



## Rhizospheric environment and crop productivity: A review

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### ABSTRACT

Dwarf architecture of wheat and rice plants and their extensive cultivation made India a nation of food surplus. Realisation of higher crop yield required intensive use of fertilizers and water, which in turn resulted in over-exploitation of natural resources, leading to decline in factor productivity, soil organic C content, groundwater table and multiple-nutrient deficiencies. Therefore, it has become essential to manage natural resources to sustain health and fertility status of the soil for maintaining adequate supply of water and nutrients to the crop plants. The rhizospheric environment, which regulates the dynamics of water and nutrient availability as well as their uptake by the roots from the soil, is crucial in this regard. Soil organic matter plays a key role in sustaining soil health. It has been envisaged that increase in the use of legumes in crop rotation, green manuring, organic mulches, farmyard manure (FYM), residue recycling, biological N<sub>2</sub> fixers and mycorrhizal associations along with effective use of soil microbes hold the key to sustain appropriate rhizospheric environment and crop productivity.

**Key words:** Balanced nutrition, Biological N<sub>2</sub> fixation, Crop productivity, Residue recycling, Rhizosphere, Rice-wheat rotation, Sugarcane, Water use efficiency

India attained self-sufficiency in food in the 1970s through the crop improvement programme of the ICAR, in collaboration with international institutes like CIMMYT and IRRI. However, this accelerated growth could not be sustained for longer period, and since 1990s India is witnessing deceleration in agricultural growth rates. Indian agriculture is now at a cross road, facing serious challenges to sustain the productivity level attained during the green revolution period. Declining arable land, stagnating irrigation potential, increasing salinisation or alkalinisation, multiple nutrient deficiencies, pollution hazards, increasing cost of inputs, and the erratic monsoon and climate change are putting enormous pressure on agricultural production. This irrepressible situation is creating a dismal future for the largest segment of the Indian population, which even today lives a frugal existence and is dependent largely on agriculture for its livelihood. A paradigm shift in the thinking is essential to arrest these inimical threats that are looming large to subvert the food security of India.

Several diagnostic surveys have pointed out that reduction in the content of soil organic C, emergence of multiple nutrient deficiencies and decline in factor productivity are the main causes of such falling trends in agricultural productivity, which need to be addressed immediately (IARI, 1995; Pasricha and Aulakh, 1997; Ladha *et al.*, 2000). In other words, deteriorating soil health is un-

able to sustain the intensive agriculture and an ever increasing burden of improving the productivity. In a nutrient limiting environment, hybrids are not in a position to perform at their fullest potential. Therefore, to sustain the productivity and for its further improvement there is a need to improve the status of soil health, the rhizospheric environment, to ensure adequate nutrient supply to the crop plants. Rhizosphere acts as the conduit between the plant root and soil, ensures a steady supply of water and nutrients to the crop plants, and helps in realising the productivity potential of a new crop type. In this communication, the research done on rhizospheric environment is reviewed and the strategies to improve it for further increasing the crop productivity, especially in the Indo-Gangetic Plains, are discussed.

In spite of its immense importance, roots seldom receive due attention of the researchers because of underground habitat and inherent difficulty in studying them. However, of late a growing interest on roots is being observed among researchers world-wide, because of the mounting pressure on efficient food production from limited resources, global warming and pollution. The growth of root system is dependent on the soil properties, which directly influence its development and spread. However, being a dynamic system, roots also modify soil properties to its own advantage. The interface between the root and soil is highly complex and their boundaries are frequently ill defined. Metabolites are released from roots into the soil, which change its chemical and physical properties,

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and also attract, stimulate and provide necessary ecological niche to the various micro-organisms for their proliferation.

### RHIZOSPHERE

When Hiltner (1904) first coined the term 'rhizosphere', it was employed in the specific context of the interaction between various bacteria and legume roots in his studies on the value of green manuring. However, over the years, rhizosphere has changed in its definition and scope. Rhizosphere is now defined as the zone of soil surrounding a plant root, where the biology and chemistry of soil are influenced by the root. This zone is about 1 mm wide but has no distinct edge. It is an area of intense biological and chemical activity influenced by compounds exuded by the root and by the micro-organisms feeding on these compounds. As plant root grows through the soil, it leaves border cells and releases water soluble compounds such as amino acids, sugars and organic acids, which act as the food for the microorganisms (Foster, 1986; Jones, 1998; Gregory, 2006). Thus due to the regular food supply the micro-biological activity in the rhizosphere is much greater than in the soil that is away from the plant roots. In return, the micro-organisms provide or increase the access of nutrients to the plants. All these activities make the rhizosphere the most dynamic environment in the soil, which directly influences the plant growth and reproduction (Lamont, 2003). Therefore, the sustenance of health and fertility of soil is essential to stabilize crop productivity. For this reason, the rhizosphere has been taken as the 'last frontier in agricultural science'.

An understanding of rhizosphere is central to the development of many social goals, including the development of sustainable agricultural systems, mitigation of climate change, cleaning-up of contaminated sites, preserving human and animal health and increasing the biodiversity. In this scenario, it is important to initiate multi-disciplinary research to develop, evaluate and integrate rhizo-technologies to improve crop productivity in a sustainable manner.

#### Root hairs

The major dynamic component of rhizosphere is root hair. Root hairs are produced as specialized projections from modified epidermal cells and appear just below the zone of root elongation. Subsequent growth of root hairs is under genetic, hormonal and environmental control, with many regulators acting at several stages of development. Root hairs play an important role for the contact of root and soil through the formation of rhizo-sheaths and in the acquisition of water and nutrients (Hawes *et al.*, 2003; Gregory, 2006). High level of  $H^+$ -ATPase activity has been

demonstrated in root hairs as well as their involvement in the uptake of Ca, K,  $NO_3$ ,  $NH_4$ , Mn, Zn, Cl, and P (Gilroy and Jones, 2000). Several studies have shown that differences in P uptake between plant species and genotypes are due to variation in root hairs. This is largely due to the capability of long root hairs with sufficient density that can intercept P at some distance from the actual root surface. Using a hairless mutant of the root (bald root barley, *brb*), Gahoonia and Nielsen (2003) demonstrated the importance of root hairs in plant nutrition and plant survival. Root hairs also have an effective internal mechanism for the transport of P. It is noteworthy that P-transport promoter is not present in other epidermal cells, indicating that the P uptake is primarily via root hairs rather than through the whole of the root surface (Gahoonia *et al.*, 1997).

#### Root architecture

Root architecture is the spatial configuration of a root system in the soil. It is used to describe distinct aspects of the shape and size of root systems that largely influence the nutrient gathering capacity (van Noord and de Willigen, 1987). Root architecture is important because most of the resources that plants use from the soil are heterogeneously distributed and are subjected to local depletion (Robinson, 1994). Under such a situation, development and spatial growth of any root system will be governed by the nutrient dynamics in the soil and specific requirement of a particular nutrient by the plant. The root architecture of a crop plant varies significantly with the cultivation practices used, e.g. plants propagated through cuttings, layerings etc. always have different root architecture compared with those grown from the seed. In a crop like sugarcane, the interculture operations shear roots and delimit the root command area. In fact, these interculture operations hasten the root proliferation due to the induction of growth hormones as a result of root injury. In transplanted rice, when the seedlings are uprooted for transplanting, the root architecture is changed altogether and new roots are formed to support the plant, and the root command area changes accordingly. Most of the cultural practices followed in the crops induce more intensive root architecture by reducing the root command area.

#### Rhizo-deposition

Roots are known to exude different compounds in the soil, e.g. low molecular weight, water soluble compounds like glucose; high molecular compounds like polysaccharide mucilage and various enzymes; lysates from sloughed-off root cells; and gases like  $CO_2$ , ethylene and hydrogen cyanide (Jensen, 1994; McCully, 1999; Gregory, 2006). In practical terms, it is impossible to distinguish

exudates from secretions, because both are usually considered together as exuded materials. The rhizo-deposits are an important substrate for the soil microbial community and there is a complex interplay between this community and the quantity and type of compounds released. Addition of rhizo-deposits to the soil can increase the rate of decomposition of native organic matter, which varies with the species of plant used and the C : N ratio of the deposits (Dikes *et al.*, 2004). In a pot study, Cheng *et al.* (2003) observed two- to four-fold increase in the rate of decomposition of organic matter with soybean and wheat plants in comparison with the control (without plant). This rhizosphere priming effect is responsible for the major component of the total soil efflux. Estimates of rhizo-deposition vary quite markedly up to 40% of the dry matter produced by the plants (Martin and Merckx, 1992; Jensen, 1994; Dikes *et al.*, 2004).

