Chapter 9
Soil Quality and Plant-Microbe Interactions in the Rhizosphere

Debarati Bhaduri, Sharmistha Pal, T.J. Purakayastha, K. Chakraborty, R.S. Yadav, and Mohd. Sayeed Akhtar

Abstract The rhizosphere is a microenvironment contrastingly different from non-rhizosphere soil. The high microbial activity in the rhizosphere leads to better cycling and availability of nutrients and improves chemical soil quality indicators. The biological soil quality indicators are improved in rhizosphere due to enhanced microbial activities either in terms of microbial biomass carbon, dehydrogenase activity, activities of various hydrolytic enzymes e.g., phosphatases, sulfatases, proteases, amidases and glucosidase responsible for breakdown of organically bound nutrients in soil. Over the last two decades lot of interests developed on soil quality research due to degradation in soil quality by anthropogenic activity. Besides being a rich source of carbon and energy for the heterotrophic organisms, plant roots exudates secrete a variety of carbonaceous materials that can act as a binding agent to increase stability of soil aggregates. The adoption of proper soil, crop, nutrient and organic manure management strategies has the direct impact on the soil quality. However, it may also be affected indirectly by the plant microbe interactions. This article focuses on induced changes in the rhizosphere ecology by plant microbe interactions and also to integrate these changes to soil quality indicator of unified soil in the sustainable agriculture soil management practices.

D. Bhaduri (✉) • K. Chakraborty • R.S. Yadav
ICAR-Directorate of Groundnut Research, Junagadh 362001, Gujarat, India
e-mail: debarati.ssiari@gmail.com; koushik_iari@rediffmail.com; yadavrs2002@gmail.com

S. Pal
ICAR-Indian Institute of Soil and Water Conservation, Research Centre,
Chandigarh 160019, India
e-mail: sharmistha.ars@gmail.com

T.J. Purakayastha
Division of Soil Science and Agricultural Chemistry, ICAR-Indian Agricultural
Research Institute, New Delhi 110012, India
e-mail: tpurakayastha@gmail.com

M.S. Akhtar (✉)
Institute of Tropical Agriculture, Universiti Putra Malaysia,
43400 UPM Serdang, Darul Ehsan, Selangor, Malaysia
e-mail: sayeedbot@yahoo.co.in

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9.1 Introduction

Soil is gradually renewable over the human time scale of decades to centuries. Soil is fragile and easily degraded when misused and mismanaged. Soil is unequally distributed among geographical regions of the world because of limitation of climate and slope gradient, and is fixed in location and cannot be transported (Lal 2013). The toll of soil erosion in natural ecosystems occurs at the steady rate and cumulative impacts cumulative effects on the soil quality. Worldwide, erosion rates range from a low of 0.001–2 t/ha/year on relatively flat land with grass and/or forest cover to rates ranging from 1 to 5 t/ha/year on mountainous regions with normal vegetative cover (Pimentel and Kounang 1998). According to Crosson (1997) approximately 24 billion tons of fertile soils are lost annually from world agricultural system. However, Lal and Stewart (1990) and Wen (1998) reported that 6.6 billion tons of soils per year are lost in India and 5.5 billion tons are lost annually in China. The term soil quality received considerable scientific attention during the 1990s (Lal 1993, 1997, 1999; Doran and Parkin 1994; Doran et al. 1996; Carter et al. 1997; Bezdicek et al. 1996; Karlen et al. 1997). The interest is quite logical as the soil always remains at receiving end of all irresponsible anthropogenic activities. Soil performs various functions and one of the major functions is to act as a supporting medium for plants or food crops feeding the human and animal population. The condition of our soils ultimately determines human health by serving as a major medium for food and fibre production and a primary interface with the environment, influencing the quality of the air we breathe and water we drink. Thus, there is a clear linkage between soil quality and human and environmental health. As such the health of our soil resources is a primary indicator of the sustainability of our land management practices (Doran et al. 2002).

Plant-microbial interactions is a matter of discussion among scientific fraternity for quite a few time, as it directly linked with microbiologists, agronomists, soil scientists, botanists and pathologists. Plant-microbial interaction can influence the crop production as an applied aspect other than relating with issue of basic science research. But how the plant-microbial interaction impacts various soil processes and therefore changes in soil quality as a cumulative effect have not been much highlighted earlier. As a complex functional state, soil quality on the other hand, cannot be measured directly, but soil quality may be inferred from management-induced changes in soil properties known as soil quality indicators (Bouma 2002). Such indicators are measurable soil attributes that influence the capacity of soil to perform crop production or environmental functions and are sensitive to change in land use, management and conservation practices. Traditionally, soil quality research focused primarily on chemical and physical properties because of their simple analytical methods (Larson and Pierce 1991). Moreover, it has been suggested by Islam and Weil (2000) that soil biological properties can serve as early and sensitive indicators of agro-ecosystems in response to soil management practices. Integrated soil quality indices based on a combination of soil properties provide a better indication of soil quality than individual parameters.

Karlen et al. (1994) developed a soil quality index through 'Conceptual Framework model' to quantify parameters such as chemical, biological and physical properties that interact in a complex way to give a soil its quality. Further, Andrews et al. (2004) designed a "Soil Management Assessment Framework" for soil quality assessment, where indicators were selected based on the management goals, associated soil functions and other site-specific factors. A valid soil quality index would help to interpret data from different soil measurements and show whether management and land use are having the desired results for productivity, environmental protection, and health (Granatstein and Bezdicek 1992).

In recent years, soil quality research has focused on the linkages among the following: management practices and systems; observable soil characteristics; and soil processes and performance of soil functions (Lewandowski and Zumwinkle 1999). Choosing the appropriate soil attributes to include in an index must include consideration of soil function and management goals that are site specific and user-oriented and must focus on sustainability rather than just crop yields. These indices would be useful in ascertaining the fragility of soil and for understanding how improved management might strengthen its resilience (Chaudhury et al. 2005).

9.2 Role of Plant Roots in Modifying Rhizosphere Environment

Soil organic matter is one of the key components in maintaining soil fertility, soil quality, and agricultural sustainability. The rhizosphere has strongly influenced by plant roots and also has a significant role in regulation of soil organic matter decomposition and nutrient cycling (Dijkstra et al. 2013). The presence of live roots significantly controls the rate of original soil organic matter decomposition through the rhizosphere effect. Soil food webs are mainly based on three primary carbon sources: root exudates, litter or residues, and soil organic matter. These carbon sources vary in their availability and accessibility to soil organisms, and can thus; increase the carbon flow and biodiversity within the food web. Processes that are shared both by roots and associated microorganisms are commonly referred as rhizosphere processes, such as: exudation of soluble compounds, water uptake, nutrient mobilization by roots and microorganisms, rhizosphere-mediated soil organic matter decomposition, and the subsequent release of CO_2 through respiration. In this way, rhizosphere processes serve as are major gateways for nutrients and water. Roots leak carbohydrates, amino acids, organic acids, and a number of other complex compounds that feed the microorganisms in the rhizosphere. Each plant species leaks its own unique signature of compounds into the rhizosphere. The more diverse the plant community above ground the more diverse the community below ground.

