al. (2014)
Integrated soil fertility management	It involves the combined application of mineral and organic nutrient sources such as animal manures, household composts, crop residues, leguminous cover crops, to leguminous and nonleguminous trees and shrubs as major nutrient sources to crops	Maize-based systems	Sub-Saharan Africa	General increase in crop yields and soil organic carbon	Agegnehu, Vanbeek, and Bird (2014) , Chivenge, Vanlauwe, and Six (2011) , Gentile, Vanlauwe, Chivenge, and Six (2008) , Vanlauwe et al. (2011)
Alternate wetting and drying irrigation approach	An irrigation technique where water is applied to the field a number of days after disappearance of ponded water	Rice cropping systems	South Asia	It saves irrigation water without any significant effect on crop yield	Devkota et al. (2013) , Huda et al. (2016) , Pandey et al. (2014) , Rejesus, Palis, Rodriguez, Lampayan, and Bouman (2011) , Tyagi, Kumari, and Singh (2010)
Urea deep placement technology	An approach used in increasing nitrogen use efficiency by reducing ammonia volatilization, surface runoff, and increasing nitrogen uptake	Rice cropping systems	South Asia/ sub-Saharan Africa	It increases crop yields and reduction in the use of chemical fertilizer and GHG emissions	Bandaogo et al. (2015) , Gaihre et al. (2015) , Huda et al. (2016)

production of food where demanded, regulating this demand, minimizing food wastage while formulating policies to reduce damages, minimize threats, share losses in the global process of food production to create a more resilient environment for all people amidst extreme weather events (Godfray & Garnett, 2014; USAID, 2017).

9.2.3 Mitigation

The CSA presents reducing GHG emissions in the present food system. The need for mitigation in current agricultural food production system has been identified as crucial to reducing future climate change and as an important necessity to meeting the 2°C target of the Paris Agreement (Wollenberg et al., 2016). Therefore CSA focuses on the integration of mitigation approaches in the entire food ecosystem, particularly in the food supply and demand chains to attain the global mitigation ambition (Mbow et al., 2019).

9.3 Sources of climate impacting gases

9.3.1 Methane

CH₄ is produced from the organic decomposition of material in the absence or limited supply of oxygen. It is an important GHG, making up 16% of GHG emissions (Aydin, 2008; Aydin, Karakurt, & Aydiner, 2010). Recently the concentration of CH₄ has doubled in the atmosphere despite being in a stable concentration for many years (Aksay, Ketenoğlu, & Kurt, 2005). Compared to CO₂, the changing rate of CH₄ is lesser, however, its global warming potential is as much as CO₂ (Aksay et al., 2005; Kruger & Franklin, 2006). CH₄ is released from natural and anthropogenic sources. Natural sources contribute about 40% of the global CH₄ emissions, whereas anthropogenic sources released 60% of the global CH₄ emission (Karakurt, Aydin, & Aydiner, 2012). Anthropogenic sources of CH₄ are grouped according to sectoral bases in Table 9.2.

Table 9.2 Anthropogenic sources of greenhouse gases (methane, carbon dioxide, and nitrous oxide).

Sources			
Energy	Industry	Agriculture	Waste
- Coal mining activities - Oil and natural gas activities - Stationary and mobile combustion - Biomass burning	- Chemical production - Iron and steel production - Metal production - Mineral products - Petrochemical production - Silicon carbide production	- Manure management - Enteric fermentation - Rice cultivation - Other	- Landfilling of solid waste - Wastewater - Waste combustion - Use of solvent and other products

9.3.2 Carbon dioxide

Climate change is one of the major environmental threats facing humanity. CO₂ is considered as one of the main GHGs. There are both natural and anthropogenic sources of CO₂. Natural sources are respiration, ocean release, and decomposition, whereas anthropogenic sources are shown in Table 9.2.

9.3.3 Nitrous oxide

Globally, between 40% and 50% of the approximately 16 Tg N₂O-N year⁻¹ emitted in 1990s is attributed to human activities. Since then, expansion in agriculture land area and increase in fertilizer application has resulted in the growth of N₂O concentration (Solomon, Manning, Marquis, & Qin, 2007). Currently, the major anthropogenic sources of N₂O emission are agriculture, biomass combustion, industry, and reactive nitrogen from indirect emission via leaching, runoff, and atmospheric deposition (Galloway et al., 2004). Compared to other sources of emission, agricultural soil emission will dominate due to the widespread application of nitrogenous fertilizers and increasing use of manure coped with population growth (Reay et al., 2012).

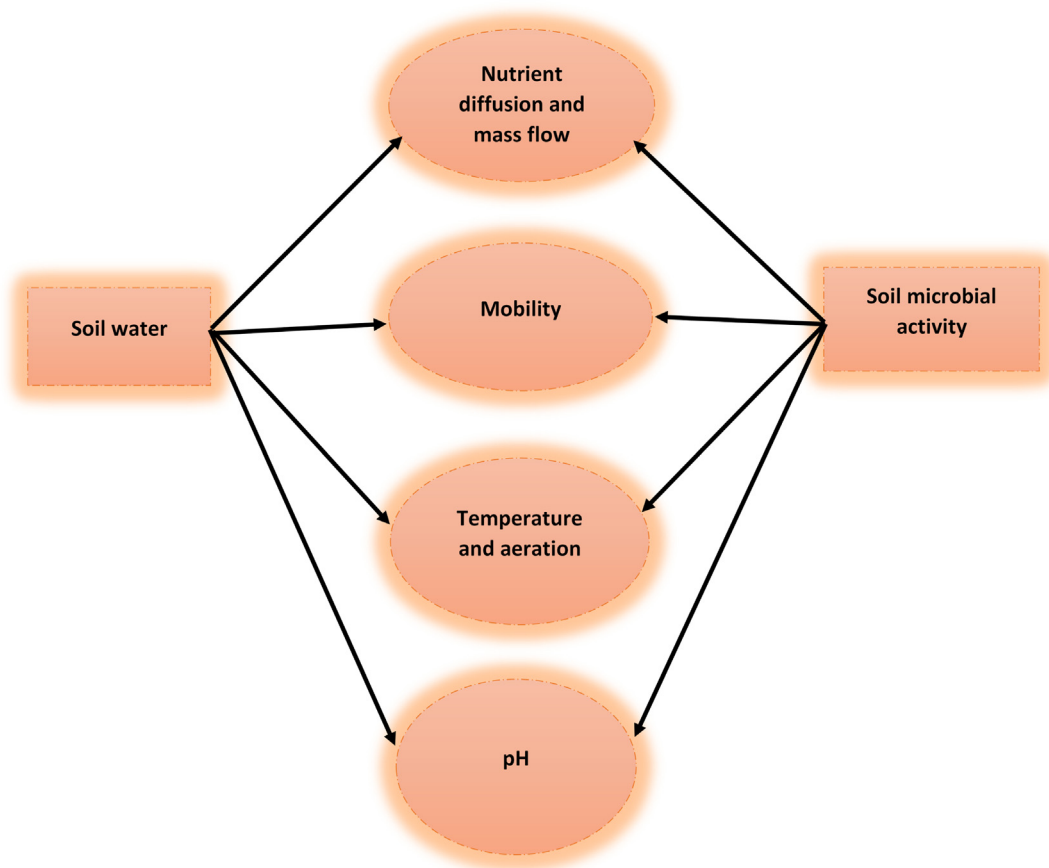
9.4 Soil agroecosystem and microbial communities as engines of ecosystem function

Soils represent a highly diverse and an essential part of the planet ecosystem (Ajibade, Adelodun, Ajibade et al., 2021). One gram of soil is estimated to contain nearly one billion bacterial cells, 200 million fungal hyphae, and a numerous quantity of mites, arthropods, nematodes, and earthworms (Bardgett, 2005; Roesch et al., 2007). Since, most of the agroecosystem biodiversity are found in the soil (Graham et al., 2016; Young & Crawford, 2004), the relationships between these microbial communities and ecosystem services have been established (Wagg et al., 2014; Zavaleta, Pasari, Hulvey, & Tilman, 2010) and microbial data have been used in improving carbon and nitrogen cycling predictions, crop yield and quality, and soil productivity (Powell, Welsh, & Hallin, 2015; Reed, Algar, Huber, & Dick, 2014).

9.4.1 Soil properties impact on microbial diversity and services

9.4.1.1 Soil water

Understanding the presence and movement of water in soil is one the most important characteristics of soil as a habitat for diverse microbial life. Soil water potential is the key measure of the activity (matric, osmotic, and pressure potentials) of water in the soil (Smith & Mullins, 2000). Water dissolves ions and nutrients and carries them along with other dissolved gases and heat and as well microorganisms and their predators (Cairns, Impa, O'Toole, Jagadish, & Price, 2011). Without the movement of water in the soil, microbial movement through soils will be poorly affected (Yang & van Elsas, 2018). Soil water also protects soil microorganisms from desiccation. The dynamic of bacterial population is greatly affected with increased soil moisture content by providing network

**FIGURE 9.3**

The fundamental relationships between soil water-influenced properties and processes, and soil microbial activity.

individual aggregates. Vargas and Hattori (1990), for instance, showed that aggregate connectivity determined the level of bacterial predation. The physicochemical relationships that modulate soil water and biological activity in schematic picture are presented in Fig. 9.3. Hence, it is important to stress that the physical and chemical factors influenced the interaction between soil water and microbial activity.

9.4.1.2 Soil temperature

The distribution and the activity of soil microorganism is affected by temperature. Soil temperature is a combination of incident solar energy, modified by several other factors. An example is the reflectance (an amount of incident solar energy reflected back by the soil–plant system) which depends on the soil color and vegetation type. Another is the soil moisture. The specific heat

Table 9.3 The classification of soil microorganisms according to temperature scales.

Category of microbes		Temperature range (°C)	Optimum growth (°C)
Psychrophile		– 5–20	15
Mesophile		15–45	37
Thermophile	Moderate	40–70	60
	Extreme: (hyperthermophile)	65–95	85

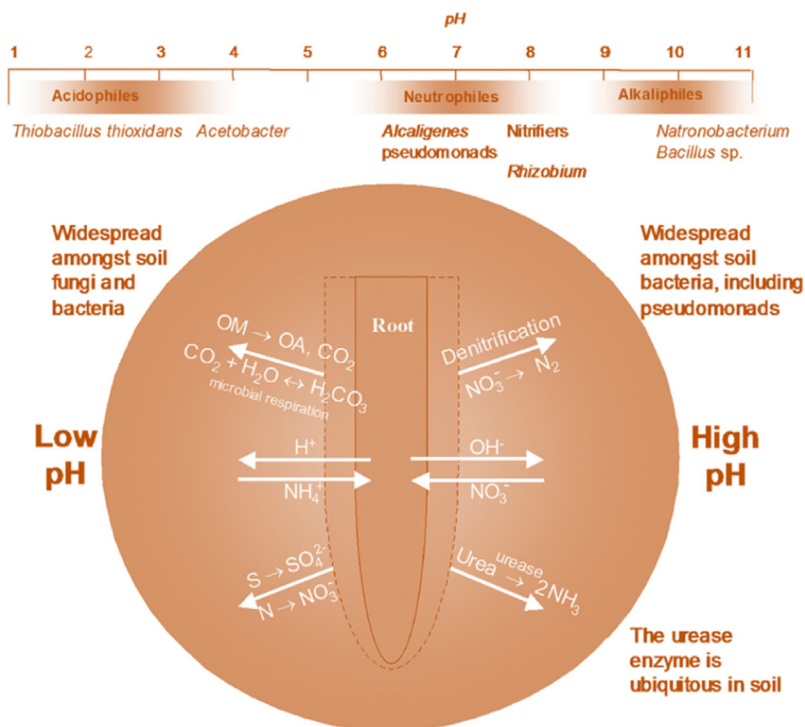
capacity of the soil and the soil moisture determined the extent to which a unit soil is warmed by a unit net of radiation. In addition to this, seasonal factors including edaphic parameters such as soil type or depth and the vegetation type impacts soil temperature. Temperature is a main driver of certain physicochemical and physiological reaction as well as being a strong selective force. As the result, its significant importance in the soil and soil microbial communities can show on the basis of temperature range of values (Table 9.3). There is an approximately doubling rate in the biochemical activity at every 10°C rise between 0°C and 30°C/35°C within the average mesophilic microbial communities (van Elsas, 2019). Soil temperature directly affects microbial physiology and indirectly by altering changes in nutrients and substrate diffusion and water activity (Killham, 1994). For example, the diversity and activity of the rhizosphere microbial community is crucial to the quantity and quality of rhizosphere C flow and is temperature dependent (Meharg & Killham, 1989). Also, the accumulation of ammonium in temperate-climate soils in autumn and spring is as the result of observed difference in low-temperature activity of the ammonification and nitrification processes as shown in the scheme below (van Elsas, 2019).

