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ReviewArticle

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Influence of Rhizosphereic Biogeochemical Processes on Plant Nutrition

Lokesh Patil[1*], Hamsa, N.[1], Adiveppa, M. Asangi and Harimohan Meena[1]

[1]Ph. D scholar, Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, GKVK, Bengaluru 560065, India

*Corresponding Author E-mail: lokeshgpatil925@gmail.com

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ABSTRACT

The rhizosphere is the soil zone adjacent to plant roots. A number of processes takes place at rhizosphreic region like interaction between bio molecules and clay minerals, interaction between abiotic components and sorption and desorption processes. Plants exude a variety of organic compounds and inorganic ions which are involved in interaction processes. Micro-orgnisms present in the rhizosphere also are involved in the rhizosphreic proceses. All these processes lead to physical, chemical and biological change that indirectly affect solubilization, mobilisation of nutrient elements and their uptake by plants. As, nutrient availability to plants is influenced by the rhizospheric processes and their root-development system, improving plant root growth and proper management of rhizosphere region can improve nutrient availability. At this point of time, though the studies on influence of rhizosphereic biogeochemical processes on plant nutrition is limited, we try to review the studies on the concept.

Key words: *Rhizosphere, Biotic and abiotic components, Interaction, Plant exudates, Nutrient availability.*

INTRODUCTION

Plant developmental processes are controlled by internal signals that depend on the adequate supply of mineral nutrients by soil to root and root to shoot. Thus, the availability of plant nutrients can be a major constraint to plant growth in many environments of the world, especially the tropics where soils are extremely low in nutrients thus limiting the crop productivity. Plants take up most of mineral nutrients through the rhizosphere where microorganisms interact with root exudates. Plant root exudates consists of a complex mixture of organic acid anions, phytosiderophores, sugars, vitamins, amino acids, purines, nucleosides, inorganic ions (e.g. HCO^{3-}, OH^-, H^+), gaseous molecules (CO_2, H_2), enzymes and root border cells which have major direct or indirect effects on the acquisition of mineral nutrients required for plant growth. Rhizosphere was described for the first time by Lorenz Hiltner in 1904. It varies with the plant species and the soil, generally considered at 2 mm distance from the root surface known as rhizoplane.

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Biogeochemical processes at rhizosphere

A number of processes take place at rhizosphere as it is the most active region in soil. Some of those processes that influence plant nutrition directly or indirectly are given below-

1. Interactions between biomolecules and clay minerals- Rhizosphere soil exhibits differences in physicochemical properties and mineralogy compared with bulk soil. It is a major active microsite where interactions among roots, symbiotic microorganisms, bacteria, soil constituents like minerals and organic substances, and soil solution take place and are involved in solubilization and insolubilization processes. Plant exsudes OH^- or H^+ to equilibrate the anion-cation balance, mineral weathering will be increased in the rhizosphere. Chelating root exudates and organic compounds released by microorganisms as well as organic acids are involved in the weathering of minerals and in the subsequent release and transformations of Fe and Al at root-soil interface. Their solubilisation capabilities depend on their chemical composition, nature of clay minerals and the mineral element considered[20]. Such processes of acid dissolution and complexation of minerals due to metabolites are considered as indirect weathering processes. Some bacteria, including anaerobic species and fungi can attack mineral surfaces and thereby mobilize constituents of the mineral or indirectly with a metabolically produced ligand that form a highly soluble product with a mineral component[12]. Clay minerals, pH, organic ligands are the most important factors which influence the release and phase transformation of Al and Fe at soil plant interface and the mineralogy, order, particle size, specific surface area and reactivity of the metal precipitation products towards nutrients and pollutants. The increased weathering of minerals in the rhizosphere induces changes in the abundance and the forms of metals at soil-root interface, as compared to the bulk soil.