At the global scale, rhizosphere processes utilize approximately 50 % of the energy fixed by photosynthesis in terrestrial ecosystems, contribute roughly 50 % of the total CO_2 emitted from terrestrial ecosystems, and mediate virtually all aspects of nutrient cycling. Therefore, plant roots and their rhizosphere interactions are at the center of many ecosystem processes. However, the linkage between rhizosphere processes and soil organic matter decomposition is not well understood though it is often large in magnitude. The study of Dijkstra and Cheng (2007) has indicated that the rate of soil organic matter decomposition can be accelerated by as much as 380 % or inhibited by as much as 50 % by the presence of live roots. On the other hand, microbial growth is limited by supply of fresh organic carbon that directly linked with plant biomass production. Plants have a clear cut effect to modify the functional and structural composition of microbes present in rhizosphere (Dey et al. 2012). But this effect of rhizosphere priming varies with plant phenology, seasonal and temporal variations and soil mineral nutrients applied (Cheng et al. 2003). With help of improved knowledge and up-to-date technologies for studying the rhizosphere organization will facilitate greater understanding in this aspect.

9.3 Role of Microbes in Rhizosphere Zone

Microorganisms are the tiniest forms of life; still their role towards ecosystem sustainability cannot be ignored. Being present in numerous genus and species in soil and even a lot as unexplored carrying useful metabolic processes are influenced by several ecological factors like moisture, temperature, organic matter, rhizosphere structure of plant, and plant diversity etc. They are also described to be affected by some crop management practices like tillage, irrigation, nutrient, organic and green manuring, mulching and few others. Microorganisms play a key role in nutrient cycling and energy flow. Potentiality of biological nitrogen fixation as low-cost source of nitrogen and phosphorus solubilization by phosphate solubilizing bacteria and phosphorus mobilization by arbuscular mycorrhizal fungi is already well-known among scientific community. Comparing the rhizosphere effect on microbes, the rhizosphere/bulk soil ratios are found to be ranged from 2–20, 10–20 and 5–10 for bacteria, fungi and actinomycetes, respectively (Dey et al. 2012). Soil microorganisms are also recognized as potential indicator of some ecological stresses such as heat, moisture, salts, heavy metals, pesticides and contaminants. Microbial abundance and diversity was found to be reduced under soil perturbations and pollution. Even their changing metabolism and functions are also significant in the present context of climate change. Probably their sensitivity towards such imposed condition proved them as effective soil quality indicators. However, it is important to screen those useful microbial indicators that can vary from one ecosystem to another like agriculture, pasture and forests. Microbes present in the rhizosphere thus have a prominent role to play as sensitive ecological indicator. Though, these microbial indicators have some merits and demerits and should be selected on the basis of measurement protocols, reproducibility and easiness of interpretation that can immensely represent soil quality and health.

9.4 Rhizosphere Ecology

The term 'rhizosphere' was coined by Hiltner (1904) to describe the narrow zone of intense bacterial activity around legume roots, via root stimulation of any soil inhabiting organism. Currently, it is described as the zone of soil surrounding the root which is affected by it. As the definition has changed from the specific to the more general, so the width of the rhizosphere itself has also broadened, from a very narrow zone extending at most 1–2 mm from the root surface, to one extending several centimetres in the case of nutrient or water depletion profiles, or several tens of centimetres for volatile compounds released by the root. Perhaps the only recognizable characteristic of the original definition is that the rhizosphere is operationally described in terms of a concentration gradient between the root surface and the bulk soil.

9.4.1 The Rhizosphere Effect

As seeds germinate and roots grow through the soil, the release of organic material provides the driving force for the development of active microbial populations in a zone that includes plant root and surrounding soil in a few mm of thickness. This phenomenon is referred as the rhizosphere effect (van Veen et al. 2007). Broadly, there are three distinct components recognized in the rhizosphere; the rhizosphere *per se* soil, the rhizoplane, and the root itself. The rhizosphere is thus the zone of soil influenced by roots through the release of substrates that affect microbial activity. The rhizoplane is the root surface, including the strongly adhering root particles. The rhizosphere effect can thus be viewed as the creation of a dynamic environment where microbes can develop and interact.

9.4.2 The Rhizosphere as a Battle Field

The number and diversity of microorganisms are related to the quantity and quality of the exudates but also to the outcome of the microbial interactions that occur in the rhizosphere. Soil biota e.g. bacteria, fungi, micro-fauna and the plant root are themselves embedded in food webs and thus interactions with consumers or predators in the microbial as well as macro and mesofaunal world are important to understand rhizosphere processes. A high number of soil microbes attained properties enabling them to interact more efficiently with roots and withstand the quite challenging conditions of rhizosphere life. The rhizosphere inhabiting microorganisms competing each other for water, nutrients and space and sometimes improve their competitiveness by developing an intimate association with plant. This process can be regarded as an on-going process of micro-evolution in low-nutrient environments, which are quite common in natural ecosystems (Schloter et al. 2000).

9.4.3 Alteration of Soil Characteristics in Rhizosphere

As a consequence of normal growth and development, a large range of organic and inorganic substances are secreted by roots into the soil, which inevitably leads to changes in its biochemical and physical properties (Walker et al. 2003). Various functions have been attributed to root cap exudation including the maintenance of root-soil contact, lubrication of the root tip, protection of roots from desiccation, stabilization of soil micro-aggregates, and selective adsorption and storage of ions (Hawes et al. 2000). Root mucilage is a reasonably studied root exudate that is believed to alter the surrounding soil as it is secreted from continuously growing root cap cells (Sims et al. 2000). Young (1995) found that rhizosheath soil was significantly wetter than bulk soil and suggested that exudates within the rhizosheath increase the water holding capacity of the soil. Furthermore, it has recently been proposed that in dry soil, the source of water to hydrate and expand exudates is the root itself. The root exudation plays a major role in maintaining root-soil contact in the rhizosphere by modifying the biochemical and physical properties of the rhizosphere and contributing to root growth and plant survival. However, the exact fate of exuded compounds in the rhizosphere, and the nature of their reactions in the soil, remains poorly understood. The rhizosphere inhabiting microorganisms compete for water, nutrients and space and sometimes improve their competitiveness by developing an intimate association with plant (Hartmann et al. 2009). These microorganisms play important roles in the growth and ecological fitness of their host.