9.4.1.3 Soil pH

Soil pH is a key determinant for the distribution and activity of soil microbes. The pH of the soil is the combination of several processes and parameters. One these factors is the parent rock from which the soil is formed (e.g., acidic soils may be a product from rocks such as granite, whereas chalks and limestones may give alkaline soils) and as well as the degree to which the mineral weathering occurred. Based on this, at varying degrees, soil pH affects a wide range of biological and microbial processes. Fig. 9.4 shows the pH-modifying activity which occurs at different scale from microbial habitat to the entire bulk soil. Besides being driven by plants, many of these processes are microbial and animal based and thus creating a mosaic of variable pH conditions in the soil. Hence, with different physiological preferences for specific pH condition, different microbial groups (acidophiles i.e., low pH; alkaliphiles, i.e., high pH) as shown in the Fig. 9.4 are favored in soils at different pH conditions.

9.4.1.4 Soil organic matter

Soil organic matter (SOM) is one of the crucial factors in determining microbial activities in the soil. Nutrient cycling, soil aggregates, and water-holding capacity of the soil are mediated by SOM (Cillis, Maestrini, Pezzuolo, Marinello, & Sartori, 2018). Hence, sustainable agricultural development and soil health can be greatly affected by SOM depletion. The carbon (soil organic carbon) present in SOM serves the as largest sink and source of carbon in the biosphere, and hence, GHG

**FIGURE 9.4**

The pH classification of soil microorganism and key pH-modifying activities which provide microhabitats with different pH situations.

Note: OM: Organic Matter; OA: Organic Acids.

van Elsas, J.In.D. 2019. *The Soil Environment*. J.D. van Elsas, J.T. Trevors, A. S. Rosado, P. Nannipieri (Eds), *Modern Soil Microbiology*, 3rd Edition, CRC Press, Boca Raton. ISBN: 9780429059186. <https://doi.org/10.1201/9780429059186>

emissions are impacted by any small changes in SOM mineralization (Wang et al., 2015). Biological sequestration of CO₂ is one of the means to mitigate the increasing concentration of GHG concentration in the atmosphere. Hence, the biological sequestration of carbon in the soil represents the net CO₂ removal into long-lived sinks, or pools, or carbon from the atmosphere (Lal, 2008). The diversity of soil bacteria is determined by SOM as an overarching edaphic factor (Fierer, Schimel, & Holden, 2003; Hu et al., 2014). This is because energy required by soil microorganisms is obtained on organic matter decomposition (Allison, Wallenstein, & Bradford, 2010; Trivedi, Anderson, & Singh, 2013). On global scales, findings have shown that SOM content play crucial role in determining the diversity and communities of soil bacteria (Fierer & Jackson, 2006; Liu et al., 2014; Zhou et al., 2016). Results from meta-analyses on a continental scale have shown that high SOM content has microbial biomass carbon peaks in the areas (Wieder, Boehner, & Bonan, 2014; Xu, Thornton, & Post, 2013). Delgado-Baquerizo et al. (2016) concluded that total soil organic carbon content shapes the diversity patterns of bacteria.

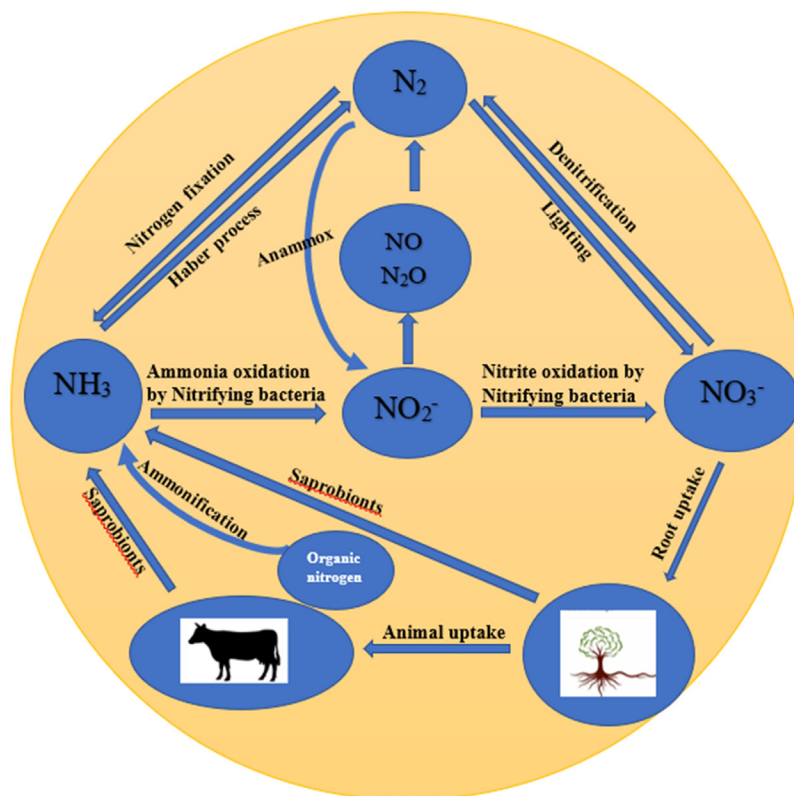
9.5 Beneficial soil microorganisms for CSA

9.5.1 Nitrogen-fixing bacteria

The CSA requires the development of new strategies to reduce the application of chemical fertilizer, especially the use of chemical nitrogen (N) fertilizers that are responsible for environmental pollution including groundwater contamination, greenhouse effects, and destruction of the ozone layers due to their chemical production and application (Htwe, Moh, Soe, Moe, & Yamakawa, 2019; Lally et al., 2017; Zhang et al., 2015). Over the years, intensive agriculture has depended heavily on the use of chemical N fertilizers which are often not immediately assimilated by plant and sometimes lost to denitrification, volatilization, runoff, and leaching (Romero-Perdomo et al., 2017). Globally, about 4×10^{15} tons of N as dinitrogen are present in the atmosphere and approximately 20 folds are bound in sedimentary and primary rocks beneath the earth crust (Gallon & Chaplin, 1987). Except converted to ammonia, none of these sources of N are not accessible to plant (Welbaum, Sturz, Dong, & Nowak, 2004). Industrially, N can be fixed by Haber-Bosch process or biologically, by some prokaryotes. Industrial fertilizers provide significantly large quantity of N; however, biological nitrogen fixation provides most of the fixed N in the soil and water ecosystem (Hernandez, 2002). Nitrogen-fixing bacteria can be symbiotic, free-living, or associative, inhabitant of rhizosphere and bulk soil, which transforms atmospheric N_2 to organic N compounds for plant and other organism nutrients (Fig. 9.5). This process is called biological nitrogen fixation (BNF) (Howard & Rees, 1996).

Global terrestrial BNF is estimated to contribute nearly 100 and 290 million tons of N year⁻¹ (Cleveland et al., 1999), of which field agricultural crops contribute 40–48 million tons year⁻¹ (Galloway, Schlesinger, Levy, Michaels, & Schnoor, 1995; Jenkinson, 2001). Estimated symbiotic nitrogen fixers (cyanobacteria), free-living bacteria, and associative (endophytic) bacteria contribute 7–80, 15, and 36 kg of N ha⁻¹ year⁻¹, respectively (Elkan, 1992). Although studies have shown successful examples of nonsymbiotic BNF for cereal crops, especially for sugar cane where endophytic diazotrophs played an important role in the biological fixation of N to the plant, there are still some controversies as to what extent this occurs (Hoefsloot, Termorshuizen, Watt, & Cramer, 2005). For the most part, symbiotic nitrogen fixers have been studied to produce biologically active materials such as amino acids, phytohormones, and vitamins; encourages morphological, geometric, and physiological development of root systems; as well as the capacity of free-living nitrogen fixers to mobilize sparingly soluble materials to promote plant growth (Gupta, 2012; Hoefsloot et al., 2005).

Among nonsymbiotic nitrogen-fixing bacteria (associative), the genus *Azospirillum* has been widely studied and reported to have the capacity to improve plant roots development, and increase water and nutrient uptake by plant roots, thus impacting plant growth and yield (El Zemrany et al., 2007; Gupta, 2012). Other genera such as *Pseudomonas*, *Enterobacter*, *Bacillus*, *Acetobacter*, *Azoarcus*, *Citrobacter*, *Azotobacter*, *Paenibacillus*, *Clostridium*, *Gluconacetobacter*, *Herbaspirillum*, *Klebsiella*, and *Burkholderia* have been reviewed (Hayat, Ali, Amara, Khalid, & Ahmed, 2010; Reis & Teixeira, 2015; Shamseldin, Abdelkhalek, & Sadowsky, 2017) and explored for potential use as biofertilizers (Table 9.4). Besides nitrogen-fixing bacteria, other soil microorganisms such as mycorrhizal fungi contribute to the fixation of N and helps bacteria in the decomposition of SOM (Artursson, Finlay, & Jansson, 2006; Azcón, Ruiz-Lozano, & Rodriguez, 2001).

**FIGURE 9.5**

Nitrogen cycle.

Hence, owing to the positive relationships among bacterial species and their impacts on crop growth and yield, even extreme conditions such as salinity, the integration of bacterial biofertilizers in food production systems will help to reduce or replace the use of chemical fertilizers.

9.5.2 Phosphate-solubilizing microorganisms

Globally, the production of synthetic phosphate fertilizers is energy intensive and requires a US \$4 billion per annum expenditure on energy to meet the worldwide phosphate-based fertilizer demand (Goldstein, Rogers, & Mead, 1993). In addition, nearly 75%–90% of phosphatic fertilizers added to the soil is precipitated by metal cation complexes (Stevenson, 1986). Also, while naturally embedded phosphate in farm soils can nourish and support crop production for over 100 years (Goldstein et al., 1993), phosphorus deficiency is a common phenomenon in agricultural soils worldwide (Chouyia et al., 2020). In contrast, discharge of phosphorus without treatment is also a problem for sustainable environmental health (Guadie et al., 2014, 2020). Hence, the need

Table 9.4 Example of nitrogen-fixing bacteria used as biofertilizers to improve crop yield and quality in recent studies.

Bacterial inoculant(s)	Experiment	Crop	Effect	Reference
<i>Azotobacter chroococcum</i>	Greenhouse	Tomato	Promoted plant growth, stress tolerance, and nutrient assimilation efficiency under moderate and severe salinity	Van Oosten et al. (2018)
<i>Azotobacter</i> sp.	Greenhouse	Strawberry	Maximum values for growth, yield, and quality parameters	Chandramohan and Goyal (2021)
<i>Azospirillum</i> sp.	Greenhouse	Strawberry	Significantly growth and yield parameters of strawberry	
<i>A. chroococcum</i>	Glasshouse	Cotton	Promoted seed germination and growth	Romero-Perdomo et al. (2017)
<i>Azoarcus</i> sp.	Greenhouse	Rice	Promoted rice growth and enhancing the zinc content of rice grains in low nitrogen input paddy fields	Sakoda et al. (2019)
<i>Azospirillum</i> sp.	Greenhouse	Rice and maize	Significantly increased seed germination, plant height, root and shoot fresh, and dry weights.	Ibrahima et al. (2020)
<i>Herbaspirillum frisingense</i>	Greenhouse	<i>Miscanthus</i> × <i>giganteus</i> stem	Improved the shoot sprouting and establishment success, appears to colonize the shoot and has long-lasting effects on the rhizome microbiome diversity	Liu and Ludewig (2020)
<i>H. frisingense</i>	Field trial	<i>Miscanthus</i> × <i>giganteus</i> stem		
<i>Pseudomonas fluorescens</i>	Greenhouse	<i>Brassica napus</i>	Effectively colonized, improved growth, and also increased plant biomass	Lally et al. (2017)
<i>P. fluorescens</i>	Field conditions		Enhanced growth was observed from the height, stem, leaves and increased pod biomass	
<i>Bacillus megaterium</i>	Greenhouse	Hybrid <i>Pennisetum</i>	Increased nitrogen content in the root, stem, and leaf	Kamal, Liu, Qian, Wu, and Zhong (2020)
Coinoculation of <i>Bradyrhizobium</i> and <i>Streptomyces griseoflavus</i>		Mung bean, cowpea, and soybean	Significantly promoted plant growth, nodulation, nitrogen fixation, and higher seed yield	Htwe et al. (2019)
<i>Klebsiella</i> sp.		Oat seedlings (<i>Avena sativa</i>)	Enhanced plant growth under salt stress condition	Sapre, Gontia-Mishra, and Tiwari (2018)

to explore an alternative source of phosphate to ease the dependence on fossil energy in the production of synthetic phosphate fertilizers globally. The role of rhizospheric microorganisms in mineral phosphate solubilization has been known since 1903. Phosphate-solubilizing microorganisms has the ability to convert insoluble phosphatic compounds in soil into soluble forms

and make them available to plants (Fig. 9.6) (Kang, Ha, Lee, & Maheshwari, 2002; Pradhan & Sukla, 2006).