Due to respiration, the roots release CO<sub>2</sub> in the rhizosphere, which combining with water forms carbonic acid and this in turn helps in the solubilization of rock phosphate. Crops like buckwheat, sweet clover, alfalfa etc., which release higher amount of CO<sub>2</sub>, are more efficient in gathering P from the soil. Further, the plant does release organic acids; as a result the pH of the rhizosphere goes at the level where solubility of P increases and becomes available to the root hairs responsible for P uptake (Gahoonia and Nielsen, 1992).

The soil environment around the roots exercises great influence on their growth in the acquisition of water and nutrients by them from the soil. The soil factors that influence and shape the rhizospheric environment are discussed below:

#### **Soil and plant nutrients**

Plant absorbs nutrients in the form of ions, which are transported to the roots by mass flow, root interception and diffusion. As roots extend through the soil mass, they come in close contact with ions adsorbed on the soil particles. The root-soil interface (rhizosphere) represents an abrupt change in the nature of the medium in which ions move from their original location in the soil to the protoplasm of the plant (Hinsinger, 1998). The soil is essentially a three-phase system, consisting of irregularly arranged soil particles, a more or less continuous liquid phase and a gaseous phase filling the remainder of the soil volume. The surface of the roots growing in the soil is covered with soil particles, in which bacteria, fungi, mycorrhiza and other micro-organisms are present. The composition of the liquid and gaseous phases in the rhizospheric region differs from the soil that is away from the roots. Therefore, exudations from roots, shedding of border cells of roots and dead root hairs, and the microbial decomposition in

the rhizosphere influence the translocation of nutrients to roots considerably (Gregory, 2006).

The availability of soil nutrients to plants in a three-phase system of solids-liquids-gases is influenced by the activity of numerous associated microbiota with roots. The most reactive components of the solid phase are the clay and humus, which are characterized by a high surface charge and a large specific surface. The clay-humus complex exhibits the exchange phenomenon. Humus is of special interest, as it is one of the main indicators of soil health and fertility. In most soils a large proportion of the organic material reacts with the inorganic colloids to form clay-organic complex, and this reaction exerts an important influence on the physical, chemical and biological properties of the soils. Humus usually consists of humic acid, fulvic acid and humin.

The number and type of roots influence plant nutrition owing to differences in depth and spread of the root system and variation in the surface area due to branching. In general, dicots have higher cation exchange capacity (CEC) than the monocots. Hinsinger (1998) reported that high yielding varieties usually meet greater nutrient requirements through the higher CEC of their roots.

#### **Soil nitrogen**

Available N in the soil, the N<sub>2</sub> received through biological fixation and rain water, the N released from decomposition of plant residues and other organic wastes, and finally the N received through fertilizers constitute a major source of N to the plants in any cropping system. The soils of tropical climate with high annual temperature sustain less amount of N than that of the temperate climate with low annual temperature. Due to this geographical limitation, Indian soils are low in N content. The alluvial soils of the Indo-Gangetic plain are silty and have a low N level. In the north-western tract, the high temperatures and low rainfall limit N accumulation. In the north-eastern and eastern regions, high temperature accelerates the loss of N. The high mean annual temperature of the central and peninsular India hinders N accumulation in the soils (Jenny and Raychaudhuri, 1960). The total N content in the soil ranges from less than 0.02% in subsoils to more than 2.5% in peats.

The crop plants cannot take N in its elemental form and need conversion to a usable form. The conversions take place in the following ways:

- Fixation by symbiotic micro-organisms, especially in the roots of legumes
- Fixation by free-living microorganisms in the soil
- Reaching soil as one of the oxides of N produced by the atmospheric electric discharges, and
- Lastly that fixed by the activity of humans in the vari-

ous industrial processes and fertilizer production.

Thus N is in dynamic equilibrium with the various fixed forms. There is also process of release of elemental N, which mainly takes place through the activities of the micro-organisms and other chemical processes. However, it should be kept in mind that legume fixation of N is maximum only when the level of available soil N is minimum, and the soil pH is a major factor for both the survival of *Rhizobium* as well as the quantity of fixed N.

Plants absorb most of their N in the  $\text{NH}_4^+$  and  $\text{NO}_3^-$  forms, whose uptake is complicated because the plants usually have access to both the forms. The  $\text{NO}_3^-$  is often the dominant source of N, since it generally occurs in higher concentrations than  $\text{NH}_4^+$ . Moreover, relative ease of its movement through soil facilitates its absorption by the plants. Ideally  $\text{NH}_4^+$  is the preferred N source, as the energy will be same when it is used instead of  $\text{NO}_3^-$  for synthesis of protein. It is often a significant source of N for plants, especially during early growth stage. Uptake of  $\text{NH}_4^+$  may have several advantages like stimulation of P uptake, acidification of high pH soils near the root surface (rhizosphere) etc. The principles of ion-exchange generally influence the adsorption and mobility of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  forms;  $\text{NH}_4^+$  is retained briefly against leaching because of adsorption by soil colloids, whereas  $\text{NO}_3^-$  form is not so retained. This difference is more pronounced in fine textured soil than in coarse textured soil.

The application of urea as the preferred N fertilizer imparts some imbalance in the micronutrient status of soil, which affects overall soil fertility for crop growth. In soil, urea is acted upon by the enzyme urease (mostly from bacteria and fungi), which converts it to unstable carbamates. Greatest activity of urease occurs in the rhizosphere where microbial activity is high and where it may be excreted from roots. The activity of rhizosphere urease varies depending on the plant species and the prevailing weather condition. The decomposition of ammonium carbamate releases  $\text{NH}_3$ , which helps increase the soil pH in close proximity of urea granules. Under favourable soil condition, the urea hydrolysis proceeds rapidly and the urea nitrogen is transformed to  $\text{NH}_4^+$  form and gets adsorbed in soil. Concentration of free  $\text{NH}_3$  and volatilization of  $\text{NH}_3$  increases substantially with rise in the pH above 7.

### Soil phosphorus

In soil the P exists in the form of many primary and secondary compounds. The apatite group of primary minerals is the basic source of soil P, accounting about 95% of the P. The phosphate compounds in soils may be grouped as fluoro-carbonate and hydroxyphosphates of Fe, Al, Ti, Mn, Ca and Mg. However, quantitatively the phosphates

of Fe, Mg and Ca are most important in plant nutrition.

Krantz *et al.* (1949) compared the relationship between root development and P utilization by different crops and found that extensive root system of maize exploited more soil P than limited root system of potato. Consequently the former used more P from the soil and less from the fertilizer, whereas it was the reverse with potato. Thus in P-limiting condition, maize is much better off than potato. Similarly, dwarf wheat, in general, having greater CEC than the tall wheat, responds better to the applied fertilizers. In contrast the plant with low ion-exchange capacity absorbs less of the divalent and more of the monovalent cations. Crops also differ in their P requirement and P gathering capacity. Legumes absorb more P than the cereals.

Phosphorus deficiency decreases the gravitropic sensitivity of both tap root and the basal roots, resulting in shallower root system. It was hypothesized that shallower root system was a positive adaptive response to low soil-P availability; first, concentrating roots in surface soil layers where P availability was highest, and the second, reducing spatial competition for P among roots of the same plant. Ge *et al.* (2000) found that plants with shallower root system acquired more P per unit carbon cost than those of deeper root system.

