Chapter 5

Soil Microorganisms and their Role in Ecosystem Functioning

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Abstract

The productivity and sustainability of the world's ecosystems are thought to depend on the activity of soil microbial populations. Soil support processes like nutrient cycling, carbon sequestration involved in different ecosystem services. Soil heath and fertility plays an important role in crop production and productivity. Thus, it constitutes the basis of terrestrial ecosystems. Microorganisms that live in different conditions of the soil that is bacteria and fungi, undertake these tasks primarily. Certain interactions between populations of soil microorganisms are advantageous to one or both individuals; some interactions are detrimental to one participant. Undoubtedly, the diversity of microbial populations in soil is immense, but our understanding of the factors that affect microbiome makeup is appalling. The interaction between different microbial community's support soil health, and accelerate the breakdown of hazardous pollutants. This chapter clarified structure of microbial ecosystem as well as how microbes participate in different processes occurring in soil ecosystem for maintaining its stability and sustainability including carbon and nitrogen cycles, biodegradation or waste cycling, heavy metals detoxification etc.

Keywords: Soil microbes, Nutrient cycling, Biodegradation, Ecosystem

I. INTRODUCTION

Soil systems are very complex as made up of multiple components high temporal and spatial variability, making the study of their functionality and life a labour-intensive problem; to succeed, collaborative efforts among numerous compatible and complementary specialists are required." One of the key issues in ecology—the framework and equilibrium of biological systems—cannot be resolved without knowledge of the numbers functional and structural organisation of soil microbial communities, hence soil microbiologists unquestionably belong to this group of like-minded professionals. It should be kept in mind that microorganisms, which are primarily found in soils, make up between 60 and 90 percent of the biomass on the planet as a whole (Meybeck *et al.,*1982). The vast metabolic variety of soil microbes means their activities drive or contribute to the periodic cycling of each of the key elements (e.g. C, N, P), and this cycling affects the functions and structure of the soil ecosystems in addition to the ability of soils to offer services to others (Jackie Aislabie and Julie R. Deslippe, 2013). Microbes also play major role in reducing pollutants in soil ecosystem through heavy metal as well as waste recycling, thus increasing the soil fertility.

In soil microbes exist in the form of microcolonies constituting different microbial spaces as biofilm (benefiting) or colonies constituting single species(competing) each other. Soil microbiome constitutes all the microorganisms residing in soil interacting with each other through quorum sensing. Thus, most of the ecosystem services involve contribution of bacteria, fungi as well as archea as a whole. Also, they are specific in the activities they involved. Therefore, studying microbial biomass structure and their individual role in different processes responsible for smooth ecosystem functioning has a great importance.

II. STRUCTURE OF SOIL MICROBIAL BIOMASS

Soil microbial population density estimation is crucial for comprehending the microbial activities taking place in the soil. The biotopes with the highest concentration of cells of bacteria in many examined soils are found in forest litter, sod, and higher humus layers, where bacterial population density is 5–10 times greater than that in mineral horizons. Except from gray forest soil, which has a 4 times higher (12%) prokaryotic fraction, most soil types have no more than 3% prokaryotic biomass (Mason-Jones *et al.*, 2022). Tens of tons of total microbial biomass are often found in chernozem, soddypodzolic, and chestnut soil, compared to multiple tons in gray forest soil. Only 8 to 33% of biomass is presented by spores, with the majority (55–90%) falling on the mycelium of the fungus (Dobrovol'skaya *et al.,* 2015). Fungi therefore completely dominate the soil microbial population in terms of biomass where as in case of numbers its bacteria. In addition to carrying out crucial ecological tasks like decomposition and nutrient cycling, soil microorganisms such as archae, bacteria, viruses, protozoa and fungus also interact symbiotically with plants. Each of them defined with their own function and importance.