A great number of saprophytic bacteria belonging to the genera *Agrobacterium*, *Serratia*, *Gordonia*, *Chyseobacterium*, *Achromobacter*, *Erwinia*, *Burkholderia*, *Micrococcus*, *Flavobacterium*, *Rhodococcus*, *Proteus*, *Citrobacter*, *Klebsiella*, *Enterobacter*, *Arthrobacter*, *Bacillus*, *Delftia*, *Phyllobacterium*, *Pseudomonas*, *Azotobacter*, and *Aspergillus*, and fungi also belonging to the genera *Penicillium*, *Aspergillus*, and *Trichoderma* has been reviewed and studied for their ability to increase P content and improve plant growth (Elhaissofi et al., 2020; Zhang et al., 2018). Generally, fungi exhibit greater phosphate-solubility capability to bacteria and mycorrhizal fungi are the most powerful phosphate mobilizers (Brundrett, Bougher, Dell, Grove, & Malajczuk, 1996). Therefore the use of phosphate-solubilizing microorganism as microbial inoculants (Table 9.5) in CSA to reduce or replace chemical phosphate fertilizers will provide an attractive, eco-friendly, and low-cost alternative to explore native sources of soil P (Khan, Zaidi, & Wani, 2007; Kumar et al., 2015).

9.5.3 Mycorrhizal fungi

A wide group of fungi that are monophyletic and also forms a mutualistic relationship with most agricultural land crops are known as arbuscular mycorrhizal (AM) fungi. These fungi have their unique ability to enhance the uptake of nutrients and increase productivity in plants as well as influencing several other ecological functions (Powell & Rillig, 2018; Smith & Smith, 2011). Typically,

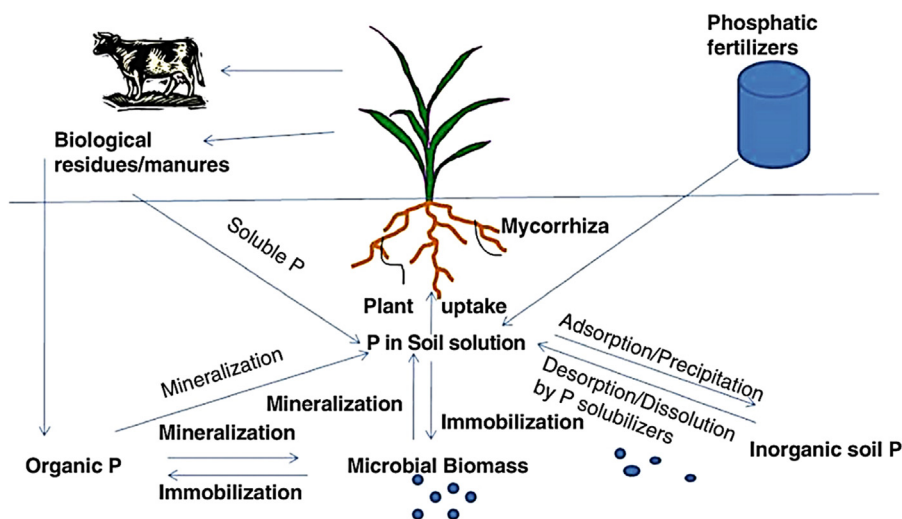


FIGURE 9.6

Mechanism of phosphate solubilizing microbes.

Shrivastava M., Srivastava P.C., D'Souza S.F. (2018) Phosphate-Solubilizing Microbes: Diversity and Phosphates Solubilization Mechanism.

In: Meena V. (eds) Role of Rhizospheric Microbes in Soil. Springer, Singapore. https://doi.org/10.1007/978-981-13-0044-8_5

Table 9.5 Example of P-solubilizing microorganisms used to improve plant growth and yield.

Microbial inoculant(s)	Plant	Reference
Combination of <i>Trichoderma harzianum</i> , <i>Pseudomonas</i> sp., and <i>Bacillus amyloliquefaciens</i>	Maize	Mpanga et al. (2019)
Coinoculation of <i>Penicillium oxalicum</i> and <i>Bacillus subtilis</i>	Maize	Wang et al. (2020)
<i>Pseudomonas tolaasii</i> , <i>Pseudomonas koreensis</i>		Viruel et al. (2014)
<i>Talaromyces aurantiacus</i> and <i>Aspergillus neoniger</i>		Zhang et al. (2018)
Combination of consortium of arbuscular mycorrhizal fungi, <i>Aspergillus niger</i> , and <i>Penicillium brevicompactum</i>	Coffee	Rojas et al. (2019)
<i>Bacillus circulans</i>	Tomato	Mehta, Walia, Kulshrestha, Chauhan, and Shirkot (2015)
<i>Enterobacter ludwigii</i>	Rice	Lee et al. (2019)
Combination of <i>Enterobacter asburiae</i> , <i>Acinetobacter</i> sp., <i>Bacillus cereus</i>	Wheat and maize	Teng et al. (2019)
Coinoculation of <i>Pantoea cyripedii</i> and <i>Pseudomonas plecoglossicida</i>		Kaur and Reddy (2014)
<i>Pseudomonas</i> spp.		Elhaissofi et al. (2020)
<i>Pantoea</i> sp.	Tomato	Sharon, Hathwaik, Glenn, Imam, and Lee (2016)
Combination of <i>Trichoderma harzianum</i> , <i>Pseudomonas</i> sp., <i>Bacillus amyloliquefaciens</i> , <i>Paenibacillus mucilaginosus</i> , and <i>Penicillium</i> sp.	Maize	Microorganisms Editorial Office (2019)
<i>Aspergillus niger</i> , <i>Penicillium pinophilum</i>	Barley	Acevedo, Galindo-Castañeda, Prada, Navia, and Romero (2014)
<i>Streptomyces roseocinereus</i>		Chouyia et al. (2020)

studies have shown that AM fungal biomass abundance, spore numbers, and root colonization levels decrease with increase soil depth. However, over 50% of AM fungal are found 30 cm beneath the soil ([Higo et al., 2013](#)) and at a depth of 8 m outside agricultural settings ([de Araujo Pereira, Santana, Bonfim, de Lourdes Mescolotti, & Cardoso, 2018](#)). Below 30 cm and in elevated CO₂ experiment, AM communities in the subsoil respond differently to environmental changes compared to those of the topsoil ([Rillig & Field, 2003](#)). Crop performance and ecosystem processes have been attributed to the abundancy and unique characteristic of AM fungi in subsoil ([Sosa-Hernández et al., 2018](#); [Wortmann, Quincke, Drijber, Mamo, & Franti, 2008](#)). Considering the role of subsoil AM fungi in reducing CO₂ and N₂O associated with agriculture, several studies have reported that in subsoil C cycling, soil aggregates are improved via hyphal enmeshment of soil aggregates and extracellular polymers production ([Rillig & Mummey, 2006](#)). This is due the disruption of hyphal networks in the subsoil are lesser, thus leading to increasing aggregate-protected organic matter residence time ([Lehmann, Leifheit, & Rillig, 2017](#)). Therefore the presence of mycorrhizal hyphae in the subsoil encourages the stabilization of soil aggregates as the result of contributing greatly to SOM protection and sequestration. The interactions between soil microbes resulting into competition for nutrients can be encouraged in a soil with good structure and improved soil pore connectivity. Hence, the indirect reduction in decomposition activity leading to

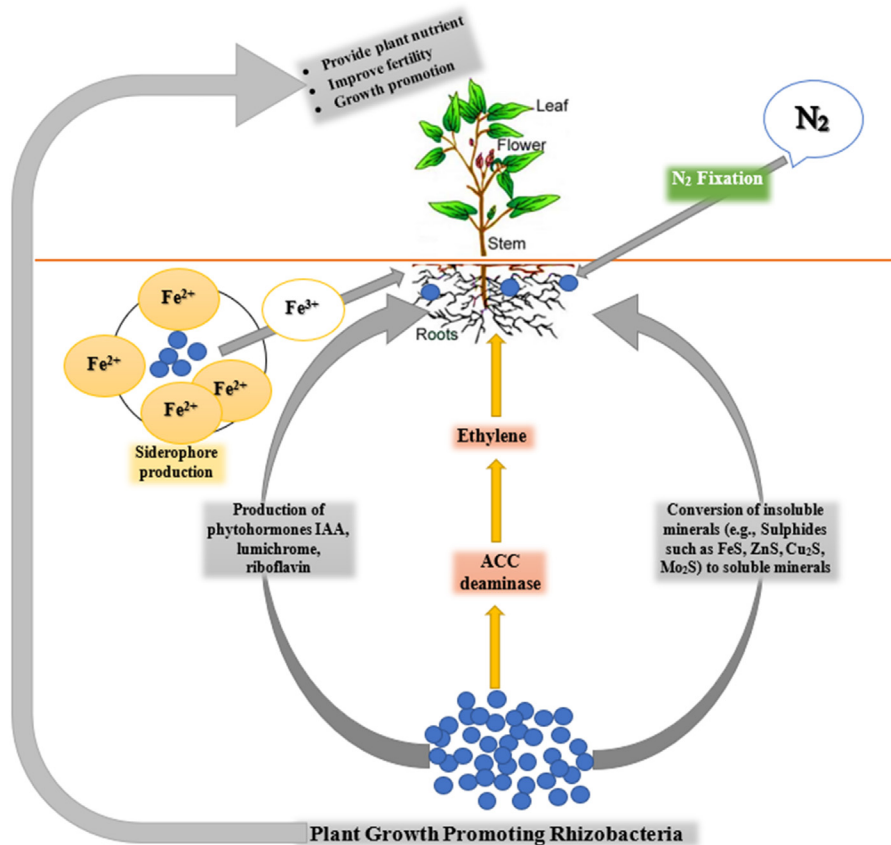
the addition or stabilization of carbon can be possible if AM fungi can outcompete decomposers for nutrients. Also, AM fungi has been identified to have negative effect on N_2O emission in agricultural lands (Storer, Coggan, Ineson, & Hodge, 2018). This is due to the readiness of AM fungi to take up and outcompete nitrifiers for NH_4^- .

9.5.4 Potassium-solubilizing microorganisms

Potassium (K), besides N and P, is an important nutrient needed for plant growth and development and also, these three elements form the synthetic NPK fertilizers used in intensive agriculture to improve seed germination, root development, crop yield, resistance to pests and diseases, etc. (Meena et al., 2016). Although K is the seventh most abundant element in the earth crust, nearly 98% of it is not available directly for plant uptake (Zörb, Senbayram, & Peiter, 2014). The use of K-solubilizing microorganisms provide an eco-friendly, viable, and a more realistic approach to solubilizing K from mineral and rocks and make it accessible to plant for absorption (Gundala, Chinthala, & Sreenivasulu, 2013). The use of bacterial species for the solubilization of K can be dated centuries ago (Aleksandrov, Blagodyr, & Ilev, 1967), and an extensive review on the role of K-solubilizing microbes in sustainable food production system was carried out by Sattar et al. (2019). Some examples of K solubilizers used for enhancing plant growth include *Bacillus mucilaginosus* (Abou-el-Seoud & Abdel-Megeed, 2012), *Bacillus subtilis* (Leaungvutiviroj, Ruangphisarn, Hansanimitkul, Shinkawa, & Sasaki, 2010), *Bacillus cereus* (Badr, 2006), *Pseudomonas* sp. (Lynn, Win, Kyaw, Latt, & Yu, 2013), *Bacillus pasteurii* (Youssef, Seddik, & Osman, 2010), *Enterobacter hormaechei* (Prajapati, Sharma, & Modi, 2013), *Arthrobacter* sp. (Keshavarz Zarjani, Aliasgharzad, Oustan, Emadi, & Ahmadi, 2013), *Enterobacter cloacae* and *Klebsiella variicola* (Zhang & Kong, 2014), *Paenibacillus mucilaginosus* (Liu, Lian, & Dong, 2012), and *Paenibacillus glucanolyticus* (Sangeeth, Bhai, & Srinivasan, 2012).

9.5.5 Plant growth—promoting microorganisms

Changing climatic conditions will accelerate the occurrence of plant diseases, degradation of cultivable farm lands, and unprecedented increase in the demand for food. However, the use of plant growth—promoting microorganisms (PGPMs) could play a significant role in CSA because of their ability to increase soil fertility, enhance growth, seed germination, and crop yield, and mediate biological control against various plants diseases (Herman, Nault, & Smart, 2008; Sawamoto, 2008). The PGPMs are rhizobacteria that colonize the plant roots and rhizosphere to enhance plant growth. The PGPMs enhanced crop production through diverse mechanisms including the production of phytohormones such as cytokinins, auxins, and gibberellins to regulate plant growth, ethylene to suppress the production of stress hormones (Abhilash, Dubey, Tripathi, Gupta, & Singh, 2016; Groppa, Benavides, & Zawoznik, 2012), and collaborating with nitrogen fixers to increase the uptake of N, phosphate solubilizer to solubilize inorganic and (or) organic phosphates in the soil (Liu et al., 1992), and siderophore producers that chelate iron (Fig. 9.7) and make it available to the plant root (Bowen & Rovira, 1999; Glick, 1995). Also, indirectly through the production of antibiotics or cell wall lytic such as chitinases and inducing plant defense mechanisms, PGPMs inhibit pathogens (Jetiyanon & Kloepper, 2002; Sarma, Yadav, Singh, & Singh, 2015). The PGPMs such as *Trichoderma harzianum*, *Sclerocystis* sp., *Rhizobium*, *Bacillus megaterium*, *Klebsiella*,

**FIGURE 9.7**

The multidimensional mechanism of plant growth-promoting microorganisms (PGPMs).

