

Microbial Based Land Restoration Handbook

Plant-microbe interaction is a powerful and promising link to mitigate the various kinds of stresses like drought, salinity, heavy metals, and pathogenic effects. It is more beneficial for crop improvement and sustainable approaches for reclamation of problematic soils. Taking a multidisciplinary approach, this book explores the recent uses of plant-microbe interactions in ecological and agricultural revitalization beyond normal agriculture practices and offers practical and applied solutions for the restoration of degraded land to fulfill human needs with food, fodder, fuel, and fiber. It provides a single comprehensive platform for soil scientists, agriculture specialists, ecologists, and those in related disciplines.

Features

- Presents cutting-edge microbial biotechnology as a tool for restoring degraded lands
- Explores the aspects of sustainable development of degraded lands using microbe inspired land remediation
- Highlights sustainable food production intensification in nutrient poor lands through the innovative use of microbial inoculants
- Explains the remediation of polluted land for regaining biodiversity and achieving United Nations Sustainable Development Goals
- Includes many real-life applications from South Asia offering solutions to today's agricultural problems

This book will be of interest to professionals, researchers, and students in environmental, soil, and agricultural sciences, as well as stakeholders, policy makers, and practitioners with an interest in this field.

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Microbial Based Land Restoration Handbook

VOLUME 1

Plant-Microbial Interaction and Soil Remediation

Edited by
Umesh Pankaj and Vimal Chandra Pandey



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Dedication

This book is dedicated to our beloved mothers.

—Umesh Pankaj and Vimal Chandra Pandey

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13 Plant-Soil-Microbe Interaction for Organic Production of Oilseeds

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13.1 INTRODUCTION

Organic crop production concerns the use of natural materials for plant nutrition in association with limited eco-friendly pesticides, along with ecological engineering concepts. Use of inorganic nutrient sources and/or pesticides, even though they have contributed to food production, established significant adverse effects on soil fertility, as well as macro- and microfauna biodiversity. The issue has assumed center stage since it has been established that the use of inorganic chemical nutrients has decelerated the soil microbial growth vigor (Wang et al. 2018), led to a reduction in composition (Fierer et al. 2012), impacted the diversity of soil microbial population, particularly the bacterial communities (Li et al. 2014; Huang et al. 2019), and could weaken the plant-microbe linkages since carbon from plant biomass is sparsely available to microbes (Huang et al. 2019). Relative abundance of Proteobacteria and Actinobacteria was positively correlated with the chemical N application rate, while a reverse in Chloroflexi in sesame (Wang et al. 2018) and Acidobacteria (Ramirez et al. 2012) has been noticed. Hence, the typical role of microbes is considered to be an acceptable solution to plant nutrition, and microbial biocontrol approaches have been

recognized for pest and disease management globally. Soil microbiota, which primarily involves beneficial bacteria and fungi, has diverse modes of action. Culturable microbes isolated and cultured from this source are reported to contain little or no toxic compounds to non-target species as well as human beings; albeit the successful use depends on sound awareness of the physiological reaction of plants to the bioagents. The plant-microbe generally establish an intimate, dynamic relationship that allows them to coexist (Nihorimbere et al. 2011) through synergistic effect (Mendes et al. 2011) to boost plant health. To further understand the processes, an understanding of the Tritrophic relationship between the soil, plant and the microbes is required.

In essence, soil microbes have a central role to play in controlling soil health and preserving plant quality. The techniques that manipulate soil microbiota are required to make the conducive soil into a suppressive one. This can also be accomplished by supplementing exogenous microbiota provided by selective biocontrol agents, organic amendments, for example, compost. Restoration of soil fertility and promotion of soil suppressiveness have been reported as a result of organic manure applications. Furthermore, integration of organic amendments and biocontrol agents effectively manage several soilborne pathogens. Research conducted elsewhere in the world has indicated that rhizosphere inhabiting microorganisms are a potential and effective management tactic to manage pests and diseases (Kerry 2000), besides serving as a supply of plant nutrients. This chapter explores the microbial biodiversity of oilseed crops, their mechanism of nutrient availability and abiotic and biotic stress mitigation in oilseed crops, and the tritrophic interactions between soil, plant and microbes.

13.2 MICROBIAL DIVERSITY IN OILSEED CROP SOIL ECOLOGY

The soil ecosystem around the plant root system is regarded as one of the most active interfaces on earth (Berendsen et al. 2012), where nutrient related interactions takes place between plants, soil and microbes, particularly the bacterial community in the rhizosphere (Jiménez et al. 2020). Depending on the terrestrial microhabitat of the organisms, their behavior and interaction with other organisms varies. Among the different microbes, rhizobacteria and mycorrhizal fungi are the most influential class in the rhizosphere, reported to take part in soil aggregation at various levels (Rillig and Mummey 2006). Diversity of microbiomes has been well documented in oilseed based production systems. Groundnut and soybean, two important leguminous oilseed crops inherently associated with bacterial strains through nodule-bacteria symbiosis to fix atmospheric nitrogen. *Chloroflexi*, *Acidobacteria*, *Actinobacteria*, and *Proteobacteria* (Levy et al. 2018) are the common phylae associated with oilseed crops. Among them, *Acidobacteria* is the most abundant phylae found in the terrestrial ecosystem (Barns et al. 1999). A wide variety of bacterial species associated with soybean rhizosphere is enriched with bacterial species through the nodule-bacteria association (Ziegler et al. 2013), which produces siderophores for aiding phosphate solubilization and nitrogen fixation. Other than Bradyrhizobium, rhizosphere fungal communities with highest abundance of Ascomycota and Basidiomycota were noticed (Sugiyama, 2019). A few specific microbes found in groundnut rhizosphere are *Alcaligenes faecalis*, *Agrobacterium tumefaciens*, *Azotobacter chroococcum*, *Aerobacter aerogenes*, *Bacillus subtilis*, *B. cereus*, *Citrobacter freundii*, *Clostridium*

perfringens, *Enterobacter aerogenes*, *Flavobacterium lutescens*, *Klebsiella pneumoniae*, *Micrococcus varians*, *M. luteus*, *Proteus vulgaris*, *Pseudomonas fluorescens*, *P. aeruginosa*, *Streptococcus faecalis*, *S. pyogenes*, *Rhizobium japonicum* and *Serratia marcescens* in a sandy loam soil (Babadoko and Pacy 2011).

Irrespective of the nutrient source, the population of Proteobacteria was multiplied linearly with plant-derived carbon substrates (Philippot et al. 2013), needing further exploration (Wang et al. 2018) in sesame soils. A little over 189 plant growth promoting endophytic bacteria have been reported in Sunflower (leaves, stems, flowers and roots) in its short span of a life cycle (Bashir et al. 2020) of one-fourth of a year. Bacterial strains belonging to *Klebsiella*, *Enterobacter*, *Novosphingobium*, *Asticcacaulis*, *Grimontella*, *Microbacterium*, *Pantoea*, *Acinetobacter*, *Chryseobacterium*, *Herbaspirillum*, *Variovorax*, *Moraxella*, *Mitsuaria*, *Shinella*, *Sphingobium*, *Serratia* and *Xanthomonas* (Ambrosini et al. 2012) as well as *Enterobacter* and *Burkholderia* were noticed in sunflower. Recently, phosphorus mobilizer *Alcaligenes faecalis* has also been isolated by Shahid et al. (2012) from the roots of sunflower. It is of particular interest to note that microbiomes associated with soybean (Xu et al. 2009) and canola (Farina et al. 2012) remained dynamic at various growth stages of the plant, possibly due to nutritional balances (Chaparro et al. 2013). A high abundance of Proteobacteria, Actinobacteria and Bacteroidetes were noticed in Canola (Cordero et al. 2020). *Bacillus brevis*, *B. amyloliquefaciens*, *B. megaterium*, *Erwinia amylovora*, *P. fluorescens*, *P. chlororaphis*, *P. putida*, *P. marginalis*, *P. syringae*, *Micrococcus luteus*, *Comamonas acidovorans* (Graner et al. 2003), *Agrobacterium*, *Burkholderia*, *Enterobacter* (Dunfield and Germida, 2003), *Serratia plymuthica* and *S. proteamaculans* (Abuamsha et al. 2011) have been reported in oilseed rape. For example, canola harbored 20% more microbes at the rosette stage over the normal population and decreased as the plant approach senescence stage. Analysis of canola microbiome revealed the abundance of *Enterobacter*, *Burkholderia*, *Agrobacterium* and *Pseudomonas* genera (Farina et al. 2012), with the majority belonging to the *Proteobacteria* phylum.

Soybean, accommodated more bacterial communities during the seedling stage than maturity stage with abundance of the phyla *Actinobacteria*, *Acidobacteria*, *Proteobacteria* (Wang et al. 2020) *Bacteroidetes*, *Nitrospirae*, *Firmicutes* and *Verrucomicrobia* (Xu et al. 2009). *Acidobacteria* plays a pivotal role in carbon cycling through degradation of plant parts, including cellulose and lignin. Notwithstanding this fact, their relationship in the rhizosphere is yet to be explored (Ward et al. 2009). *Proteobacteria* and *Actinobacteria* genera have been demonstrated to exhibit traits associated with the plant disease suppression (Mendes et al. 2011), while *Bacteroidetes* have a significant role in nitrogen cycling by denitrification (Chaparro et al. 2012).