9.4.4 Root Exudation and Nutrient Availability

Root exudation is the release of organic compounds from living plant roots into the surrounding soil; it is a ubiquitous phenomenon. Roots release compounds via at least two potential mechanisms, and the rates of exudation *sensu stricto* vary widely among species and environmental conditions. At the moment of exudation and thereafter, the organic materials are subject to microbial attack, and thus cannot be enriched and separated from the roots in the natural environments. In this context, root exudation has been quantified by measuring the production of labelled CO_2 in the rhizosphere of ^{14}C-labelled plants. It has been estimated that approximately 40 % of the total amount of carbohydrates produced by photosynthesis is released into the soil surrounding roots (Akhtar and Siddiqui 2008). Root exudates are mainly composed of water soluble sugars, organic acids, and amino acids, but also contain hormones, vitamins, amino compounds, phenolics and sugar phosphate esters. Release of these low molecular weight compounds is a passive process along the steep concentration gradient which usually exists between the cytoplasm of intact root cells (millimolar range) and the external soil solution (micromolar range).

It is assumed that both the qualitative and quantitative compositions of root exudates are affected by various environmental factors, including pH, soil type, oxygen status, light intensity, soil temperature, nutrient availability and the presence of microorganisms. The composition of root exudates is also largely dependent on the plant species and plant developmental stages (Jaeger et al. 1999). It is estimated at the maturity that the rhizodeposition of N amounted to 20 % of the total plant nitrogen (Jensen 1996). Low concentrations of some nutrients such as K^+, Na^+ and Mg^{++} readily stimulate the activity of major enzymes of the glycolytic pathway, namely phosphofructokinase and pyruvate kinase, which together regulate glycolysis in plant cells (Plaxton 1996). Individual micronutrients are similarly important components of major enzymes, which regulate all biological processes. So low nutrient availability can create constraint to plant growth in many environments of the world, especially the tropics where soils are extremely deficient in these oligoelement nutrients (Pinton et al. 2007). Some species typically exude organic acid anions in response to P and Fe deficiency or phytosiderophores due to Fe and Zn deficiency (Haynes 1990). Root exudates, on the other way provides nutritional source to several bacteria inhabiting in rhizosphere that takes part in nutrient cycling in soil (Jaeger et al. 1999).

9.5 Rhizosphere Effect on Soil Quality Indicators

Soil is a dynamic, living, natural body that is vital to the function of terrestrial ecosystems and represents a unique balance between physical, chemical and biological factors. Quality of soil as distinct from health is largely defined by the ability of soil to perform various intrinsic and extrinsic functions. Hence number of definitions has drawn attraction over the time. Quality is represented by a suite of physical, chemical and biological properties that together (i) provide a medium for plant growth; (ii) regulate and partition water flow and storage in the environment; (iii) and serve as an environmental buffer in the formation and destruction of environmentally hazardous compounds (Larson and Pierce 1991). Soil qualities can be defined as inherent attributes of soil that are inferred from soil characteristics of indirect observations e.g. compatibility, erodibility and fertility. The ability of soil to support crop growth which includes factors such as degree of tilth, aggregation, organic matter content, soil depth, water holding capacity, infiltration rate, pH changes, nutrient capacity and so forth (Grassini et al. 2010; Piedallu et al. 2011).

The soil quality has been defined by scientists as the "fitness for use" (Doran et al. 2002), and by others as the "capacity of a soil to function" (Doran and Parkin 1994; Karlen et al. 1997). According to Arshad and Coen (1992) soil quality is "the sustaining capability of a soil to accept, store and recycle water, and energy for production of crops at optimum levels while preserving a healthy environment".

Karlen et al. (1992) defined soil quality as "the ability of the soil to serve as a natural medium for the growth of plants that sustain human and animal life". Soil quality refers to its ability to sustain productivity and maintain environmental quality (Lal 1993). "The capacity of a soil to function within boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health", was the definition of soil quality put forth by Doran and Parkin (1994). Lal and Stewart (1995) described soil quality as the inherent attribute of soil and to characteristics and processes that determined the soil's capacity to produce economic goods and services and regulate the environment. Sims et al. (1997) proposed a non-polluted soil criterion for soil quality, that they refer soil quality as the clean state of soil. According to Holden and Friestone (1997) soil quality is the degree to which the physical, chemical and biological characteristics of the soil to attenuate environmental pollution. The soil quality definition given by Karlen et al. (1997) mentioned as "The capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". It can be conceptualized as a three-legged stool, the function of which requires an integration of three major components-sustained biological productivity, environmental quality and plant and animal health. Sojka and Upchurch (1999) defined soil quality in terms of distinct management and environmental condition specific to one soil under explicit circumstance for a given use.

Soil quality traditionally has focused on, and has been equated with agricultural system productivity. Crop yield is an important indicator of system productivity that is, in part, dependent upon soil quality. Crop yield can serve as a bioassay for several interacting factors such as soil, water, air, disease, germplasm, and management. Crop yield alone, however, is an incomplete measure of system productivity. Soil quality may better represent system productivity and function. Soils have biological, chemical and physical properties that interact in a complex way to give a soil its quality or capacity to function. Indicators of soil quality should give measures of the capacity of the soil to perform these functions (Larson and Pierce 1991; Doran and Parkin 1994). The soil quality indicators could be used to measure changes caused by soil and crop management practices. Efforts to quantify soil quality are increasing throughout the world and several physical and chemical indicators have been identified (Karlen and Stott 1994). However it is very closely linked to soil biological properties also. Most of the indicators are governed by rhizosphere either by direct or indirect way.

The package of indicators used for assessing soil quality, can vary from location to location depending on the kind of land eg. Rangeland, wasteland, agricultural land or land use, soil function and soil forming factors (Arshad and Coen 1992; Helkamp et al. 1995). Henceforth, indicators should be easily measured and measurement should be reproducible (Gregorich et al. 1994). The proper approach in defining soil quality and health must be holistic, not reductionistic. However, it would be unrealistic to use all ecosystems or soil attributes as indicators, so a minimum dataset consisting of a core set of soil attributes encompassing chemical, physical and biological soil properties are selected for soil quality assessment (Larson and Pierce 1991).

9.5.1 Rhizosphere Effect and Physical Soil Quality Indicators

Soil physical characteristics are a necessary part of soil quality assessment because they cannot be easily improved (Karlen and Cambardella 1996; Wagnet and Hutson 1997). Larson and Pierce (1991) summarized the physical indicators of soil quality as those properties which influence crop productivity by:

1. Whether a soil can accommodate unobstructed root growth and provide pore space of sufficient size and continuity for root penetration and expansion
2. The extent to which the soil matrix will resist deformation
3. The capacity of soil for water supply and aeration.