Trichoderma viride, *Nostoc*, *Anabaena*, *Frankia*, *Penicillium* sp., *Clostridium*, and *Glomus* sp. are regarded as important PGPMs. However, the genera *Bacilli* and *Pseudomonads* are the most studied (Podile & Kishore, 2007). Under salt stress, PGPMs have shown positive outcomes in plants such as improved germination, drought resistance, increased yield and plant growth, and enhanced shoots and roots weight.

9.6 Biological control mechanisms

9.6.1 Soil microorganisms for weed management

In agricultural systems, weed management is one of the crucial determinants limiting crop yield and responsible for about 37% of the global agricultural production losses (Ferreira & Reinhardt,

2016; Yandoc, Roskopf, Pitelli, & Charudattan, 2006). Although the use of chemical herbicides has proven effective, the excessive use of chemical herbicides has contaminated groundwaters, contributed to global warming and affected human health, and more also, weeds developed resistant to chemical herbicides or evolution in new varieties of weed flora due to prolonged application (Ahmad, Nadeem, Naveed, & Zahir, 2016; Kumar et al., 2015; Parewa, Yadav, Rakshit, Meena, & Karthikeyan, 2014). Also, the use of farm machinery or mechanical method for weed management is labor intensive, expensive for poor farmers, and contributed to GHG emissions through machine emissions (Kennedy & Kremer, 1996; Sindhu, Khandelwal, Phour, & Sehwat, 2018). Hence, increasing public awareness about public health and environmental protection has led to restrictions in the use of synthetic chemical herbicides for weed control in many countries and the need for viable, eco-friendly, and cost-effective alternative (Gnanavel, 2015; Kennedy & Kremer, 1996; Sindhu et al., 2018). The use of microorganisms as alternative provides eco-friendly and realistic means of suppressing weed growth and establishment in agriculture (Li & Kremer, 2006; Patil, 2013), thus reducing synthetic herbicide usage. As shown in Table 9.6, several microorganisms including rhizosphere bacteria such as *Pseudomonas fluorescens* (Li & Kremer, 2006; Zermane, Souissi, Kroschel, & Sikora, 2007), *Erwinia herbicola*, *Alcaligenes* sp. and *Flavobacterium* sp. (Kremer, Begonia, Stanley, & Lanham, 1990), *Pseudomonas fluorescens*, *P. syringae* pv. *tobaci* and *tagetis* (Zdor, Alexander, & Kremer, 2005; Zidack & Quimby, 2002), *Xanthomonas campestris* (Imaizumi, Nishino, Miyabe, Fujimori, & Yamada, 1997; Tateno, 2000), *Serratia plymuthica*, *Xanthomonas* sp. (Patil, 2013), *Streptomyces levis* (El-Sayed, El-Aziz, & Abouzaid, 2014), *Xanthomonas campestris* (Boyette & Hoagland, 2015) and *Serratia marcescens* (Juan et al., 2015); and fungi such as *Colletotrichum gloeosporioides* f. sp. *Aeschynomene* (Boyette, Gealy, Hoagland, Vaughn, & Bowling, 2011), *Colletotrichum gloeosporioides* f. sp. *Malvae* (Mortensen, 1988), *Colletotrichum orbiculare* (Harata & Kubo, 2014), *Colletotrichum truncatum* (Boyette, 1991; Hynes, Chumala, Hupka, & Peng, 2010), *Phoma chenopodicola* (Cimmino et al., 2013), *Phoma herbarum* (Ray & Vijayachandran, 2013), *Phoma macrostoma* (Bailey, Pitt, Falk, & Derby, 2011), and *Sclerotinia minor* (Abu-Dieyeh & Watson, 2007) have been used as bioherbicides.

Table 9.6 Various commercially produced bioherbicides in the world.

Trade name	Target weed	Active microorganism
Lubao	Dodder	<i>Colletotridium gloeosporioides</i>
DeVine	Strangler vine	<i>Phytophthora palmivora</i>
Organo-Sol	Leguminous weeds	<i>Lactobacillus</i> sp.
CASST	Sickle pod, coffee senna	<i>Alternaria cassia</i>
Myco-Tech	Deciduous tree species	<i>Chondrostereum purpureum</i>
Hakatak	<i>Hakea sericea</i>	<i>Colletotridium acutatum</i>
DrBioSedge	Yellow nut sedge	<i>Puccinia canaliculate</i>
Collego	Northern joint vetch	<i>Colletotrichum gloeosporioides</i> f. sp. <i>aeschynomene</i>
Camperico	Annual bluegrass	<i>Xanthomonas campestris</i> pv. <i>poae</i>
Chontrol	Alders and other hard woods	<i>Chondrostereum purpureum</i>
BioMal	Round-leaved mallow	<i>Colletotrichum gloeosporioides</i> f. sp. <i>malvae</i>
Phoma	Broad-leaved weeds	<i>Phoma macrostoma</i>

9.6.2 Microorganisms for plant pathogen control

The future CSA will heavily depend on the integration of beneficial soil microorganisms in the current agricultural systems as biocontrol agents to reducing the use of agrochemicals in crop production to foster a more sustainable environment (Haggag & Mohamed, 2007). Plant pathogens include fungi are the most visible threats to sustainable food production, and the decreasing efficacy of the fungicides as well as risks associated with fungicide residues on the leaves and fruit have highlighted the need for a more effective and safer alternative control measures (Gupta, 2012; Haggag & Mohamed, 2007). Biological control of plant pathogens has received increasing attention as a promising supplement or alternative to chemical control in recent years. Biological control of plant disease is defined as “the involvement of the use of beneficial microorganisms, such as specialized fungi or yeast or bacteria to attack and control the plant pathogens (i.e., fungi, bacteria, nematodes, or weeds) and the diseases they are causing” (Boukaya et al., 2018). Biological control is a potent means of reducing the damage caused by plant pathogens (Haggag, 2002; Jeyarajan & Nakkeeran, 2000). A number of bacteria such as *Bacillus* sp., *Actinoplanes* sp., *Pseudomonas* sp., *Streptomyces* sp., and fungi such as *Cladovrhinum foecundissimum*, *Fusarium* sp., *Penicillium oxalicum*, *Pythium peviplocum*, and *Talavomyces flarus* has been used to control diseases in agricultural and horticultural crops (Whipps, 2001). However, the greatest challenge in biological controls remains that some soils are suppressive to one pathogen and may not be suppressive to another; hence, the specificity in term of soil–plant–microbe interactions for disease suppression exists (Gupta, 2012).

9.7 Agricultural management practices and mitigation

9.7.1 Impact on soil microorganisms

Soil microorganisms and soil microbial processes have largely impacted the changes in agricultural land management by causing changes in nutrients and input in the soil. Their effects reveal the changes in the quantity and quality of biomass that remain in the soil and their spatial distribution and variation (Welbaum et al., 2004). Unsuitable agricultural land management practices have proven to be responsible for significant decrease in soil quality and soil microbiome (Beare, Coleman, Crossley, Hendrix, & Odum, 1995; Sparling, 1997). The structure and function of soil microbial communities in a normal functioning terrestrial agroecosystem can be drastically altered by the use of excessive pesticides, thus impacting the soil fertility (Pampulha & Oliveira, 2006). Due to mechanical destruction, desiccation, reduce pore volume, soil compaction, and disruption in the chain of food supply, agricultural land subjected to tillage experienced decrease in the quantity of soil microbiota (Giller, 1996). Although the application of some organic fertilizers, manures, and sewage sludge will improve the quantity and functions of soil microorganisms (Almario, Moënne-Loccoz, & Muller, 2013; Ruppel, Torsvik, Daae, Øvreås, & Rühlmann, 2007), however, the prolonged exposure of land to manures and sewage sludge for instance can cause the introduction fecal microbial flora into the soil and potential impact on the endogenous structure of microorganisms (Soupir, Mostaghimi, Yagow, Hagedorn, & Vaughan, 2006). The fallow period during crop rotation can reduce soil microbial diversity and soil quality (Zelles, Bai, Beck, & Besse, 1992). Hence, it is

clearly obvious that land management practices play a critical role in improving the microbial impact on food productivity and the attainment of climate-smart soil model.

9.7.2 Agricultural soils' mitigation practices and future directions

9.7.2.1 Soil carbon sequestration through improved management

The largest terrestrial pool for organic carbon (C) is present in the soil which is three times higher than the current quantity of CO₂ present in the atmosphere and 240 times than compared to those emitted from petroleum fuel at the current annual rate (Ciais et al., 2014). Hence, by any means necessary, substantial C sink can be achieved by increasing the net soil C storage potential. This can be achieved by striking the balance between the rate at which C addition and loss occurs in agroecosystems. Improved management practices that increase C input include crop rotations, residue retention, improved varieties or species of plant with great root mass for C deposit in the deepest layer slowing down turnovers, adoption of fallow period, irrigation in water-limited systems, and additional fertilizer input to increase productivity in nutrient-deficient systems (Table 9.1). Although additional fertilizer and water inputs to improved crop yield would increase non-CO₂ emissions (Shcherbak, Millar, & Robertson, 2014), the intensity of these emissions, especially in GHG emissions per unit yield could reduce provided that a gainful increase in yield avoids the conversion and degradation of native ecosystems for agriculture somewhere else (Burney, Davis, & Lobell, 2010; Foley et al., 2011), which is a strong mitigation alternative. Also, less or zero tillage can offer many croplands to sequester C (Ogle, Breidt, & Paustian, 2005; Six, Elliott, & Paustian, 2000). Improved fire prevention and management in fire-prone ecosystems and the shift from annual to perennial crop farming can also increase C sequestration (Conant, Paustian, & Elliott, 2001; Scholes & Scholes, 2013). However, the key knowledge gaps in soil C sequestration still includes understanding (1) the relationship between the chemistry of organic matter, surface interactions of minerals, and the saturation of C, (2) the interactions between differential temperature sensitivities and organic, and (3) subsoil organic matter accretion, turnover, and stabilization. Also, the understanding of the soil–plant microbiome interactions to enhance C sequestration in the rhizosphere is needed as shown in emerging findings that microbial sources of organic matters are more stabilized as to those directly originated from plant.

9.7.2.2 Soil carbon sequestration through exogenous carbon input

The addition of biochar and composts from external (offsite) sources can increase soil C sequestration, thus resulting in the net removal of CO₂ from the atmosphere (Paustian et al., 2016). However, because they are plant-derived C and from external systems, a broader understanding into their life-cycle assessment and impact on GHG production particularly their removal, transport, and processing, alternative end uses, interactions with other soil GHG-releasing activities, and their synergies with the fixation and retention of plant-derived in situ is needed. Compared to fresh plant residues, both compost and biochar decomposed slowly and can remain in the soil for several decades (Lehmann & Joseph, 2015; Ryals, Hartman, Parton, DeLonge, & Silver, 2015), despite the impact of soil conditions such as moisture, temperature, and texture (Schmidt et al., 2011). Also, there is need for comparable study on the time dependence of soil N₂O and CH₄ emissions on which less research attention has been given. Hence, with the enhancement of plant growth occur

in amended soils (Ryals et al., 2015; Whitman, Nicholson, Torres, & Lehmann, 2011), understanding this feedback will give a head to exploring other persistent amendments.

9.7.2.3 Soil management to reduce N_2O emission

Agricultural soil such as arable soils compared to other anthropogenic sources emit more C to the atmosphere (Smith et al., 2008; Smith, Clark et al., 2014). Since this major radiative force (N_2O) comes from cropland, reducing the flux present a substantial mitigation opportunity including minimizing ground and surface waters nitrate pollution and other environmental impacts (Fig. 9.2). Also, N_2O is produced in soils by microbial activity during nitrification and denitrification. Since there are limited numbers of evident terrestrial sinks for N_2O , abatement therefore could be best attained by reducing emission of N_2O from already known sources. This could further be achieved by monitoring other environmental factors such as soil N, oxygen, and C, and their impact on the production of N_2O , as well the use of soil additives to biochemically inhibiting some N_2O conversion pathways. Moreover, N conservation can be attained by using advanced statistical and quantitative modeling to better predict the needed amount of N to crops, applying fertilizer within the root zone rather soil surface broadcast, and apply fertilizer when it is mostly needed by plants.

9.7.2.4 Soil management to reduce CH_4 emissions

The breakdown of organic compounds occurred mostly in the soil by microorganism under anaerobic conditions, which contributes more than one-third of global CH_4 emissions (Ciais et al., 2014). As such, wetlands and rice cultivation soil provide the large source of soil-mediated CH_4 worldwide (Ciais et al., 2014). In contrast, well-aerated soils such as unmanaged upland and forest soils also act as the largest sinks for CH_4 from the atmosphere via CH_4 oxidation (Le Mer & Roger, 2001). Soil CH_4 fluxes is largely determined by aeration, substrate availability, temperature, and N inputs (Segers, 1998); hence adequate soil management provide a radical sink for adjusting CH_4 fluxes. Also, methanotrophs (bacteria or archea that metabolize CH_4) affect the soil chemistry CH_4 (Levine, Teal, Robertson, & Schmidt, 2011) of which little is known. Therefore the future research on agricultural soil should give regards to the net climate forcing effects of any soil management approach.

