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Role of Microorganisms in Soil Fertility

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Microorganisms play a definite and very useful role in soil fertility. Usually people think that microbes are agents of disease, however, they perform many other beneficial activities in the Biosphere (the portion of the earth consisting of soil, water, and air). The beneficial microorganisms help in the decomposition of toxic waste and other pollutants, and above all, they add to the soil fertility. The role they play in improving the soil fertility has become a subject of intense investigations during the recent past. The purpose of this article is to explore the role they play in soil fertility, plant nutrition, and above all crop yield.

A renowned microbiologist, Jacob Lipman, once remarked, "a soil devoid of microorganisms is a dead soil". Fertile soils contain a wide variety of microbes which include different species of bacteria, fungi, protozoa, algae, and viruses. Mostly, they are found in the rhizosphere (the region of soil closely surrounding the plant-roots) where they decompose organic matter (plant and animal debris, human waste and dead microbes) into humus. Humus is composed of well decomposed organic matter. Organic matter is composed of molecules of celluloses, hemicelluloses, sugars, lignins, waxes, nucleic acids, proteins, and amino acids. These molecules, in turn, are made up of various types of elements. Essential elements required by most plant species along with their chemical properties are shown in table 1.

Table 1 lists 16 elements that are essential for healthy plant growth and seed production. It is apparent from the above table that plants absorb most of the elements in the ionic form (cations and anions) baring a few which are absorbed in the molecular ionic form (e.g. nitrogen, phosphorus, sulfur, boron, molybdenum, and hydrogen). Regardless of the molecular source of these elements (organic matter or inorganic fertilizers), they must be broken down into simpler ionic forms before they can be absorbed by the plant roots or shoots. The conversion of complex molecular compounds into ionic forms is carried out by microorganisms either directly or indirectly. The process is called "mineralization".

Mineralization can be visualized as preparation of plant food by microorganisms. The whole process can be metaphorically comprehended. Imagine that microorganisms are "cooks", the rhizosphere is a "kitchen", soil organic matter + fertilizers are "groceries", and microbial enzymes are cooking "recipes". The complex compounds from the organic matter are broken down into simple ionic elements (nitrogen, phosphorus, and sulfur dishes). The plants happily enjoy these dishes prepared by the microbial cooks in the rhizosphere kitchen using enzymatic recipes. Various elements go through cooking cycles called nitrogen cycle, carbon cycle, sulfur cycle, and phosphorus cycle.

A. Nitrogen Cycle:

Primary source of nitrogen for plants is atmospheric nitrogen gas (N_2). Microorganisms are absolutely required to transform N_2 into plant food. Four steps are involved in the N_2 cycle.

a. **Nitrogen Fixation:** Three types of bacteria fix N_2 in plant.
    1) Cyanobacteria (photo-synthesizing) fix N_2 in tropical trees.
    2) Actinomycetes (Filamentous bacteria) fix N_2 in most trees or shrubs.

3) Rhizobium species fix N_2 in legumes.

Rhizobium is most important in N_2 cycle. All rhizobia are aerobic (need oxygen) but can live in the soil saprophytically until they come in contact with root hair. Root hair respond to invasion by curling around the bacterium. Enzymes from bacteria degrade the root hair cell wall and create a "door" by which they get into the root cells. One cell may contain several thousand of bacteria. Inside the cell they make cells divide to form a "nodule" in which they store N_2 in the form of ammonium (NH^+_4) by reducing N_2 from the atmosphere. The host plant provides the bacteria ATP energy from metabolism of carbohydrates, and bacteria, in turn, provide ammonium by fixing it in the nodules. The bacterial enzyme used in nitrogen fixation is called nitrogenase.

b. **Ammonification:** Nitrogen fixing bacteria bring atmosphere N_2 as ammonia into the biological world but it is not readily available to most organisms including plants. When plants and animals die and produce organic matter, which contains nitrogen in proteins and amino acids, it is decomposed by microorganisms. In this process ammonium is released through a process called "deamination".

c. **Nitrification:** Ammonium obtained from above two processes is converted to nitrates (NO_3^-) by the help of microorganisms. First step is oxidation of ammonium into inorganic nitrate (NO_2^-) by Nitrosomonas bacterial species. Second step is to convert nitrite into nitrate (NO_3^-) with the help of Nitrobacter bacterial species. Nitrates are taken up by the plants as food.