13.3 PLANT-SOIL-MICROBE: TRITROPHIC INTERACTION

13.3.1 SOIL-MICROBE INTERACTIONS

Soil is a warehouse of microbes to the tune of 1×10^4 to 5×10^5 , can be detected per gram of soil, the diversity of which varies with soil texture and nutrient composition (Schloss and Handelsman 2006). The majority of the complex rhizosphere microbiome

food webs are reliant on the plant released nutrients (Mendes et al. 2013). Soil pH, nutrient content and temperature do play a key role in the soil microbial composition and population. It has also been reported that soil deficit in micronutrients render the plants more susceptible to the pathogens infection. For example, lowering the concentration of secondary (Ca and Mg) and micro nutrients (Na and Fe) and increasing the concentration of K, Cu and Zn in the soil was found to minimize the root rot incidence (*Macrophomina phaseolina*) in sesame (Narayanaswamy and Gokulakumar 2010). Manganese is one of the key elements that make the plants immune to the pathogens through inhibition of the induction of aminopeptidase, an enzyme essential for fungal growth (Dordas 2008). Soil deficit in manganese (Mn) decrease the metabolism of nitrogen and affects photosynthetic rate of the plants. This can be corrected by the addition of *B. subtilis* to the soil that reduce Mn^{4+} to Mn^{2+} , which can easily be taken up by the plants. When entered into the plant system, the reduced form of Mn strengthens the plant defense mechanism (Hoagland and Arnon 1938).

The beneficial effects of arbuscular mycorrhizal fungi (Gianinazzi et al. 2010) may influence CO_2 fixation by plants, through an increase in the “sink effect” and supply of photo-assimilates to the roots (Begum et al. 2019). Soilborne fungi deposits metabolites into the soil and affects the beneficial microbes’ density. Addition of micronutrients to the soil eliminates this issue by suppressing the effect of pathogenic species in the soil. The investigation of Duffy and Defago (1997) confirmed that whenever the external supplementation limited the soil micronutrient zinc, it resulted in a drastic reduction in the composition of fusaric acid produced by *Fusarium oxysporum* f.sp. *radices-lycopersici* and enhanced the antibiotic production of *P. fluorescens* CHAO.

Soil salinity is another factor limiting the oilseed productivity that can be managed through the application of salt tolerant PGPR (Rodriguez and Redman 2008). Under salinity, due to the elevated level of Na^+ , growth of the plant and uptake of K will be affected (Islam et al. 2015). Application of salt tolerant PGPR protects the plants from harmful effects of excessive concentration of Na^+ by binding Na^+ in the root zone through the production of exopolysaccharides and biofilms (Qurashi and Sabri 2012). Application of PGPR under salt stress conditions is reported to improve the availability of N, P, K, Zn, Fe, Cu and Mn, macro- and micronutrients. The key appliance of disease suppression by the microbes, antibiosis and competition could not be easily transferred from one soil unit to another, whereas the unique clamp-down effect triggered by parasitism and predation is easily transferable between soils, as it involves only a few microbial taxonomic classes. Thus, soil properties play a significant role in the suppression of soilborne disease causing microbes, either directly or indirectly, due to the close association of several factors. Knowledge of soil factors is very important for the adaption of biocontrol treatments in various soil environments. It will also provide a basis for the inclusion of biocontrol agents with the best agronomic practices to exploit and manipulate the soil microbiota for improvised disease control.

13.3.2 MECHANISMS

While contact between microbes and plants occur at every phase of plant growth and development by signaling molecules, when soil is also taken into account,

biochemical, physiological and molecular processes also come into the picture. In principle, plants, typically transfer about 20 to 40% of photosynthetically fixed carbon to their roots in order to sustain root growth. Biochemically, plants produce an array of compounds with different molecular weights, as released as root exudates, which are used as cues for attraction of soil microbes (Haichar et al. 2014). Thus, the root system plays a crucial role in interacting with the microbe-soil complex, functions as a chemical factory and mediates this interaction. In return, these microbes interact with the plant in various ways, as the plant released volatile compounds are made up of CO₂, alcohol and aldehydes (Dudareva et al. 2004). To access nitrogen from the soil, plants are reliant on soil microbes, which possess the metabolic routes to depolymerize and convert the organic forms of N (Bonkowski 2004; Richardson et al. 2009) under organically managed conditions.

The chemical composition of root secretions and its type can alter the microbial diversity of the soil and may prevent the population spurt of harmful microbes; hence, the importance of root and microbe secretion is increasingly recognized (De-la-Peña and Loyola-Vargas 2014). The plant roots may also secrete strigolactones, a terpenoid and flavonoids (Bais et al. 2006; Venturi and Fuqua 2013; Massalha et al. 2017), besides carbohydrates, organic acids, vitamins and are reported to attract and support the beneficial bacteria development such as *Enterobacter cloacae* in the spermosphere and rhizosphere for their carbon requirement (Madhaiyan et al. 2010). As a complementary interaction, the microbes release volatile phytohormones promoting plant growth and bestow immunity to the plants. Rhizodeposits produced account from 5 to 30% of the total plant fixed C (Bekku et al. 1997; Hutsch et al. 2002; Dennis et al. 2010) into their direct surroundings; spermosphere, phyllosphere, rhizosphere and mycorrhizosphere (Frey-Klett et al. 2007; Raaijmakers et al. 2009; Vorholt 2012) are found to be the main sources of organic carbon that attract microbes toward them (Whipps 1990). Plants identify those compounds released by the microbes and change their growth and defense responses accordingly (Bais et al. 2006).

The compounds released by the plants may either be low molecular weight compounds (sugars and simple polysaccharides such as fructose, glucose, maltose, mannose, etc., amino acids such as arginine, aspartic, cysteine and glutamine; organic acids viz., acetic acid, ascorbic, benzoic and malic acids and phenolic compounds) or high molecular weight compounds (mucilage and proteins), which serve as signaling molecules to attract microbes since microbes use these compounds as carbon source for their nutrition (Schulz and Dickschat 2007). ATP-binding cassette (ABC) transporters have a significant role to play in the development of exudate compounds (Badri et al. 2008), which are primarily released through diffusion, vesicle transportation and ion exchange (Neuman and Romheld 2007) from the plant roots. It is an interesting phenomenon that when a pathogen infests a plant, it damages root cells and allows the mucilage to escape, which raises the amount of carbon in the rhizosphere, and attracts the beneficial microbes (Campbell and Greaves 1990) toward the roots. Any change in the composition of root exudates can, therefore, alter the diversity of soil microbial consortia. Chemotaxis is yet another process through which the roots release carbohydrates and amino acids to attract the beneficial microbes (Somers et al. 2004).

Plants physiologically change their rhizosphere under unfavorable conditions to allow the microbes to colonize the root zone. Under waterlogged conditions, soil could not hold oxygen within its particles. Physiological alteration of the plants during such adverse conditions contributes oxygen to the rhizosphere, which are otherwise utilized by the rhizosphere microbes. Under these oxygen rich environments, iron loving bacteria uses the excess free oxygen to oxidize the soluble mineral FeS, and Fe plaque gets precipitated on the root surfaces as oxidized coatings (Uren 2007). Due to the accumulation of iron on the surface of rhizosphere, plants can easily get Fe out of the soil. The other physiological adaptation includes acidification of the rhizosphere, which is possible through the reduction of pH a variety of ways, for example, reduction of insoluble manganese oxide by the roots and the production of organic acids (Figure 13.1). These metabolites serve as signaling molecules that help the colonization of microbes by the rhizosphere (Berg and Smalla 2009). Microbes also use quorum-sensing mechanisms to change their metabolism. Plants secrete a number of chemicals that mimic the quorum signals provided by the bacteria that lead to the alteration of bacterial activity in the rhizosphere (Bauer and Mathesius 2004). Since rhizosphere microbes *viz.*, *Pseudomonas*, *Bacillus*, *Paenibacillus*, actinomycetes and arbuscular mycorrhizal fungi and (AMF) enhance nutrient absorption (Cummings, 2009), as well as resistance to biotic (De Vleeschauwer and Hofte 2009) and abiotic stresses (Zhang et al. 2008; Berendsen et al. 2012; Selvakumar et al. 2012) termed rhizosphere soil microbiomes and the associated microbial community as the second genome of the plant.

Production of the iron chelating compound for e.g. siderophores, commonly produced by fungi as well as bacteria, is pronounced in fluorescent pseudomonads known for the suppression of soilborne pathogenic microbes. Uptake of ferric ion

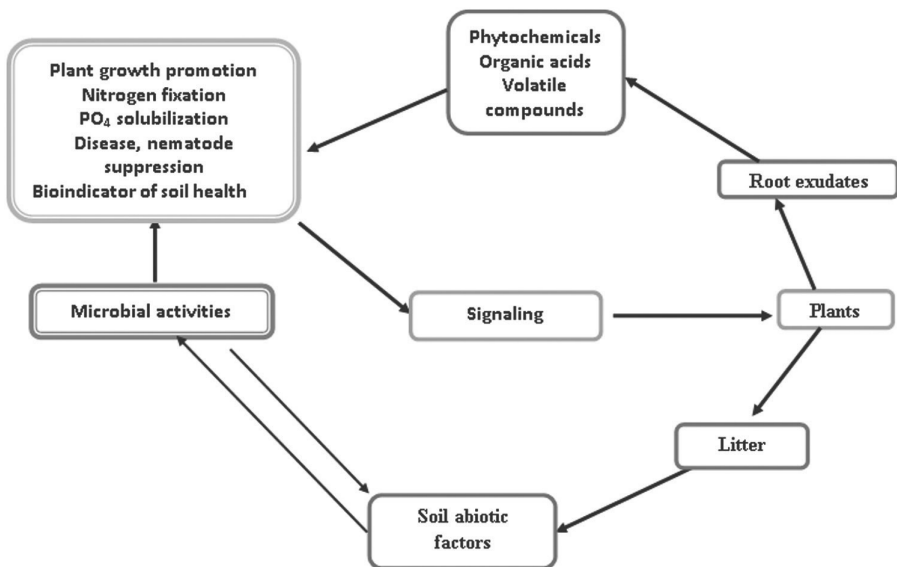


FIGURE 13.1 Role of soil microorganism in plant growth and molecular signaling.

