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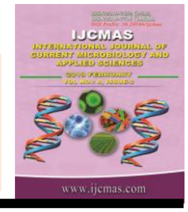

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Rhizosphere Management: A Novel Approach for Improving the Crop Productivity

Arvind Kumar*, V.P. Singh, D.S. Pandey and Rajeew Kumar

Department of Agronomy, G.B. Pant University of Agriculture and Technology, Pantnagar, Udham Singh Nagar (UK) 263145, India

**Corresponding author*

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A B S T R A C T

This paper can be focused on rhizosphere management to improve plant performance and soil health. The rhizosphere is the interacting soil zone between plant and soil biota. It could affect the plant nutrient availability through soil biological activity. It can be manipulated through plant management (selection of plant species, change in cropping pattern, intercropping etc.), soil management (addition of organic carbon or organic manure), microbial management (selection of biotic community), and system approach where plant, soil and microbial can be improved simultaneously. So, rhizospheric management can help us to improve soil health and plant productivity.

Introduction

The increasing inputs use, enhanced nutrient losses from soil, and increased stress (biotic and abiotic) on a plant that causes low NUE and plant performance (Bommerco *et al.*, 2013). In India, It creates more focus on nutrient management, especially synthetic fertilizer to satisfy the crop demand as well as food demand. We haven't much concern toward soil rhizospheric properties and plant characters (plant sink capacity, root capacity, and root morphology), plant nutrient utilization to enhance crop productivity (Neumann *et al.*, 2009; Zhang, *et al.*, 2010). Plants don't only use the soil as supporting material but plant releases some organic substances that influence the soil properties. This plant influenced soil volume can be known as rhizosphere (Dessaux *et al.*, 2016). In the early 19 century, this biologically more active soil volume near root zone termed as "rhizosphere" (Hartmann, 2008). The rhizosphere is the root adjacent area which causes the favorable environment to the growth of plant through microbial activity (*Rhizobium*, *Azotobacter*, Mycorrhizae fungi and Cyanobacterium) that is prerequisite for improving NUE and efficient crop production (Haichar *et al.,* 2012). The crop output can be enhanced through integrated management of synthetic fertilizers, crop growing practices, and soil-plant interactions without hampering on ecosystem process (Ryan *et al.,* 2009).

Now a day's alteration required to address the rhizospheric issues *i.e.* detection, analysis of root system under field condition, study the root mediated physicochemical properties into rhizosphere for root activity evolutions, molecular and physiological characterization of rhizosphere related regulatory processes and rhizosphere manipulating strategies for improving crop productivity (Neumann *et al.*, 2009). The physical, biological and chemical behavior is the output of many complexes, and interacting rhizospheric processes that affected by the plant mechanism, soil type, environmental factors and the microbial communities itself (Ryan *et al.*, 2009). The healthy soil biology can be managed through technological interventions, improvement, and breeding of the soil biotic community for improving as plant growth, nutrient uptake, and root characteristics. Also, the plants could be selectively engineered for various novel and interested beneficial plant traits. Plants availability of nutrients can also be improved by the application of soil amendments (Ryan *et al.*, 2009). Further, it can be enhanced by utilizing the plant root microbe communications into genetic engineering through several meditating chemical compounds. So, we require much attention toward study the rhizospheric environment and the root system of plants to improving the yield potentials of our crops to meet the food demand projected for next half century (Zhang, *et al.,* 2010). This review is done with the aim of strengthening up the knowledge of rhizospheric physicochemical, biological process and their management through various plant, soil, microbial approaches, plant and microbiome engineering methods. Also to intensely the attention toward rhizosphere enrichment and feeding for improving plant use efficiency.

Rhizosphere

The word "rhizosphere" to refered by the Greek word "*Rhiza*" which means root (Hiltner, 1904; Hartmann *et al.,* 2008). Basically, The rhizosphere is the part of soil which is most affected by the mutual relationship of plant and microbial communities and differentiated from bulk soil (Haichar *et al.,* 2014). It helps to improve the plant nutrients availability and biological activity through plant driven carbon as Rhizodeposits (Larsen *et al.,* 2015). This biological activity can be influenced by the various factors like a plant, soil, and climate that is known as "rhizospheric effect". It can be presented by R/E ratio. The R/E ratio can 2 to 20 showed normal range. (Whipps, 2001). The extent of rhizosphere in the soil can be depended upon the root system and microbial community because the vigorous root system and VAM can significantly increase the rhizospheric zone. The plant release compounds and microbial activity are a help to determine the spread of rhizospheric influence in the soil. According to this rhizosphere can be categories into different layers which spread from plant root to bulk soil (McNear Jr., 2013).