Bacteria, along with archaea, are the smallest independently living, single-celled organisms on earth, with typical cells measuring 0.5 to 1.0μ m in diameter (Shukla, R. S., and Chandel, P. S., 2014). Some bacteria commonly found in soils, like the Actinomycetales, are capable of developing branching filaments. These bacteria are of different shapes like cocci, rod, spiral etc. They have typical circular double standard DNA lack up of nuclear membrane. We now know that archaea are widespread and are found with bacteria in many different environments, including soil. In the beginning, they were assumed to exclusively exist in extreme environments and were frequently referred to as "extremophiles". All life forms can be classified into three domains according to molecular phylogenetic methods based on comparisons of 16S ribosomal rRNA sequences (Woese *et al.,* 1990). Archaea is more closely linked to Eukarya than Bacteria considering its phylogeny. Due to their eukaryotic status, fungi are more closely linked to plants and animals compared to archaea or bacteria. The nuclei of fungal cells are membrane-bound and contain DNA-containing chromosomes, just like those of all eukarya, including humans. They also have organelles that are attached to membranes, like mitochondria. The cell wall of fungi is made up of glucans and chitin. Microbes can be broadly categorized as either autotrophs or heterotrophs. Heterotrophs utilize organic compond as a source of energy and carbon, while autotrophs use energy from either sunlight or inorganic substances (Fe^{2+}, nitrite or nitrate) to fix atmospheric carbon dioxide to make building blocks of life that is carbohydrates, lipids, and proteins(Gomez Perez. , 2018)

Considering diversity of bacteria in soil Acidobacteria, Proteobacteria and Actinobacteria are prominent and frequently abundant, whereas Verrucomicrobia, Firmicutes, Chloroflexi, Gemmatimonadetes, Planctomycetes and Bacteroidetes are typically fewer in number. Overall the relative abundance of the major bacterial phyla varies between different soils samples. *Burkholderia, Collimonas,* and members of the Rhizobiaceae family are among the proteobacteria, the most diverse metabolic group that are frequently found in the rhizosphere. *Streptomyces, Arthrobacter, Rhodococcus* and *Mycobacterium* are among the actinobacteria that form the subclass Actinobacteridae, isolated from soil (Aislabie *et al*., 2013).

III. MICROBES IN SOIL FORMATION

Physical, chemical, and biological processes work together to create the soil from the parent materials and maintain its fertility. Topography, time, climate, parent material, and the plants and soil microbes present all have an impact on the qualities of the soil that is created (Semenov, A. M., and Đukić, D. A, 2020). But the kind of microbe, its function, and the amount of microbial biomass all play a significant role in determining the nutrients that are readily available for plant growth (Schulz *et al.*, 2013). The kinds, functional identities, and microbial biomass therefore play a crucial role in nutrient transformation, nutrient storage, and nutrient cycling, which can be a reliable marker of the soil quality, the ecosystem functioning and the stability of the below-ground food web (Taunton *et al.,* 2000).

IV. MICROBES AND NUTRIENT CYCLING

1. Carbon Cycle

Microbes are crucial to the cycling of nutrients such as carbon, phosphorus and nitrogen necessary for life in soils. Although cyanobacteria and surface-dwelling algae, both free-living and symbiotic as lichens, can considerably contribute to carbon fixation in particular habitats, plants are the principal producers of organic material in terrestrial ecosystems. Autotrophic bacteria mostly can fix carbon dioxide within soil and the saprotrophs ultimately finish it converting back these organic matters to carbon dioxide through common living processes like respiration. Besides, nonliving organic materials can be ultimately recycled by heterotrophic bacteria and fungi. Some of them follow the process of decomposition (degradation of nonliving organic matter to form energy) and mineralization (complete degradation of organic compound to inorganic one such water, carbon dioxide and ammonia. Numerous bacteria, especially those are members of the Actinobacteria and Proteobacteria. breakdown soluble organic compounds including organic acids and sugars (Eilers *et al*., 2010). Additionally, some microorganisms, such as Bacteroidetes, aid in the breakdown of more resistant carbon compounds like cellulose, lignin, and chitin. Microbes are exceptional in that they can degrade organic material anaerobically (fermentatively), resulting in the fermentation of organic compounds into organic acids and the production of gases like hydrogen and carbon dioxide. Methanogens may use the hydrogen in strictly anaerobic circumstances to break down carbon dioxide and ultimately produce methane gas. Acetate, methylamine and methanol can all be converted by some methanogens into methane and carbon dioxide (Rother, M., & Metcalf, W. W., 2004).