### Soil potassium

The K nutrition of plants and the Ca and Na contents of soils are often closely linked. More than 95% of the soil K is found within the crystal lattices of silicate minerals. The feldspars and micas constitute the major K-bearing minerals, which on weathering release K in the soil. The clay minerals (mostly 1 : 1 type) also contribute to the K pool. The K availability in Indian soils averages around 1.5%. Its availability varies in different soils, with the lowest availability in alluvial soil and the highest in black soil. The fixation of exchangeable K and liberation of non-exchangeable K play key role in the dynamics of soil K. Fixation varies with the type of weather conditions, i.e. wet or dry. However, there always exists equilibrium in this regard; fixation is not entirely an irreversible phenomenon - fixation and liberation occur simultaneously but rates vary depending on the available conditions and soil minerals. The reserves of non-exchangeable K in the soil affect the exchangeable K content of the soil, resulting in buffering towards the equilibrium. The importance of K fixation lies in the fact that it not only regulates the supply of soil K to plants and protects it against leaching but also regulates the available Ca : K balance in the soil. A wider ratio leads to serious physiological disturbances in plants. The K uptake by plants depends on the degree of development of root system. In general, dicots give better response to K application than the monocots. The K absorption

from the soil solution is plentiful when aeration is adequate. When  $\text{CO}_2$  is in excess, the absorption of nutrients decreases in the order  $\text{K} > \text{N} > \text{P} > \text{Ca} > \text{Mg}$ . Inadequate cultivation, compactness of the soil and waterlogging decrease the oxygen concentration, and hence reduce the uptake of K by plants (Kanwar, 1986).

The response of crops to applied fertilizers directly depends on the chemical composition of the soil in respect of available plant nutrients. Soils differ widely in their chemical composition because of differences in their parent material or in the type of weathering. In general, sandy soils are deficient in K. This deficiency is due to K-deficient nature of the parent material. On the contrary, clay soils as prevalent in the Indo-Gangetic alluvium are derived from potassium-aluminium feldspars, which are rich in K and thus K is not a limiting factor for the normal crop productivity.

#### **Soil calcium**

Calcium is another essential nutrient for plant growth. However, its importance is more evident in acid and alkali soils rather than in neutral soils. The amount of Ca removed by the crops depends on the nature of the crop. Generally, legume and root crops require more Ca than cereals. Prolonged cropping of alfalfa, which removes considerable amounts of Ca from the soils, may greatly deplete soil reserves of Ca in a short time. Large amount of Ca is lost through drainage water due to leaching by rain and irrigation water or through interaction of fertilizers and manures. The loss of Ca increases with increase in permeability of the soil and with the increase in rainfall. The light-textured soils suffer a greater loss of Ca than the heavy-textured soils. The main cause of the formation of acid soil in the humid region is the loss of Ca and Mg through leaching.

#### **Soil magnesium**

Magnesium is required by all green plants, as it joins the porphyrin rings for the synthesis of chlorophyll and also takes part in phosphate transport. Addition of magnesium fertilizers also increases the efficiency of phosphatic fertilizers. The Mg content of soils depends on the nature of parent material, the degree of weathering, the texture of the soil, the intensity of cropping and the management practices followed. Similar to the loss of Ca, that of Mg through leaching is very high. In the jute growing lateritic soils of West Bengal, Mg deficiency is widespread. In fact the deficiency of Mg is more widespread in India than what is being realised. However, the available data are too scanty to arrive at any definite conclusion about it. The exchangeable Mg in the soil is considered available Mg, but attempts to correlate it with Mg removed by the crops

have not been very successful. However, the association of Mg deficiency in grasses with 'tetany' disease of cattle in European countries needs rethinking in Indian context too, as most of the fodder requirement in India is met from the straws of rice and wheat.

#### **Soil sulphur**

Sulphur is needed for the formation of sulphur-containing amino acids, proteins and enzymes. The major reserve of S in the soils is the organic forms, which is made available through biological decomposition, whereas its primary source is the sulphides contained in plutonic rocks, which are converted into sulphates through the process of weathering. Some of the sulphides are dissolved, some precipitated and some are reduced even to elemental S, depending on the condition of the location. In humid regions the main form of S in soils is organic sulphur, whereas in arid zones the sulphates of Ca, Mg, Na and even K predominate (Katyal *et al.*, 1997)

#### **Soil micronutrients**

Zinc is one of the most uniformly distributed elements in rocks, occurring at various stages of development, and is approximately proportional to the sum of Fe + Mg. The concentrations of Co, Cu and Zn in the soils are lower than that present in the material from which they are derived. These nutrients are usually held on organic and inorganic surfaces. The divalent forms of Fe and Mn are less strongly held by soil surfaces than of Co, Cu and Zn. It has been observed that a pH around 6.5-7.0 is most favourable for the availability of most of the micronutrients. Zinc content in Indian soils varies from 10 ppm to 300 ppm, whereas Fe content varies from 0.46 to 27.50% (Kanwar, 1976).

#### **Soil-microbial community**

Biological environment of fertile soils is teeming with life on all size scales, from microfauna (with body widths less than 0.1 mm) to mesofauna (up to 2 mm) and macrofauna (up to 20 mm). The most numerous soil organisms are the unicellular microfauna. It has been estimated that 1 kg soil may contain 500 billion bacteria, 10 billion actinomycetes (filamentous bacteria) and nearly 1 billion fungi besides the members from animal kingdom. The microbial community (Table 1) plays a decisive role in the sustenance of crop productivity, as many of them have evolved along with and have established a mutualistic / symbiotic relationship over the years, helping plants to increase their fitness and adaptability in diverse ecosystems (Subba Rao, 1986). Mining and gainful employment of these micro-organisms in crop production systems will shape the agriculture of this century, and this may be

**Table 1.** Effect of a summer legume (greengram) on microbial biomass and population in soil at 0-15 cm depth, at New Delhi, 1993-94

Treatment	Microbial biomass ( $\mu\text{g/g}$ soil)		Microbial population (no./g soil)					
	Wheat harvest	Rice harvest	Bacteria ( $\times 10^5$ )	Actinomycetes ( $\times 10^4$ )	Fungi ( $\times 10^4$ )	<i>Azotobacter</i> ( $\times 10^3$ )	<i>Azospirillum</i> ( $\times 10^4$ )	PSB ( $\times 10^2$ )
Rice crop (1993)								
Fallow	185	219	55	0.5	0.2	25	1.2	
Greengram (SR)	198	225	115	1.5	1.0	92	18.7	4.0
Greengram (SI)	244	315	195	6.5	1.8	210	41.7	6.5
Wheat crop (1993/94)								
Fallow			40	0.4	0.5	14	0.015	1.2
Greengram (SR)			42	38.0	0.6	35	0.250	2.5
Greengram (SI)			65	140.0	0.9	65	0.750	4.2

Source: IARI (1995)

SR = Stover removal; SI = stover incorporation; PSB = phosphate-solubilizing bacteria

termed as 'The century of microbes'. The well-being of humans will surely rest on them. In general, these microbes are heterotrophs and fulfil their energy requirements from the plant source. The bulk of these microbes are saprophytes and their proliferation needs adequate supply of organic matter in the soil.

The soil flora and fauna play an important role in soil development. Micro-biological activity in the root zone is important to soil acidity and for nutrient cycling. Soil particles and pore spaces provide micro-niches for the action of micro-organisms responsible for carbon- and nitrogen-cycling. Soil humus provides the nutrient reservoirs, and soil biomass provides the chemical pathways for cycling (Subba Rao, 1986; Lynch, 1990). With the active involvement of micro-organisms, the carbon in dead biomass is converted to  $\text{CO}_2$  under aerobic condition and to organic acids or alcohols in anaerobic conditions. Under highly anaerobic conditions, methane ( $\text{CH}_4$ ) is formed. The production of methane in rice ecosystem is a recognised contributor to global warming. The  $\text{CO}_2$  produced can be used by photosynthetic micro-organisms or by higher plants to create new biomass and thus initiate the carbon cycle again.

The most common soil bacteria come under the genera *Pseudomonas*, *Bacillus*, *Clostridium*, *Arthobacter*, *Flavobacterium*, *Chromobacterium*, *Sarcina*, *Mycobacterium*, *Achromobacter* etc. However, in the ecological niche of rhizosphere the dominant bacterial genera are: *Pseudomonas*, *Arthobacter*, *Agrobacterium*, *Azotobacter*, *Mycobacterium*, *Flavobacterium*, *Cellulomonas*, *Micrococcus* etc. Amino acid-requiring bacteria dominate in this niche. Thus the composition of bacteria around rhizosphere is influenced by the crop plant in question, soil amendments, rhizo-deposition (influenced by foliar application of agrochemicals) and artificial introduction of other microorganisms. For soil health and fertility, abun-

dance of  $\text{N}_2$ -fixing bacteria has greater significance.