2. Interaction between abiotic and biotic soil components in the rhizosphere and formation of organo-mineral complexes- Root exudates like low molecular mass organic ligands and biopolymers such as proteins (enzymes), nucleotides, polysaccharides and lipids interact with clay minerals, OH-Al and OH-Fe species and/or microorganisms form organo-mineral complexes at rhizosphere[43]. Microorganisms-mineral complexes formed by electrostatic or hydrophobic interaction between microorganisms and minerals are other common complexes at soil-plant interface. Microorganisms participate in the formation of organo-mineral complexes which these complexes provide substrates and protection. They contribute to the formation of organo-mineral complexes excreting polysaccharides and proteins.

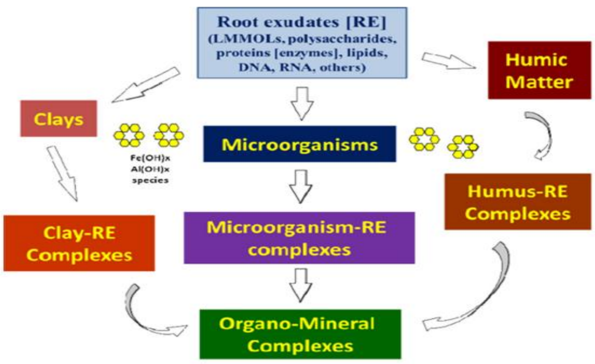

Fig. 1: Rhizosphereic Interactions of root exudates with soil components

Source: Violante and Caporale, 2015

3. Sorption and desorption processes at rhizosphere- Mobility of elements at rhizosphere is affected by sorption-desorption reactions that play a major role in their bioavailability. Soil components responsible for the sorption of nutrients and pollutants include phyllosilicates, soil organic matter, carbonates, variable charge minerals, microorganisms and organo-mineral complexes. Sorption of elements onto soil components is influenced by many factors as pH, nature of the sorbents, redox reactions, presence of foreign ions as indicated by Violante[40]. Polyvalent cations (*e.g*. Zn, Cu, Cd, Co, Ca) may be strongly adsorbed on the edge sites of phyllosilicates due to the presence of –SiOH or –AlOH groups capable of chemisorbing these ions. Organic matter and variable charge minerals (metal oxides, allophanes, imogolite) are much more effective scavenger of polyvalent cations, because complexation processes are the dominant binding mechanisms[21]. For example, Free-living bacteria and their extracellular macromolecular products (e.g. fibrils) can accumulate metal ions and may have mineral coatings with bound metals on their surfaces[5].

Major physical, chemical, and biological changes in the rhizosphere

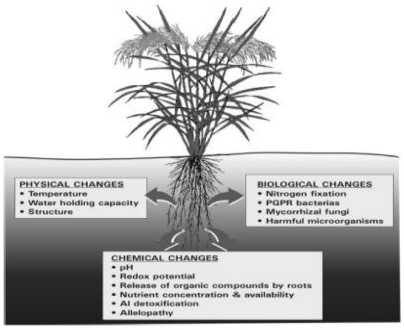

Fig. 2: Major physical, chemical, and biological changes in the rhizosphere[9]

1. Chemical changes- This article mainly emphasizes on the biological and chemical changes that occur in the rhizosphere to make nutrients available to plants. Several chemical changes take place in the rhizosphere due to plant root and soil environmental interactions. Among these changes

a. Soil pH- is one of the most important chemical properties that influence nutrient solubility and hence, the nutrients availability to plants. At lower pH availability of most micronutrients is higher, except that of molybdenum and decreases with increasing soil pH. Availability of N and P is lower at lower pH. The changes in rhizosphere pH are associated with differences in cation/anion uptake and release of H^+ or OH^- (HCO^{3-}) by plant roots. The pH also changes with the excretion of organic acids by roots and by microorganism activities in the rhizosphere. CO_2 produced by roots and microorganisms respiration can dissolve in soil solution and may form carbonic acid and lower the pH. Root excretion of H^+ in the rhizosphere is an effective mechanism for improving uptake of micronutrients except Mo[10].