Physical conditions of a soil have direct and indirect effects on crop production and environmental quality (Fig. 9.1). These include parameters that are relatively static (standard soil profile characteristics, rooting depth, morphological features, texture etc.) and sensitive parameters (bulk density, aggregate stability, penetration resistance etc.).

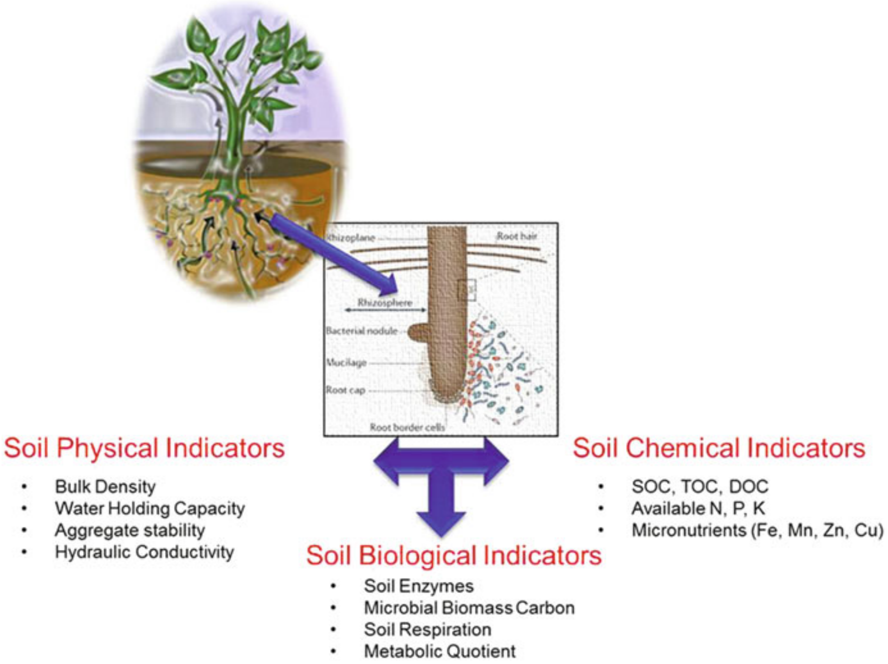

Fig. 9.1 Effect of soil quality indicators on the rhizospheric soil

9.5.1.1 Bulk Density

Bulk density is considered as one of the most important dynamic property of soil. It varies with structural condition of the soil that is altered by cultivation, compression, animal grazing, agricultural machinery, weather and others. Soil bulk density also can serve as an indicator of soil compaction and relative restriction to root growth (Arshad et al. 1996).

Bulk density is reported to be influenced by various manuring and fertilization practices. Nambiar (1994) reported that incorporation of farm yard manure at the rate 10–15 t ha^{-1} annually for many years brought about a slight reduction in bulk density in almost all the soils indicating improvement in soil physical properties. The effect of 10 years of rice-rice rotation showed that the lowest bulk density (1.26 Mg m^{-3}) was recorded with paddy straw incorporation along with 50 % NPK, hence incorporation of organic matter along with fertilizer had significantly increased the porosity (Oguike et al. 2006). The bulk density (0–15 cm) ranged from 1.39 Mg m^{-3} for 100 % NPK plus farm yard manure to 1.47 Mg m^{-3} for control under maize-wheat crop rotation of LTFE in inceptisol (Masto et al. 2007). Puddling is another important management practice which significantly influences the soil bulk density. It is reported that bulk density increases when the puddled soils undergo desiccation in a lowland-upland e.g. rice-wheat situation because of soil shrinkage (Sharma et al. 2005).

9.5.1.2 Aggregate Stability

Aspects of soil structure are quantitatively characterized by determining the stability of aggregates. The amount and quantity of organic matter, types of clay, wetting and drying, freezing and thawing, type and amount of electrolytes affecting colloidal dispersion, biological activity, cropping and tillage system affect soil aggregates. Aggregate stability is an important measure of soil quality for crop establishment, water infiltration and resistance to erosion and compaction (Beare and Bruce 1993).

Either the application of application of NPK with farm yard manure or sewage compost and continuous green manuring increased the percentage of aggregate stability (Sur et al. 1993). Fallow plots had the maximum readily decomposable organic matter from the natural grasses with extensive root system might have provided the protection cover to the aggregates leading to high aggregate stability (Rawat et al. 1996). The beneficial effect of balanced fertilization on soil structure may be because the role played by phosphate ions in binding the soil particles or due to greater amount of organic residues produced in fertilized plots. Higher value of aggregate stability obtained under farm yard manure or blue green algae may be due to certain polysaccharides formed during decomposition of organic residues by microbial activity (Mishra and Sharma 1997).

9.5.1.3 Hydraulic Conductivity

The rate at which water flows through soil affects many properties of the soil, including infiltration, drainage, nutrient flow within the soil, and soil erosion. Hydraulic conductivity values provide a potential measure for comparing the impact of different management practices on water flow, be it either cropping system, or tillage and nutrient management. Paddy caused greater reduction in hydraulic conductivity than wheat, which may be attributed to reorientation of particles into impermeable crust at the surface and the deposition of finer particles in lower layers forming a flow restricting layer in puddled rice cultivation. Hence tillage for rice caused a significant reduction in saturated hydraulic conductivity (Sharma et al. 2005). While hydraulic conductivity in residue-covered no-till soil increased due to improved macroporosity (Blanco-Canqui and Lal 2007). Application of NPK fertilizers (Schjonning et al. 2005), organic materials in combination with fertilizers (Oguike et al. 2006), and combined use of farm yard manure and blue green algae (Mishra and Sharma 1997) reported to increase soil's hydraulic conductivity.

9.5.1.4 Water Holding Capacity

Water holding capacity is the amount of water retained by the soil after it has been saturated. Water holding capacity depends on the number and size of pores that are primarily governed by the texture, structure, organic matter and mineralogy of the soil. Incorporation or substitution of nitrogen by organic materials increased the maximum water holding capacity than the chemical fertilizer alone (Reddy et al. 1999). However, the maximum water holding capacity in no-tilled soil was due to change in soil organic carbon content (Masto 2004).

9.5.2 Rhizosphere Effect and Carbon Dynamics

Carbon dynamics in soil is directly related with rhizosphere zone. Carbon mineralization and subsequent release of CO_2 is governed either by respiration activity of root tissues or microbial cells present in the root vicinity (Melillo et al. 2002). On the other hand, Carbon sequestration implies to trap carbon in the soil so that the carbon loss from soil can be prevented (Lal 2008). Deposition of root tissues along with leaf litters and stems of plant contribute here.