Rhizospheric layers

The rhizosphere can be influenced by the root development and root release compounds into the soil. So, on the basis of relative proximity, Rhizodeposits and microbial influences, the rhizosphere divided into 3 layers that spread from root out layer to adjacent soil (McNear Jr., 2013).

a. The endorhizosphere are the most intense rhizospheric activity zone at the outer layer of the plant root surface.

b. The rhizoplane is the intermediate zone or actual root-soil interface zone which inner layer directly surrounded to the root including the root epidermis and mucilage and out layer to ectorhizosphere.

c. The ectorhizosphere which is outer most layer of rhizosphere up to bulk soil.

The rhizosphere manipulations

The plant and biotic communities are the crucial factors that influence the rhizosphere because both are the parts of rhizosphere and help to shape the rhizosphere. However, these basic factors some external factor also influence the rhizosphere development by influencing the activity and development of plant and microbial communities likewise temperature, moisture, aeration, organic matter etc.

Role of plants in rhizosphere development

Plant root plays most active role in designing the soil and rhizospheric environment (Costa *et al.,* 2006; Haichar *et al.,* 2012). The plant community assimilates the photosynthates and shifted them toward the root and various plant parts which can be further use for plant physiological and metabolic requirements (Larsen *et al.,* 2015). The plant community help to design the rhizosphere by the plant root system and releasing various low and high molecular weight carbon compounds which are the source of food for microbial communities which influences the rhizosphere biology and signaling (Jones *et al.,* 2009). The rhizospheric shape is the functions of microbial colonization within root and rhizosphere, properties and amount of root released compounds, plant and microbial interaction and signaling and plant resistance factors (Haichar *et al.,* 2014). The sensing and signaling, diversifying exudation produced from plants and selective activity of microbes can be considered for the rhizospheric activity because plant influences the microbial activity significantly through releasing of the various carbon compounds (Lange *et al.,* 2015). These carbon compounds are known as Rhizodeposits which having various forms of organic substances exudates from the plant root (Jones *et al.,* 2009). Plant shoot and root litter deposition also add much amount of organic substances into the soil that can be used by microbial communities to drive the various soil processes *viz.,* mineralization, immobilization, nitrification, denitrification, carbon cycling, and P solubilization etc. (Jones *et al.,* 2009). The plant community influences the microbial population, their abundance, and activity with the root system (Philippot *et al.,* 2009). The rhizospheric zone can accelerate the microbial activity in root zone with more exudation of organic compounds from plant communities with the response of various factors as plants, soil and climatic factors (Larsen *et al.,* 2015). All the rhizospheric biota, their activity, and various rhizospheric processes are affected by the plant root system and their amount of carbon exudates. So, the plants play crucial role in the rhizosphere development and their community (Table 1).

Role of microbes in rhizosphere development

A plant interacts with their biotic environments through secretion of more variable compounds into the rhizosphere (van Dam and Bouwmeester, 2016) which made Soil more diverse in its biological habitat. The soil is consist of millions of bacteria, widespread fungal hyphae, number of nematodes, protozoans, earthworms and other arthropods (Bardgett and Van der Putten, 2014). All the rhizospheric community has oligotrophic in nature so it occurs near the root surface where carbon found in abundance

(). It influences the plant nutrients dynamics through root and microbial activity (Philippot *et al.,* 2013; Larsen *et al.,* 2015). This biological activity can be managed by the plant through secretions and diffusion of various forms of low and high molecular weight carbonic substances (McNear *et al.,* 2013).