b. Redox potential- Redox potential is a chemical process by which electrons are given up or acquired. Root activity alters rhizosphere redox potential through respiratory oxygen consumption and ion uptake or exudation. Lindsay[24], enlisted Redox reactions occur with various forms of elements *viz.* Mn (Mn^{2+} and Mn^{4+}), Fe (Fe^{2+} and Fe^{3+}) and Cu (Cu^+ and Cu^{2+}). Primary source of electrons for biological redox reactions in soil is organic matter, but aeration, pH and root and microbial activities also influence these reactions.

c. Release of organic compounds- Plant roots not only absorb water and nutrients to support plant growth, but also release organic and inorganic compounds into the rhizosphere[9]. These compounds affect microbial population and availability of nutrients. The release may occur as an active exudation, a passive leaking, the production of mucilage, or with the death and sloughing of root cells. Sugars and amino acids released in the rhizophere provide energy for microorganisms in the rhizosphere, which mineralize or solubilize many nutrients. Acids reduce the pH and improve the availability of many micro and macro nutrients. Release of mucilages protects the root tips from injury and desiccation, as well as playing a role in nutrient uptake through the mucilages, pH-dependent cation exchange capacity[22].

2. Biological changes- An important biological change associated with the rhizosphere is root colonization by many types of beneficial and harmful microorganisms. plant- beneficial microorganisms include nitrogen (N_2)-fixing bacteria, freeliving N-fixing bacteria, plant-growth-promoting rhizobacteria, saprophytic microorganisms, bicontrol agents, and mycorrhizae fungi.

a. Nitrogen (N_2) fixing bacteria - Nitrogen fixation is defined as the conversion of molecular nitrogen (N_2) to ammonia and subsequently to organic N utilization in biological processes. Microorganisms responsible for biological N fixation are symbiotically living in the roots of higher plants and also in association with roots as well as free-living organisms in the rhizosphere. A major portion of biological N is fixed by species of Rhizobium and Bradyrhizobium living in symbiosis with legume roots.

b. Nitrogen fixation by free-living and root-associated bacteria

c. Plant growth promoting rhizobacteria- Direct influence is related to increased solubilization and uptake of nutrients and production of phytohormones, whereas indirect effect is associated with pathogen suppression, production of Fe-chelating siderophores, and antibiotics, and the induction of plant resistance mechanisms[33].

d. Mycorrhizal Fungi- Mycorrhizae associated with crop plants are primarily arbuscular mycorrhizal fungi (AMF). The AMF improve host-plant nutrition by improving the acquisition of P and other minerals, especially the low-mobile micronutrients Zn, Fe, and Cu[26]. Harrier and Watson[17] found that P is the most important nutrient taken up by the extra-radical hyphae and influx of P in roots colonized by AMF fungi that can be three to five times higher than in an non-mycorrhizal roots. Mycorrhizae are also involved in the nutrient cycling *viz.* solubilization, mineralization) hence found to improve nutrient availability in rhizosphere soil[26].

e. Beneficial microorganisms and modes of action- Plant-beneficial microbial interactions can be roughly divided into three categories[32].

i. First, those microorganisms that in association with plants, are responsible for its nutrition (*i.e*., microorganisms that can increase the supply of mineral nutrients to the plant). Saprophytic microorganisms are responsible for many vital soil processes, such as decomposition of organic residues in soil and associated soil nutrient mineralization or turnover processes.

ii. Second, there is a group of microorganisms that stimulate plant growth indirectly by preventing the growth or activity of pathogens. Such microorganisms are referred as biocontrol agents.

iii. A third group involves those microorganisms responsible for direct growth promotion by production of phytohormones.