TABLE 1: ESSENTIAL ELEMENTS REQUIRED BY PLANTS

Element Name	Chemical Symbol	Form Available to Plants: Ionic	Form Available to Plants: Common Name	% Concentration in Dry Tissue
Nitrogen	**N**	**$N0^-_3$, NH^+_4**	**Nitrate, Ammonium**	**1.5**
Potassium	**K**	**K^+**	**Potash**	**1.0**
Phosphorus	**P**	**$H_2PO^-_4$, HPO_4^{2-}**	**Phosphoric Acid**	**0.2**
Calcium	**Ca**	**Ca^{2+}**	**Calcium**	**0.5**
Magnesium	**Mg**	**Mg^{2+}**	**Magnesium**	**0.2**
Sulfur	**S**	**SO_4^{2-}**	**Sulfate**	**0.1**
Zinc	**Zn**	**Zn^{2+}**	**Zinc**	**0.002**
Iron	**Fe**	**Fe^{2+}, Fe^{3+}**	**Ferrous**	**0.01**
Manganese	**Mn**	**Mn^{2+}**	**Manganese**	**0.005**
Copper	**Cu**	**Cu^{2+}, Cu^+**	**Copper**	**0.0006**
Boron	**B**	**H_3BO_3**	**Boric Acid**	**0.002**
Molybdenum	**Mo**	**MoO_4^{2-}**	**Molybdate**	**0.00001**
Chlorine	**CI**	**CI-**	**Chloride**	**0.01**
Oxygen	**O**	**O_2,H_2O**	**Oxygen**	**45.0**
Carbon	**C**	**CO_2**	**Carbon Dioxide**	**45.0**
Hydrogen	**H**	**H_2O**	**Water**	**6.0**

d. **Denitrification:** Denitrification is an anaerobic process carried out by a certain bacterial species by which nitrates are reduced back to atmospheric nitrogen (N_2). This process completes the nitrogen cycle.

In addition to above specific microbial species, many other microorganisms decompose proteins present in the organic matter. Among them *Pseudomonas*, *Bacillus*, and *Micrococcus* are important. Additionally some fungal species such as *Alternaria*, *Aspergillus*, *Penicillium*, and *Rhizopus* also release nitrogen in ammonium form. However, fungi release less nitrogen for plants and keep most of it for their own growth.

In the end a fair statement can be made which states that, "no microorganisms, no nitrogen, no plants".

B. Phosphorus Cycle:

Phosphorus is second to Nitrogen in importance as food for plants. It is found in both organic and inorganic forms in the soil. Primary source of organic phosphorus compounds in the soil is the vast quantity of vegetation and crop debris. In plants, this element is found in compounds such as phospholipids, DNA, phosphorylated sugars and coenzymes. The phosphorus components of these compounds formulate from 15-25 percent of total phosphorus in the soil. This organic source of phosphorus is ready to be release by microorganisms.

Microorganisms release bound organic and inorganic phosphorus through four processes.

a. Alteration of solubility of inorganic compounds of phosphorus
b. Mineralization of organic compounds with the release of inorganic phosphorus
c. Immobilization of inorganic phosphorus into the plant cell
d. Bringing about oxidation and reduction of inorganic phosphorus compounds.