(Fe³⁺) from the soil into their cells renders the iron inaccessible to the pathogens, which creates a competition (Kloepper et al. 1999) between *Pseudomonas* and pathogens for nutrients. The 3-hydroxy-2-butanone, an elicitor compound production by the *Bacillus* spp. provided a persuasive effect on the infestation of the pathogens (Rudrappa et al. 2008). Another significant plant-soil-microbe interaction is through fixation of atmospheric nitrogen (von der Weid et al. 2002) and solubilization of phosphorus (Deepa et al. 2010).

The essential components of soil nitrogen cycle are mineralization and immobilization of nitrogen by soil microbes. Microbial enzymes breakdown organic nitrogenous molecules to produce ammonia (NH₃), which increases the quantity of plant-available nitrogen in soils. A proportion of the nitrogen in the transformed organic material is utilized by microbial tissue, while the rest is liberated (mineralized) as inorganic nitrogen. Some of the genus of nitrogen fixing bacteria includes *Alcaligenes*, *Beijerinckia*, *Campylobacter*, *Derxia*, (Rennie 1980), *Azospirillum*, (Li and Castellano 1987), *Klebsiella*, *Pantoea*, *Bacillus*, *Azotobacter* (Kennedy et al. 1997), *Pseudomonas*, and *Burkholderia*. In general, summer recorded the largest population of ammonifying bacteria in soil under diverse crops, while winter reported the lowest. Insoluble IP, such as Ca₃(PO₄)₂, AlPO₄, and FePO₄, as well as insoluble/soluble organic phosphorus (OP), such as phytate, which accounts for 80% of soil OP, require phosphorus-solubilizing microorganisms (PSM) to convert into orthophosphate, which may be taken by plants and bacteria. The majority of P in soils exists in inorganic insoluble form (Ca₃(PO₄)₂) and organic insoluble/soluble form (phytate and nucleic acid) and, hence, only a small amount can be directly digested by plants (Neal et al., 2017). To solubilize the insoluble inorganic phosphates as well as insoluble/soluble organic phosphates, phosphorus-solubilizing microorganisms (PSM) are essential, which convert insoluble form into orthophosphate, which may be taken by the plants. Fertilizer use degrades soil quality and decreases phosphorus availability (Liu et al. 2018). Application of phosphorus solubilizing microorganisms with multiple P source using abilities gives a new strategy to improving soil quality in order to reach the goal of sustainable agriculture.

PGPR plays a crucial mechanism of reducing the quantum of ethylene in the plants during stress condition since its production (Glick et al. 2007) accelerates due to the accumulation of 1-aminocyclopropane-1-carboxylic acid (ACC), a precursor in the biosynthetic pathway of ethylene (Zapata et al. 2017). This interrupts normal functioning of the plant through impairment in the root growth (Figure 13.1). When PGPR are integrated, they release ACC deaminase and disintegrate and α -ketobutyrate (Singh et al. 2015), thus reducing ethylene concentration in the root zone and root growth is not compromised (Glick et al. 2007). Furthermore, in the plant roots, synthesis of indole acetic acid, activates the enzyme ACC synthase to transform S-adenosylmethionine to ACC (Gravel et al. 2007), which is subsequently absorbed by PGPR through root exudation and ultimately disintegrates through bacterial ACC deaminase, thus preventing the plant from suffering the negative effects of ethylene (Yaish et al. 2015). Yang et al. (2008) were of the optimistic view that PGPR usage might reduce the external application of fertilizers.

A wide range of microorganisms use the mechanism of competition toward the ecological niches and food through which they contribute to the reduction of

pathogen infestation. Compounds released by root exudates in response to the chemical signals from soil microbes are a function of soil type (Rovira 1969), biotic, abiotic components (Tang et al. 1995) and plant age (De-la-Pena et al. 2010). As they are associated by identifying the compounds secreted by the roots against particular beneficial microbes, it may be possible to culture the beneficial microbes on their own in the roots that provide protection from deleterious species.

13.4 SOIL-PLANT-MICROBE: POSSIBLE INTERVENTIONS

13.4.1 MANAGEMENT INTERVENTIONS

In developing a successful organic farming protocol, development of a complex microbiome network in a phylogenetic context is the key for a high degree of negative correlation between the biocontrol microbes and disease causing organisms. Utilization of PGPR, which could be a major component of integrated nutrient management program (Yang et al. 2008), has been articulated in the recent past. Endophytic asymbiotic diazotrophic bacteria reported to fix atmospheric nitrogen in canola (Puri et al. 2016) could well be integrated in the organic package for nitrogen supplementation. Disease suppression is a significant phenomenon of healthy soil induced by soil microbes through the combined antagonistic mechanisms of the microbes. In healthy soil, soil microbiota interact with soil organic matter to achieve synergistic results in disease suppression and strengthening the soil structure (Bronick and Lal 2005) through increased microbial activity (Bulluck et al. 2002). The presence of various microbial biomes in the soil provide basal protection against a wide range of biotic stresses and hence become an essential component in the determination of soil health (Kibblewhite et al. 2008). Supplementation of selected beneficial microbiota, along with organic substrates for their proliferation increase suppression against soilborne pathogens (Puglisi et al. 2009) with a rider that efficacy vary, depending on the soil pathogen density (Ruano-Rosa and Mercado-Blanco 2015). In contrast, organic amendments could improve disease severity (Bonanomi et al. 2007) under rare circumstances. Synergistic interaction of microbes is a natural phenomenon seen in organic soil through which many soilborne pathogen are suppressed (Wan et al. 2017).

Compost is typically rich in nutrients with bountiful microbes possibly triggering the process of resistance against various soilborne pathogens. Few notable references include resistance to *F. oxysporum* f.sp. *melonis* in vegetable by sewage sludge compost (Cotxarrera et al. 2002) and *V. dahliae* of cotton by olive mill compost (Aviles and Borrero 2017) through enhanced microbial activity (Berendsen et al. 2012). These soils are typically colonized by a wide group of microorganisms from which several strains have been documented to induce resistance against abiotic stresses (Melero-Vara et al. 2011). Efficiency of beneficial microbes in the soil is a function of physicochemical properties of organic matter such as pH, electrical conductivity, presence of macro and micronutrients content and the pathogen load in the soil (Hadar and Papadopoulou 2012). Use efficiency of cheap sources of P, namely rock phosphates, was improved along with organic amendments and P solubilizers viz., *Aspergillus awamorii*, *P. striata* and *B. polymyxa* meeting P nutrition of

soybean and mustard crops (Qureshi and Narayanasamay 1999 and Qureshi and Narayanasamy 2005). Despite conflicting information, integrated management strategies with the combined use of organic amendments, biocontrol agents and biofertilizers will certainly provide control of various soilborne pathogens (Cretoiu et al. 2013; Zhang et al. 2014). Pre-fumigation of soil combined with the incorporation of organic amendments and/or bio fertilizers induce shifts in the soil microbiota population, which play a crucial role in the control of soilborne pathogens (Deng et al. 2019).

Hence, pre fumigation with composts, biochar and undecomposed plant residues followed by the addition of plant residues, either alone or with organic amendments or biocontrol agents (Himmelstein et al. 2014; Torres et al. 2015), increases disease suppressiveness, thereby suggesting possible recovery in the fertility of the soil. Evidence shows that soil pre-fumigation with ammonium bicarbonate, along with compost, impaired *Ralstonia solanacearum*, through alteration of the beneficial bacterial and fungal population in the soil and spurt in new beneficial taxa (Antoniou et al. 2017). Addition of compost added macro- and micronutrients to the soil (Evanylo et al. 2008) also improved organic carbon content in the soil (Hemmat et al. 2010), its structure (Celik et al. 2004) and water-holding capacity (Caravaca et al. 2002), thereby raising the crop productivity (Zaccardelli et al. 2013) through containment of the soilborne pathogens (De Corato 2020). Compost may enhance soil microbiota (Zhen et al. 2014), decrease it (Martinez Blanco et al. 2013) or leave it unaffected (Nair and Ngouajio 2012). Addition of green compost, either agro or agro industries wastes, accounted for a greater diversity of microorganism functioning against *Verticillium*, *Rhizoctonia*, *Pythium* and *Phytophthora*. Composted animal manure has been reported to suppress *Fusarium* wilt, as it contains *Trichoderma*, *Aspergillus*, *Penicillium*, *Streptomyces*, *Pseudomonas* and *Bacillus* (Xiong et al. 2017). However, to be a successful biocontrol agent, its stability under field conditions is essential for evaluating its efficacy (Sommermann et al. 2018). However, it is postulated that long term supplementation of plant residues combined with biocontrol agents could manipulate soil microbiota (Yang et al. 2019)

Incorporation of organic amendments certainly modifies the soil microbiota community (De Corato 2020). Adding compost helps the growth of abundant soil microbiota populations. Amplicon sequence of compost derived microorganisms showed a wide abundance and diversity of bacterial and fungal species (De Corato et al. 2019) in the composted soil. Sustainable production of oilseed to satisfy rising demand is a herculean task. Biotic and abiotic stress exerted on the crop contributes to a greater rise in the crop yield reductions (Selvakumar et al. 2012). Inoculation of oilseed crops with beneficial microbes improves crop production. Among the numerous microorganisms, plant growth promoting rhizobacteria is a versatile community of complex bacterial taxa capable of promoting the supply of plant nutrients, growth and disease suppression (Morrison et al. 2017). Manipulation of soil microbiome in the oilseed ecosystem would support the plant by increasing plant production and decreasing the biotic and abiotic stresses imposed on them. Inoculation of *P. fluorescens* strain, LBUM677 in Canola (*Brassica napus*), Soybean (*Glycine max*) and Corn gromwell (*Buglossoides arvensis*) was reported to improve oil yield (Cumberford and Hebard 2015), in addition to plant growth promotion effects.