The plant root released carbonic substances is popularly known as Rhizodeposits (Jones *et al.,* 2009). However, microbes can also release some carbon compounds used by the plant as a nutrient source, biocontrol agent and signaling compounds for soil biotic community. The extent of release of these organic substances can determine the rhizospheric volume because more availability of exudates can create a more diverse and wide rhizospheric activity zone. However, this can be depended on decomposition rate and carbon storage into the soil system (Lange *et al.,* 2015). The rhizospheric microbial community benefited the soil ecosystem by serving functions of decomposing of organic matter, nutrients availability through solubilization and mobilization, root pests control and rhizospheric signaling (Jones *et al.,* 2009; Philippot *et al.,* 2013). However, various pathogenic microbes, denitrifying bacteria, protozoan, and nematodes are deleterious to rhizospheric processes. This process can help to shape the rhizosphere because Rhizodeposits supported the biome activity in the soil system. The rhizospheric microbial community functions and structure have been influenced by soil types and host plant and soil environment conditions (Haichar *et al.,* 2008). So, the soil biotic community which is under the influence of plants can also play an important role in designing the rhizosphere through various biological processes such as nutrient mobilization, signaling pathway, and biocontrol agents.

Other factors

Other factors such as soil structure, temperature, water movement, aeration, soil pH and heavy metals concentration into the soil cause severely adverse impacts on both plant and biotic community development which influence the rhizosphere designing. Soil erosion accelerated by unsustainable agricultural activities can break down the soil structure which that negatively coincided with rhizospheric development (Jiang *et al.,* 2007). The temperature above and below the optimum temperature can alter the behavior of plant root exudation and microbial activity (Fageria and Stone, 2006). The change in soil water holding capacity might be cause for alteration of soil biology, plant root development, physiology of exudation, microbial mobilization and activity (Haichar *et al.,* 2014). Aeration helps to regulate the better decomposition. Soil pH and heavy metal influence the plant and microbial physiology through soil acidification and redox reactions which can be altering the rhizospheric processes (Rajkumar *et al.,* 2012). These changes in soil pH can increase the nutrients availability to plant especially N, P, Ca, Mg, Fe and Zn (McNear *et al.,* 2013). The healthy soil biology can be encouraged through supply of organic residues, crop residue management, apply compost/ manure, reduced tillage, minimum compaction, minimum use of pesticides along with growing cover crop or rotate the crop or intercrop for synergistic rhizosphere shaping (Li *et al.,* 2007; Zimmerman *et al.,* 2011; Pittelkow *et al.,* 2014; Bender *et al.,* 2016).

Rhizosphere management to improve soil and plant productivity

Rhizospheric management is the strategic management of plant, soil, and microbiota for improving the nutrient use efficiency, soil health, and plant productivity (Ryan *et al.,* 2009). Hence, the green revolution can't help for further increase in food production and the dependency on it causes a decline in soil health and crop productivity. So, we need to focus on the crop, soil and biological management strategies (Bender *et al.,* 2016). These can categories under different management strategy and applied at various levels for gain maximum benefits. These management practices help us through manipulating specified biological communities and by improving the general biodiversity of rhizospheric soil (Dessaux *et al.,* 2016). All the management categories are as follow:-

Crop management

Crop management considers both individual plant-based or complex diversified plant community management where both are modified or improved for efficient use of soil and plant resources. The individual plant-based root system can be improved for better rhizospheric activity (Bardgett *et al.,* 2014). Lange *et al.,* (2015) reported that the plant community can significantly enhance the microbial activity into the soil by improving soil organic matter status. Plants are the play an important role in rhizosphere designing through influencing soil biology. Bender *et al.,* (2016) reviewed that the soil biology can be enhanced through the development of efficient, diverse and complementary approaches such as selection of the crop species and crop rotations. It can hasten the crop performance in particular soil environment due to improving the soil biology (Deguchi *et al.,* 2007). The combined use of diversified selective crops and their cultivars provide an opportunity to exploit the soil biota, their traits and functions (Vandermeer *et al.,* 1998). The soil biota and their processes are also accelerated in diverse cropping pattern by improved soil health. we can modify the soil biodiversity temporally (e.g., cover cropping and crop rotation) and spatially (e.g., intercropping and mixed cropping) through crops which gave the positive effect on agroecosystem (Li *et al.,* 2007). Which can help to manage the cropping system inherently and reduces the external input use (Bender *et al.,* 2016)? Moreover, the crop management system can provide an opportunity to hastening the soil biotic potential, soil health, and crop performance.