Mineralization and immobilization are particularly important in the phosphorus cycle in nature. Both are medicated by microorganisms.

a. Mineralization: Different microorganisms release elemental phosphorus from different phosphorus containing compounds present in the organic matter. The enzymes they produce to release phosphorus are collectively called phosphatases. Both bacterial and fungal species produce these enzymes. Bacterial species belonging to genera Streptomycetes, Pseudomonas, and Bacillus are of particular importance. Fungal species of Aspergillus, Penicillium, and Rhizopus can also release phosphorus.

b. Immobilization: Microorganisms decompose organic matter and produce available forms of phosphorus. First of all microorganisms build their own population by immobilizing phosphorus in their own cells. During this period they create phosphorus deficiency in the soil which can be fulfilled by phosphorus fertilizers. It is therefore desirable to add only those bacterial species that release elemental phosphorus from the organic matter.

c. Solubilization: In addition to organic source of phosphorus, inorganic compounds (calcium, phosphate) are abundant in the soil. But they are unavailable to the plants and need to be solubilized by microorganisms. Bacterial species of genus *Pseudomonas*, *Bacillus*, and *Mycobacterium* solubilize bound phosphorus and make it available to the plants. Microorganisms solubilize phosphorus by producing organic acids such as nitric and sulfuric acid. Acids convert phosphorus salts of calcium, iron, aluminum, and magnesium into dibasic and monobasic phosphates which are taken up by the plants.

Phosphorus released from organic and inorganic sources is transformed by microorganisms into phosphoric acids ($H_2PO_4^-$ and $H_2PO_4^{-2}$) which are readily absorbed by the plants. It is interesting to note that the fertilizer industry does this chemically to produce orthophosphoric acid, microorganisms do the same organically.

C. Sulfur Cycle:

Sulfur is the fourth major element required for healthy plant growth. It is an essential component of the amino acids (cysteine, cysteine, methionine, and vitamin B complex) required for protein synthesis. Sulfur is also required for nodule formation in leguminous crops (alfalfa, beans, lupins, vetches, etc). Sulfur is primarily available to plants in the sulfate form (SO_4^{-2}).

Sulfur is often present in the soil in suboptimal quantities, therefore, sulfur based fertilizers are needed. The main reserve of sulfur in the soil is the organic matter. Organic sulfur can only be released by microorganisms. Sulfur cycle in soil is analogous to nitrogen cycle and microbes are the sole agents to convert organic sulfur into available inorganic forms such as sulfates. Four processes of sulfur metabolism operate in the soil, i.e. mineralization, immobilization, oxidation, and reduction. These steps are utilized in biological sulfur cycle.

In the soil, organic sulfur is bound as hydrogen sulfide (H_2S). Bacterial species of the genus *Thiobacillus* and *Beggiatoa* oxide H_2S to elemental sulfur (S). Elemental sulfur aggregates as crystals inside the phototropic species of bacterium *Chromatium*. Other bacterial species of *Chlorobium* and *Ectothiorhodospira* also oxidize hydrogen sulfide but release elemental sulfur into the soil. Elemental sulfur is oxidized first to sulfite (SO_3^-) followed by sulfuric (H_2SO_4) acid produced by *Thiobacillus thiooxidans*. These bacteria grow well under acidic soils (pH 2.0 – 3.5) and can be used to reduce alkalinity in the soil by applying sulfur. Sulfates are eventually reduced to sulfides (H_2S) by another bacterial species of genus *Desulfovibrio*. These bacteria work under anaerobic conditions. That is why in water lodged soils the sulfur becomes unavailable to plants. Also, H_2S made by *Desulfovibrio* causes death to nematodes and many pathogenic fungi in the soil.

D. Potassium Utilization:

Potassium occurs in ionic (K^+) form in the soil and is taken up as such by the plants. No special bacterial decomposition is required. However, organic and inorganic acids produced by microorganisms help to solubilize potassium locked into rocks. Potassium is required for sugar translocation and starch formation in the plants. It helps root growth and is also toxic to fungal diseases. It increases quality and size of fruits, grains, nuts, and vegetables (tuberous vegetables such as potato).