The modes of action of PGPR involve complex mechanisms to promote plant growth, development and protection. Important among them are biofertilization (increasing the availability of nutrients to plant), phytostimulation (plant growth promoting, usually by the production of phytohormones) and biocontrol (controlling diseases, mainly by the production of antibiotics and antifungal metabolites, lytic enzymes and induction of plant defense responses). Example- *Pseudomonas* and *Bacillus* genera

Root-induced changes of ionic concentrations in the rhizosphere

The major function of plant roots is the uptake of water and nutrients. This results in either the accumulation or depletion of all the ions present in the soil solution in the rhizosphere. This process occurs both for mineral nutrients and for other, nonessential elements (*e.g*., Si) and possibly for toxic elements[19]. The nature and intensity of the ionic concentrations changes depend on the correspondence of the requirements of the plant and the supply by the soil. Nutrients such as Ca or Mg, which usually occur at large concentrations in the soil solution[11], may be transferred by mass flow to the root-soil solution interface at a greater flux than required by the root. Nutrients uptake results in a decrease in their concentration in the soil solution near plant roots, this depletion generates a concentration gradient and diffusion of ions toward the roots takes place.

Influence of rhizosphereic processes on Plant Nutrient Availability –

In rhizosphere, competition exists among the roots of neighboring plant species for space, water, mineral nutrients[34]. The rhizosphere also consists of several micro and macro organisms like bacteria, fungi, virus etc and other insects. Root–root, root-microbe, and root-insect communications of continuous occurrence in this zone Hence, rhizosphere is considered as biologically active soil zone.

1. Nitrogen-

The rhizospheric bacteria fix atmospheric N2 in the soil in organic form and it is easily used by plants[39]. The application of nitrogen fertilizers leave residual effect on soil which modifies the rhizosphere pH through chemical reactions[13].

Dong S and Shu, 2001 found the existence of strong interaction among varies nutrients in the rhizosphere, phosphorus showd depletion in rhizosphere and the depletion zone remains larger in $(NH_4)_2SO_4$ than KNO_3 applied plot. The responses of potassium, calcium, magnesium, copper, zinc, manganese and Fe concentrations in the rhizosphere to nitrogen fertilizers varies with species crop and kind and amount of nutrient treatments.

Nitrogen sources affect the rhizosphere pH via three mechanisms as given by Marschner, 1997 (i) displacement of H^+/OH^- adsorbed on the solid phase; not associated with any plant activity

(ii) nitrification/denitrification reactions; not associated with any plant activity and

(iii) release/uptake of H^+ by roots in response to NH_4/ NO_3 ratio uptake. This is directly related to the uptake of nutrient and affects in the rhizosphere region.

The NH^+_4 /NO^-_3 ion uptake can change rhizosphere pH up to 2 units higher or lower compared with bulk soil[29]. Generally, in oxidized soils, NO^-_3 is the dominant ion and under reduced soil conditions (flooded rice), NH^+_4 is the dominant ion. Symbiotic organisms such as rhizobia and to lesser extent nonsymbiotic bacteria such as Azospirillum, can augment plant uptake of N via N fixation. mobilization of non-exchangeable NH^+_4 -N in the soil-root interface may be increased by nitrifying and hetrotrophic microorganisms with a higher activity in the rhizosphere, influencing the equilibrium between non-exchangeable NH^+_4 and NH^+_4 in the soil solution, thus favoring the release of NH^+_4 from interlayer of the clay minerals[3]. A 2-year field experiment on greenhouse cucumber double-cropping systems examined the effects of nitrogen management in rhizosphere and planting of sweet corn as a catch crop in the summer fallow period on cucumber yield and soil Nmin dynamics compared to conventional practices. Cucumber fruit yields were not significantly affected by root zone N management and catch crop planting despite a decrease in N fertilizer application of 53 % compared to conventional N management. Root zone N management efficiently and directly reduced N losses by 44 % and 45 % in 2005 and 2006, respectively. Sweet corn, the summer catch crop, depleted Nmin residue in the soil profile of 1.8 m at harvest of winter–spring season cucumber by 304–333 kg N ha^{-1}, which contributed 19– 22 % reduction in N loss. Compared to conventional N management, N loss was reduced by 56 % under root zone N management and catch crop planting[14]. Clayton *et al*.[6] studied the effects of elevated CO_2 (eCO_2) and soil N status on wheat rhizosphere activity and residue decomposition and also N recovery from crop residues with different N status by different plant treatments. They found that for wheat, eCO_2 reduced the negative rhizosphere effect, resulting in greater rates of decomposition and recovery of N from field pea residues, but only when N fertilizer was added but not for field pea residue.