9.8 Conclusion

This study demonstrated that soil microbial community is essential to achieving food security under climate change while they mitigate GHG emissions and improve soil fertility. This study further summaries microbial strategies in CSA as realistic, inexpensive, and eco-friendly technology that should be pursued. This study provided a deep understanding of microbial technologies, soil and plant interactions under CSA scenario. This study stressed the need for climate change adaptation and mitigation while improving food production in the current food system. Finally, this study contributes to understanding of how climate changes affect soil microbes and ecosystem processes, and how agricultural practices under CSA interventions can achieve climate change adaptation, GHG mitigation, and food security.

References

- Abhilash, P. C., Dubey, R. K., Tripathi, V., Gupta, V. K., & Singh, H. B. (2016). Plant growth-promoting microorganisms for environmental sustainability. *Trends in Biotechnology*, 34(11), 847–850.
- Abou-el-Seoud, I. I., & Abdel-Megeed, A. (2012). Impact of rock materials and biofertilizations on P and K availability for maize (*Zea Maize*) under calcareous soil conditions. Saudi. *Journal of Biological Sciences*, 19(1), 55–63.
- Abu-Dieyeh, M. H., & Watson, A. K. (2007). Efficacy of *Sclerotinia minor* for dandelion control: Effect of dandelion accession, age and grass competition. *Weed Research*, 47(1), 63–72.
- Acevedo, E., Galindo-Castañeda, T., Prada, F., Navia, M., & Romero, H. M. (2014). Phosphate-solubilizing microorganisms associated with the rhizosphere of oil palm (*Elaeis guineensis* Jacq.) in Colombia. *Applied Soil Ecology*, 80, 26–33.
- Agegnehu, G., Vanbeek, C., & Bird, M. I. (2014). Influence of integrated soil fertility management in wheat and tef productivity and soil chemical properties in the highland tropical environment. *Journal of Soil Science and Plant Nutrition*, 14(3), 532–545.
- Ahmad, M., Nadeem, S. M., Naveed, M., & Zahir, Z. A. (2016). *Potassium-solubilizing bacteria and their application in agriculture. Potassium solubilizing microorganisms for sustainable agriculture* (pp. 293–313). New Delhi: Springer.
- Ajibade, F. O., Adelodun, B., Ajibade, T. F., Lasisi, K. H., Abiola, C., Adewumi, J. R., & Akinbile, C. O. (2021). The threatening effects of open dumping on soil at waste disposal sites of Akure City, Nigeria. *International Journal of Environment and Waste Management*, 27(2), 127–146.
- Ajibade, F. O., Adelodun, B., Lasisi, K. H., Fadare, O. O., Ajibade, T. F., Nwogwu, N. A., ... Wang, A. (2021). Environmental pollution and their socioeconomic impacts. In A. Kumar, V. K. Singh, P. Singh, & V. K. Mishra (Eds.), *Microbe mediated remediation of environmental contaminants*. Woodhead Publishing, Elsevier. Available from <http://doi.org/10.1016/B978-0-12-821199-1.00025-0>.
- Aksay, C.S., Ketenoglu, O., & Kurt, L. (2005). *Global warming and climatic change (in Turkish)*. S.Ü. Fen Ed. Fak. Derg., 1(25), 29–41. https://dergipark.org.tr/en/pub/sufefd/issue/23134/247140#article_cite.
- Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: The 2012 revision*.
- Allison, S. D., Wallenstein, M. D., & Bradford, M. A. (2010). Soil-carbon response to warming dependent on microbial physiology. *Nature Geoscience*, 3(5), 336–340.
- Almario, J., Moënné-Loccoz, Y., & Muller, D. (2013). Monitoring of the relation between 2, 4-diacetylphloroglucinol-producing *Pseudomonas* and *Thielaviopsis basicola* populations by real-time PCR in tobacco black root-rot suppressive and conducive soils. *Soil Biology and Biochemistry*, 57, 144–155.
- Artursson, V., Finlay, R. D., & Jansson, J. K. (2006). Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. *Environmental Microbiology*, 8(1), 1–10.
- Aydin, G. (2008). *Coalbed methane use technologies and analysis of methane emissions from energy production (in Turkish)*. Doctoral dissertation, Master Thesis. Graduate School of Natural and Applied Sciences, Karadeniz Technical University.
- Aydin, G., Karakurt, I., & Aydiner, K. (2010). Evaluation of geologic storage options of CO₂: Applicability, cost, storage capacity and safety. *Energy Policy*, 38(9), 5072–5080.
- Azcón, R., Ruiz-Lozano, J. M., & Rodriguez, R. (2001). Differential contribution of arbuscular mycorrhizal fungi to plant nitrate uptake (15N) under increasing N supply to the soil. *Canadian Journal of Botany*, 79(10), 1175–1180.
- Badr, M. A. (2006). Efficiency of K-feldspar combined with organic materials and silicate dissolving bacteria on tomato yield. *Journal of Applied Sciences Research*, 2, 1191–1198.
- Bailey, K. L., Pitt, W. M., Falk, S., & Derby, J. (2011). The effects of *Phoma macrostoma* on nontarget plant and target weed species. *Biological Control*, 58(3), 379–386.

- Baloch, M. A., & Suad, S. (2018). Modeling the impact of transport energy consumption on CO₂ emission in Pakistan: Evidence from ARDL approach. *Environmental Science and Pollution Research*, 25(10), 9461–9473.
- Bandaogo, A., Bidjokazo, F., Youl, S., Safo, E., Abaidoo, R., & Andrews, O. (2015). Effect of fertilizer deep placement with urea supergranule on nitrogen use efficiency of irrigated rice in Sourou Valley (Burkina Faso). *Nutrient Cycling in Agroecosystems*, 102(1), 79–89.
- Bardgett, R. (2005). *The biology of soil: A community and ecosystem approach*. Oxford University Press.
- Beare, M. H., Coleman, D. C., Crossley, D. A., Jr., Hendrix, P. F., & Odum, E. P. (1995). A hierarchical approach to evaluating the significance of soil biodiversity to biogeochemical cycling. *Plant and Soil*, 170, 5–22.
- Ben, J. M., & Hadhri, W. (2018). The dynamic causal links between CO₂ emissions from transport, real GDP, energy use and international tourism. *International Journal of Sustainable Development & World Ecology*, 25(6), 568–577.
- Boukaya, N., Goudjal, Y., Zamoum, M., Chaabane Chaouch, F., Sabaou, N., Mathieu, F., & Zitouni, A. (2018). Biocontrol and plant-growth-promoting capacities of actinobacterial strains from the Algerian Sahara and characterisation of *Streptosporangium becharense* SG1 as a promising biocontrol agent. *Biocontrol Science and Technology*, 28(9), 858–873.
- Bowen, G. D., & Rovira, A. D. (1999). *The rhizosphere and its management to improve plant growth*. *Advances in agronomy* (Vol. 66, pp. 1–102). Academic Press.
- Boyette, C. D. (1991). Host range and virulence of *Colletotrichum truncatum*, a potential mycoherbicide for hemp sesbania (*Sesbania exaltata*). *Plant Disease*, 75(1), 62–64.
- Boyette, C. D., Gealy, D., Hoagland, R. E., Vaughn, K. C., & Bowling, A. J. (2011). Hemp sesbania (*Sesbania exaltata*) control in rice (*Oryza sativa*) with the bioherbicidal fungus *Colletotrichum gloeosporioides* f. sp. *aeschnomene* formulated in an invert emulsion. *Biocontrol Science and Technology*, 21(12), 1399–1407.
- Boyette, C. D., & Hoagland, R. E. (2015). Bioherbicidal potential of *Xanthomonas campestris* for controlling *Conyza canadensis*. *Biocontrol Science and Technology*, 25(2), 229–237.
- Brundrett, M., Bougher, N., Dell, B., Grove, T., & Malajczuk, N. (1996). *Working with mycorrhizas in forestry and agriculture* (No. 435–2016-33680). Canberra: Australian Centre for International Agricultural Research.
- Burney, J. A., Davis, S. J., & Lobell, D. B. (2010). Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences United States of America*, 107(26), 12052–12057.
- Cairns, J. E., Impa, S. M., O'Toole, J. C., Jagadish, S. V. K., & Price, A. H. (2011). Influence of the soil physical environment on rice (*Oryza sativa* L.) response to drought stress and its implications for drought research. *Field Crops Research*, 121(3), 303–310.
- Chandramohan, R. G., & Goyal, R. K. (2021). Growth, yield and quality of strawberry as affected by fertilizer N rate and biofertilizers inoculation under greenhouse conditions. *Journal of Plant Nutrition*, 44(1), 46–58.
- Chivenge, P., Vanlauwe, B., & Six, J. (2011). Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant and Soil*, 342(1–2), 1–30.
- Chouyia, F. E., Romano, I., Fechtali, T., Fagnano, M., Fiorentino, N., Visconti, D., & Pepe, O. (2020). P-solubilizing *Streptomyces roseocinereus* MS1B15 with multiple plant growth-promoting traits enhance barley development and regulate rhizosphere microbial population. *Frontiers in Plant Science*, 11.
- Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., & Jones, C. (2014). *Carbon and other biogeochemical cycles. Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 465–570). Cambridge University Press.
- Cillis, D., Maestrini, B., Pezzuolo, A., Marinello, F., & Sartori, L. (2018). Modeling soil organic carbon and carbon dioxide emissions in different tillage systems supported by precision agriculture technologies under current climatic conditions. *Soil and Tillage Research*, 183, 51–59.

- Cimmino, A., Andolfi, A., Zonno, M. C., Avolio, F., Santini, A., Tuzi, A., & Evidente, A. (2013). Chenopodolin: A phytotoxic unarranged ent-pimaradiene diterpene produced by *Phoma chenopodolica*, a fungal pathogen for *Chenopodium album* biocontrol. *Journal of Natural Products*, 76(7), 1291–1297.
- Cleveland, C. C., Townsend, A. R., Schimel, D. S., Fisher, H., Howarth, R. W., Hedin, L. O., & Wasson, M. F. (1999). Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. *Global Biogeochemical Cycles*, 13(2), 623–645.
- Conant, R. T., Paustian, K., & Elliott, E. T. (2001). Grassland management and conversion into grassland: Effects on soil carbon. *Ecological Applications*, 11(2), 343–355.
- de Araujo Pereira, A. P., Santana, M. C., Bonfim, J. A., de Lourdes Mescolotti, D., & Cardoso, E. J. B. N. (2018). Digging deeper to study the distribution of mycorrhizal arbuscular fungi along the soil profile in pure and mixed *Eucalyptus grandis* and *Acacia mangium* plantations. *Applied Soil Ecology*, 128, 1–11.
- De Pinto, A., Cenacchi, N., Kwon, H. Y., Koo, J., & Dunston, S. (2020). Climate smart agriculture and global food-crop production. *PLoS One*, 15(4), e0231764.
- Delgado-Baquerizo, M., Maestre, F. T., Reich, P. B., Trivedi, P., Osanai, Y., Liu, Y. R., ... Singh, B. K. (2016). Carbon content and climate variability drive global soil bacterial diversity patterns. *Ecological Monographs*, 86(3), 373–390.
- Devkota, K. P., Manschadi, A. M., Lamers, J. P. A., Humphreys, E., Devkota, M., Egamberdiev, O., & Vlek, P. L. G. (2013). Growth and yield of rice (*Oryza sativa* L.) under resource conservation technologies in the irrigated drylands of Central Asia. *Field Crops Research*, 149, 115–126.
- El Zemrany, H., Czarnes, S., Hallett, P. D., Alamertery, S., Bally, R., & Monrozier, L. J. (2007). Early changes in root characteristics of maize (*Zea mays*) following seed inoculation with the PGPR *Azospirillum lipoferum* CRT1. *Plant and Soil*, 291(1–2), 109–118.
- Elhaissofi, W., Khourchi, S., Ibnayasser, A., Ghoulam, C., Rchiad, Z., Zeroual, Y., & Bargaz, A. (2020). Phosphate solubilizing rhizobacteria could have a stronger influence on wheat root traits and aboveground physiology than rhizosphere P solubilization. *Frontiers in Plant Science*, 11, 979.
- Elkan, G. H. (1992). *Biological nitrogen fixation systems in tropical ecosystems: An overview. Biological nitrogen fixation and sustainability of tropical agriculture* (pp. 27–40). Chichester: Wiley.
- El-Sayed, M. H., El-Aziz, Z. K. A., & Abouzaid, A. M. (2014). Efficacy of extracellular metabolite produced by *Streptomyces levis* strain LX-65 as a potential herbicidal agent. *Journal of American Science*, 10(11).
- Erenstein, O., & Laxmi, V. (2008). Zero tillage impacts in India's rice–wheat systems: A review. *Soil and Tillage Research*, 100(1–2), 1–14.
- Erenstein, O., Sayre, K., Wall, P., Hellin, J., & Dixon, J. (2012). Conservation agriculture in maize-and wheat-based systems in the (sub) tropics: Lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. *Journal of Sustainable Agriculture*, 36(2), 180–206.
- FAO. (2001). *Food insecurity in the world 2001* (p. 8) Rome, Italy: Food and Agriculture Organization of the United Nations. Available from <http://www.fao.org/3/a-y1500e.pdf>.
- FAO. (2010). Climate smart agriculture: Policies, practices and financing for food security, adaptation and mitigation. In *Paper prepared for Hague Conference on Agriculture, Food Security and Climate Change*. Available from <http://www.fao.org/docrep/013/i1881e/i1881e00.htm>.
- FAO. (2016). *The state of food and agriculture*. Rome, Italy: Food and Agriculture Organization of the United Nations. Available from <http://www.fao.org/3/a-i6030e.pdf>.
- FAO. (2018). *The future of food and agriculture: Alternative pathways to 2050* (p. 228) Rome, Italy: Food and Agriculture Organization of the United Nations.
- FAO., IFAD., UNICEF., WFP., & WHO. (2018). *The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition* (p. 202) Rome, Italy: Food and Agriculture Organization of the United Nations.