### $\text{N}_2$ -fixers

Beijerinck was the first to isolate  $\text{N}_2$ -fixing bacteria from root nodules in 1888, and by 1895 Nobbe and Hiltner produced the first laboratory culture of *Rhizobia* under the trade name Nitragin. The systematic study of biofertilizers in India was started in 1920 by N.V. Joshi. The work of De (1939) introduced the blue-green algae for  $\text{N}_2$  fixation in the rice ecosystem. Since then a lot of progress has been made in this direction and presently biofertilizer-producing industries have come up to meet the growing need.

The  $\text{N}_2$ -fixing bacteria may be broadly classified into two groups – free-living and symbiotic. In the symbiotic nature  $\text{N}_2$  fixation is assured, and much work in this direction has been carried out on *Rhizobium*. These bacteria live freely in the soil and in the rhizosphere of both leguminous and non-leguminous plants, but can have symbiotic association only with leguminous plants by forming nodules in the root. However, the origin of leguminous plants and the evolution of bacterial symbiosis have still remained speculative. Of late, association of *Rhizobium* with plants other than those from Leguminosae, as an endophyte has opened-up new arena of research to harness benefit from such associations.

It has been shown by various workers that in the soil with low N status, plant encourages nodulation, whereas in soil having adequate N availability or foliar feeding of urea, nodulation gets affected. One has to strike a balance between fertilizer application and use of  $\text{N}_2$ -fixing bacteria without compromising the productivity and profitability of the system.

The free-living forms like *Azotobacter*, *Clostridium* etc. provide enough opportunity for their gainful employment in this regard. Moreover, these bacteria produce growth

hormones and other plant growth-promoting substances and also guard against several pathogens through antibiosis. However, due to their free-living nature, they require adequate supply of organic matter in the soil for their proliferation and realisation of benefit. The population of *Azotobacter* in the rhizosphere of crop plants and in uncultivated soil is generally low. Many a times inoculation of soil does not yield the desired result, and therefore repeated applications have to be made to improve their population.

Recently the role of endophytic acetic acid bacteria in plant health has come in prominence. These bacteria like *Gluconacetobacter* reside in plant (sugarcane) as an endophyte and help not only in  $N_2$  fixation but also in growth promotion and plant defence (Suman *et al.*, 2005).

The blue-green algae (Cyanobacteria) are another group of atmospheric  $N_2$ -fixers that help in the N economy in the various crop-production systems. Rice ecosystem provides a congenial environment for the growth of  $N_2$ -fixing blue-green algae. Moreover, they also produce several growth-promoting substances that also help boost the growth of rice plant. Some blue-green algae also exist in association with other organisms. The association of *Anabaena* with the aquatic fern *Azolla* is of special significance in rice system. The blue-green algae, *Anabaena azollae* fixes atmospheric  $N_2$ . The advantage of *Azolla* lies in its fast multiplication and its higher green-compost yield than the green-maturing crops like *dhaincha* and sunnhemp.

### **Phosphate and sulphate solubilizers**

Solubilization of phosphates by micro-organisms depends on the soil pH. In neutral and alkaline soils having high content of Ca, precipitation of calcium phosphates takes place. Micro-organisms readily dissolve such phosphates and make these available to the root. On the contrary, acid soils are generally poor in Ca, and the phosphates get precipitated as the compound of Fe or Al, which are not easily mineralized by the soil microflora. Many bacteria (*Bacillus*, *Pseudomonas*) and fungi (*Aspergillus*, *Penicillium*) actively take part in the process of solubilization of soil P (Gaur, 1985).

These micro-organisms, which actively help in P solubilization and increase the availability of P to roots, modify their activities when P is easily available through the application of fertilizer P. Therefore to utilize full potential of P solubilizers, P application through fertilizers should be avoided. Increasing response to P application over the years indicates a decreasing availability of P through the microbial route. This microbial mining needs to be strengthened to reduce the burden of fertilizer P application.

Mycorrhiza is a symbiotic fungus-root association, which increases the P-gathering capacity of plant roots from the soil. Frank (1885) was the first to notice such an association in forest trees. Today it has been realised that mycorrhiza is of very common occurrence in plants, and it is estimated that 90% of the terrestrial plants have such associations. There are two kinds of mycorrhiza, viz. ecto- and endo-mycorrhiza. In the ecto-type the fungus forms a mantle of hyphae around the root; only a few haustoria go inside the root cortex for food. This type of mycorrhiza is prevalent with trees and, in general, trees growing in mountainous region have such an association (Brundrett, 2002). In the other type, i.e. endo-mycorrhiza, the fungus enters the cells and forms vesicle-arbuscule; and hence it is termed as vesicular arbuscular mycorrhiza (VAM). The nutrition benefit to the host plants arising from mycorrhiza has received considerable attention due to their positive influence in the uptake of P. The fungal hyphae increase the absorbing surface for P and ensure prolonged supply, because the root epidermis behind the root hairs has limited capability of P uptake due to the absence of the critical enzyme. Limitation of mature root portion in P uptake has led to increase in P availability through symbiotic association with fungi (mycorrhiza) and in P-deficient soil this has become the norm. The other advantage of the mycorrhiza is the barking effect; they deter several pathogenic fungi and bacteria by blocking their access to root directly and indirectly through antibiosis (Brundrett, 2002; Jones *et al.*, 2004).

The inorganic component of the soil S is in the form of  $SO_4^{2-}$ , which constitutes only a minor portion of the total S content in the soil. The bulk of soil S comes from organic matters in the form of S-containing amino acids and vitamins. Micro-organisms play a major role in the process of mineralization of sulphates and their availability to roots.

### **Soil organic matter**

The second major component of soil is organic matter produced by different soil organisms. The total organic matter in the soil, except identifiable undecomposed or partially-decomposed biomass, is called humus. This solid, dark-coloured component of the soil plays a significant role in the control of soil fertility, in the cycling of nutrients, and in the detoxification of hazardous compounds. Humus consists of biological molecules such as proteins and carbohydrates as well as the humic substances (polymeric compounds produced through microbial action that differ from metabolically active compounds).

The processes by which humus is formed are not understood fully, but there is an agreement that four stages of development occur in the transformation of soil biomass

into humus: (i) decomposition of biomass into simple organic compounds; (ii) metabolization of the simple compounds by microbes; (iii) cycling of carbon, hydrogen, nitrogen, and oxygen between organic matter of the soil and the microbial biomass; and (iv) microbe-mediated polymerization of the cycled organic compounds. The investigation of molecular structure in humic substances is of special interest in current research. Although it is not possible to describe the exact molecular configuration of humic substances, these molecules essentially contain hydrogen ions that dissociate in fresh water to form molecules bearing a net negative charge.

Much of the molecular framework of soil-organic matter, however, is not electrically charged. The uncharged portions of humic substances can react with synthetic organic compounds such as pesticides, fertilizers, solid and liquid waste materials and their degradation products. Humus, either as a separate solid phase or as a coating on mineral surfaces, can immobilize these compounds or in some instances detoxify them significantly.

Soil organic matter virtually runs the life processes in the soil and is taken as the indicator of soil health and fertility. Organic C content of the soil varies widely, depending on the nature of soil, prevailing weather (temperature and water) and plant geography. In general, temperate soils have higher organic C (1.2-2.5%) than the tropical or subtropical soil (0.5-0.6%). However, it is not easy to increase the organic C content in the subtropical environment of Indo-Gangetic plains. Long-term fertility experiments in this region of India have indicated that green manuring improves the organic C status and thereby increases the use and efficiency of applied N, P and K, but the prevailing weather parameters (moisture and temperature) hinder the accumulation of high soil organic C for long period (Yadav and Prasad, 1992; Nambiar, 1994; Singh *et al.*, 1994; Abrol *et al.*, 1997).