2. Nitrogen Cycle

Nitrogen is necessary for all living things since it is a component of both proteins and nucleic acids. While plants need relatively depolymerized nitrogen sources like single amino acids like glycine and inorganic nitrogen sources like ammonium and nitrate, animals get their nitrogen from organic sources (Schimel and Bennett, 2004). The majority of microorganisms can grow by using ammonium or nitrate. Microbes carry out several process like nitrogen fixation, denitrifi cation, dissimilatory nitrate reduction to ammonia (DNRA), anammox and nitrification etc. The rates of these microbial processes frequently restrict ecosystem productivity since nitrogen is frequently the key limiting nutrient for the production of plant biomass in terrestrial ecosystem.

Ammonification is the process through which organic soil matter breaks down and releases ammonium. Only bacteria and archaea are capable of biological nitrogen fixation, or N-fixation, which is the conversion of nitrogen gas in the atmosphere to ammonium. The function of ecosystems depends heavily on N-fixation since it is the only natural method by which fresh N enters the biosphere. The enzyme nitrogenase catalyzes the process of n-fixation. Due to its great sensitivity to oxygen, this enzyme needs an atmosphere with low oxygen levels to function. N-fixation costs a lot of energy because it uses 16 moles of ATP for every mole of N fixed. N-fixation produces ammonium, which is absorbed into amino acids, which are then polymerized into proteins. N-fixing bacteria thrive in nitrogen-restricted environments. N-fixation is carried out by bacteria that coexist with plants in symbiotic partnerships, such as *Rhizobium, Frankia* and *Mesorhizobium* as well as free-living microbes like *Azotobacter, Clostridium, , Burkholderia* and various methanogens (Gupta *et al.,* 2017).

Ammonia (ammonium ions) is oxidized during nitrification, first into nitrite and later nitrate. A few autotrophic bacterial species and Crenarchaea appear to be the only organisms in soil that can nitrify, which is an aerobic process. Different microbial species carry out the two phases of nitrification, which are the production of nitrite and then nitrate. In soil, *Nitrosospira, Nitrosomonas*, or the crenarchaeum N*itrososphaera* are responsible for the oxidation of ammonia to nitrite, while *Nitrobacter* and *Nitrospira* are responsible for the oxidation of nitrite to nitrate (Jung *et al.,* 2011). When oxygen is scarce, soluble nitrogen oxides are utilized as an alternate electron acceptor during denitrification, a kind of microbial respiration. It entails the sequential conversion of nitrate, nitrite, and nitric oxide (NO) into nitrous oxide, a greenhouse gas, or harmless nitrogen gas. It generally happens in places that have been flooded and turned anaerobic. Numerous phylogenetically distinct soil bacteria, including those belonging to the Actinobacteria, Proteobacteria and Firmicutes, as well as fungus and other soil eukaryotes, have been found to be capable of denitrification.

Alcaligenes or Escherichia coli are examples of facultative anaerobic bacteria that can reduce nitrate to nitrite in a process known as dissimilatory reduction of nitrate. These species either excrete the nitrite it produces or, some microorganisms convert the nitrite they produce to ammonia by reducing it to hydroxylamine. Organisms do not denitrify, which means they do not create gaseous nitrogen compounds. Ammonium is oxidized by anammox bacteria in anaerobic conditions to nitrogen gas. Anammox bacteria have been found in bulk soils, soil near nitrogen-fixing plants, agricultural soil, and permafrost soil. Some bacteria can take part in various nitrogen cycle processes. Members of the genera *Azospirillum, Rhizobium* and *Bradyrhizobium* for instance, can fix nitrogen and denitrify at the same time (Ming *et al.*, 2021). Additionally, nitrifying bacteria like *Nitrosomonas* are capable of denitrification, which is referred to as nitrifier denitrification.

3. Phosphorus Cycle

Phosphorus transformation occurred in nature through microbes in two ways:

- They mineralize organic P (phosphate esters-most common form) to inorganic phosphate in a process catalyzed by phosphatase enzymes, those are produced by different bacteria and fungi;
- They convert insoluble that is immobilized P to soluble P in a process through the production of organic acids;

Thus, they release enough P for their own use as well as plants.