- Ferreira, M. I., & Reinhardt, C. F. (2016). Allelopathic weed suppression in agroecosystems: A review of theories and practices. *African Journal of Agricultural Research*, 11(6), 450–459.
- Fierer, N., & Jackson, R. B. (2006). The diversity and biogeography of soil bacterial communities. *Proceedings of the National Academy of Sciences United States of America*, 103(3), 626–631.
- Fierer, N., Schimel, J. P., & Holden, P. A. (2003). Variations in microbial community composition through two soil depth profiles. *Soil Biology and Biochemistry*, 35(1), 167–176.
- Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., & Balzer, C. (2011). Solutions for a cultivated planet. *Nature*, 478(7369), 337–342.
- Gaihire, Y. K., Singh, U., Islam, S. M., Huda, A., Islam, M. R., Satter, M. A., & Shah, A. L. (2015). Impacts of urea deep placement on nitrous oxide and nitric oxide emissions from rice fields in Bangladesh. *Geoderma*, 259, 370–379.
- Gallon, J. R., & Chaplin, A. E. (1987). *An introduction to nitrogen fixation*. Cassell.
- Galloway, J. N., Dentener, F. J., Capone, D. G., Boyer, E. W., Howarth, R. W., Seitzinger, S. P., ... Vöosmarty, C. J. (2004). Nitrogen cycles: Past, present, and future. *Biogeochemistry*, 70(2), 153–226.
- Galloway, J. N., Schlesinger, W. H., Levy, H., Michaels, A., & Schnoor, J. L. (1995). Nitrogen fixation: Anthropogenic enhancement-environmental response. *Global Biogeochemical Cycles*, 9(2), 235–252.
- Gentile, R., Vanlauwe, B., Chivenge, P., & Six, J. (2008). Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. *Soil Biology and Biochemistry*, 40(9), 2375–2384.
- Giller, P. S. (1996). The diversity of soil communities, the ‘poor man’s tropical rainforest’. *Biodiversity & Conservation*, 5(2), 135–168.
- Glick, B. R. (1995). The enhancement of plant growth by free-living bacteria. *Canadian Journal of Microbiology*, 41(2), 109–117.
- Gnanavel, I. (2015). Eco-friendly weed control options for sustainable agriculture. *Science International (Dubai)*, 3(2), 37–47.
- Godfray, H. C. J., & Garnett, T. (2014). Food security and sustainable intensification. *Philosophical transactions of the Royal Society B: biological sciences*, 369(1639), 20120273.
- Goldstein, A. H., Rogers, R. D., & Mead, G. (1993). Mining by microbe. *Bio/Technology*, 11(11), 1250–1254.
- Graham, E. B., Knelman, J. E., Schindlbacher, A., Siciliano, S., Breulmann, M., Yannarell, A., ... Foulquier, A. (2016). Microbes as engines of ecosystem function: When does community structure enhance predictions of ecosystem processes? *Frontiers in Microbiology*, 7, 214.
- Groppa, M. D., Benavides, M. P., & Zawoznik, M. S. (2012). Root hydraulic conductance, aquaporins and plant growth promoting microorganisms: A revision. *Applied Soil Ecology*, 61, 247–254.
- Guadie, A., Belay, A., Liu, W., Yesigat, A., Hao, X., & Wang, A. (2020). Rift Valley Lake as a potential magnesium source to recover phosphorus from urine. *Environmental Research*, 184. Available from <https://doi.org/10.1016/j.envres.2020.109363>.
- Guadie, A., Xia, S., Jiang, W., Zhou, L., Zhang, Z., Hermanowicz, S. W., ... Shen, S. (2014). Enhanced struvite recovery from wastewater using a novel cone-inserted fluidized bed reactor. *Journal of Environmental Sciences*, 26(4), 765–774.
- Gundala, P. B., Chinthala, P., & Sreenivasulu, B. (2013). A new facultative alkaliphilic, potassium solubilizing, *Bacillus* sp. SVUNM9 isolated from mica cores of Nellore District, Andhra Pradesh, India. *Research & Reviews: Journal of Microbiology and Biotechnology*, 2(1), 1–7.
- Gupta, V. V. (2012). Beneficial microorganisms for sustainable agriculture. *Microbiology Australia*, 33(3), 113–115.
- Haggag, W. M. (2002). Sustainable agriculture management of plant diseases. *Journal of Biological Sciences*, 2(4), 280–284.
- Haggag, W. M., & Mohamed, H. A. A. (2007). Biotechnological aspects of microorganisms used in plant biological control. *American-Eurasian Journal of Sustainable Agriculture*, 1(1), 7–12.

- Harata, K., & Kubo, Y. (2014). Ras GTPase activating protein Colra1 is involved in infection-related morphogenesis by regulating cAMP and MAPK signaling pathways through CoRas2 in *Colletotrichum orbiculare*. *PLoS One*, 9(10), e109045.
- Hayat, R., Ali, S., Amara, U., Khalid, R., & Ahmed, I. (2010). Soil beneficial bacteria and their role in plant growth promotion: A review. *Annals of Microbiology*, 60(4), 579–598.
- Herman, M. A. B., Nault, B. A., & Smart, C. D. (2008). Effects of plant growth-promoting rhizobacteria on bell pepper production and green peach aphid infestations in New York. *Crop Protection*, 27(6), 996–1002.
- Hernandez, G. (2002). Chair's comments: Biological nitrogen fixation and sustainable agriculture. *Nitrogen Fixation: Global Perspectives*, 339–342.
- Higo, M., Isobe, K., Yamaguchi, M., Drijber, R. A., Jeske, E. S., & Ishii, R. (2013). Diversity and vertical distribution of indigenous arbuscular mycorrhizal fungi under two soybean rotational systems. *Biology and Fertility of Soils*, 49(8), 1085–1096.
- Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1491), 543–555.
- Hoefsloot, G., Termorshuizen, A. J., Watt, D. A., & Cramer, M. D. (2005). Biological nitrogen fixation is not a major contributor to the nitrogen demand of a commercially grown South African sugarcane cultivar. *Plant and Soil*, 277(1–2), 85–96.
- Howard, J. B., & Rees, D. C. (1996). Structural basis of biological nitrogen fixation. *Chemical Reviews*, 96(7), 2965–2982.
- Htwe, A. Z., Moh, S. M., Soe, K. M., Moe, K., & Yamakawa, T. (2019). Effects of biofertilizer produced from *Bradyrhizobium* and *Streptomyces griseoflavus* on plant growth, nodulation, nitrogen fixation, nutrient uptake, and seed yield of mung bean, cowpea, and soybean. *Agronomy*, 9(2), 77.
- Hu, Y., Xiang, D., Veresoglou, S. D., Chen, F., Chen, Y., Hao, Z., ... Chen, B. (2014). Soil organic carbon and soil structure are driving microbial abundance and community composition across the arid and semi-arid grasslands in northern China. *Soil Biology and Biochemistry*, 77, 51–57.
- Huda, A., Gaihre, Y. K., Islam, M. R., Singh, U., Islam, M. R., Sanabria, J., & Jahiruddin, M. (2016). Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. *Nutrient Cycling in Agroecosystems*, 104(1), 53–66.
- Hynes, R. K., Chumala, P. B., Hupka, D., & Peng, G. (2010). A complex coacervate formulation for delivery of *Colletotrichum truncatum* 00–003B1. *Weed Technology*, 24(2), 185–192.
- Ibrahima, M., Adounigna, K., Amadou, H. B., Christiane, A., de, O. P., & Ivanildo, I. M. (2020). A Malian native *Azospirillum* sp. Az6-based biofertilizer improves growth and yield of both rice (*Oryza sativa* L.) and maize (*Zea mays* L.). *African Journal of Microbiology Research*, 14(7), 286–293.
- IFAD. (2012). *Climate smart smallholder agriculture: What's different?* Rome, Italy: International Fund for Agricultural Development (IFAD), No. IFAD Occasional Paper 3.
- Imaizumi, S., Nishino, T., Miyabe, K., Fujimori, T., & Yamada, M. (1997). Biological control of annual bluegrass (*Poa annua* L.) with a Japanese isolate of *Xanthomonas campestris* pv. *poae* (JT-P482). *Biological Control*, 8(1), 7–14.
- Jenkinson, D. S. (2001). The impact of humans on the nitrogen cycle, with focus on temperate arable agriculture. *Plant and Soil*, 228(1), 3–15.
- Jetiyanon, K., & Kloepper, J. W. (2002). Mixtures of plant growth-promoting rhizobacteria for induction of systemic resistance against multiple plant diseases. *Biological Control*, 24(3), 285–291.
- Jeyarajan, R., & Nakkeeran, S. (2000). *Exploitation of microorganisms and viruses as biocontrol agents for crop disease management. Biocontrol potential and its exploitation in sustainable agriculture* (pp. 95–116). Boston, MA: Springer.

- Juan, Y. A. N. G., Wei, W. A. N. G., Peng, Y. A. N. G., Bu, T. A. O., Zheng, Y. A. N. G., Zhang, L. H., & Dong, J. G. (2015). Isolation and identification of *Serratia marcescens* Ha1 and herbicidal activity of Ha1 'pesta' granular formulation. *Journal of Integrative Agriculture*, 14(7), 1348–1355.
- Kamal, N., Liu, Z., Qian, C., Wu, J., & Zhong, X. (2020). Improving hybrid *Pennisetum* growth and cadmium phytoremediation potential by using *Bacillus megaterium* BM18-2 spores as biofertilizer. *Microbiological Research*, 242, 126594.
- Kang, S. C., Ha, C. G., Lee, T. G., & Maheshwari, D. K. (2002). Solubilization of insoluble inorganic phosphates by a soil-inhabiting fungus *Fomitopsis* sp. PS 102. *Current Science*, 82, 439–442.
- Karakurt, I., Aydin, G., & Aydinler, K. (2012). Sources and mitigation of methane emissions by sectors: A critical review. *Renewable Energy*, 39(1), 40–48.
- Kaur, G., & Reddy, M. S. (2014). Influence of P-solubilizing bacteria on crop yield and soil fertility at multilocal sites. *European Journal of Soil Biology*, 61, 35–40.
- Kay, S., Rega, C., Moreno, G., den Herder, M., Palma, J. H., Borek, R., . . . Jäger, M. (2019). Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe. *Land Use Policy*, 83, 581–593.
- Kennedy, A. C., & Kremer, R. J. (1996). Microorganisms in weed control strategies. *Journal of Production Agriculture*, 9(4), 480.
- Keshavarz Zarjani, J., Aliasgharzad, N., Oustan, S., Emadi, M., & Ahmadi, A. (2013). Isolation and characterization of potassium solubilizing bacteria in some Iranian soils. *Archives of Agronomy and Soil Science*, 59(12), 1713–1723.
- Khan, M. S., Zaidi, A., & Wani, P. A. (2007). Role of phosphate-solubilizing microorganisms in sustainable agriculture—A review. *Agronomy for Sustainable Development*, 27(1), 29–43.
- Killham, K. (1994). *Soil ecology*. Cambridge University Press.
- Knox, J., Hess, T., Daccache, A., & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3), 034032.
- Kremer, R. J., Begonia, M. F. T., Stanley, L., & Lanham, E. T. (1990). Characterization of rhizobacteria associated with weed seedlings. *Applied and Environmental Microbiology*, 56(6), 1649–1655.
- Kruger, D., & Franklin, P. (2006). The methane to markets partnership: Opportunities for coal mine methane utilization. In *11th United States/North American mine ventilation symposium* (pp. 3–8).
- Kumar, A., Bahadur, I., Maurya, B. R., Raghuwanshi, R., Meena, V. S., Singh, D. K., & Dixit, J. (2015). Does a plant growth-promoting rhizobacteria enhance agricultural sustainability? *Journal of Pure and Applied Microbiology*, 9(1), 715–724.
- Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 815–830.
- Lally, R. D., Galbally, P., Moreira, A. S., Spink, J., Ryan, D., Germaine, K. J., & Dowling, D. N. (2017). Application of endophytic *Pseudomonas fluorescens* and a bacterial consortium to *Brassica napus* can increase plant height and biomass under greenhouse and field conditions. *Frontiers in Plant Science*, 8, 2193.
- Le Mer, J., & Roger, P. (2001). Production, oxidation, emission and consumption of methane by soils: A review. *European Journal of Soil Biology*, 37(1), 25–50.
- Leaungvutiviroj, C., Ruangphisarn, P., Hansanimitkul, P., Shinkawa, H., & Sasaki, K. (2010). Development of a new biofertilizer with a high capacity for N₂ fixation, phosphate and potassium solubilization and auxin production. *Bioscience, Biotechnology, and Biochemistry*, 74(5), 1098–1101.
- Lee, K. E., Adhikari, A., Kang, S. M., You, Y. H., Joo, G. J., Kim, J. H., . . . Lee, I. J. (2019). Isolation and characterization of the high silicate and phosphate solubilizing novel strain *Enterobacter ludwigii* GAK2 that promotes growth in rice plants. *Agronomy*, 9(3), 144.