The availability and quality of organic C play the key role in the soil health, which in turn plays the crucial role in crop productivity. The organic C component may be divided into three broad categories: (i) that contributed by plants during root growth; (ii) humus-reserved organic C in soil in terms of left-over plant residues over time and microbial biomass; and (iii) the added organic materials in the soils in terms of plant residues and organic manures.

### **Soil water**

The biological activity in the rhizosphere depends on the availability of soil water. Adequate soil moisture in the rhizosphere is essential for the growth of both root and shoot, in addition to the growth of soil microbiota. Apart from it, water is also essential for increasing the fertilizer-use efficiency. Two things have been clearly brought out

as a result of experimentation over the years. First, the added fertilizers are meaningless unless sufficient water is available to support a response. Secondly, it is futile to increase the plant-available water unless soil-fertility problems are attended for ensuring adequate nutrient supply. Management practices that reduce the runoff or decrease evaporation are always beneficial in improving the water-use efficiency (WUE). In fact, WUE can be maximized only by managing the precipitation throughout the year.

### **Quality of ground and irrigation waters**

The ground water may be termed fossil water like fossil fuel. The water as is available today is the result of leaching and accumulation below the ground over several geochemical ages. Hence it has its own limitation due to the nature of its origin, availability in the various soil profiles and contents of salts in it. Moreover, it has limited renewability. Ground water, due to its freedom from harmful microbial content, is preferred for human consumption and use, especially in rural areas.

The development of optimum irrigation potential for maximizing the net profit per unit of water and land area will depend upon the agroclimatic conditions and the ability of individual farmers of the area in using other inputs like fertilizers, besides water. A major proportion of ground water in the Gangetic belt, as in the states of Punjab (41%), Haryana (67%), Rajasthan (84%) and Uttar Pradesh (63%) is brackish (Manchanda, 1993), and hence the good-quality water is scarce for assured irrigation.

Removal of all harmful salts from the soil surface is neither possible nor practicable. Therefore, it is essential to minimize their adverse effects on seed germination and crop growth. It has been noticed that salts move with water and accumulate in the surface soil or at the top of furrow ridge, as water evaporates leaving salts behind. Therefore, plantings at the top of the ridge as well as in the centre of wider ridges result in greater damage to the crops. There is always lower salt concentration in north-west slope than in the south-east slope.

It is also known that high sodicity and high soil pH conditions encourage loss of applied N through volatilization. Low organic matter content further accelerates N deficiency in the crops grown in sodic soils, and deficiencies of Fe, Mn and Zn tend to be frequent when water containing high alkalinity is used (Abrol and Gupta, 1994). Crops like sorghum and Indian mustard tolerate high salinity of irrigation water if non-saline water was substituted for pre-sowing irrigation (Abrol and Gupta, 1994). Thus the strategy to seed on conserved soil moisture or use non-saline water during early growth stages and poor quality water at later stages appears promising. However, it is a short-term measure to the actual problem. Obviously, the

use of brackish water (and for that matter any water other than rain water), having salt content will increase the level of concentration of the salt in soil and will render the soil less productive over time. This is increasingly being felt in the area where ground water and canal irrigation system are in place since the 1960s. For soil health and fertility, these irrigations have become a necessary evil. Nevertheless, for the sustenance of crop productivity, it cannot be done away with. A judicious blend is necessary according to the crop and available irrigation system, so that the salts added due to irrigations are removed from the soil. Similarly, judicious use of fertilizers will increase the use efficiency of both water and fertilizer. It is time to get the available dryland technologies to irrigated ecosystem also to reduce the irrigation requirement and to save this precious resource.

### Soil compaction

Soil compaction brings soil particles (aggregates) closer by narrowing down the pore spaces, reducing the soil volume and increasing the bulk density. The nature and type of compaction vary with the following: (i) parent material involved in the process of soil-profile formation (natural pan), (ii) rapid oxidation of organic matter, and (iii) drying and shrinkage as well as tillage operations under undesirable soil moisture (induced hard pan). A fair degree of soil compaction is essential for mechanical support to the plant. However, excessive compaction is highly detrimental in crop production, as it deteriorates soil structure. A feature of the compacted soil is the formation of a pan-layer, caused by the pressure of tillage equipments during various farm operations. Unlike topsoil, subsoil is not loosened annually and thus compaction becomes cu-

mulative, and overtime a homogeneous compacted layer is formed. The pan-layer is less permeable to roots, water and oxygen than the soil below and it restricts the function of the subsoil.

Compaction of soil beyond critical limit (specific to soil-plant combination) may cause increased mechanical impedance to root penetration and development, reduced aeration and permeability to water, altered moisture availability, and increased thermal conductivity of the soil. A poor aeration of soil reduces plant growth and induces loss of soil N and production of greenhouse gases. Reduced infiltration capacity results in surface runoff, leading eventually to flooding, erosion and loss of top soil and nutrients. The inclusion of legumes in rice-wheat cropping system decreases bulk density and improves hydraulic conductivity of the soil (Table 2). Further, the compaction may be ameliorated by increasing the soil organic C content and by sub-soiling. This will also help in improving rhizospheric environment of the soil.

### STRATEGIES TO IMPROVE RHIZOSPHERIC ENVIRONMENT

The following strategies are suggested to improve the rhizospheric environment for increasing crop productivity:

#### *Suitable crop and cropping system*

Inclusion of legumes in cropping systems is important. The inherent advantage of legume crop is addition of N through biological nitrogen fixation (BNF) (Table 3). Besides this, legumes also help in nutrient recycling from deeper soil layers, minimise soil compaction, increase the content of soil-organic matter, break the weed and pest cycles, and minimise harmful allelopathic effects. All these benefits make legumes suitable for improving the soil health and fertility. The legumes can be grown as a green manure or as a catch crop during lean period between two crops, or as substitute to anyone crop of the rotation. However, the constraints like cost of raising a green manure legume due to long duration of the legume restrict its integration in cereal-cereal systems on a large scale. Even the development of short-duration and uniformly maturing varieties of summer legumes (blackgram and greengram) and short- to extra-short duration of pigeonpea in recent years have not made much dent on inclusion of grain legumes in the cropping systems (Singh *et al.*, 2005). In the irrigated ecosystems where rice and wheat are predominantly cultivated, accumulation of salts in active soil layers is posing serious threat to the growth and survival of legumes. Despite the beneficial potential of legumes in sustaining soil health and fertility, they are not getting the necessary foothold to stay as an integral part of the cropping systems in irrigated lands. Without the aid of

**Table 2.** Effect of summer greengram on bulk density (BD) and hydraulic conductivity (K) of soil in a rice-wheat system, at New Delhi, 1993-95

Treatment	BD (Mg/m <sup>3</sup> )		K (cm/h)	
	d <sub>1</sub>	d <sub>2</sub>	d <sub>1</sub>	d <sub>2</sub>
<i>50 days after puddling (1993)</i>				
Fallow	1.59	1.62	3.37	3.30
Greengram (SI)	1.57	1.62	3.74	3.67
<i>Rice harvest (1993)</i>				
Fallow	1.59	1.63	3.90	3.21
Greengram (SI)	1.54	1.60	4.01	4.16
<i>Wheat harvest (1993/94)</i>				
Fallow	1.59	1.64	3.92	3.75
Greengram (SI)	1.54	1.60	5.62	5.36
<i>Wheat harvest (1994/95)</i>				
Fallow	1.56	1.60	3.76	3.60
Greengram (SI)	1.51	1.55	4.39	4.07

d<sub>1</sub>: 0-15 cm; d<sub>2</sub>: 15-30 cm; SI=stover incorporation  
Source: IARI (1995)

**Table 3.** Amount of N released into the soil by various legumes

Crop	N released (kg/ha)
Blackgram ( <i>Vigna mungo</i> )	38.3
Greengram ( <i>Vigna radiata</i> )	34.5
Cowpea ( <i>Vigna unguiculata</i> )	50.3
Horse gram ( <i>Macrotyloma uniflorum</i> )	27.1
Lentil ( <i>Lens culinaris</i> )	32.8
Pea ( <i>Pisum sativum</i> )	59.4
Khesari ( <i>Lathyrus sativus</i> )	54.9
Clusterbean ( <i>Cyamopsis tetragonoloba</i> )	55.7
Sunnhemp ( <i>Crotalaria juncea</i> )	75.0
Berseem ( <i>Trifolium alexandrinum</i> )	54.2
Dhaincha ( <i>Sesbania aculeata</i> )	68.9

Source: Singh *et al.* (1981)

legumes, one has to tailor the soil microbiota to improve soil health and fertility, as they are the most abundant soil organisms, playing decisive role in the nutrient mining and its subsequent availability to plant roots. The scavenging potential of these microbes should also be gainfully utilised to make the rhizosphere more favourable for root to grow. To improve the overall efficiency of rice-wheat system, as practised in the irrigated ecosystem of Indo-Gangetic plains, major research efforts have to be geared around these types of favourable microbial associations (both fungi and bacteria) to reduce the requirement of fertilizer application, especially of N and P.