Generally, oilseed crops grown under stressful conditions suffer iron deficiency. Inoculation of PGPR allows the plants to extract more micronutrient element iron from the soil environment in order to reduce the harmful effects of stress. Recently, inoculation of microbes in the rhizosphere has been suggested to minimize heavy metals and salt stress by enhancing the antioxidant enzyme (Islam et al. 2015). *Paenibacillus polymyxa* P2b-2R, an endophytic diazotroph isolated from lodge pole pine tree tested on canola increased biomass by 27% 2 months after bacterial inoculation which could fix around 20% of atmospheric nitrogen (Puri et al. 2016). Inclusion of plant growth promoting microbes in the crop packages helps the plant through the systemic activation of defense mechanisms against pests and pathogens. Application of PGPRs are reported to activate the defense genes such as chitinase, proteinase inhibitors and lipoxygenase to protect the plant from infection (Saravanakumar et al. 2007) in peanut and dual inoculation of sulfur oxidizing bacteria, along with *Ochrobactrum intermedium* (Paulucci et al. 2015) was also beneficial. Further complementary interaction between S-oxidizing bacteria and rhizobia promoted the oil content of groundnut grown in sulfur deficit soils (Anandham et al. 2007). Antagonistic rhizobacteria must be predominant in rhizosphere soils of sunflower (Rangeshwaran and Prasad 2000) in order to contain *Sclerotium* rot of sunflower.

The sunflower crop is mainly prone to water and salinity stress besides the accumulation of heavy metals which limit crop productivity (Ali et al. 2013). Sunflower growth is also impaired by the deficiency of nitrogen (Dordas and Sioulas, 2008). Jalilian et al. (2012) observed improved productivity of sunflowers when microbes were inoculated in combination with N fertilizers, in addition to upgrading plant water status (Singh et al. 2015). Inoculation of PGP bacteria strains, *Pseudomonas fluorescens* biotype F and *P. fluorescens* CECT 378T were reported to alleviate salinity-induced stress in sunflowers (Kiani et al. 2016). Similarly, the PGPR strains, *Ralstonia eutropha* (B1) and *Chrysiobacterium humi* (B2) protected the crop from metal toxicity by preventing the crop from the uptake of heavy metals viz., Zn and Cd (Ana et al. 2013).

Inoculation of *B. licheniformis* MML2501, *Bacillus* sp. MML2551 and *P. aeruginosa* MML2212 reduced sunflower necrosis disease (SND), which otherwise reduced sunflower productivity by 90% (Bhat et al. 2002; Lavanya et al. 2005). Wherever salinity is a threat to soybean production impairing crop yield (Rahman et al. 2008), either inoculation of PGPR improved crop growth (Kang et al. 2014) through the regulation of stress hormones or through PGPR interaction with *Rhizobium* spp. (Drogué et al. 2013). The beneficial association of PGPR strains viz., *Streptomyces* (Tokala et al. 2002), *Azotobacter* (Wu et al. 2012), *Bacillus* (Atieno et al. 2012), *Serratia* (Zahir et al. 2016), *Azospirillum* (Aung et al. 2013) has been reported, in addition to *Bradyrhizobium diazoefficiens* USDA110 and *B. japonicum* THA6 (Prakamhang et al. 2015). An improvement in the number of root hairs and nodules and secretions of flavonoids was found when Rhizobia was co-inoculated with PGPR over rhizobia inoculation alone (Ramans et al. 2008). Hence, it has been proposed that inoculation of mixture of suitable strains would be more successful for soybean than the inoculation of single bacterial strains.

When performing artificial inoculation experiments, emphasis should be given to the impact of artificially inoculated microbes on the modification of native microbial

populations. This knowledge is important firstly, to study the adverse effects of inoculated microbiota on natural soil microbial communities and secondly, to consider the indirect effect of inoculated PGPR strains on the plants. Experimental and technical methodology used to describe the effect of PGPR on soil microbiome is an important consideration to be taken into account when analyzing the findings of such studies. Supplementation of bioagents could mobilize soil nutrients and reduce the need of fertilizer application. Soil microbiota, through the production of secondary metabolite compounds, such as 2,4-DAPG (Raaijmakers et al. 1997), iturin and surfactin (Kinsella et al. 2009), tubercidin, phosphalactomycin, candicidin (Shekhar et al. 2006) and lytic enzymes such as β -1,3-glucanase, chitinase, hydrolases and chitinase (De La Cruz et al. 1993) could allow a strong binding with the plants toward the suppression of pathogens. As an added benefit, growth hormones, auxin (Da Mota et al. 2008) and cytokinin (Timmusk et al. 1993) are also produced, which impart indirect resistance to the plants against abiotic and biotic stresses.

13.4.2 DETERMINANTS

Shaping of the rhizospheric microbiome is dictated by the plant species and the healthy soil (Berg and Smalla 2009; Bakker et al. 2012) underpins the significance of plant-soil-microbe interactions. Furthermore, edaphic features such as soil nutrients, pH and moisture content may have a major effect in the alteration of rhizosphere microbial population (Bakker et al. 2020). Management strategies that are being adopted to enhance nutrient release and to fight pests and diseases could also improve the composition of the soil microbiome population (Lumini et al. 2011). Agricultural practices that ratify and promote beneficial microbes can contribute to improved yield of the crops over the long term. Crop rotation and intercropping have played a major role in altering soil microbial populations. Long term monoculture of a single crop promotes the abundance of soilborne pathogens and decreases crop yield due to a decline in soil chemical properties and soil microbiota composition. Diverse distribution frequencies and transmission mechanisms of biocontrol agents had a direct effect on the rhizosphere. Conventional agricultural practices, which depend primarily on the use of chemical insecticides and fungicides (Krauss et al. 2011), minimize soil microbiome levels. On the other hand, the practice of organic farming would promote microbial diversity (Sugiyama et al. 2010).

13.5 CONCLUSION AND FUTURE PROSPECTS

Increased demand for the production of organic foods has called for more environmentally sustainable agricultural activities. The existence of a healthy microbiota can be the key to acquiring healthier plants. Recently, several studies have started to illustrate the significance of plant-microbiome interaction and its effect on plant health and productivity. Involvement of microbiota will increase natural soil suppression against soilborne pathogens whenever soil properties deteriorate, rendering a decline in crop yields. A significant group of microorganisms play a vital role in enhancing plant health in oilseed environment. A wide range of microbes found in the soil rhizosphere provides an opportunity for genetic variation and exploitation

of microbes. Both bacterial and fungal microbiomes facilitate the growth and development of various oilseed crops, both directly and indirectly under normal and stressful conditions. Root exudates serve as signaling molecules and play a crucial role in the manipulation of microbes. Further research should be carried out to determine the composition of root exudate that will enable the culture of particular beneficial microbes to produce more productive plants. In addition, the ecological function of soil microbiomes should be further explained in order to obtain a deeper understanding of the microbial population network inhabiting the soil. Agronomic practices appeared to be the best methods for increasing soil suppression by microbiomes. As a result, best agronomic methods to increase soil suppression can be put in place that can transfer wild soil microbiota to beneficial microbial consortia. It can be inferred that by following effective agronomic methods such as the addition of compost, crop rotation, intercropping and soil pre fumigation with eco-friendly molecules, problems in the suppression of soilborne diseases can be resolved through the manipulation of soil microbiomes in healthy agroecosystems. Manipulation of microbes by organic farming has been shown to improve the productivity of oilseed crops and reduce their biotic stress. While plant-microbe interactions are very reliable, the underlying mechanisms still need to be studied to optimize and popularize the use of soil microbial cultures in an effective way. In general, a significant change in microbial community composition is imminent after the addition of an amendment, be it organic or inorganic; hence, suitable mechanisms need to be developed for complementary use of organic and/or microbial fertilization, in addition to chemical fertilization. Probing into the interaction of plants and microbes at a molecular level with the aid of stable isotopes and biochemical markers can enhance the understanding for the identification of chemicals involved in the interaction process. Detection and application of a variety of beneficial microbial strains could also play a central role as biofertilizers and biopesticides, which will reduce the use of fertilizers and agrochemicals in oilseed crops.