9.5.2.1 Soil Organic Carbon

Soil organic matter has long been considered the key quality factor of soil. Soil organic matter is a source and a sink of plant nutrients and is important in maintaining soil tilth, improving aeration and infiltration of water, promoting water retention, reducing erosion and controlling the efficacy and fate of applied pesticides (Gregorich et al. 1994). Amongst the various attributes organic matter content is the most important determinant of soil quality. Therefore, the evaluation of soil quality should be taken into account the multifarious beneficial function of organic matter (Gill et al. 2006).

Changes in soil organic carbon over a long-term period showed an observable trend. The annual addition of farm yard manure had increased initially the soil organic carbon content rapidly and then grows slowly as a steady state. Johnston (1994) reported that organic carbon in agricultural soils is found to be constant for about 100 years in both unmanured and manured plots supplied with NPK fertilizers. Application of farm yard manure Application of farm yard manure visibly enhanced the soil organic carbon content in various cropping systems (Iqbal et al. 2012).

9.5.2.2 Microbial Biomass Carbon

The microbial biomass is the living component of soil organic matter (Jenkinson and Ladd 1981) excluding the macrofauna and plant root. In many models of organic matter formation microbial biomass is used as a precursor to more stable fraction of organic matter (Parton et al. 1987). About 95 % of the total soil organic matter is non-living, therefore, relatively stable or resistant to change, decade may be required to observe in measurable changes in soil organic matter. It provides an indication of soil ability to store and recycle nutrients and energy and also serves as a sensitive indicator of change and future trends in organic matter levels and equilibria (Gregorich et al. 1994). Microbial biomass carbon is a relatively small (approximately 1–4 % of total soil organic carbon), labile fraction that quickly responds to C availability and also strongly influenced by management practices and system perturbations (Smith and Paul 1990).

No-tillage has been shown an improvement in microbial biomass carbon as compared to conventional tillage site (Purakayastha et al. 2008). Whereas many researches have cited that reported that the application of farm yard manure leads to higher content of microbial biomass carbon (Bucher 1999; Rudrappa et al. 2006) with the increasing microbial biomass level per unit soil organic matter and caused a shift in organic matter equilibrium. Other than farm yard manure, organic amendments also supply readily decomposable organic matter in addition to increasing root biomass and root exudates due to increased crop growth, so further improve the microbial biomass carbon content in soil (Goyal et al. 1999; Manjaiah et al. 2000).

9.5.2.3 Soil Respiration

Soil respiration is the production of CO_2 or consumption of O_2 as a result of the metabolic processes of living organisms at the rhizosphere and in the soil. Soil respiration has been used as a useful measure of soil activity. However all the microbial biomass in the soil is not in active stage and with the increase in microbial biomass the dormant cells also increase. The term ‘dormant’ is based on the assumption that under field condition energy limitations allow only small parts of the total potentially active population to be active at any given time. The majority exist as vegetative cell with lower metabolic activity (Heim et al. 2002).

Soil respiration is a well-established parameter to monitor decomposition (Birkas et al. 2008), but soil respiration is also highly variable and can show wide natural fluctuation depending on substrate availability, moisture and temperature. The great variability in soil respiration means that this measure taken alone is very difficult to interpret in terms of soil health (Brooks 1995). For valid comparison between soils, respiration measurements must normally be made under controlled laboratory conditions. Again, interpretation of respiration in terms of soil health or quality is problematic. Rapid decomposition of organic matter is not necessarily desirable because stable organic matter has an important role in soil physical and chemical characteristics. On the other hand, the decomposition of organic residues to release plant nutrients at times of plant demand is a desirable character. Influence of organic matter added to soil on carbon mineralization has increased the soil respiration ability (Rudrappa et al. 2006). However, Jassal et al. (2005) stated that seasonal pattern also plays a key role in determining CO_2 evolution rates from soil.

9.5.2.4 Metabolic Quotient

Microbial metabolic quotient (qCO_2) also known as respiratory quotient, is the ratio of carbon mineralized to microbial biomass carbon. As per the reported literature, the average soil respiratory activity increased with increasing levels of farm yard manure application but respiratory activity as a percent of microbial biomass carbon decreased with increasing levels of manure application (Lupwayi et al. 1998).

A more stable microbial population and a greater microbial efficiency in utilizing carbon substrates lead to lower the metabolic quotient (Purakayastha et al. 2008), which is desirable for carbon sequestration, often found low under the agricultural sites (Smith 2002) than the pasture and uncultivated lands. On the other way, High microbial quotient has been reported with long-term N or recent cattle manure applications and low with recent N applications (Fauci and Dick 1994). NPK plus organic treatments was most efficient in preserving C in soil as exhibited lower quotient (Rudrappa et al. 2006; Majumder et al. 2008).

Effect of fertilizer and manure applications on metabolic quotient depends on the nutrient status of the soil, with applications enhancing qCO_2 in non-nutrient stressed situations, while the opposite true under nutrient stress so the difficulty persists in ascribing differences in metabolic quotient to disturbance and stress limit the usefulness of metabolic quotient as a diagnostic indicator of soil quality (Wardle and Ghani 1995). However, it clearly does have potential when used in conjunction with other biochemical and microbial analyses.

9.5.3 Rhizosphere Effect and Soil Nutrient Dynamics

Measurement of nutrient cycling and concentration of elements that may be potential contaminants or of those needed for plant growth and development often determined by other chemical indicators of soil such as pH, salinity, organic carbon and cation exchange capacity. Karlen et al. (1992) suggested that total and available plant nutrients, and nutrient cycling rates should be included in chemical soil quality assessment. Larson and Pierce (1991) chose those chemical properties that either inhibits root growth or that effect nutrient supply due to the quantity present or the availability. Reganold and Palmer (1995) used chemical parameters related to nutrient availability as measures of soil quality including CEC, total N and P, pH and extractable P, S, K, Mg, Ca.

9.5.3.1 Available Nitrogen

Nitrogen being a primary nutrient element to crop plants controls their vegetative and reproductive growth. It supplies majorly from soil available nitrogen either organic or inorganic forms, constantly converts to readily-available forms (NH_4^+, NO_3^-) through certain biochemical interventions, mostly carried out by native microbial population in soil. Rhizosphere also contributes in supplying nitrogen via biological nitrogen fixation by nodule formation in leguminous crops. The regular incorporation of farm yard manure in soil enhanced nitrogen build up remarkably (Jenkinson 1991), however that varies among soil types (Nambiar 1994), but optimal to super optimal dose of fertilizer nitrogen showed little and gradual improvement in the soil available nitrogen.