In this context sugarcane-based cropping systems, though followed in 2 million ha area in the irrigated ecosystem of north India, may provide an opportunity to maintain soil health and fertility status. Higher root biomass, much deeper roots and greater contribution of organic matter through plant residues (Yadav and Verma, 1995), as well as fixation of N through the associations of some  $N_2$ -fixing bacteria and increase in P availability through mycorrhiza, provide the requisite strength to this system for its mass adoption. Moreover, due to wide spacing of cane rows, wheat can be accommodated easily in the sugarcane system as a companion crop without appreciable decline in yield. Companion cropping of greengram and blackgram in sugarcane system during summer or monsoon is also feasible (Yadav, 1982). This provides 30% economy in N fertilizer use. After harvest of the legumes, decomposition of roots, leaves etc. also contributes towards N need of the sugarcane (Yadav, 1981). The ameliorating effect of sugarcane in taking up salts from the soil is well documented, which provides necessary breathing space for the legume roots to survive. Similarly, intercropping of short green manure crop of *dhaincha* is also possible (Singh *et al.*, 1993). It not only checks the initial weed growth but also improves rhizospheric environment, besides providing benefit of  $N_2$  fixation. In fact, wheat

production in the districts of U.P. where sugarcane commands >20% area, has not only stabilised over the years but has also shown increasing trend in productivity. Moreover, energy crisis due to the soaring prices of fossil fuel, is fast transforming sugarcane as the 'energy crop' of future for the production of renewable green fuel ethanol. Time has come to modify the rice-wheat rotation as prevalent in the irrigated ecosystem into rice - sugarcane + wheat - ratoon sugarcane - rice system with incorporation of green manure catch crop.

The choice of efficient crops and cropping systems will depend on several factors. In most of the field crops only a part of the total dry matter produced is taken as the crop yield. The dry mass accumulation depends on: (i) size and efficiency of the source that produces the dry matter and the effective period of such accumulation, and (ii) the portion of the dry mass taken as the economic product or more valued product. The need for sustainability and stability of any cropping system is that the crops engaged in rotation should complete their life cycle or the period of economic viability in the available time frame. The time used by the crops for growth and yield is determined by the inherent ability of the plant (its physiology) to translate the available resources to the economic yield. This is exemplified by the introduction of dwarf, short-duration, fertilizer-responsive and photo-insensitive varieties of wheat and rice that changed the face of Indian agriculture. Short-duration (requiring less time to produce the economic product) along with photo-insensitiveness has provided the necessary opportunity to expand these varieties to the non-traditional areas of cultivation.

Spatial complementarity of resource use has been found in canopies. A two-tier root system combining a shallow-rooted species with a deep-rooted one may result in better efficiency of the production system in intercropping scenario, provided the upper profile is less tapped by the deep-rooted partner. In practice, this combination is difficult to find. However, it has been observed that root lengths of intercropped systems are often greater than of the sole crops, resulting in an overall increase in resource use. In legume or non-legume systems, this may arise from a specific complementarity of resource use, in which the legume meets some of its N requirement through its biological fixation, making less demand for soil N, and thus allowing non-legumes to have larger share of soil N (Yadav, 1982). If the supply of N exceeds the demand, a mechanism of temporary storage is required in the root zone. In most cases rainfall accelerates leaching of N to the deeper soil layers, and in that situation a deeper-rooted partner in the mixed cropping scenario always acts as a safety net for N.

### **Tillage**

Change in the rhizospheric environment starts with the tillage (in contrast to zero-tillage concept that embarks upon minimum disturbance of soil). Tillage is the manipulation of the soil into a desired condition by mechanical means. Agriculture has developed with development of tools or implements like pulverization, cutting, or movement of soil etc. Soil is essentially tilled to change its structure, to kill weeds and to manage crop residues. Modifications of soil-structure is often necessary to facilitate the germination of seed, root growth as well as water intake and storage. Elimination of weeds is important, because they compete for water, nutrients and light. Crop residues on the surface must be managed to provide conditions suitable for germination and growth of the crop.

Another significant impact of tillage is the development of hard pan just below the root zone, inhibiting proper drainage and thereby impacting the crop growth. Such hard pans are more prevalent with increasing levels of mechanization and use of heavy machinery. These hard pans must be shattered to increase the water-holding capacity of the soil and allow the roots greater access to deeper soil layers for mining of nutrients, especially for the deep-rooted crops. Introduction of sugarcane in rice-wheat rotation provides in-built mechanism of shattering the hard pan at the end of sugarcane ratoon crop, when deep tilling is essential to uproot the stubbles. Moreover, sugarcane, due to its much deeper root system than of rice and wheat, traps nutrients from beyond the root zone of rice and wheat.

It is envisaged that deep ploughing or subsoil chiselling should be used as a standard practice, at least once in 2 or 3 years in areas where rice-wheat rotation is the predominant cropping system, to improve rhizospheric environment. One may resort to conservation tillage in irrigation-limiting condition.

### **Planting method**

The rhizospheric environment of any crop may be modified depending on the method used for planting or sowing. Row crops always provide uniform and better opportunity to every plant to develop its rhizosphere domain for uptake of water and nutrients. The economy and efficiency of inputs depend on their actual utilization and transformation into economic yield. A pretty long time has been taken to switch over from the traditional broadcasting of seeds to raise crops in rows. However, the practice of broadcasting is still continuing in crops like oilseeds (rapeseed and mustard, sesame) and pulses (chickpea, lentil). It is urged that benefits of sowing seeds in rows even in low-value crops should be realised as it improves the yield performance.

Furrow-irrigated raised bed (FIRB) planting has been put to use in wheat to increase the water economy and efficiency of fertilizer use. This has now been widely used for intercropping wheat with sugarcane, where three rows of wheat are sown on raised beds and sugarcane is planted in the furrows, which act as the irrigation channel. This practice provides wheat rhizosphere the optimum environment to proliferate without any interference of the sugarcane rhizosphere, as it remains well below the rhizosphere of the former crop.

The ring-pit method of sugarcane planting (Singh *et al.*, 1984) provides another opportunity in tailoring the rhizosphere to improve the use efficiency of water and nutrients (Yadav and Kumar, 2005). It significantly reduces the water wastage, as water is easily delivered in the root zone without much loss in the inter-pit spaces. Moreover, this method provides a greater opportunity of using drip irrigation in sugarcane. This method of planting incidentally breaks the hard pan at the very beginning, pits usually go beyond 50 cm depth and this helps in mining of nutrients from much deeper soil layers due to development of rhizosphere at a depth much below than that in the conventional plantings.

### **Intercropping**

The intercropping, though appears more sound, has its own limitations. It is well known that the initial period of 15-45 days after sowing for most of the crops is very important and any weed growth in this period adversely affects productivity of the crop. If the intercrop is taken in this period it will grow as weed for the main crop and will pull down the yield. Therefore, tailoring of the agronomy of intercrops is essential to increase the profitability and efficiency of the dual system. Moreover, care has to be taken to suit the need of soil health and fertility. The key issue of competition of roots in crop-crop situation (mixed cropping, catch crop, relay crop etc.) for water, nutrients and other associated microflora and fauna has to be addressed to increase the sustainability of the system. Temporal complementarity was best documented for increasing the yields in intercropping system involving sorghum and pigeonpea. These two crops have maturity period of typically 100 and 180-200 days, so that the major demands for resources such as light, water and nutrients differ in time. The result is that the intercrops make better use of resources over time than the two sole crops (Natarajan and Willey, 1980). However, the advantage is more difficult to assess below the ground because of the time-consuming and destructive nature of measurements involved. Katayama *et al.* (1996a) measured the root growth of four crops (sorghum, pearl millet, groundnut and cowpea) grown either as sole crops or intercropped with pigeonpea.