REFERENCES

- Abuamsha, R., Salman, M., Ehlers, R.U. 2011. Differential resistance of oilseed rape cultivars (*Brassica napus* sp. *oleifera*) to *Verticillium longisporum* infection is affected by rhizosphere colonization with antagonistic bacteria, *Serratia plymuthica* and *Pseudomonas chlororaphis*. *Biocontrol* 156: 101–112.
- Ali, M., Ali, M., Ramezani, A., Far, S.M., Sadat, K., Moradi-Ghahderijani, M., Jamian, S.S. 2013. Application of silicon ameliorates salinity stress in sunflower (*Helianthus annuus* L.) plants. *International Journal of Agriculture and Crop Science* 6: 1367–1372.
- Ambrosini, A., Beneduzi, A., Stefanski, T., Pinheiro, F.G., Vargas, L.K., Passaglia, L.M.P. 2012. Screening of plant growth promoting rhizobacteria isolated from sunflower (*Helianthus annuus* L.). *Plant and Soil* 356: 245–264.
- Ana, P.G.C.M., Moreira, H., Franco, A.R., Rangel, A.O.S.S., Castro, P.M.L. 2013. Inoculating *Helianthus annuus* (sunflower) grown in zinc and cadmium contaminated soils with plant growth promoting bacteria effects on phytoremediation strategies. *Chemosphere* 92(1): 74–83.
- Anandham, R., Sridar, R., Nalayini, P., Sa T. 2007. Potential for plant growth promotion in groundnut (*Arachis hypogaea* L.) cv. ALR-2 by co-inoculation of sulfur-oxidizing bacteria and Rhizobium. *Microbiological Research* 162(2): 139–53.

- Antoniou, A, Tsolakidou, M.D., Stringlis, I.A., Pantelides, I.S. 2017. Rhizosphere microbiome recruited from suppressive compost improves plant fitness and increases protection against vascular wilt pathogens of tomato. *Frontiers in Plant Science*. 8: 2022, 1–16. <https://doi.org/10.3389/fpls.2017.02022>.
- Atieno, M., Herrmann, L., Okalebo, R. Lesueur, D. 2012. Efficacy of different formulation of *Bradyrhizobium japonicum* and effect of co-inoculation of *B. subtilis* with two different strains of *Bradyrhizobium japonicum*. *World Journal of Microbiol Biotechnology* 28(7): 2541–2550.
- Aung, T.T., Tittabutr, P., Boonkerd, N., Teaumroong, N. 2013. Co-inoculation effects of *Bradyrhizobium japonicum* and *Azospirillum* sp. on competitive nodulation and rhizosphere eubacterial community structures of soybean under rhizobia-established soil conditions. *African Journal of Biotechnology* 12: 2850–2862.
- Aviles, M., Borrero, C. 2017. Identifying characteristics of *V. dahliae* wilt suppressiveness in olive mill composts. *Plant Disease* 101(9): 1568–77.
- Babadoko, A M., Pacy O.G. 2011. Rhizosphere bacterial flora of groundnut (*Arachis hypogaea*). *Advances in Environmental Biology* 5(10): 3196–3202.
- Badri, D.V., Vargas, L.V.M., Broeckling, C.D., De la Pena, C., Jasinski, M., Santelia, D., Martinoia, E., Sumner, L.W., Banta, L.M., Stermitz, F., Vivanco, J.M. 2008. Altered profile of secondary metabolites in the root exudates of Arabidopsis ATP-binding cassette transporter mutants. *Plant Physiology* 146: 762–771.
- Bais, H.P., Weir, T.L., Perry, L.G., Gilroy, S., Vivanco, J.M. 2006. The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology* 57: 233–266.
- Bakker, A.H.M.P., Berendsen, R.L., Van Pelt, J.A. et al. 2020. The soilborne identity and microbiome-assisted agriculture: Looking back to the future. *Molecular Plant* 13(10): 1395–1402.
- Bakker, M.G., Manter, D.K., Sheflin, A.M., Weir, T.L. Vivanco, J.M. 2012. Harnessing the rhizosphere microbiome through plant breeding and agricultural management. *Plant Soil* 360: 1–13.
- Barns, S.M., Takala, S.L., Kuske, C.R. 1999. Wide distribution and diversity of members of the bacterial kingdom Acidobacterium in the environment. *Applied Environmental Microbiology* 65(4): 1731–1737.
- Bashir, S., Iqbal, A., Hasnain, S. 2020. Comparative analysis of endophytic bacterial diversity between two varieties of sunflower *Helianthus annuus* with their PGP evaluation. *Saudi Journal of Biological Science*. 27(2): 720–726.
- Bauer, W.D., Mathesius, U. 2004. Plant responses to bacterial quorum sensing signals. *Current Opinion in Plant Biology* 7(4): 429–433.
- Begum, N., Qin, C., Ahanger, M.A., Raza, S., Khan, M.I., Ashraf, M., Ahmed, N., Zhang, L. 2019. Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. *Frontiers in Plant Science* 19: 1068.
- Bekku, Y., Kimura, M., Ikeda, H., Koizumi, H. 1997. Carbon input from plant to soil through root exudation in *Digitaria adscendens*, and *Ambrosia artemisiifolia*. *Ecol Res* 12: 305–312.
- Berendsen, R.L., Pieterse, C.M.J., Bakker, P.A.H.M. 2012. The rhizosphere microbiome and plant health. *Trends in Plant Science* 17(8): 478–86.
- Berg, G., Smalla, K. 2009. Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. *FEMS Microbiol Ecology* 68: 1–13.
- Bhat, A.I., Jain, R.K., Chaudhary, V., Reddy, M.K. 2002. Sequence conservation in the coat protein gene of tobacco streak virus isolates causing necrosis disease in cotton, mung bean, sunflower and sunhemp in India. *Indian Journal of Biotechnology* 1(4): 350–356.

- Bonanomi, G., Antignani, V., Pane, C., Scala, F. 2007. Suppression of soil borne fungal diseases with organic amendments. *Journal of Plant Pathology* 89: 311–324.
- Bonkowski, M. 2004. Protozoa and plant growth: The microbial loop in soil revisited. *New Phytology* 162: 617–631.
- Bronick, C., Lal, R. 2005. Soil structure and management: A Review. *Geoderma* 124: 3–22.
- Bulluck, L.R., Brosius, M., Evanylo, G.K., Ristaino, J.B. 2002. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Applied Soil Ecology* 19: 147–160.
- Campbell, R., Greaves, M. P. 1990. Anatomy and community structure of the rhizosphere. In *The Rhizosphere*. Ed. J M Lynch (Essex: John Wiley & Sons Ltd.), 11–34.
- Caravaca, F., Hernandez, T., Garcia, C., Roldan, A. 2002. Improvement of rhizosphere aggregate stability of afforested semiarid plant species subjected to mycorrhizal inoculation and compost addition. *Geoderma* 108: 133–144.
- Celik, I., Ortas, I., Kilic, S. 2004. Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. *Soil and Tillage Research* 78: 59–67.
- Chaparro, J.M., Badri, D.V., Bakker, M.G., Sugiyama, A., Manter, D.K., Vivanco, J.M. 2013. Root exudation of phytochemicals in *Arabidopsis* follows specific patterns that are developmentally programmed and correlate with soil microbial functions. *PLoS One* 8(2): e55731.
- Chaparro, J.M., Sheflin, A.M., Manter, D.K., Vivanco, J.M. 2012. Manipulating the soil microbiome to increase soil health and plant fertility. *Biology and Fertility of Soils* 48: 489–499.
- Cordero, J., de Freitas, J.R., Germida, J.J. 2020. Bacterial microbiome associated with the rhizosphere and root interior of crops in Saskatchewan. *Canadian Journal of Microbiology* 66, 71–85.
- Cotxarrera, L., Trillas, M.I., Steinberg, C., Alabouvette, C. 2002. Use of sewage sludge compost and *Trichoderma asperellum* isolates to suppress *Fusarium oxysporum* f sp *melonis* wilt of tomato. *Soil Biology and Biochemistry* 34: 467–476.
- Cretoiou, M.S., Korthals, G.W., Visser, J.H.M., Van Elsas, J.D. 2013. Chitin amendment increases soil suppressiveness toward plant pathogens and modulates the actinobacterial and oxalobacteraceal communities in an experimental agricultural field. *Applied and Environ Microbiology* 79: 5291–5301.
- Cumberford, G., Hebard, A. 2015. Ahiflower oil: A novel non-GM plant-based omega-3+6 source. *Lipid Technology* 27: 207–210.
- Cummings, S.P. 2009. The application of plant growth promoting rhizobacteria (PGPR) in low input and organic cultivation of graminaceous crops; potential and problems. *Environmental Biotechnology* 5: 43–50.
- Da Mota, F.F., Gomes, E.A., Seldin, L. 2008. Auxin production and detection of the gene coding for the auxin efflux carrier (AEC) protein in *Paenibacillus polymyxa*. *Journal of Microbiology* 46(3): 257–264.
- De Corato, U. 2020. Disease-suppressive compost enhances natural soil suppressiveness against soilborne plant pathogens: A critical review. *Rhizosphere* 13: 100192.
- De Corato, U., Patruno, L., Avella, N., Lacolla, G., Cucci, G. 2019. Composts from green sources show an increased suppressiveness to soilborne plant pathogenic fungi: Relationships between physicochemical properties, disease suppression, and the microbiome. *Crop Protection* 124: 104870.
- De la Cruz, J.M.R., Lora, J.M., Hidalgo-Galiego, A., Dominguez, F., Pintor-Toro, J.A., Llobell, A., Benitez, T. 1993. Carbon source control on β -gluc Masciarelli seschitobiose and chitinase from *Trichoderma harzianum*. *Annual Review of Microbiology* 159: 316–322.
- De Vleeschauwer, D., Hofte, M. 2009. Rhizobacteria-induced systemic resistance. In: *Advances in botanical research*. Ed. L.C. Van Loon (Burlington: Elsevier), 51: 223–281.