In order to liberate phosphate from the insoluble mineral P, mycorrhizal fungus produces oxalate. A key tactic used by plants to overcome P constraint is the mobilization of P by fungal symbionts. For instance, in response to P deficiency of host, a number of ectomycorrhizal basidiomycetous fungi express high-affinity phosphate transporters in extraradical hyphae (Plassard and Dell, 2010). P-solubilizing bacteria have been discovered in pasture soils in the Proteobacteria (particularly *Pseudomonas*), Bacteroidetes, Actinobacteria and Firmicutes (Mander *et al.*, 2012). There is documentation that regular applications of fertilizers high in phosphorus can change the diversity of Arbuscular mycorrhizal fungus and Actinobacteria and in pasture soils (Wakelin *et al.*, 2012). *Thermonospora, Saccharopolyspora* and *Thermobifida* are related actinobacterial genus responsible for phosphorus solubilization. *Micromonospora sp., Streptosporangium sp., Actinomadura sp., Rhodococcus sp., Actinoplanes sp.* And *Nocardia sp*. Are actinobacteria that produce phosphatase enzymes that have been categorized based on their alkaline or acid activity, depending on the response (Jain *et al.*, 2022).

V. MICROBES AND WASTE RECYCLING

Naturally occurring microorganisms, notably bacteria and fungus, have developed an amazing number of detoxification and biodegradation mechanisms to deal with compounds that are harmful to the environment or human health. For bioremediation, these microbial strategies are being used. In these researches, enrichment cultures are set up to detect the biotransformation of pollutants under a variety of environmental circumstances, such as oxygen availability, pH, nutrient availability etc. *Mycobacterium, Pseudomonas* and *Sphingomonas* three heterotrophic soil bacteria have frequently been linked to oil breakdown. For instance, *Pseudomonas* has been extensively researched, and the genes and enzymes involved in the solely aerobic degradation of phenanthrene, alkanes, naphthalene and monoaromatics are well known. Likewise, fungus and bacteria break down chemicals. For instance, atrazine was used as sole source of nitrogen and carbon by *Arthrobacter nicotinovorans* HIM that was isolated from a New Zealand agricultural soil. The bacteria also break the related triazine substances cyanazine, propazine, terbuylazine, and simazine in addition to atrazine (Aislabie *et al*., 2005).

Under co-metabolic conditions (i.e. with alternatives for growth like sawdust, corn cobs or straw), ligninolytic fungi like the white rot fungus *Phanaerochaete chrysosporium* may digest a wide spectrum of environmental pollutants like pentachlorophenol and dioxin. This remarkable capacity has been related to the lignin degradation pathways that these fungi have developed (Barr and Aust, 1994). With a variety of diverse chemical structures, such as organochlorines, organophosphonates, carbamates, s-triazines, triazinones, acetanilides, and sulfonylureas, actinomycetes are also responsible for the breakdown of pesticides (Bhatti *et al.*, 2017). It had been reported that local soil actinomycetes degraded the pesticide Diuron (a kind of phenylurea) in soil (Mohapatra *et al*., 2022).

VI. MICROBES IN DETOXIFICATION OF HEAVY METALS

The chemical affinity that metals have for thiol groups on biomolecules like proteins may make them harmful to soil bacteria. Copper, lead, and other metals can all be sequestered in extra cellular polymeric substances (EPS) (Harrison *et al.*, 2007). Detoxification through ion reduction within cells is the second process occured in microbial cells. For instance, mercury reductase (encoded by the merA gene) may convert Hg^{+2} to Hg^0, and because Hg^0 has a low evaporation point, thus diffuses out of the cell (Nies, 1999). Ions are extruded from the cell by efflux systems in the third mechanism. By removing metals from the cytoplasm, the cation/proton antiporter Czc, which is found, for instance, in *Alcaligenes eutrophus*, enables resistance to Cd^{2+}, Zn^{2+}, and Co^{2+} from the environment through the cell barrier (cell membrane) (Silver and Phung, 1996). These heavy metal microbial transformations are being used for bioremediation of heavy metal-containing pollutants to detoxify soil ecosystems.

VII. CONCLUSION

Microbial communities play a critical role in the soil's ability to maintain homeostasis by eliminating contaminants and delivering essential ecosystem services like soil fertility, resilience, and stress tolerance. The quantity and variety of microorganisms in the soil rhizosphere are the primary determinants of soil health in sustainable agriculture. The composition, productivity, and sustainability of plants are influenced by the variety and abundance of soil and rhizosphere microorganisms. Thus, Microbes are a unique bioresource that can be used for a variety of ecosystem functions, including bio-geochemical cycling, reducing greenhouse gas emissions and restoring damaged terrestrial ecosystems, etc. Their roles in soil ecosystem management are diverse and essential for the future sustainable agriculture development goals.

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