The total root length and the distribution of root length in the profile for the two cereals were unaffected by the cropping systems, whereas those of the legumes were significantly reduced by intercropping. The largest reduction in length was for pigeonpea in all crop combinations, especially before harvest of the companion crops. Root growth of pigeonpea improved substantially after harvest of the companion crops and reached similar values to the sole crops at maturity. However, pigeonpea took less N from both soil and fertilizer than sole pigeonpea crop, and thus it was apparent that biological N<sub>2</sub> fixation has played a role in meeting the N requirement (Katayama *et al.*, 1996b).

Intercropping suppresses weeds better than sole cropping and thus provides an opportunity to utilize the crops themselves as a tool of weed management. This involves the inclusion of rapid-growing, early-maturing and good canopy structured crops like cowpea or greengram as intercrops between two rows of the main crop. The suppression of weed in smother cropping or intercropping systems is mainly due to increased leaf-area index and light interception.

The allelopathic effects of most of the weed flora in different crop combinations have to be worked out. For that matter, any suitable intercrop ranging from green manure crop to the legumes has to be evaluated in detail for their use in the improvement of soil fertility and soil reclamation. For example, root exudates of marigold are known to inhibit nematodes, and it may be put to use where nematode problem is putting limitations in harnessing productivity potential of the target crop. A critical study of allelo-chemicals as well as chemicals released by the preceding crop roots and residues on decomposition have to be taken into account and this arena is wide open to fine tune the crop rotation or the intercrop to be used (Olofsdotter, 2001; Bertin *et al.*, 2003).

### **Rhizo-deposition and bio-remediation**

The rhizo-deposition is the most important function that plant plays for the smooth functioning of roots. About 40% of the photosynthates are released by the roots to modify the rhizosphere environment. In wheat 3% of the photosynthate reaches root, just in 1 hour. This provides enough scope to modify the rhizosphere environment through the application of various chemicals at the phyllosphere (Gregory and Atwell, 1991; Jensen, 1994; Salt *et al.*, 1998). Foliar feeding of N and P is well known but its impact on root is yet to be unravelled. Can spraying of urea save the basal requirement of N for pulses? Will the spray application of P improve the initial root growth and aid in N fixation? There are hundreds of questions that need satisfactory answer to take advantage of hitherto

untapped potential of rhizo-deposition. This will open an opportunity to modify the rhizosphere in such a way that the beneficial micro-organisms that predominate in the rhizosphere will not only be helping in the economy of mineral nutrients and fertilizers but also be providing necessary support to combat soil pathogens as well as pathogens of the above-ground parts through induced systemic resistance.

### **Green manuring**

Low organic C content in Indian soils is a major limiting factor for improving the productivity. In north-west India, predominantly practised rice-wheat system has forced legumes to go out from the crop sequences, thus making the soil poorer in fertility. Moreover, shortage of pulses arising due to limited cultivation of legumes is also haunting the administration to provide the necessary dietary intake of proteins to the population. Therefore, it is necessary to devise ways and means to reintroduce pulses in rice-wheat cropping system without affecting the farmer's profitability. Understanding this necessity, efforts are constantly being made for the reintroduction of legumes in this belt. Researches were targeted at the production of short- to very short-duration legumes, legumes that can withstand higher salt stress and the legumes that are hardy enough to stay in dry periods. However, poor yield in most cases became the major deterrent for their wide acceptance by farmers. Introduction of sugarcane in the rice-wheat rotation may provide an opportunity to take at least one crop of pulse during the summer. The goal of improving the rhizosphere resides with the pulses and more research has to be directed to breed pulses that can thrive well in the irrigated ecosystem of rice and wheat.

When pulses are not available or not at all profitable, the next important alternative is to have short green manure crop to increase the status of organic C in the soil. If it is not possible to increase for a long term, at least it should be used to improve the organic C content for the duration of the main crop so that the efficiency of other inputs is increased (Beri *et al.*, 1989). Even a short-duration of green manure crop, say for 4 weeks, may be taken as an intercrop. *Sesbania aculeata* (*dhaincha*) most popularly used as green-manure crop between two crops, may be taken as intercrop in sugarcane in the upland condition (Singh *et al.*, 1993). Similarly, in rice *Sesbania rostrata* due to the nodulation on aerial parts provides an opportunity to be used as green manure crop between rice rows (Singh *et al.*, 2003; Yadav, 2003). Even a green manure catch crop may be taken to this effect at the end when rice is at the stage of maturity. In wheat system similar approach may be taken to spread the seed of green manure crop with the last irrigation at milk or dough stage. The

practice of burning the left-over straw after harvest through combine has to be abandoned in favour of the green manure catch crop. This should follow with a deep ploughing with pre-monsoon shower to incorporate both cereal and legume biomass into the soil. This will improve the quality of organic matter in the soil and thus will improve the nutrient availability to the plants. The benefit of green manuring even in this special situation will be far more than the cost of seed and labour.

### **Residue recycling**

#### **Mulches**

Traditionally mulches were used to conserve soil moisture. Besides, these mulches may be gainfully employed to serve several purposes, viz. (i) to suppress weed growth, (ii) to release allelochemicals and other leachates for the suppression of harmful micro-organisms, (iii) to produce growth-promoting substances and (iv) to increase the status of organic C in the soil.

Mulches provide different kinds of ecological niches in the subsystem of crop environment. They encourage the proliferation of micro-arthropods, earthworms and other beneficial micro-organisms that bring about changes in the status of soil fertility. Due to mulching, evaporation is reduced from the soil surface, which prevents the build-up of salt concentration in the root zone to the toxic level. It provides more stable humid atmosphere for the proliferation of microbes and thus facilitates the release of locked-in nutrients.

Mulching can be done with trash (Yadav *et al.*, 1994), where sufficient dry leaves or crop residues are available to cover the inter-row spaces in sufficient thickness. Similarly, organic farm wastes may be used for this purpose (Yadav and Prasad, 1992). However, maintenance of a proper C : N ratio is essential to prevent any harmful effects that retard crop growth. In sugarcane system, introduction of *Trichoderma* for *in situ* rotting of mulch provides several advantages, viz. (i) the quick decomposition of trash reduces the lock-in period of nutrients; (ii) during the process *Trichoderma* releases several growth hormones and elicitors that boost-up cane growth (Yadav, *et al.*, 2008), and (iii) it strengthens the defence of plants against pathogens directly by poaching on the pathogens and indirectly by induction or activation of defence related enzymes.

#### **Organic manures**

Due to the limitations on accumulation of organic C on long-term basis in the irrigated ecosystem, a short-term strategy is necessary to increase its level. The level of organic C determines the health of soil by meeting the C requirement of various micro-organisms. It helps in the

process of microbial-aided mineralization, sequestration of nutrients and fixation of N as well as increasing the availability of nutrients to plant roots. The status of soil organic C determines the quality and availability of nutrients in the rhizosphere. Residue recycling is an important component to increase the level of organic C in the soil. Farmyard manure is universally recommended for this purpose. However, due to various limitations the farmers are hardly able to put its recommended dose (10 t/ha). Organic manures are essential to increase the organic C of the soil and support a number of other beneficial micro-organisms in it. These organisms not only thrive on this source but also produce plant growth-promoting substances in the rhizosphere and also produce various compounds that offer antibiosis as well as fortify plant defence through the induction of systemic resistance. More researches are warranted in this direction to have system of organic agriculture.

#### **Problem soil and poor quality water**

The plant root and soil interface (rhizosphere) always contain a thin film of water for the steady flow of nutrients. The concentration of salts in the available water not only determines the availability of nutrients for uptake by the plants but also the level of tolerance of the plant roots to the excessive concentration of undesired salts. In legumes it not only damages the roots but also makes the environment unfavourable for the *Rhizobium* to have a symbiotic association and nodulation.