E. Microbial Transformation of Micronutrients:

- Iron: Iron is essential for chlorophyll formation in plants. It is often in abundance in western soils. Its deficiency occurs due to excessive zinc and manganese in the soil and causes chlorosis of young leaves. Iron occurs in pyrite form, a typical iron disulfide which is slowly oxidized to iron sulfate ($FeSO_4$) by bacterial species *Thiobacillus thiooxidans*. Organically iron forms complexes with sugars and simple organic acids in the soil. Organically bound iron is attacked by bacteria of genus *Pseudomonas*, *Bacillus*, *Klebsiella*, *Streptomycetes*, and some filamentous fungal species.

- Manganese: Manganese and iron are essential for chlorophyll formation. It is taken up by the plant in the ionic (Mn^{++}) form. In plants it exists in several oxidization states (divalent manganous ion, tetravalent manganous ion). Divalent form (Mn^{++}) is absorbed by plants but tetravalent (Mn^+_4) need to be transformed by microflora. Bacterial genus *Bacillus, Arthrobacter, Pseudomonas*, and *Klebsiella* release ionic manganese from complex compounds ($MnCO_3$). Manganese oxidizers varies from soil to soil but they often account for 5-15 percent of total microflora in the soil.

F. Metabolism of other Micronutrients:

Metabolism of other micronutrients, copper (Cu^{++}), boron (H_3BO_3), zinc (Zn^{++}), molybdenum (MoD_4), and chlorine (CI) is not known to involved microorganisms, as yet. However, they are very important for plant health. For example, plants require molybdenum to transform nitrate nitrogen into amino acids, and legumes cannot fix nitrogen molybdenum.

Boron is taken up by plants as boric acid (H_3BO_3) and plays a definitive role in cell differentiation of actively dividing meristematic cells. Copper is a co-factor in several enzyme activity in plants. Similarly chlorine has been found to be important in carrying out the photosynthesis in plants.

Life without Microorganisms:

Soil organic matter holds more than 95% of soil nitrogen, 5-60% of total phosphorus and about 30% of soil sulfur. Availability of these nutrients is conditional to the decomposition of organic matter by microorganisms. Lack of microorganisms may result in:

a. Accumulation of organic matter which can adversely affect the soil fertility by clogging the soil texture.
b. Accumulation of Humus can result in locking the carbon and other important component of plant skeletons (celluloses and hemicelluloses).
c. Extensive utilization of fertilizers which will cause water and soil pollution.

Microorganisms and fertilizers:

Microorganisms cannot supply enough nutrients for plants. Therefore the use of chemical fertilizers is evident. It is important to use high grade chemical fertilizers having low salt index and high solubility otherwise they can harm the soil fertility by adding undesirable heavy metals and increasing salt index. High grade fertilizers are analogous to **"fast food outlets"**and also help build high microbial population in the soil. Efficiency of microbial activity is directly related to their number in the soil, therefore, it is a **"microbial number game"**. If the number in the soil is inadequate, microbes should be added along with the liquid fertilizers. Practice of adding microorganisms through fertilizers or otherwise is now recognized as a viable additional source of increasing soil fertility. Research has shown that a fertile soil should display a vertical variation of microorganisms of the magnitude shown in Table 2.

- Conclusion: Microorganisms (cooks) use raw Organic matter from the soil and artificial fertilizers (groceries) to cook plant food in the rhizosphere (kitchen) using enzymes (recipes).

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TABLE 2: DISTRIBUTION OF MICROORGANISMS IN SOIL				
Depth		Organisms per gram of soil		
(CMS)	Aerobic-Bacteria	Anaerobic-Bacteria	Actinomycetes	Fungi
3-8	7,800,000	1,950,000	2,080,000	119,000
20-25	1,800,000	379,000	245,000	50,000
35-40	472,000	98,000	49,000	14,000
65-75	10,000	1,000	5,000	3,000
135-	100	400		3,000