- Deepa, C., Dastager, S.G., Pandey, A. 2010. Plant growth-promoting activity in newly isolated *Bacillus thioparus* (NII-0902) from Western ghat forest, India. *World Journal of Microbiology and Biotechnology* 26(12): 2277–2283.
- De-la-Peña, C., Badri, D.V., Lei, Z., Watson, B.S., Brandao, M.M., Silva-Filho, M.C., Sumner, L.W., Vivanco, J.M. 2010. Root secretion of defense related proteins is development dependent and correlated with flowering time. *Journal of Biological Chemistry* 285: 30654–30665.
- De-la-Peña, C., Loyola-Vargas, V.M. 2014. Biotic interactions in the rhizosphere: A diverse cooperative enterprise for plant productivity. *Plant Physiology* 166: 701–719.
- Deng, X., Zhang, N., Shen, Z., Zhu, C., Li, R., Falcao Salles, J., Shen, Q. 2019. Rhizosphere bacteria assembly derived from fumigation and organic amendment triggers the direct and indirect suppression of tomato bacterial wilt disease. *Applied Soil Ecology* 147: 103364.
- Dennis, P.G., Miller, A.J., Hirsch, P.R. (2010) Are root exudates more important than other sources of rhizodeposits in structuring rhizosphere bacterial communities? *FEMS Microbiol Ecology* 72: 313–327.
- Dordas, C. 2008. Role of nutrients in controlling plant diseases in sustainable agriculture. A review. *Agronomy for Sustainable Development* 28(1), 33–46.
- Dordas, C.A., Sioulas, C. 2008. Safflower yield, chlorophyll content, photosynthesis, and water use efficiency response to nitrogen fertilisation under rainfed conditions. *Industrial Crops and Products* 27: 75–85.
- Drogue, B., Combes-Meynet, E., Moenne-Loccoz, Y., Wisniewski-Dye, F., Combaret, P.C. 2013. Control of the cooperation between plant growth promoting rhizobacteria and crops by rhizosphere signals. In: *Molecular Microbial Ecology of the Rhizosphere*. Eds. F.J. de Bruijn (NJ, USA: John Wiley & Sons, Inc), 281–294.
- Dudareva, N., Pichersky, E., Gershenzon, J. 2004. Biochemistry of plant volatiles. *Plant Physiology* 135(4):1893–1902.
- Duffy, B.K. and Defago. 1997. Improves biocontrol of *Fusarium* crown and root rot of tomato by *pseudomonas fluorescens* and represses the production of pathogen metabolites inhibitory to bacterial antibiotic biosynthesis. *Phytopathology* 87(12): 1250–1257.
- Dunfield, K.E., Germida, J.J. 2003. Seasonal changes in the rhizosphere microbial communities associated with field-grown genetically modified canola (*Brassica napus*). *Applied Environmental Microbiology* 69(12): 7310–7318.
- Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M., Haering, K. 2008. Soil and water environmental effects of fertilizer, manure and compost based fertility practices in an organic vegetable cropping system. *Agriculture, Ecosystem and Environment* 127: 50–58.
- Farina, R.A., Beneduzi, A., Ambrosini, A., Campos, S.B., Lisboa, B.B., Wendisch, V., Vargas, L.K., Passaglia, L.M.P. 2012. Diversity of plant growth promoting rhizobacteria communities associated with the stages of canola growth. *Applied Soil Ecology* 55: 44–52.
- Fierer, N., Lauber, C.L., Ramirez, K.S., Zaneveld, J., Bradford, M.A., Knight, R., 2012. Comparative metagenomic, phylogenetic and physiological analyses of soil microbial communities across nitrogen gradients. *ISME Journal* 6, 1007–1017.
- Frey-Klett, P., Garbaye, J., Tarkka, M. 2007. The mycorrhiza helper bacteria revisited. *New Phytologist* 176: 22–36
- Gianinazzi, S., Gollotte, A., Binet, M.-N., van Tuinen, D., Redecker, D., Wipf, D. 2010. Agroecology: The key role of arbuscular mycorrhizas in ecosystem services. *Mycorrhiza* 20(8): 519–30.
- Glick, B.R., Todorovic, B., Czarny, J., Cheng, Z., Duan, J., McConkey, B. 2007. Promotion of plant growth by bacterial ACC deaminase. *Critical Reviews in Plant Sciences* 26 (5–6): 227–242.

- Graner, G., Persson, P., Meijer, J., Alstrom, S. 2003. A study on microbial diversity in different cultivars of *Brassica napus* relation to its wilt pathogen, *Verticillium longisporum*. *FEMS Microbiology Letters* 224: 269–276.
- Gravel V., Antoun H., Tweddell R.J. 2007. Growth stimulation and fruit yield improvement of greenhouse tomato plants by inoculation with *Pseudomonas putida* or *Trichoderma atroviride*: Possible role of indole acetic acid, (IAA). *Soil Biology and Biochemistry* 39: 1968–1977.
- Hadar, Y., Papadopoulou, K.K. 2012. Suppressive composts: Microbial ecology links between abiotic environments and healthy plants. *Annual Review of Phytopathology* 50: 133–153.
- Haichar, F.Z., Santaella, C., Heulin, T., Achouak, W. 2014. Root exudates mediated interactions belowground. *Soil Biology and Biochemistry* 77: 69–80.
- Hemmat, A., Aghilinategh, N., Rezaeinejad, Y., Sadeghi, M. 2010. Long term impacts of municipal solid waste compost, sewage sludge and farmyard manure application on organic carbon, bulk density and consistency limits of a calcareous soil in central Iran. *Soil and Tillage Research* 108: 43–50.
- Himmelstein, J.C., Maul, J.E., Everts, K.L. 2014. Impact of five cover crop green manures and actinovate on fusarium wilt of watermelon. *Plant Disease* 98: 965–972.
- Hoagland, D.R., Arnon, D.I. 1938. The water culture method for growing plants without soil. *Circular* 347. Berkeley, California: University of California Agricultural Experiment Station.
- Huang, R., McGrath, S.P., Hirsch, P.R., Clark, I.M., Storkey, J., Wu, L., Zhou, J., Liang, Y. 2019. Plant–microbe networks in soil are weakened by century-long use of inorganic fertilizers. *Microbial Biotechnology* 12(6): 1464–1475.
- Hutsch, B.W., Augustin, J., Merbach, W. 2002. Plant rhizodeposition-an important source for carbon turnover in soils. *Journal of Plant Nutrition and Soil Science* 165: 394–407.
- Islam, F., Yasmeen, T., Ali, S., Ali, B., Farooq, M.A., Gill, R.A., 2015. Priming-induced antioxidative responses in two wheat cultivars under saline stress. *Acta Physiologia Plantarum* 37: 153.
- Jalilian, J., Modarres-Sanavya, S.A., Saberli, S.F., Asilan, K.S. 2012. Effects of the combination of beneficial microbes and nitrogen on sunflower seed yields and seed quality traits under different irrigation regimes. *Field Crops Research* 127: 26–34.
- Jiménez, J.A., Novinscak, A., Filion, M. 2020. Inoculation with the Plant Growth-Promoting Rhizobacterium *Pseudomonas fluorescens* LBUM677 Impacts the Rhizosphere Microbiome of Three Oilseed Crops. *Frontiers in Microbiology* 11: 569366.
- Kang, Y., Shen, M., Yang, X., Cheng, D., Zhao, Q. 2014. A plant growth-promoting rhizobacteria (PGPR) mixture does not display synergistic effects, likely by biofilm but not growth inhibition *Microbiology* 83(5): 666–673.
- Kerry, B.R. 2000. Rhizosphere interaction and the exploitation of microbial agents for the biological control of plant parasitic nematodes. *Annual Review of Phytopathology* 38: 423–441.
- Kiani, M., Gheysari, M., Mostafazadeh-Fard, B., Majidi, M.M., Karchani, K., Hoogenboom, G. 2016. Effect of the interaction of water and nitrogen on sunflower under drip irrigation in an arid region. *Agricultural Water Management* 171:162–172.
- Kibblewhite, M.G., Ritz, K., Swift, M.J. 2008. Soil health in agricultural systems. *Transactions of the Royal Society of Biological Sciences* 363: 685–701.
- Kinsella, K., Schulthess, C.P., Morris, T.F., Stuart, J.D. 2009. Rapid quantification of *Bacillus subtilis* antibiotics in the rhizosphere. *Soil Biology and Biochemistry* 41: 374–379.
- Kloepper, J.W., Rodriguez- Ubana, R., Zehnder, G.W., Murphy, J.F., Sikora, E., Fernandez, C. 1999. Plant root–bacterial interactions in biological control of soilborne diseases and potential extension to systemic and foliar diseases. *Australasian Plant Pathology* 28: 21–26.