The strategy of substituting a part of inorganic N through organic source (FYM, green manure) has proved very useful with saline water irrigation. Farmyard manure nutritive value but it also influences leaching of salts through improvement in soil-physical properties. Though the saline waters are rich in Ca and Mg, crops like wheat, mustard and cotton respond well to gypsum application when grown on saline soils or irrigated with saline water (EC > 6 dS/m, Cl > 80%). This happens due to the reduced availability of S to plants at higher Cl content in saline waters. Similarly, the soils irrigated with Cl-rich water (Cl = 70% or more) responded to nearly 50% higher P application because the Cl ions reduced the availability of soil P to the plants (Manchanda, 1993).

It is known that salts tend to accumulate on the ridges when using furrow irrigation in ridge-furrow methods of planting or sowing. With each irrigation, the salts will leach out of the soil under the furrows and accumulate on the ridges due to evaporation. This practice of ridge-furrow method of irrigation will reduce the concentration of salts from the root zone and will temporarily provide a better soil environment for root as well as crop growth. This system may be made more effective by changing the

patterns of falling sun-rays on the ridge so that sun-rays help accumulate the salts more in one side by differential evaporation from the soil surface. Moreover, it has been established that ridge-furrow system alone can economize the water requirement by 30-50% without affecting the yield. Sprinkler and drip irrigation systems offer the highest economy of water but their use is mostly restricted to vegetable and horticulture crops.

In acid soils, Al toxicity is a recognised factor that limits plant growth and crop productivity. Similarly, accumulation of heavy metals in different soils as a consequence of industrialization is rendering many soils unfit to support crop growth. This situation may be tackled using plants that may directly utilise these compounds and reduce their toxicity or by taking up the help from the rhizosphere community of microbes to detoxify these chemicals. As a genus, *Pseudomonas* is well known for such scavenging activities and amelioration of soils. It is high time that these microbes be channelized in the crop-production systems, directly or through the transfer of desired microbial genes in the crop plants to carry out the scavenging acts on their own. Similarly, these molecular and genetic resources have to be utilized to incorporate the desired genes governing tolerance be it such as Al, Ni, Cd or the other heavy metals or the excess of certain salts of Na, Mg etc. in the crop variety to sustain the level of productivity without direct intervention of the rhizosphere.

The direct contribution by plants has become handy in many cases such as reclamation of problem soils. This indicates a possibility to modify the choice of plant with the genes from the plants that thrive well in that environment. It is imperative to look into the natural ecosystem that is thriving well in this area; if not available, one has to understand the nuances of the undisturbed systems available elsewhere.

### CONCLUSIONS

The success of breeding efforts infused requisite impetus in agriculture, making India self-reliant in food. Through the use of dwarf wheat and rice, India produced enough food in the shortest period of time. This quick production has led to over-exploitation and degradation of the natural resources, especially the soil and ground water. Over the years a fatigue is increasingly being felt to sustain the production level, decline in factor productivity is mounting enormous pressure on the increasing cost of production. Moreover, this situation is further accentuated by global warming, pollution and above all the erratic monsoon. In totality Indian agriculture is now facing much greater challenges to manage two square meals a day for the 1.2 billions of its populace.

In this regard, maintenance of soil health and fertility is

crucial so that the rhizosphere remains in a position to provide the required nutrients to the crop plants. The soil micro-organisms, nature's own nutrient miners, have critical role to play in arresting the decline in factor productivity in a sustainable manner. One has to tailor these micro-organisms to suit the crop rhizosphere so that the bounty of soil nutrient reserve becomes available. Besides residue recycling and extensive use of green manure crops, emphasis has to be given to the biological N<sub>2</sub> fixation, P and S solubilization, bioremediation and improvement in the organic C content of the soil. The scarcity of P in the soil of irrigated ecosystem may be reduced through the introduction of suitable mycorrhizal fungi for different crops. The precious water may be conserved through mulches, deep tillage, and irrigation management, and its application water as per the crop requirement. Resource conservation should be the buzz word in the sustenance of agriculture in future.

Tailoring the crops for better root growth and healthy rhizosphere environment through breeding may become handy to ease out this situation. Lastly the government support should come forward to encourage the farmers to adopt conservation agriculture, because in the initial phase of conservation the agricultural monetary returns are low, acting as the major deterrent for its adoption.

### FUTURE LINES OF WORK

Development of hard pan under rice-wheat system in irrigated ecosystem as well as continuous shallow cultivation in other cropping systems is the main cause of deterioration of rhizospheric environment, which leads to the impairment of nutrient availability, root growth and restriction of subsoil contribution. Therefore, research on tillage management should be the priority. Different tillage practices should be incorporated in the regular agronomic management of soil to discourage hard-pan formation. Similarly, research on intercultural practices has to be undertaken for increasing the root mass and better rhizosphere to increase the nutrient-use efficiency.

The role of legumes in rice-wheat system especially in the Indo-Gangetic plains has to be redefined in the light of the phasing out legumes from the cropping systems of this region, leading to the decline in soil health, fertility and factor productivity. Despite the mission-mode approach, the productivity of pulses has not increased to the desired level, which has become a stumble block in the food and nutrition security of the masses. It is amply clear from the foregone treatment that several research gaps have to be filled through extensive research efforts to sustain soil health, and for better rhizosphere environment and crop productivity. Detailed investigations on periodic shifts in soil biota, soil health, soil fertility and crop productivity

are needed to sustain adequate food-supply system.

Similarly, exclusion of legumes in the Indo-Gangetic plains has put BNF in the back seat, severely limiting their contribution in N economy and mobilisation of other nutrients from the subsoil. In this context research efforts have to be geared to utilise the services of other free-living N<sub>2</sub>-fixers like *Azotobacter* and other bacteria and efficient use of *Anabaena* etc. to help in the N economy. Research on VAM has to be tailored to utilise their P-crunching capability for the crop plants of irrigated ecosystem. Similarly, research has to be targeted on other cellulose decomposers like *Trichoderma* to release locked-in nutrients quickly and efficiently as well as for the production of beneficial compounds in the rhizosphere.

In the emerging scenario of irrigated ecosystem, foliar feeding of nutrients or other chemicals appears promising in the light of increasing cost of these inputs. It is increasingly becoming apparent that through foliar feeding one can modify the rhizosphere. Research is needed in this direction to increase the preponderance as well as the affinity of beneficial micro-organisms in the rhizosphere not only to increase the nutrient availability and their sustained release but also to check the development of soil pathogens.

Research has to be geared to the identification of efficient cropping systems not only to boost economic returns but also to improve the soil health and fertility. It is obvious that allelopathic effect of crop plants determines the predominance of some weed species in the crop. The crop can further be modified to check such weed growth. Wheat varieties may be fortified with genes to produce allelochemicals that are inimical to *Phalaris minor*. Similarly, an idea may also be mooted to disarm the weeds from exerting harmful allelopathic effects on crop plants through genetic engineering; even if the weeds are present and compete with the crops, their damage potential is minimized to an acceptable level (below the economic injury). This way it may be possible to reduce requirement of energy often needed to make the field weed free.

Technology of taking staggered intercrop-green manure has to be developed both in space and time for sustenance of higher level of organic C in the soil, which holds the key for greater activity of other micro-organisms. Similarly, research has to be directed to increase the level and quality of organic matter in the soil through *in situ* incorporation of organic residues in the soil and their faster decomposition.

Change in plant geometry and planting or sowing techniques need to be relooked into in the light of their influence on the type and extent of rhizosphere. These non-monetary inputs have a great potential to increase the nutrient-use efficiency.

It is imperative that breeding endeavour is needed to increase the plant competence to accept the N<sub>2</sub>-fixing bacteria in its fold possibly through encouragement of symbiotic association e.g. nodule-forming *Rhizobium* in legumes, and to the near commensality of acetic acid bacteria in sugarcane. Similarly, the proliferation of free-living N<sub>2</sub>-fixing species like *Azotobacter* in and around rhizosphere through the release of suitable substrates in the rhizosphere by the root may be encouraged.

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