9.5.3.2 Available Phosphorus

Phosphorus content of most of the soils is usually and only a very small proportion of the total P is present in available form. In contrast to certain inorganic N compounds which are not stable in soil and are subjected to volatilization and leaching, P is relatively stable and is not subject to such losses. The low solubility of P is partly responsible for the relative low availability of this nutrient to the plant (Mengel and Kirkby 1982). Continuous cropping without fertilization and manuring decreased the available P content in soil (Srinivasarao et al. 2013) whereas application of P-fertilizers had shown to increase the content of available P even with continuous cropping (Kumar and Yadav 2005).

9.5.3.3 Available Potassium

Although not much pronounced and studied, soil available potassium has the role to maintain soil quality. As this element present in the soil in a single cationic form (K^+) and transforms from non-exchangeable to exchangeable and soluble forms for maintaining equilibrium, no other biochemical factors plays any role in K-dynamics. Root uptake of K occurs mostly by diffusion mechanism. Balanced application of farm yard manure, farm yard manure plus NP fertilizer, or NPK fertilizer, increased the effectiveness of the K applied (Blake et al. 1999). Long-term usage of organic amendments such as groundnut shells and farm yard manure along with inorganic fertilizers is reported to enrich both the exchangeable and nonexchangeable-K forms in K-deficient Alfisol (Srinivasarao et al. 2010, 2013).

9.5.3.4 Available Micronutrients

Intensive cropping with high yielding varieties fertilized with high analysis fertilizers catalyzed the rapid depletion of available micronutrients. Enhanced removal of the micronutrients caused by the realization of higher yields without their supplementation has already made some of these nutrients as yield-limiting.

Continuous application of chemical fertilizers was accompanied by a drop in the available Zn (Nambiar 1994; Mathur 1997; Kumar and Yadav 2005) and Cu content (Singh and Nambiar 1986). But incorporation of farm yard manure along with NPK either maintained the available Zn at the initial level or raised it due to enhanced mobilization of the available micronutrients in the surface and sub-surface soils (Bellaki and Badanur 1997). However, Mishra et al. (2006) reported that application of green manure of Sesbania with farm yard manure and wheat straw is advantageous for sustained supply of Zn to rice wheat cropping system soils. On the other hand, continuous use of NPK resulted in an increase in the acidity which in turn increased the available micronutrient status in soil (Setia and Sharma 2004) as a result available Fe content was ascribed to the enhanced solubilization of Fe induced by the intensification of soil acidity (Nambiar 1994).

9.5.4 Biological and Biochemical Changes in Rhizosphere

Soil quality does not just depend on the physical and chemical properties of the soil but it is very closely linked to its biological properties also. Biological properties include size and diversity of the microbial, macro and microfaunal biomass, enzyme quantities and activities, mineralizable C, N, P, S etc., respiration and soil organic matter content (Fig. 9.2). Biological processes provide the resilience and buffering capacity to ameliorate stress (Karlen et al. 1992).

Soil biota is considered an important and labile fraction of soil organic matter involved in energy and nutrient cycling. It has been well established that the more dynamic characteristics such as microbial biomass, soil enzyme activity and soil respiration respond more quickly to changes in crop management practices or environmental conditions than do characteristics such as total soil organic matter (Dick 1992; Doran et al. 1996).

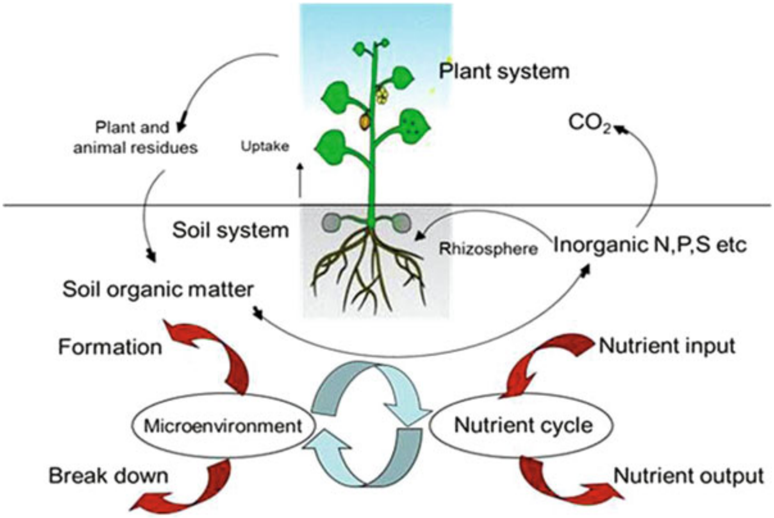

Fig. 9.2 Role of microbial biomass in the cycling of nutrients in rhizosphere

9.5.4.1 Potentially Mineralizable Nitrogen

Potentially mineralizable nitrogen is one of the most important potential indicators for use to assess the function of ecological habitat and biodiversity (Cardoso et al. 2013). Reduction in the soil's natural ability to provide nitrogen, which they attribute to interactions between organic matter and soil microbes, may even hamper the crop yield (Cassman and Pingali 1995). The effect of green manure in improving the potentially mineralizable N was more pronounced (Kang et al. 2005). Thus, the potential mineralizable nitrogen has been selected as soil biological indicator to assess to soil quality (Doran and Parkin 1994; Hseu et al. 1999).

9.5.4.2 Enzymes Activity

Enzymes are important soil components involved in the dynamics of soil nutrient transformation. Enzyme activity in the soil environment is considered to be a major contributor of overall soil microbial activity (Frankenberger and Dick 1983) and, also to soil quality (Dick 1994). For the mineralization of the organic substrate to occur, both the synthesis and the activity of a specific enzyme complex are needed. These later processes may be linked to the presence of countless factors directly implicated in the mechanism of enzyme synthesis and secretion (Martens et al. 1992).

Dehydrogenase

Dehydrogenases reflect the total range of oxidative activity of soil microflora and consequently may be associated to be a good indicator of microbiological activity (Watts et al. 2010). Dehydrogenase was highly sensitive to the inhibitory effects associated with large fertilizer addition (Manjaiah and Singh 2001; Masto et al. 2007) suggested an optimum and balanced application of nutrients that led to significant increase in dehydrogenase activity. Whereas, the dehydrogenase activity was stimulated by the application of organic manures (Goyal et al. 1999; Kang et al. 2005), even the effect is much pronounced in saline and alkaline soils (Rao and Pathak 1996).

Phosphatase

Phosphatases are a group of enzymes that catalyze hydrolysis of esters and anhydrides of phosphoric acid, so they are meant to play critical roles in P cycles in soil ecosystems (Speir and Ross 1978). Phosphomonoesterases have been the most studied soil enzymes as they have shown activity both under acidic and alkaline conditions, according to its optimal pH, and because they act on low molecular P-compounds including nucleotides, sugar phosphates and polyphosphates (Makoi and Ndakidemi 2008). Due to the relative importance of this enzyme in soil organic-P mineralization and plant nutrition, their assay in soil assumes more importance. As the alkaline phosphatases are derived from microorganisms only, the acid phosphatases are secreted both by plant roots and microorganisms in rhizosphere (Chhonkar et al. 2002). Being such an important enzyme in soil system phosphatase activity in temperate grassland, are found to have a strong correlation with other soil properties such as pH, total N, organic P and clay content (Turner and Haygarth 2005).