Soil management

Soil management practices are done with the aim to improve tilth, weed-free condition, for preparation of stale seedbed and alteration of soil biotic potential as well as a reduction in economic assets. Soil biology can be hampered through tillage practices. However, it can provide an opportunity to improve nutrient use efficiency through promoting decomposition and mineralization activity of inorganic and organic sources (Zimmerman *et al.,* 2011). The soil biotic potential can be hastened through improved soil management practices such as zero tillage, strip tillage, minimum tillage with the addition of cover crop and manures (Pittelkow *et al.,* 2014). These soil management systems favor the soil biota development and decrease soil-borne pest infestation and weed population in a crop field (Mader *et al.,* 2002). In the last half century, it found that soil amendments can be enhanced the soil health and plant output (Ryan *et al.,* 2009). The N fixation and VAM activity can be accelerated by the biochar (Guerena *et al.,* 2015). Biochar can increase the pH of acidic soils, water holding capacity of soil and hasten the rate of organic matter decomposition by enhancing the soil biological activity (Zimmerman *et al.,* 2011). Dessaux *et al.,* (2016) reviewed that the application of carbon-rich substrate such calcium silicate, organic residues, coal fly ash, and organic manure can improve soil biology, carbon status, mineralization and soil quality. Di Gregorio *et al.,* (2006) reported that the inorganically accelerated *Sinorhizobium* sp. can significantly alter the soil biology and performance of *Brassica spp*. Lange *et al.,* (2015) reported the addition of the organic matter can significantly accelerate the soil biological activity which helps to improvements in soil health, plant productivity through soil conservation and enhancing the soil boil diversity. So, all these added organic and inorganic soil amendments are helped to improving the soil health and plant performence.

Microbiological management

Soil biotic community help to improve the plant performance through solubilizing and mobilizing the organic and inorganic sources of nutrients and help to provide them to plant root such as PGPRs, VAM etc. (Ceballos *et al.,* 2013).

Soil and seedling inoculation with the biotic community has positively influenced crop performance. Such as legumes inoculation with *rhizobia* spp. gave an opportunity to reduce plant external nitrogen demand due to nitrogen fixation (Vargas *et al.,* 2000). However, these benefits mostly vary with soil type, plant type and environmental conditions (Kohl *et al.,* 2016). In organic farming, agricultural pests control has also employed the biocontrol agents (*Trichoderma, Pseudomonas, and Bacillus*) which induce the plant systemic resistance against the pathogenic attack (Pieterse *et al.,* 2014). Ryan *et al.,* (2009) reviewed that the biotic community help to the production of certain types of the stress hormone, enzymes and another antibiotic which help to plant withstand under various stress conditions. So, the improvement in soil microbiota can help to improve plant productivity and provide environment safety.

Rhizospheric biota management through Holobiont approach

Researches evident that both plants and soil biota can shape the rhizosphere in collaborations (Bulgarelli *et al.,* 2012). So, it has important for research purpose to breeding the plant community for improving the rhizospheric biodiversity with targeted functioning for crop plants (Muller and Sachs, 2015). The integration of plant and rhizospheric biota behavior with different breeding strategies can be fulfilling the requirements of agricultural sustainability (Chaparro *et al.,* 2012). For example, root exudation and carbon allocation into rhizosphere have the source of energy for root symbionts (Walder and van der Heijden, 2015). The more carbon excreting crops can increase the rhizospheric biota and their activity. However, specified plant microbiome providing an opportunity for altering plant features, suppression of diseases (Mendes *et al.,* 2011) and plant flowering time etc (Panke-Buisse *et al.,* 2015). For example, a Bacillus spp. genetically altered for nitrogen fixation mechanism for production of higher concentrations and amount of plant hormones (Arkhipova *et al.,* 2005; Kim and Timmusk, 2013).

A combined three-strain consortium such as *Bacillus* spp., *Pseudomonas*, *Rhizobium* or *Bradyrhizobium* which is improved nitrogen fixers could provide great opportunity of a diverse and complex natural rhizospheric biological functioning (Ahkami *et al.,* 2017). The reduction in denitrification and Nitrogen losses from the soil through decreasing microbial activity by plants can improve the NUE (Skiba *et al.,* 2011). The integrated development of plant and their rhizospheric microbiome can be an important step toward rhizospheric exploitation for better plant use efficiency (Bardgett *et al.,* 2014). The research focused toward development and selection of the plant root and genotypes that have multitrait such as root developmental plasticity, WUE and root nutrient uptake will increase the crop yields in the changing climate (Ahkami *et al.*, 2017) (Table 2).