- Krauss, J., Gallenberger, I., Steffan-Dewenter, I. 2011. Decreased functional diversity and biological pest control in conventional compared to organic crop fields. *PLoS One* 6(5): e19502.
- Lavanya, N., Ramiah, R.M., Sankaralingam, A., Renukadevi, P., Velazhahan, R. 2005. Identification of hosts for Ilarvirus associated with sunflower necrosis disease. *Acta Phytopathol Entomol. Hungarica* 40(1): 31–34.
- Levy, A., Gonzalez, I.S., Mittelviehhaus, M. et al. 2018. Genomic features of bacterial adaptation to plants. *Nature Genetics* 50: 138–150.
- Li, J.G., Ren, G.D., Jia, Z.J., Dong, Y.H., 2014. Composition and activity of rhizosphere microbial communities associated with healthy and diseased greenhouse tomatoes. *Plant Soil* 380: 337–347.
- Liu H., Shi Z., Li J., Zhao P., Qin S., Nie Z. 2018. The impact of phosphorus supply on selenium uptake during hydroponics experiment of winter wheat (*Triticum aestivum*) in China. *Frontiers in Plant Science*. 9:373. doi: 10.3389/fpls.2018.00373.
- Lumini, E., Vallino, M., Alguacil, M.M., Romani, M., Bianciotto, V. 2011. Different farming and water regimes in Italian rice fields affect arbuscular mycorrhizal fungal soil communities. *Ecological Applications* 21: 1696–1707.
- Madhaiyan M., Poonguzhali, S, Lee, J.-S., Saravanan, V.S., Lee, K.-C., Santhanakrishnan, P. 2010. *Enterobacter arachidis* sp. a plant growth-promoting diazotrophic bacterium isolated from rhizosphere soil of groundnut. *International Journal of Systematic and Evolutionary Microbiology* 60(7): 1559–156.
- Martinez-Blanco, J., Lazcano, C., Christensen, T.H., Munoz, P., Rieradevall, J., Moller, J., Anton, A., Boldrin, A. 2013. Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agronomy for Sustainable Development* 33: 721–732.
- Massalha, H., Korenblum, E., Tholl, D., Aharoni, A. 2017. Small molecules below-ground: The role of specialized metabolites in the rhizosphere. *Plant Journal* 90: 788–807.
- Melero-Vara, J.M., Lopez-Herrera, C.J., Prados-Ligero, A.M., Vela-Delgado, M.D., Navas-Becerra, J.A., Basallote-Ureba, M.J. 2011. Effects of soil amendment with poultry manure on carnation *Fusarium* wilt in greenhouses in southwest Spain. *Crop Protection* 30: 970–976.
- Mendes, R., Garbeva, P., Raaijmakers, J.M. 2013. The rhizosphere microbiome: Significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. *FEMS Microbiology Reviews* 37(5): 634–663.
- Mendes, R., Kruijt, M., De Bruijn, I., Dekkers, E., Van der Voort, M., Schneider, J.H.M., Piceno, Y.M., DeSantis, T.Z., Andersen, G.L., Bakker, P.A.H.M., Raaijmakers, J.M. 2011. Deciphering the rhizosphere microbiome for disease-suppressive bacteria. *Science* 332: 1097–1100.
- Morrison, C.K., Arseneault, T., Novinscak, A., Fillion, M. 2017. Phenazine-1-carboxylic acid production by *Pseudomonas fluorescens* LBUM636 alters *Phytophthora infestans* growth and late blight development. *Phytopathology* 107: 273–279.
- Nair, A., Nougajio, M. 2012. Soil microbial biomass, functional microbial diversity, and nematode community structure as affected by cover crops and compost in an organic vegetable production system. *Applied Soil Ecology* 58: 45–55.
- Narayanaswamy, R., Gokulakumar, B. 2010. ICP-AES analysis in sesame on the root rot disease incidence. *Archives of Phytopathology and Plant Protection* 43(10): 940–948.
- Neal A.L., Rossmann M. et al. 2017. Land-use influences phosphatase gene microdiversity in soils. *Environmental Microbiology*. 19(7):2740–2753.
- Neuman, G., Romheld, V. 2007. The release of root exudates as affected by the plant physiological status. In: *The Rhizosphere Biochemistry and Organic Substances at the Soil-Plant Interface*. Eds. R. Pinton, et al. (Boca Raton: CRC), 23–72.
- Nihorimbere, V., Ongena, M., Smargiassi, M., Thonart, P. 2011. Beneficial effect of the rhizosphere microbial community for plant growth and health. *Biotechnology, Agronomy and Society and Environment* 5(2): 327–337.

- Paulucci, N.S., Gallarato, L.A., Reguera, Y.B., Vicario, J.C., Cesari, A.B., Garcia de Lema, M.B., Dardanelli, M.S. 2015. *Arachis hypogaea* PGPR isolated from Argentine soil modifies its lipids components in response to temperature and salinity. *Microbiological Research* 173: 1–9.
- Philippot, L., Raaijmakers, J.M., Lemanceau, P., van der Putten, W.H., 2013. Going back to the roots: The microbial ecology of the rhizosphere. *Nature Reviews Microbiology* 11: 789–799.
- Prakamhang, J., Tittabutr, P., Boonkerd, N., Teaumroong, N. 2015. Proposed some interactions at molecular level of PGPR coinoculated with *Bradyrhizobium diazoefficiens* USDA110 and *B. japonicum* THA6 on soybean symbiosis and its potential of field application. *Applied Soil Ecology* 85: 38–49
- Puglisi, E., Fragoulis, G., Ricciuti, P., Cappa, F., Spaccini, R., Piccolo, A., Trevisan, M., Crecchio. 2009. Effects of a humic acid and its size-fractions on the bacterial community of soil rhizosphere under maize (*Zea mays* L.). *Chemosphere* 77 (6): 829–837.
- Puri, A., Padda, K.P., Chanway, C.P. 2016. Evidence of nitrogen fixation and growth promotion in canola (*Brassica napus* L.) by an endophytic diazotroph *Paenibacillus polymyxa* P2b-2R. *Biology and Fertility of Soils* 52(1): 119–125.
- Qurashi, A.W., Sabri, A.N. 2012. Bacterial exopolysaccharide and biofilm formation stimulate chickpea growth and soil aggregation under salt stress. *Brazilian Journal of Microbiology* 43(3): 1183–1191.
- Qureshi, A.A., Narayanasamy, G. 2005. Residual effect of phosphate rocks on dry matter yield and P uptake of mustard and wheat crops. *Journal of Indian Society of Soil Science* 53(1): 132–134.
- Qureshi, A.A., Narayanasamy, G. 1999. Direct effect of rock phosphates and phosphate solubilizers on soybean growth in Typic Ustochrept. *Journal of Indian Society of Soil Science*. 47(3): 475–478.
- Raaijmakers, J.M., Paulitz, T.C., Steinberg, C., Alabouvette, C., Moëgne-Loccoz, Y. 2009. The rhizosphere: A playground and battlefield for soil borne pathogens and beneficial microorganisms. *Plant Soil* 321: 341–361.
- Raaijmakers, J.M., Weller, D.M., Thomashow, L.S. 1997. Frequency of antibiotic-producing *Pseudomonas* spp. in natural environments. *Applied and Environmental Microbiology* 63: 881–887.
- Rahman, M., Ishii, Y., Niimi, M., Kawamura, O. 2008. Effect of salinity stress on dry matter yield and oxalate content in Napier grass (*Pennisetum purpureum* Schumach). *Asian Australasian Journal of Animal Science* 21(11): 1599–1603.
- Ramans, R., Ramaekers, L., Schelkens, S., Hernandez, G., Garcia, A., Reyes, J.L., Mendez, N., Toscano, V., Mulling, M., Galvez, L., Vanderleyden, J. 2008. Effect of *Rhizobium-Azospirillum* co-inoculation on nitrogen fixation and yield of two contrasting *Phaseolus vulgaris* L. genotypes cultivated across different environments in Cuba. *Plant and Soil* 312: 25–37.
- Ramirez, K.S., Craine, J.M., Fierer, N. 2012. Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes. *Global Change Biology* 18: 1918–1927.
- Rangeshwaran R., Prasad R.D. 2000. Biological control of sclerotium rot of sunflower. *Indian Phytopathology* 53 (4): 444–449.
- Rennie R.J. 1980. Dinitrogen-fixating bacteria: Computer-assisted identification of soil isolates. *Can. J. Microbiol.* 26:1275–1283.
- Richardson, A.E., Barea, J., McNeill, A.M., Prigent-Combaret, C. (2009) Acquisition of phosphorus and nitrogen in the rhizosphere and plant growth promotion by microorganisms. *Plant Soil* 321: 305–339.