- Lehmann, A., Leifheit, E. F., & Rillig, M. C. (2017). *Mycorrhizas and soil aggregation. Mycorrhizal mediation of soil* (pp. 241–262). Elsevier.
- Lehmann, J., & Joseph, S. (Eds.), (2015). *Biochar for environmental management: Science, technology and implementation*. Routledge.
- Levine, U. Y., Teal, T. K., Robertson, G. P., & Schmidt, T. M. (2011). Agriculture's impact on microbial diversity and associated fluxes of carbon dioxide and methane. *The ISME Journal*, 5(10), 1683–1691.
- Li, J., & Kremer, R. J. (2006). Growth response of weed and crop seedlings to deleterious rhizobacteria. *Biological Control*, 39(1), 58–65.
- Li, P., Zhao, P., & Brand, C. (2018). Future energy use and CO₂ emissions of urban passenger transport in China: A travel behavior and urban form-based approach. *Applied Energy*, 211, 820–842.
- Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., ... Hottle, R. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068–1072.
- Liu, D., Lian, B., & Dong, H. (2012). Isolation of *Paenibacillus* sp. and assessment of its potential for enhancing mineral weathering. *Geomicrobiology Journal*, 29(5), 413–421.
- Liu, J., Sui, Y., Yu, Z., Shi, Y., Chu, H., Jin, J., ... Wang, G. (2014). High throughput sequencing analysis of biogeographical distribution of bacterial communities in the black soils of northeast China. *Soil Biology and Biochemistry*, 70, 113–122.
- Liu, S. T., Lee, L. Y., Tai, C. Y., Hung, C. H., Chang, Y. S., Wolfram, J. H., ... Goldstein, A. H. (1992). Cloning of an *Erwinia herbicola* gene necessary for gluconic acid production and enhanced mineral phosphate solubilization in *Escherichia coli* HB101: Nucleotide sequence and probable involvement in biosynthesis of the coenzyme pyrroloquinoline quinone. *Journal of Bacteriology*, 174(18), 5814–5819.
- Liu, X., Zhang, S., & Bae, J. (2017). The nexus of renewable energy-agriculture-environment in BRICS. *Applied Energy*, 204, 489–49.
- Liu, Y., & Ludewig, U. (2020). Improved establishment of *Miscanthus* × *giganteus* stem propagation by *Herbaspirillum* inoculation. *Industrial Crops and Products*, 150, 112339.
- Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science (New York, N.Y.)*, 333(6042), 616–620.
- Lynn, T. M., Win, H. S., Kyaw, E. P., Latt, Z. K., & Yu, S. (2013). Characterization of phosphate solubilizing and potassium decomposing strains and study on their effects on tomato cultivation. *International Journal of Innovation and Applied Studies*, 3(4), 959–966.
- Ma, M., Yan, R., & Cai, W. (2017). An extended STIRPAT model-based methodology for evaluating the driving forces affecting carbon emissions in existing public building sector: Evidence from China in 2000–2015. *Natural Hazards*, 89(2), 741–756.
- Maurya, V. K., Gupta, S. K., Sharma, M., Majumder, B., Deebe, F., Pandey, N., & Pandey, V. (2020). Proteomic changes may lead to yield alteration in maize under carbon dioxide enriched condition. *3 Biotech*, 10, 1–24.
- Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, Y. Xu, (2019). Food Security. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.) *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. In press. https://www.ipcc.ch/site/assets/uploads/2019/11/08_Chapter-5.pdf.
- Meena, V. S., Bahadur, I., Maurya, B. R., Kumar, A., Meena, R. K., Meena, S. K., & Verma, J. P. (2016). *Potassium-solubilizing microorganism in evergreen agriculture: An overview. Potassium solubilizing microorganisms for sustainable agriculture* (pp. 1–20). New Delhi: Springer.

- Meharg, A. A., & Killham, K. (1989). Distribution of assimilated carbon within the plant and rhizosphere of *Lolium perenne*: Influence of temperature. *Soil Biology and Biochemistry*, 21(4), 487–489.
- Mehta, P., Walia, A., Kulshrestha, S., Chauhan, A., & Shirkot, C. K. (2015). Efficiency of plant growth-promoting P-solubilizing *Bacillus circulans* CB7 for enhancement of tomato growth under net house conditions. *Journal of Basic Microbiology*, 55(1), 33–44.
- Mortensen, K. (1988). The potential of an endemic fungus, *Collectotrichum gloeosporioides*, for biological control of round-leaved mallow (*Malva pusilla*) and velvetleaf (*Abutilon theophrasti*). *Weed Science*, 36, 473–478.
- Mpanga, I. K., Nkebiwe, P. M., Kuhlmann, M., Cozzolino, V., Piccolo, A., Geistlinger, J., & Neumann, G. (2019). The form of N supply determines plant growth promotion by P-solubilizing microorganisms in maize. *Microorganisms*, 7(2), 38.
- Myers, S. S., Zanolletti, A., Kloog, I., Huybers, P., Leakey, A. D., Bloom, A. J., & Holbrook, N. M. (2014). Increasing CO₂ threatens human nutrition. *Nature*, 510(7503), 139–142.
- Microorganisms Editorial Office. (2019). Erratum: Mpanga, IK; et al. The form of N supply determines plant growth promotion by P-solubilizing microorganisms in maize. *Microorganisms* 2019, 7, 38. *Microorganisms*, 7(4).
- Ogle, S. M., Breidt, F. J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, 72(1), 87–121.
- Pampulha, M. E., & Oliveira, A. (2006). Impact of an herbicide combination of bromoxynil and prosulfuron on soil microorganisms. *Current Microbiology*, 53(3), 238–243.
- Pandey, A., Vu, D. Q., Bui, T. P. L., Mai, T. L. A., Jensen, L. S., & de Neergaard, A. (2014). Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agriculture, Ecosystems & Environment*, 196, 137–146.
- Parewa, H. P., Yadav, J., Rakshit, A., Meena, V. S., & Karthikeyan, N. (2014). Plant growth promoting rhizobacteria enhance growth and nutrient uptake of crops. *Agriculture and Sustainable Development*, 2(2), 101–116.
- Patil, V. S. (2013). Rhizospheric bacteria with the potential for biological control of *Parthenium hysterophorus*. *Journal of Chemical, Biological and Physical Sciences (JCBPS)*, 3(4), 2679.
- Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, 532(7597), 49–57.
- Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., . . . Van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, 517(7534), 365–368.
- Podile, A. R., & Kishore, G. K. (2007). *Plant growth-promoting rhizobacteria. Plant-associated bacteria* (pp. 195–230). Dordrecht: Springer.
- Powell, J. R., & Rillig, M. C. (2018). Biodiversity of arbuscular mycorrhizal fungi and ecosystem function. *New Phytologist*, 220(4), 1059–1075.
- Powell, J. R., Welsh, A., & Hallin, S. (2015). Microbial functional diversity enhances predictive models linking environmental parameters to ecosystem properties. *Ecology*, 96(7), 1985–1993.
- Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, 4(8), 678–683.
- Pradhan, N., & Sukla, L. B. (2006). Solubilization of inorganic phosphates by fungi isolated from agriculture soil. *African Journal of Biotechnology*, 5(10).
- Prajapati, K., Sharma, M. C., & Modi, H. A. (2013). Growth promoting effect of potassium solubilizing microorganisms on *Abelmoschus esculantus*. *International Journal of Agriculture Science*, 3(1), 181–188.

- Ray, P., & Vijayachandran, L. S. (2013). Evaluation of indigenous fungal pathogens from horse purslane (*Trianthema portulacastrum*) for their relative virulence and host range assessments to select a potential mycoherbicide agent. *Weed Science*, 61(4), 580–585.
- Reay, D. S., Davidson, E. A., Smith, K. A., Smith, P., Melillo, J. M., Dentener, F., & Crutzen, P. J. (2012). Global agriculture and nitrous oxide emissions. *Nature Climate Change*, 2(6), 410–416.
- Reed, D. C., Algar, C. K., Huber, J. A., & Dick, G. J. (2014). Gene-centric approach to integrating environmental genomics and biogeochemical models. *Proceedings of the National Academy of Sciences United States of America*, 111(5), 1879–1884.
- Reis, V. M., & Teixeira, K. R. D. S. (2015). Nitrogen fixing bacteria in the family Acetobacteraceae and their role in agriculture. *Journal of Basic Microbiology*, 55(8), 931–949.
- Rejesus, R. M., Palis, F. G., Rodriguez, D. G. P., Lampayan, R. M., & Bouman, B. A. (2011). Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. *Food Policy*, 36(2), 280–288.
- Rillig, M. C., & Field, C. B. (2003). Arbuscular mycorrhizae respond to plants exposed to elevated atmospheric CO₂ as a function of soil depth. *Plant and Soil*, 254, 383–391.
- Rillig, M. C., & Mummey, D. L. (2006). Mycorrhizas and soil structure. *New Phytologist*, 171, 41–53.
- Roesch, L. F., Fulthorpe, R. R., Riva, A., Casella, G., Hadwin, A. K., Kent, A. D., ... Triplett, E. W. (2007). Pyrosequencing enumerates and contrasts soil microbial diversity. *The ISME Journal*, 1(4), 283–290.
- Rojas, Y. D. C. P., Arias, R. M., Ortiz, R. M., Aguilar, D. T., Heredia, G., & Yon, Y. R. (2019). Effects of native arbuscular mycorrhizal and phosphate-solubilizing fungi on coffee plants. *Agroforestry Systems*, 93(3), 961–972.
- Romero-Perdomo, F., Abril, J., Camelo, M., Moreno-Galván, A., Pastrana, I., Rojas-Tapias, D., & Bonilla, R. (2017). *Azotobacter chroococcum* as a potentially useful bacterial biofertilizer for cotton (*Gossypium hirsutum*): Effect in reducing N fertilization. *Revista Argentina de Microbiología*, 49(4), 377–383.
- Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., ... Neumann, K. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences United States of America*, 111(9), 3268–3273.
- Ruppel, S., Torsvik, V., Daae, F. L., Øvreås, L., & Rühlmann, J. (2007). Nitrogen availability decreases prokaryotic diversity in sandy soils. *Biology and Fertility of Soils*, 43(4), 449–459.
- Ryals, R., Hartman, M. D., Parton, W. J., DeLonge, M. S., & Silver, W. L. (2015). Long-term climate change mitigation potential with organic matter management on grasslands. *Ecological Applications*, 25(2), 531–545.
- Sakoda, M., Mizusawa, M., Shiotsu, F., Sakagami, N., Guo, Y., Masutomi, Y., & Nishizawa, T. (2019). *Azoarcus* sp. strain KH32C affects rice plant growth and the root-associated soil bacterial community in low nitrogen input paddy fields. *Soil Science and Plant Nutrition*, 65(5), 451–459.
- Sangeeth, K. P., Bhai, R. S., & Srinivasan, V. (2012). *Paenibacillus glucanolyticus*, a promising potassium solubilizing bacterium isolated from black pepper (*Piper nigrum* L.) rhizosphere. *Journal of Spices and Aromatic Crops*, 21(2), 118–124.
- Sapre, S., Gontia-Mishra, I., & Tiwari, S. (2018). *Klebsiella* sp. confers enhanced tolerance to salinity and plant growth promotion in oat seedlings (*Avena sativa*). *Microbiological Research*, 206, 25–32.
- Sarma, B. K., Yadav, S. K., Singh, S., & Singh, H. B. (2015). Microbial consortium-mediated plant defense against phytopathogens: Readdressing for enhancing efficacy. *Soil Biology and Biochemistry*, 87, 25–33.
- Sattar, A., Naveed, M., Ali, M., Zahir, Z. A., Nadeem, S. M., Yaseen, M., & Meena, H. N. (2019). Perspectives of potassium solubilizing microbes in sustainable food production system: A review. *Applied Soil Ecology*, 133, 146–159.
- Sawamoto, M. (2008). On the inside. *Plant Physiology*, 10, 104, –900246.