The selection of the root characters are done on the basis of the spatial and temporal development of soil biology and there functioning. The diverse rooting habits can provide a more efficient way of soil biological interventions and nutrients dynamics. So, Bardgett *et al.*, (2014) suggested that the root branching [A], root diameter [B], root specific length [C], exudation of rhizodeposits [D], VAM fungi association [E] and *rhizobia* symbiosis [F] are the most important root traits for better rhizospheric development. Desirable root traits are presented into the figure 1.

Table.1 Various plant root derivatives present into the rhizosphere

Plant derived complexes	Description	References
Exudates	Diffused from root cortex zone to the intercellular space later into the surrounding soil, broadest spectrum effect on manipulation of rhizosphere high concentration.	Jones *et al.*, 2009; Haichar *et al.*, 2014
Secretions	Secondary products of root metabolic activities released through cell via active transport and improving mobilization of insoluble to soluble compounds, as P and Fe	Jones *et al.*, 2009
Senescence derived compounds/ lysates	All degenerated compound of the roots and its cell that exerted into the rhizosphere, balance the C/N ratio of soil organic matter. It includes nucleic acids, lipids, various forms of carbohydrates and proteins.	Haichar *et al.*, 2014
Mucilage/ Mucigel	Slimy gel type coating or Gelatinous layer surrounding the root tip. It consists of cellulose, lignin, starch, pectin, and highly recalcitrant and highly diversified C decomposers	Jones *et al.*, 2009
Border cells	Sloughed off cells from the root.	Jones *et al.*, 2009; Haichar *et al.*, 2014

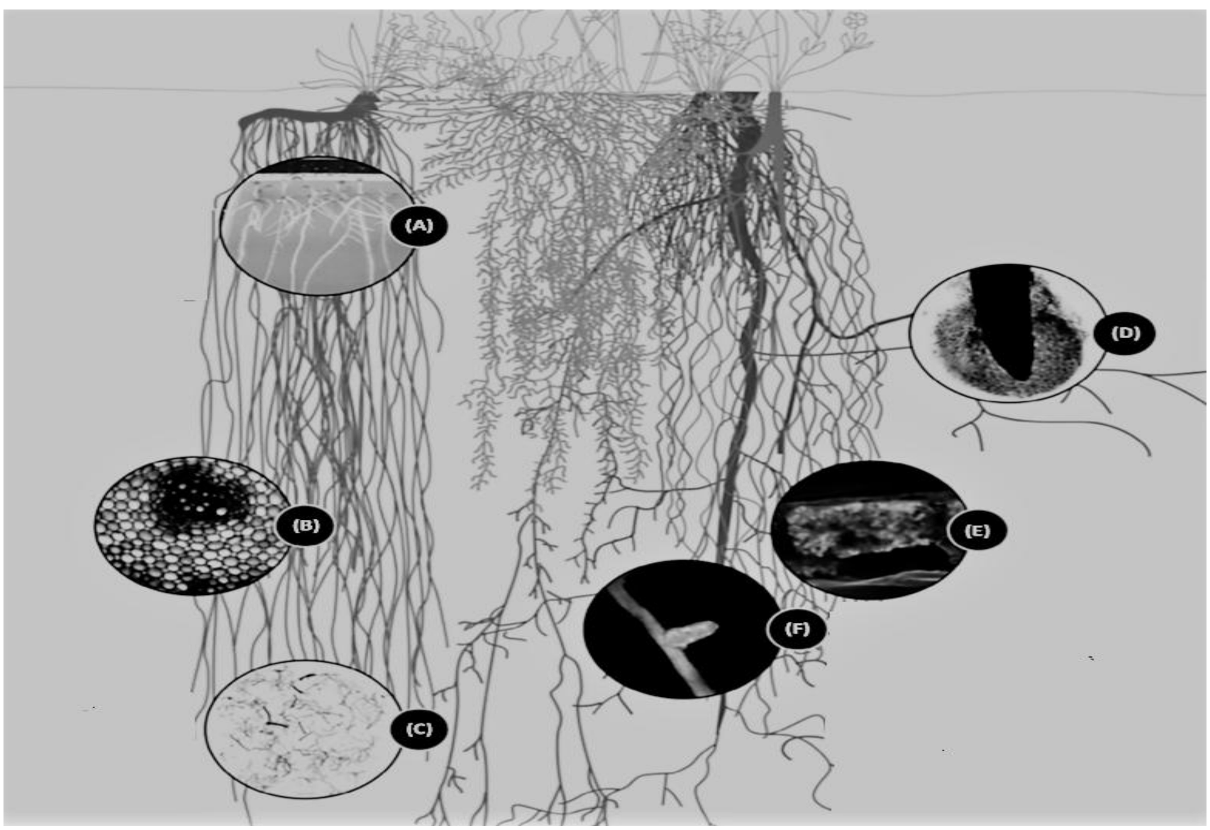
Table.2 Effect of soil biota on soil, environmental and plant functions (modified from Bender *et al.*, 2016)