β–Glucosidase

It has been established as a key soil quality indicator due to its importance in catalytic reactions on cellulose degradation, releasing glucose as a source of energy that maintains metabolically active microbial biomass in soil (Dick 1996). At the same time, its role in energy flow in the soil that directly related to labile-C and with the ability to stabilize soil organic matter. As a free enzyme in soil solution, it normally has a time-limited activity, so rapidly degrades and denatures, and its activity has been detected in soil, fungi and plants (Martinez-Salgado et al. 2010).

Urease

Urease enzymes are mainly responsible for urea hydrolysis which breaks into CO_2 and NH_3 as a result nitrogen losses take place by NH_3 volatilization and soil pH increase. As urea is supplied to soil as a major source of nitrogen fertilizers but due to the substantial nitrogen lost to the atmosphere through volatilisation, and a large share of the process is mediated by the urease enzyme thus it often proves very inefficient fertilizer practice. Soil urease originates mainly from plants and microorganisms found as both intra- and extra-cellular enzymes. However, mostly as an extracellular enzyme it represents up to 63 % of total activity in soil. (Martinez-Salgado et al. 2010); but is rapidly degraded in soil by proteolytic enzymes. Urease is widely reported to be a soil quality indicator, as its activity increases with organic fertilization and decreases with soil tillage (Saviozzi et al. 2001), also showing its influence by other factors such as cropping history, management practices, heavy metals, organic matter content, soil depth, and some environmental factors like temperature and pH (Yang et al. 2006).

9.6 Soil Quality Management *vis-a-vis* Rhizosphere Interferences

A better understanding of the basic principles of the rhizosphere ecology, including the function and diversity of inhabiting microorganisms is on the way but further knowledge is necessary to optimize soil microbial technology to the benefit of plant-growth and health in the natural environment. In sum, this can constitute overwhelming evidence indicating that an ever exploitation of plant growth promoting rhizobacteria can be a true success story in sustainable agriculture. As a consequence, current production methods in agriculture, *e.g.*, the improper use of chemical pesticides and fertilizers creating a long list of environmental and health problems will reduce.

9.6.1 Plant-Bacteria Interactions in the Rhizosphere

Microorganisms present in the rhizosphere play important roles in ecological fitness of their plant host. Plant-microbe interactions may thus be considered beneficial, neutral, or harmful to the plant, depending on the specific microorganisms and plants involved and on the prevailing environmental conditions.

9.6.1.1 Pathogenic Interactions

Roots exudates can attract beneficial organisms, but they can also be equally attractive to pathogenic populations, that many express virulence on only a limited number of host species. Plant diseases play a direct role in the destruction of natural resources in agriculture. Soil-borne pathogens cause important losses, fungi being the most aggressive. The extent of their harmful effects ranges from mild symptoms to catastrophes where large fields planted with agricultural crops are destroyed. Thus, they are major and chronic threats to food production and ecosystem stability worldwide. Common and well investigated bacterial agents include *Erwinia carotovora*, *Pseudomonas*, *Ralstonia* spp., *Streptomyces scabies*. The fungal and oomycete phytopathogens include members of *Fusarium*, *Phytophthora*, *Pythium*, *Rhizopus*, *Rhizoctonia* and *Verticillium* (Tournas and Katsoudas 2005) and amongst the forest pathogens most of them are filamentous fungi *Heterobasidion* and *Armillariella* (Asiegbu et al. 2005), and *Phytophthora* spp. (Rizzo et al. 2005).

9.6.1.2 Beneficial Microorganisms and Modes of Action

Plant-beneficial microbial interactions can be roughly divided into three categories. First, those microorganisms that, in association with plants, is responsible for its nutrition (i.e. microorganisms that can increase the supply of mineral nutrients to the plant). In this case, while most may not directly interact with the plant, their effects on soil biotic and abiotic parameters certainly have an impact on plant growth. Second, there is a group of microorganisms that stimulate plant growth indirectly by preventing the growth or activity of pathogens. Such microorganisms are referred to as biocontrol agents, and they have been well documented. A third group involves those microorganisms responsible for direct growth promotion, for example, by production of phytohormones. There has been a large body of literature describing potential uses of plant associated bacteria as agents stimulating plant growth and managing soil and plant fitness (Welbaum et al. 2004).

9.6.2 Plant Growth Promotion

9.6.2.1 Phytostimulation

Phytostimulation may directly enhance plant growth. In the processes of plant growth, phytohormones (e.g. production of indole-3-acetic acid, auxins, cytokinins, and gibberellins) play an important role. These hormones can be synthesized by the plant themselves but also by their associated microorganisms such as *Azospirillum* spp., besides having nitrogen-fixing ability (Steenhoudt and Vanderleyden 2000). Species of *Pseudomonas* and *Bacillus* can produce as yet not well characterized phytohormones or growth regulators that cause crops to have greater amounts of fine roots which have the effect of increasing the absorptive surface of plant roots for uptake of water and nutrients. The phytohormones they produce include indole-acetic acid, cytokinins, gibberellins and inhibitors of ethylene production. Indole-3-acetic acid is a phytohormone which is known to be involved in root initiation, cell division, and cell enlargement commonly produced by plant growth promoting rhizobacteria (Barazani and Friedman 2001). Auxins are quantitatively the most abundant phytohormones secreted by *Azospirillum* (Bloemberg and Lugtenberg 2001).

Furthermore, plant-associated bacteria can influence the hormonal balance of the plant. Ethylene is an important example to show that the balance is most important for the effect of hormones: at low levels, it can promote plant growth in several plant species including *Arabidopsis thaliana*, while it is normally considered as an inhibitor of plant growth and known as a senescence hormone.

9.6.2.2 Biofertilization

There are several plant growth promoting rhizobacterial inoculants currently commercialized that seem to promote growth through at least one mechanism; suppression of plant disease (termed bioprotectants), phytohormone production (termed biostimulants), or improved nutrient acquisition (termed biofertilizers). The mode of action of these biofertilizers act directly by help in the nutrient uptake or indirectly influenced the root growth and morphology (Vessey 2003). The most prominent example of bacterial nitrogen fixation is the symbiotic association between rhizobia and its legume host plants (Table 9.1). In this association bacteria metabolize root exudates (carbohydrates) and in turn provide nitrogen to the plant for amino acid synthesis. The ability to fix nitrogen also occurs in free-living bacteria like *Azospirillum*, *Burkholderia*, and *Stenotrophomonas* (Dobbelare et al. 2003). Biofertilization accounts for approximately 65 % of the nitrogen supply to crops worldwide (Bloemberg and Lugtenberg 2001). Another nutrient is sulfate, which can be provided to the plant via oxidation by bacteria (Banerjee and Yesmin 2002).