- Schmidt, M. W., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., ... Nannipieri, P. (2011). Persistence of soil organic matter as an ecosystem property. *Nature*, 478(7367), 49–56.
- Scholes, M. C., & Scholes, R. J. (2013). Dust unto dust. *Science (New York, N.Y.)*, 342(6158), 565–566.
- Segers, R. (1998). Methane production and methane consumption: A review of processes underlying wetland methane fluxes. *Biogeochemistry*, 41(1), 23–51.
- Shamseldin, A., Abdelkhalik, A., & Sadowsky, M. J. (2017). Recent changes to the classification of symbiotic, nitrogen-fixing, legume-associating bacteria: A review. *Symbiosis*, 71(2), 91–109.
- Sharon, J. A., Hathwaik, L. T., Glenn, G. M., Imam, S. H., & Lee, C. C. (2016). Isolation of efficient phosphate solubilizing bacteria capable of enhancing tomato plant growth. *Journal of Soil Science and Plant Nutrition*, 16(2), 525–536.
- Shcherbak, I., Millar, N., & Robertson, G. P. (2014). Global metaanalysis of the nonlinear response of soil nitrous oxide (N₂O) emissions to fertilizer nitrogen. *Proceedings of the National Academy of Sciences United States of America*, 111(25), 9199–9204.
- Sindhu, S. S., Khandelwal, A., Phour, M., & Sehwat, A. (2018). *Bioherbicidal potential of rhizosphere microorganisms for ecofriendly weed management. Role of rhizospheric microbes in soil* (pp. 331–376). Singapore: Springer.
- Six, J., AET, Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, 32(14), 2099–2103.
- Smith, K., & Mullins, C. E. (Eds.), (2000). *Soil analysis: Physical methods* (2nd ed.). London: Marcel Dekker.
- Smith P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., ... Tubiello, F. (2014). Agriculture, Forestry and Other Land Use (AFOLU). In: Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.) *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Smith, P., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., ... Ravindranath, N. H. (2014). *Agriculture, forestry and other land use (AFOLU)*.
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., ... Scholes, B. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 363(1492), 789–813.
- Smith, S. E., & Smith, F. A. (2011). Roles of arbuscular mycorrhizas in plant nutrition and growth: New paradigms from cellular to ecosystem scales. *Annual Review of Plant Biology*, 62, 227–250.
- Soba, D., Shu, T., Runion, G. B., Prior, S. A., Fritsch, F. B., Aranjuelo, I., & Sanz-Saez, A. (2020). Effects of elevated [CO₂] on photosynthesis and seed yield parameters in two soybean genotypes with contrasting water use efficiency. *Environmental and Experimental Botany*, 178, 104154.
- Solomon, S., Manning, M., Marquis, M., & Qin, D. (2007). *Climate change 2007—The physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Vol. 4). Cambridge University Press.
- Sosa-Hernández, M. A., Roy, J., Hempel, S., Kautz, T., Köpke, U., & Uksa, M. (2018). Subsoil arbuscular mycorrhizal fungal communities in arable soil differ from those in topsoil. *Soil Biology and Biochemistry*, 117, 83–86.
- Soupir, M. L., Mostaghimi, S., Yagow, E. R., Hagedorn, C., & Vaughan, D. H. (2006). Transport of fecal bacteria from poultry litter and cattle manures applied to pastureland. *Water, Air, and Soil Pollution*, 169 (1–4), 125–136.

- Sparling, G. P. (1997). Soil microbial biomass, activity and nutrient cycling as indicators of soil health. In C. E. Pankhurst, B. M. Doube, & V. S. R. Gupta (Eds.), *Biological indicators of soil health* (pp. 97–119). Wallingford, UK: CAB International.
- Stevenson, F. J. (1986). *Carbon balance of the soil and role of organic matter in soil fertility. Cycles of soil carbon, phosphorus, sulphur, micro-nutrients* (pp. 45–77). New York: Wiley.
- Storer, K., Coggan, A., Ineson, P., & Hodge, A. (2018). Arbuscular mycorrhizal fungi reduce nitrous oxide emissions from N₂O hotspots. *New Phytologist*, 220, 1285–1295.
- Tateno, A. (2000). United States Patent No. 6,162,763. Washington, DC: United States Patent and Trademark Office.
- Tausz-Posch, S., Tausz, M., & Bourgault, M. (2020). Elevated [CO₂] effects on crops: Advances in understanding acclimation, nitrogen dynamics and interactions with drought and other organisms. *Plant Biology*, 22, 38–51.
- Teng, Z., Chen, Z., Zhang, Q., Yao, Y., Song, M., & Li, M. (2019). Isolation and characterization of phosphate solubilizing bacteria from rhizosphere soils of the Yeyahu Wetland in Beijing, China. *Environmental Science and Pollution Research*, 26(33), 33976–33987.
- Trivedi, P., Anderson, I. C., & Singh, B. K. (2013). Microbial modulators of soil carbon storage: Integrating genomic and metabolic knowledge for global prediction. *Trends in Microbiology*, 21(12), 641–651.
- Tubiello, F., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., & Smith, P. (2013). The FAOSTAT database of greenhouse gas emissions from agriculture. *Environmental Research Letters*, 8(1), 015009.
- Tyagi, L., Kumari, B., & Singh, S. N. (2010). Water management—A tool for methane mitigation from irrigated paddy fields. *Science of the Total Environment*, 408(5), 1085–1090.
- USAID. (2017). *Ecosystem-based Adaptation and Food Security* (p. 8) Washington, DC, USA: United States Agency for International Development.
- van Elsas, J.D. (2019). The Soil Environment. In: van Elsas, J.D., Trevors, J.T., Rosado, A. S., Nannipieri, P. (Eds.), *Modern Soil Microbiology*, 3rd Edition, CRC Press, Boca Raton. ISBN:9780429059186. Available from: <https://doi.org/10.1201/9780429059186>
- Van Oosten, M. J., Di Stasio, E., Cirillo, V., Silletti, S., Ventrino, V., Pepe, O., . . . Maggio, A. (2018). Root inoculation with *Azotobacter chroococcum* 76A enhances tomato plants adaptation to salt stress under low N conditions. *BMC Plant Biology*, 18(1), 205.
- Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., & Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil*, 339(1–2), 35–50.
- Vargas, R., & Hattori, T. (1990). The distribution of protozoa among soil aggregates. *FEMS Microbiology Letters*, 74(1), 73–77.
- Viruel, E., Erazzú, L. E., Martínez Calsina, L., Ferrero, M. A., Lucca, M. E., & Siñeriz, F. (2014). Inoculation of maize with phosphate solubilizing bacteria: Effect on plant growth and yield. *Journal of Soil Science and Plant Nutrition*, 14(4), 819–831.
- Wagg, C., Bender, S. F., Widmer, F., & van der Heijden, M. G. (2014). Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proceedings of the National Academy of Sciences United States of America*, 111(14), 5266–5270.
- Wang, J., Wang, X., Xu, M., Feng, G., Zhang, W., Yang, X., & Huang, S. (2015). Contributions of wheat and maize residues to soil organic carbon under long-term rotation in north China. *Scientific Reports*, 5(1), 1–12.
- Wang, Y. Y., Li, P. S., Zhang, B. X., Wang, Y. P., Meng, J., Gao, Y. F., . . . Hu, X. M. (2020). Identification of phosphate-solubilizing microorganisms and determination of their phosphate-solubilizing activity and growth-promoting capability. *BioResources*, 15(2), 2560–2578.

- Welbaum, G. E., Sturz, A. V., Dong, Z., & Nowak, J. (2004). Managing soil microorganisms to improve productivity of agro-ecosystems. *Critical Reviews in Plant Sciences*, 23(2), 175–193.
- Wheeler, T., & Von Braun, J. (2013). Climate change impacts on global food security. *Science (New York, N. Y.)*, 341(6145), 508–513.
- Whipps, J. M. (2001). Microbial interactions and biocontrol in the rhizosphere. *Journal of Experimental Botany*, 52(Suppl. 1), 487–511.
- Whitman, T., Nicholson, C. F., Torres, D., & Lehmann, J. (2011). Climate change impact of biochar cook stoves in Western Kenyan farm households: System dynamics model analysis. *Environmental Science and Technology*, 45(8), 3687–3694.
- Wieder, W. R., Boehnert, J., & Bonan, G. B. (2014). Evaluating soil biogeochemistry parameterizations in Earth system models with observations. *Global Biogeochemical Cycles*, 28(3), 211–222.
- Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F. N., . . . van Vuuren, D. P. (2016). Reducing emissions from agriculture to meet the 2 C target. *Global Change Biology*, 22(12), 3859–3864.
- World Bank. (2013). Climate-smart agriculture. In T. Ngara (Ed.), UN City, Copenhagen, Denmark: Climate Technology Centre and Network.
- Wortmann, C. S., Quincke, J. A., Drijber, R. A., Mamo, M., & Franti, T. (2008). Soil microbial community change and recovery after one-time tillage of continuous no-till. *Agronomy Journal*, 100, 1681–1686.
- Xu, X., Thornton, P. E., & Post, W. M. (2013). A global analysis of soil microbial biomass carbon, nitrogen and phosphorus in terrestrial ecosystems. *Global Ecology and Biogeography*, 22(6), 737–749.
- Yandoc, C. B., Rosskopf, E. N., Pitelli, R. L. C. M., & Charudattan, R. (2006). Effect of selected pesticides on conidial germination and mycelial growth of *Dactylaria higginsii*, a potential bioherbicide for purple nutsedge (*Cyperus rotundus*). *Weed Technology*, 20(1), 255–260.
- Yang, P., & van Elsas, J. D. (2018). Mechanisms and ecological implications of the movement of bacteria in soil. *Applied Soil Ecology*, 129, 112–120.
- Young, I. M., & Crawford, J. W. (2004). Interactions and self-organization in the soil-microbe complex. *Science (New York, N.Y.)*, 304(5677), 1634–1637.
- Youssef, G. H., Seddik, W. M., & Osman, M. A. (2010). Efficiency of natural minerals in presence of different nitrogen forms and potassium dissolving bacteria on peanut and sesame yields. *Journal of American Science*, 6(11), 647–660.
- Zavaleta, E. S., Pasari, J. R., Hulvey, K. B., & Tilman, G. D. (2010). Sustaining multiple ecosystem functions in grassland communities requires higher biodiversity. *Proceedings of the National Academy of Sciences United States of America*, 107(4), 1443–1446.
- Zdor, R. E., Alexander, C. M., & Kremer, R. J. (2005). Weed suppression by deleterious rhizobacteria is affected by formulation and soil properties. *Communications in Soil Science and Plant Analysis*, 36(9–10), 1289–1299.
- Zelles, L., Bai, Q. Y., Beck, T., & Besse, F. (1992). Signature fatty acids in phospholipids and lipopolysaccharides as indicators of microbial biomass and community structure in agricultural soils. *Soil Biology & Biochemistry*, 24, 317–323.
- Zermane, N., Souissi, T., Kroschel, J., & Sikora, R. (2007). Biocontrol of broomrape (*Orobanche crenata* Forsk. and *Orobanche foetida* Poir.) by *Pseudomonas fluorescens* isolate Bf7–9 from the faba bean rhizosphere. *Biocontrol Science and Technology*, 17(5), 483–497.
- Zhang, C., & Kong, F. (2014). Isolation and identification of potassium-solubilizing bacteria from tobacco rhizospheric soil and their effect on tobacco plants. *Applied Soil Ecology*, 82, 18–25.
- Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, 528(7580), 51–59.

- Zhang, Y., Chen, F. S., Wu, X. Q., Luan, F. G., Zhang, L. P., Fang, X. M., ... Ye, J. R. (2018). Isolation and characterization of two phosphate-solubilizing fungi from rhizosphere soil of moso bamboo and their functional capacities when exposed to different phosphorus sources and pH environments. *PLoS One*, *13*(7), e0199625.
- Zhou, J., Deng, Y., Shen, L., Wen, C., Yan, Q., Ning, D., & Brown, J. H. (2016). Temperature mediates continental-scale diversity of microbes in forest soils. *Nature Communications*, *7*(1), 1–10.
- Zidack, N. K., & Quimby, P. C., Jr (2002). Formulation of bacteria for biological weed control using the Stabileze method. *Biocontrol Science and Technology*, *12*(1), 67–74.
- Zörb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture—status and perspectives. *Journal of Plant Physiology*, *171*(9), 656–669.

Further reading

- Rousk, J., Bååth, E., Brookes, P. C., Lauber, C. L., Lozupone, C., Caporaso, J. G., & Fierer, N. (2010). Soil bacterial and fungal communities across a pH gradient in an arable soil. *The ISME Journal*, *4*(10), 1340–1351.