Phosphorus- Its deficiency mostly occurs both in acidic and calcareous soils where P retention and precipitation is high, hence in these soils it is one of the major limiting nutritional problems for plants. The mycorrhizosphere favor the nutrient uptake, particularly P, Cu and Zn[25].

Glucose, which serves as an energy source to microorganisms, was found to have a strong effect on phosphorus mineralization in rhizosphere region[35]. According to Hamer and Marschner[16], amino acids that are mainly used as N by microorganisms have a smaller effect on P mineralization from organic sources. The mechanism involved in the microbial solubilization of P is the production of organic acids and the release of protons to the soil solution. The alkaline phosphatase activity increases from 102 to 325 % and acid phosphatase activity from 205 to 455 % in the soil adhering to the root mat as compared to the non rhizosphere soil, hence the release of P is high in rhizosphere soil than the bulk soil[36]. Amending acid soils with rock phosphates has increased available form of phosphorus and also enhanced their rate of dissolution by the rhizosphere soil[1]. Plants, fungi, and bacteria have their own ways to mobilize P. Release of protons that lead to a decrease in soil pH, the release of organic and inorganic ligands and chelators such as bicarbonate or carboxylic anion are the important mechanisms as found by Uroz 2009, that release phosphatases that mineralize in situ P. Root exudates released in the rhizosphere contain phosphate radicals that will be subject to microbial modification. Microbial processes including mineralization, immobilization, and solubilization of inorganic phosphates also influence P availability to plants. Enhanced secretion of acid phosphatases (APase) and phytases by plant roots and also by rhizosphere microorganisms under P deficient conditions may contribute to P acquisition by hydrolysis of organic P esters in the rhizosphere[31]. Saleque and Kirk[37] opined that the quantity of readily plant-available P was negligible in comparison with the quantity of P extracted by the plants in both P-fertilized and unfertilized soils. After 6 wk of rice growth, 90 % of the P taken up was drawn from acid-soluble pools. There was a small accumulation of alkali-soluble organic P and no changes in the more recalcitrant soil P pools. The zone of P depletion was 4-6 mm wide, increased with P addition and coincided with a zone of acidification. The acidification was due to H^+ generated in oxidation of Fe^{2+} by root-released O_2 and to H^+ released from the roots to balance excess intake of cations over anions.

Potassium- The original source of K is from primary minerals such as micas (biotite and muscovite), feldspar (orthoclase and microcline), and their weathering products. Availability of non-exchangeable K to plants was found to increase due to an exchange reaction and mineral dissolution in the rhizosphere[30]. Increased exudation of sugars, organic acids, and amino acids has been found in maize as a response to K limitation[31].

Iron- Microorganisms and plants release low molecular-weight compounds (chelators) which increase the Fe availability[28]. There are two different strategies to relese iron in soil as reported by Von Wiren *et al*., 1993. Strategy I plants (dicots and non-graminaceous monocots) release organic acid anions which chelate Fe. Iron solubility is also increased by decreasing the rhizosphere pH, and Fe uptake is enhanced by increased reducing capacity of the roots (Fe^{3+} to Fe^{2+}). Strategy II plants (Poaceae) release phytosiderophores that chelate Fe^{3+}. It is taken up in the chelated form as Fe-phytosiderophore. Guo *et al*.[15] found that the production of phytosiderophres in maize plants helped peanut for uptake of Fe during deficient period. Intercropping altered parameters of the rhizosphere proceses *viz*. available iron concentration and pH due to an interspecific rhizosphere effect at different stages. The significantly higher levels of ferric reductase activity and AhFRO1 and AhYSL1 expression at the vegetative stage of intercropped peanuts suggest roles for such genes in Fe uptake in the particular rhizosphere conditions under intercropping.