Functions	Through enhanced soil biota	Through improved soil biota
Soil formation	Accelerate	
Carbon sequestration	Improved	Improved
Plant nutrient uptake		Increased
Nutrient losses		Reduction
Pathogenic attack	Reduced	Reduced

Table.3 The molecularly improved PGPRs for various plant functions (modified from Ahkami *et al.*, 2017)

Bacterial Species	Plant Species	Responses	Reference
Pseudomonas simiae strain AU	Soybean	Systemic tolerance induction	(Vaishnav *et al.*, 2015)
Bacillus subtilis GB03	Arabidopsis	Salt tolerance	(Zhang *et al.*, 2010)
Gluconacetobacter diazotrophicus PAL5	Sugar cane	ABA signaling, drought tolerance	(Vargas *et al.*, 2014)
Streptomyces spp.	Chickpea	Enhanced the activity of defense mediated enzymes	(Singh and Gaur, 2017)
Azospirillum brasilense Sp245	Rice	Nitrogen fixation and higher activity the ethylene	(Vargas *et al.*, 2012)
Dietzia natronolimnaea STR1	Wheat	salinity tolerance	(Bharti *et al.*, 2016)

Figure.1 The representation of root characteristics that can be potential influences on the plant-rhizospheric interactions (modified from Bardgett *et al.*, 2014)



Plant and rhizospheric biotic community can also be improved through transgenic methods which can be helpful to develop the stress resistance cultivars or microbial stains that helpful for crop improvement (Bender *et al.*, 2016). Some of such example molecularly engineered PGPRs for stress tolerance presented in table 3. So, the plant and rhizospheric community have great importance in enhancing plant performance and soil health in a sustainable manner.

In conclusion, the climate change, population pressure, and fate of green revaluation realize the importance of belowground development for increasing crop productivity. The soil portion where plant and soil biotic community are interact known as rhizosphere. It has greater impacts on soil physiochemical and biotic activities. In soil biological properties that most variables are soil biotic population, plant growth stimulatory activity and suppressor activity and plant-microbes signaling are the important processes that governed by the rhizospheric biota and plant interferences. In this mutualistic interrelation, the plant provides carbon as the food matter to soil biota and microbes increase the mineralization and availability of nutrient to plant by atmospheric nitrogen fixation, carbon, and nitrogen mineralization, phosphorus, potassium, and micronutrients through solubilization and mobilization process. So, the plant – microbes relationships can be potential use to enhance soil health and plant productivity.

Now, we need to focus on more toward rhizospheric biota and plant relationships and the plant breeding and microbiome engineering approaches to enhancing the plant- microbe's beneficial interference. It can help to enhance the various ecosystem services via carbon, nitrogen and water cycling, carbon utilization and storage, nutrient trapping, crop production. So, the overall improvement in rhizospheric plant microbe's interference can hasten the soil health, crop productivity and reduce the environmental pollutions.

Future research orientations

The rhizosphere is the core of all the physiochemical and biological activity that essential for plant growth and development. So, more understanding of the rhizospheric processes is essential for increasing plant productivity and soil quality.

It will be done through modulating the plant and microbial community, soil management and plant breeding and microbiome engineering for improvement in plant and microbial relationships.

Plant community will be the breed for characters such as plant root developmental plasticity, higher nutrient and water uptake, more biomass production and higher production of root exudates for better plant-microbes interferences.

The biotic community will modulate for increase responses toward plant spp. by the use of biotechnology.

We shell need to development of such agrochemicals which can improved the plant microbe's interference.

The systemic approach where both plant and soil biota will be improved for better symbiosis and association through using plant breeding and biotechnological approaches.

All these aspects need to focus on future plant microbial strategies development to improvement in the rhizospheric responses toward plant community.

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