- Rillig M.C., Mummey D.L. 2006. Mycorrhizas and soil structure. *New Phytologist* 171: 41–53.
- Rodriguez, R., Redman, R. 2008. More than 400 million years of evolution and some plants still can't make it on their own: Plant stress tolerance via fungal symbiosis. *Journal of Experimental Botany* 59(5): 1109–1114.
- Rovira, A.D. 1969. Plant root exudates. *Botanical Review* 35: 35–57.
- Ruano-Rosa, D., Mercado-Blanco, J. 2015. Combining biocontrol agents and organics amendments to manage soilborne phytopathogens. In: Organic amendments and soil suppressiveness in plant disease management. Eds. M.K. Meghvansi, A. Varma (Switzerland: Springer Publishing), 457–478.
- Rudrappa, T., Czymmek, K.J., Pare, P.W., Bais, H.P. 2008. Root secreted malic acid recruits beneficial soil bacteria. *Plant Physiology* 148: 1547–1556.
- Saravanakumar, D., Muthumeena, B., Lavanya, N., Suresh, S., Rajendran, L., Raguchander, T., Samiyappan, R. 2007. *Pseudomonas* induced defense molecules in rice against leaf folder (*Cnephlocrocis medinalis*) pest. *Pest Management Science* 63: 714–721.
- Schloss, P.D., Handelsman, J. 2006. Toward a census of bacteria in soil. *PLoS Computation Biology* 2(7): e92.
- Schulz, S., Dickschat, J.S. 2007. Bacterial volatiles: The smell of small organisms. *Natural Products Reports* 24(4): 814–842.
- Selvakumar, G., Panneerselvam, P., Ganeshamurthy, A.N., Maheshwari, D.K. 2012. Bacterial mediated alleviation of abiotic stress in crops. In: Bacteria in Agrobiolgy: Stress Management. Ed. D.K. Maheshwari (New York: Springer), 205–224.
- Shahid, M., Hameed, S., Imran, A., Ali, S., Van Elsas, J.D. 2012. Root colonization and growth promotion of sunflower (*Helianthus annuus* L.) by phosphate solubilizing Enterobacter sp. Fs-11. *World Journal of Microbiology and Biotechnology* 28: 2749–2758.
- Shekhar, N., Bhattacharya, D., Kumar, D., Gupta, R.K. 2006. Biocontrol of wood rotting fungi with *Streptomyces violaceus-niger* XL-2. *Canadian Journal of Microbiology* 52: 805–808.
- Singh, N., Yadav, A., Varma, A. 2015. Effect of plant growth promoting activity of rhizobacteria on Cluster bean (*Cyamopsis tetragonoloba* L.) plant growth and biochemical constituents. *International Journal of Current Microbiology and Applied Sciences* 4(5): 1071–1082
- Somers, E., Vanderleyden, J., Srinivasan, M. 2004. Rhizosphere bacterial signalling: A love parade beneath our feet. *Critical Reviews in Microbiology* 30: 205–240.
- Sommermann, L., Geistlinger, J., Wibberg, D., Deubel, A., Zwanzig, J., Babin, D., Schluter, A., Schellenberg, I. 2018. Fungal community profiles in agricultural soils of a long-term field trial under different tillage, fertilization and crop rotation conditions analyzed by high-throughput ITS-amplicon sequencing. *PLoS ONE* 3(4): e0195345.
- Sugiyama, A. 2019. The soybean rhizosphere: Metabolites, microbes, and beyond—A Review. *Journal of Advanced Research* 19: 67–73.
- Sugiyama, A., Vivanco, J.M., Jayanty, S.S., Manter, D.K. 2010. Pyrosequencing assessment of soil microbial communities in organic and conventional potato farms. *Plant Diseases* 94: 1329–1335.
- Tang, C.S., Cai, W.F., Kohl, K., Nishimoto, R.K. 1995. Plant stress and allelopathy. In: Allelopathy: Organisms, Processes, and Applications. Eds. K.M.M.D. Inderjit, F.A. Einhellig, Acs Symposium Series. Washington: Amer Chemical Soc, 582, 142–157.
- Timmusk, S., Nicander, B., Granhall, U., Tillberg, E. 1999. Cytokinin production by *Paenibacillus polymyxa*. *Soil Biology and Biochemistry* 31(13): 1847–1852.
- Tokala, R.K., Strap, J.L., Jung, C.M., Crawford, D.L., Salove, M.H., Deobald, L.A., Bailey, J.F., Morra, M.J. 2002. Novel plant microbe rhizosphere interaction involving *Streptomyces lydicus* WYEC108 and the Pea plant (*Pisum sativum*). *Applied Environmental Microbiology* 68(5): 2161–2171.

- Torres, I.F., Bastida, F., Hernandez, T., Garcia, C. 2015. The effects of fresh and stabilized pruning wastes on the biomass, structure and activity of the soil microbial community in a semiarid climate. *Applied Soil Ecology* 89: 1–9.
- Uren, N.C. 2007. Types, amounts, and possible functions of compounds released into the rhizosphere by soil-grown plants. In: *The Rhizosphere Biochemistry and Organic Substances at the Soil-Plant Interface*. Eds. R. Pinton, Z. Varanini, P. Nannipieri, 2nd edn. (Boca Raton: CRC), 1–21.
- Venturi, V., Fuqua, C. 2013. Chemical signalling between plants and plant-pathogenic bacteria. *Annual Review of Phytopathology* 51: 17–37.
- Von der Weid, I., Duarte, G.F., Van Elsas, J.D., Seldin, L. 2002. *Paenibacillus brasilensis* sp. nov., a novel nitrogen-fixing species isolated from the maize rhizosphere in Brazil. *International Journal of Systematic and Evolutionary Microbiology* 52(6): 2147–2153.
- Vorholt, J.A. 2012. Microbial life in the phyllosphere. *Nature Review Microbiology* 10: 828–840.
- Wan, T.T., Zhao, H.H., Wang, W. 2017. Effect of biocontrol agent *Bacillus amyloliquefaciens* SN16–1 and plant pathogen *Fusarium oxysporum* on tomato rhizosphere bacterial community composition. *Biological Control* 112: 1–9.
- Wang, H., Gu, C., Liu, X., Yang, C., Li, W., Wang, S. 2020. Impact of soybean nodulation phenotypes and nitrogen fertilizer levels on the rhizosphere bacterial community. *Frontiers in Microbiology* 11: 750.
- Wang, R., Xiao, Y., Lv, F., Hu, L., Wei, L., Yuan, Z., Lin, H. 2018. Bacterial community structure and functional potential of rhizosphere soils as influenced by nitrogen addition and bacterial wilt disease under continuous sesame cropping. *Applied Soil Ecology* 125: 117–127.
- Ward, N., Challacombe, J., Jansses, P.H., Henrissat, B. 2009. Three genomes from the Phylum Acidobacteria provide insight into the lifestyles of these microorganisms in soils. *Applied Environmental Microbiology* 75(7): 2046–2056.
- Whipps, J.M. 1990. Carbon economy. In: *The Rhizosphere in Ecological and Applied Microbiology*. Ed. J.M. Lynch (Chichester: Wiley series J Wiley), 59–97.
- Wu, F., Wan, J.H.C., Wu, S., Wong, M.H. 2012. Effects of earthworms and plant growth promoting rhizobacteria (PGPR) on availability of nitrogen, phosphorus and potassium in soil. *Journal of Plant Nutrition Soil Science* 175 (3): 423–433.
- Xiong, W., Li, R., Ren, Y., Liu, C., Zhao, Q., Wu, H., Jousset, A., Shen, Q. 2017. Distinct roles for soil fungal and bacterial communities associated with the suppression of vanilla *Fusarium* wilt disease. *Soil Biology and Biochemistry* 107: 198–207.
- Xu, Y., Wang, G., Jin, J., Liu, J., Zhang, Q., Liu, X. 2009. Bacterial communities in soybean rhizosphere in response to soil type, soybean genotype, and their growth stage. *Soil Biology and Biochemistry* 41: 919.
- Yaish, M.W. 2015. Proline accumulation is a general response to abiotic stress in the date palm tree (*Phoenix dactylifera* L.). *Genetic and Molecular Research* 14(3): 9943–9950.
- Yang, W., Jing, X., Guan, Y., Zhai, C., Wang, T., Shi, D., Sun, W., Gu, S. 2019. Response of fungal communities and co-occurrence network patterns to compost amendment in black soil of Northeast China. *Frontiers in Microbiology* 10: 1562.
- Yang, J., Kloepper, J.W., Ryu, C.-M. 2008. Rhizosphere bacteria help plants tolerate abiotic stress. *Trends in Plant Science* 14(1): 1–4.
- Zaccardelli, M., De Nicola, F., Vилlecco, D., Scotti, R. 2013. The development and suppressive activity of soil microbial communities under compost amendment. *Journal of Soil Science and Plant Nutrition* 13: 730–742.
- Zahir, A., Mirza, B.S., Mclean, J.E., Yasmin, S., Shah, T.M., Malik, K.A., Mirza, M.S. 2016. Association of plant growth promoting *Serratia* spp. with root nodules of chickpea. *Research in Microbiology* 167(6): 510–520.

- Zapata, P.J., Serrano, M., Garcia-Legaz, M.F., Pretel, M.T., Botella, M.A. 2017. Short term effect of salt shock on ethylene and polyamines depends on plant salt sensitivity. *Frontiers in Plant Science* 8: 855. doi: 10.3389/fpls.2017.00855.
- Zhang, H., Kim, M.S., Sun, Y., Dowd, S.E., Shi, H., Pare, P.W. 2008. Soil bacteria confer plant salt tolerance by tissue-specific regulation of the sodium transporter HKT1. *Molecular Plant Microbe Interactions* 21: 737–744.
- Zhang, M., Li, R., Cao, L., Shi, J., Liu, H., Huang, Y., Shen, Q. 2014. Algal sludge from Taihu Lake can be utilized to create novel PGPR-containing bioorganic fertilizers. *Journal of Environment Management* 132: 230–236.
- Zhen, Z., Liu, H.T., Wang, N., Guo, L.Y., Meng, J., Ding, N., Wu, G.L., Jiang, G.M. 2014. Effects of manure compost application on soil microbial community diversity and soil microenvironments in a temperate cropland in China. *PLoS ONE* 9: e108555.
- Ziegler, M., Engel, M., Welzl, G., Schlöter, M. 2013. Development of a simple root model to study the effects of single exudates on the development of bacterial community structure. *Journal of Microbiological Method* 94: 30–36.