9.6.3 Microbial Co-operation in the Rhizosphere-Interactions for Improving Soil Quality

Soil structure is one of the most influential factors controlling soil quality. A well-aggregated soil structure ensures appropriate soil tilth, water infiltration rates, aeration, root penetrability and organic matter accumulation leading to better soil quality. The contribution of microbial co-operation in the rhizosphere to the formation and stabilization of soil aggregates has been demonstrated frequently (Miller and Jastrow 2000). Firstly, soil particles are bound together by bacterial products and by hyphae of saprophytic and arbuscular mycorrhizal fungi, into stable micro-aggregates (ranges in between 2 and 20 μm in diameter). These are bound by microbial products into larger micro-aggregates (ranges in between 20 and 250 μm in diameter), with bacterial polysaccharides acting as binding agents. Micro-aggregates are then bound into macro-aggregates (higher than 250 μm in diameter), with bacterial polysaccharides acting as binding agents and arbuscular mycorrhizal mycelia increasing the size of macro-aggregates. The effect of the arbuscular mycorrhizal fungi in co-operation with other microbes in the formation of water-stable soil aggregates is evident in different ecological situations (Requena et al. 2001), and the

Table 9.1 Multitrophic effect of rhizobacteria on the various host plants

Rhizobacteria	Agricultural crop	References
Bacillus cereus UW 85	Grain legumes	Vessey and Buss (2002)
P. fluorescens CHA0	*Arabidopsis* sp.	Iavicoli et al. (2003)
Bacillus subtilis, *B. amyloliquefaciens* IN 937, *Enterobacter cloaca*	*Arabidopsis* sp.	Ryu et al. (2003)
P. putida KD	Tomato and cucumber	Rezzonoco et al. (2005)
Pseudomonas fluorescens PCL1606	Avocado	Cazorla et al. (2006)
Bradyrhizobium and rhizobacteria	Mungbean	Shaharoona et al. (2006)
Pseudomonas brassicacearum, P. marginali, P. oryzihabitans, P. putida, Alcaligenes xylosoxidans	Indian mustard and rape	Belimov et al. (2007)
P. fluorescens WCS 365	Tomato	Kamilova et al. (2007)
Collimonas fungivorans	Tomato	Kamilova et al. (2008)
Agrobacterium amazonense	Rice	Rodrigues et al. (2008)
Bacillus subtilis FB17	*Arabidopsis thaliana*	Rudrappa et al. (2008)
Pseudomonas BA-8, *Bacillus* OSU-142, *Bacillus* M-3	Strawberry	Pirlak and Kose (2009)
Bacillus cepacia strain OSU-7	Stored potatoes	Recep et al. (2009)
Comamonas acidovorans	Kiwi	Erturk et al. (2010)

involvement of glomalin, a glycoprotein produced by the external hyphae of arbuscular mycorrhizal fungi, has been demonstrated (Wright and Upadhyaya 1998). The co-operation of microbial symbionts inoculated in the rhizosphere of target indigenous species of plants is a successful biotechnological tool to aid the recovery of desertified ecosystems.

9.7 Future Research Directions

Various bacteria and fungi colonising in the rhizosphere, carry out numerous interactive chemical processes that influence nutrition of plants, thus benefit plant growth and health, and also function-based soil quality. Thus the significance of maintaining microbial diversity in rhizosphere ecology and need-based use of microbial inoculates must take into consideration for better future scenario. It will help in achieving effective biotechnological applications, known as ‘rhizosphere technology’. In this connection, application of selected microbial consortia as plant inoculates to benefit plant production systems has gained attention. Either to maintain sustainable plant productivity or environmental quality, basic and strategic research should be carried on to improve our existing knowledge on microbial interactions in the root–soil environments. Here lies the scope of molecular and biotechnological interventions. New generation genetically-modified and environmentally-friendly microbial inoculates can be used to protect plants from disease and to promote plant growth. As future research guide, several key questions still need to be answered. Firstly, it has been reported that less than 5 % of all soil bacteria and Archaea (Curtis et al. 2002) and less than 5 % of all soil fungi (Hawksworth 2001) are culturable. Rest huge diverse population of microbes cannot be cultured. Hence, the function of these non-culturable microbes in rhizosphere ecosystems is challenging to test how these microbes alter, or respond to their environment, is less or poorly under knowledge. Secondly, there are number of unexplored species of root-associated soil microbes, those have definite roles on plant nutrition and productivity but they are yet to be identified. Finally, global climate change definitely has an influence on microbial diversity and community structure. But the changing pattern and its extent is another researchable option.

9.8 Conclusion

Degradation of land and deterioration of soil fertility is a concern for quite a long time around the globe. All such alarming issues and their possible management strategies are addressed by soil quality. Soil quality, a function-based holistic representation of soil system, is often directed by plant-microbial processes in rhizosphere. Although both the topics are not often discussed and intends to be interconnected, still it needs to be highlighted in the present scenario. Plant and microbes, as both are integral parts of rhizosphere contribute in nutrient mobilization, mediated by enzymatic interfaces. Nevertheless, some physical attributes such as aggregate stability, porosity, water retention and mobility are partially determined by the rhizosphere that altogether balances soil physical environment. But, the root system, as traditionally only believed to provide anchorage and uptake of water and nutrients, is also a chemical factory that simultaneously performing plentiful underground interactions. These happen due to mutualistic associations with beneficial microbes such as rhizobia, mycorrhizae, endophytes and plant-growth promoting rhizobacteria and parasitic interactions with other plants, pathogenic microbes e.g. fungi, bacteria, and invertebrate herbivores. Roots discharge several types of chemicals at a substantial amount that combat pathogenic microorganisms and attract beneficial ones. Every single soil quality indicator responds to changing equation of plant-microbial interactions that visibly altered by crop management practices like tillage, fertilizer and organic nutrient, amendments etc. in agricultural systems. Now-a-days research focus has been shifted to unravel the core processes that affect rhizosphere ecology. Rhizosphere ecology is depicted as highly heterogeneous microenvironments that varies with crop, species, cropping system and even with the crop cultivars, attributed by a combination of the physical architecture of the soil matrix, coupled with the rhizo-deposits, protons and other ions, gases e.g. CO_2, O_2, CH_4 etc. and that finally determines the role of roots as sinks for water and nutrients. Methodological advances will target to resolve the future research priorities for comprehensive understanding of the simultaneous processes in the rhizosphere.

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