Manganese- dynamics of Mn in the rhizosphere is similar to that of Fe. Its availability in soil solution increases with increasing acidic condition. In alkaline soils where Mn usually is insoluble the rhizosphere effect is beneficial. Availability of Mn in the rhizosphere is affected by important factors like redox condition, pH, moisture, temperature, other nutrients and heavy metal concentrations in soil solution. In rhizosphere Mn in oxidized form as Mn^{4+} will be reduced to Mn^{2+} by some rhizosphere bacteria like *Bacillus, Pseudomonas*, and *Geobacter* and fungi (*Gaeumannomyces graminis*) make Mn available for plants[8].

Zinc- Generally, Zn deficiency can be noticed in sandy loam and organic soils than silty or clayey soil, but White *et al*., 1997 reported that Zn deficiency can be reclaimed by the modification in the rhizosphere soil. They commonly provided Zn to plants through the fertilization system with chelating agents (mainly EDTA or DTPA) and obtained good results. Cakmak *et al*., 1996 bserved that long and fine plant roots architecture favor aquisition of Zn from larger soil volume, higher synthesis and release of Zn-mobilizing phytosiderophore by the roots in rhizosphere region, it promotes Zn uptake as Zn-phytosiderophore complex. Bar-Yosef *et al*.[2] reported that root excretion of H^+ at the root surface is an effective mechanism for enhancing. Zinc uptake compared with excretion of complexing agents.

Copper- Its dynamics is similar to that of zinc. The root exudation in the rhizosphere increases its availability and plant uptake of Cu[23].

Strategies for modifying rhizosphere environment to improve nutrient availability-

Water and nutrient availability to plants is influenced by their root-development system. Hence, improving plant root growth can improve nutrient availability.

By adopting the following management practices, it is possible to modify the rhizosphere environment in favor of better root development and, consequently, higher nutrient availability[9]:

(1) proper land preparation,

(2) adequate and balanced fertilization and liming;

(3) use of good-quality seeds;

(4) sowing cultivars of high yield potential,

(5) use of adequate seed rate and plant spacing;

(6) seed treatment for the control of seed-borne diseases;

(7) appropriate methods of fertilization, especially immobile nutrients;

(8) topdressing N at the right stage of crop growth (as a general rule, the best time for topdressing N in cereals is at about panicle initiation and in legumes, about one week before initiation of flowering. At these growth stages, plants have adequate root systems to absorb applied N and have N requirements to increase the number of grains),

(9) control of diseases, insects, and weeds;

(10) use of proper crop rotation;

(11) control of soil erosion;

(12) maintenance of organic matter;

(13) control of allelopathy;

(14) proper management of soil salinity and alkalinity;

(15) avoidance or minimization water deficiency; and

(16) adoption of a conservation tillage system

CONCLUSION

Rhizosphere effect on nutrient mobility and plant nutrient uptake is a key activity in crop production. Various biogeo-chemical processes occur at rhizosphere region and are responsible for nutrient solubility and availability to plants. The magnitude of bio-chemical changes varies with plant species, soil type, environmental factors and their interactions. The manipulation of root activities and its exudation from the plant in nutrient deficient conditions enhances nutrient use efficiency. Hence, rhizosphere processes are very complex in nature and dynamics and complete knowledge about them is still not available. More studies are needed to understand the changes and their interactions with plant nutrition.

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