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A REVIEW ON THE ROLE OF MICROBIAL COMMUNITIES IN MAINTAINING PLANT AND SOIL HEALTH

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Abstract

Nowadays, the concept of soil health is characterised by three fundamental parameters such as: physical, chemical and biological soil properties. These parameters are in a continuous interaction when are influenced by climatic changes, soil types and the usage of different management practices. The importance of the microbial communities in soil is represented by their ability to decompose the soil organic matter and to transform, mineralize and release essential nutrients important for plant development. In addition, they are important in the detoxification of environmental pollutants and maintenance of soil fertility. In soil, microorganisms are abundant and diverse and include some important taxonomic categories such as: bacteria, fungi, actinomycetes, algae and soil protozoa. This review is focused on the role of beneficial microorganisms in soil health, highlighting the recent advances in this topic.

Key words*: microorganisms, management practices, soil health.*

INTRODUCTION

Soil is an important fraction of the terrestrial environment, which has the quality of supporting all forms of terrestrial life. They maintain and develop life through their property of regenerating, filtering, absorbing, and transforming pollutants.

The agricultural systems sustainability has recently become an important problem all over the globe. Many of this agricultural sustainability problems were connected to soil fertility and the changes that may appear over time. When referring to soil health, it refers to the continued ability of the soil to function as a vital living ecosystem. In addition, soil health is described as well as the unique balance of chemical, physical and biological soil parameters. Soil fertility is an essential fragment of soil quality, that concentrates more on the soil productivity, which is a parameter of the soil's capacity to produce a particular crop under a certain agricultural management system. Most of the productive soils are fertile helping the plant to grow, but some of the fertile soils are unproductive due to the fact they were subjected to harmful natural factors such as drought or management system practices (Nguemezi et al., 2020). These management practices can affect soil nutrients availability through processes such as mineralization, oxidation, leaching and erosion (Liu et al., 2010). Finally, these practices can affect the existence and activities of soil microbial communities and soil structure and fertility (Musbau and Ayinde, 2021).

Modern agriculture has to face new challenges such as climate change, erosion, loss of nutrients from the soil sorption complex, contamination with pollutants and plant protection chemicals, protection of drinking water sources or depletion of soil fertility (Sharma et al., 2017). Furthermore, in modern agriculture, the chemical products for plant protection including insecticides, herbicides and fungicides are used very often to impede the crops from pests and in conclusion to increase the crop production. Once these products enter in the soil, they can perturb soil microbiota and finally the nutritional quality of soil (Kang et al., 2016).

These products for plant protection are applied often throughout the season when crops are cultivated. With every application certain amount of these products infiltrates into the soil. Due to the intensive application of products for crop protection a lot of issues, which include the soil pollution, have appeared. Besides the composition and the quantity of pesticides applied on soil, their impact on the microorganism's activity can depend as well on soil physical, chemical and biochemical parameters (Sethi et al., 2013; Arora and Sahni, 2016).

Soil microbial communities can have a strong impact on soil fertility and crop development, and on the changes in soil structure and dynamics in response to different soil management practices. They can give information about soil quality and biological complexity (Bai et al., 2018; Dusa et al., 2022).

In order to choose the right agricultural management system should be taken into account the microbiological and physio-chemical parameters of the soil. There are various studies that highlighted that most important determinants of soil microbial community structure are environmental factors (temperature, moisture and CO_2 levels), soil physical structure, soil pH and other chemical properties (Schulz et al., 2013; Kiflu et al., 2013; Musbau and Ayinde, 2021). The presence of microorganisms and their variety can be considered as sensitive measure of soil quality. The cultivation systems applied by farmers can lead to changes in the quantitative and qualitative structure of organisms which are living in the soil environment (Kladivko, 2001). In addition, it was highlighted that soil microbial communities are very sensitive to anthropogenic factors, especially agricultural activity (Kuffner, 2004).

SOIL MICROORGANISMS

Soils are a mixture of organic and inorganic matter that host a complex web of organisms that can affect the evolution of soil and various physical and chemical soil parameters. The biological activity was found to be greater in the soil superior part (0-20 cm) and it's diminishing with the soil depth.

Microorganisms are important in all nutrients cycle (N, S, P) from and in the degradation of organic residues. In addition, microorganisms encountered in soil help in the decomposition of the organic matter (OM) derived from plants and animals resulting the energy intake essential for soil functions. After that, the organic matter is transformed to biomass or converted to carbon dioxide, water, nitrogen, and other nutrients (Jacoby et al., 2017).

Microbial populations are sensitive indicators used in the measurement of soil health, a soil quality that cannot be totally defined using physicochemical tools. Microorganisms adapt rapidly to environmental conditions due to their capacity to respond to changes. Therefore, they can be utilized for the assessment of soil health, and the modifications that appear in the activity of the microbial communities (Stott, 2019).

The rhizosphere is a habitat for the development of nitrogen fixing symbiotic bacteria and mycorrhizal fungi, which increase plant performance by improving mineral nutrition. Microorganisms decompose organic matter into plant nutrients which are absorbed by plants. Plants release an increased quantity of different chemical components into the soil. Thus, these chemical compounds lead to the formation of microorganisms structure in the soil. In addition, microorganisms utilize as source of food the root secretions and can produce antibiotics that impede harmful microorganisms. On the other hand, soil microorganisms can release growth regulators and make accessible various nutrients such as P and S that can enhance plant conditions (Furtak and Gajda, 2018). In soil, microorganisms are extremely abundant and diverse and include some important taxonomic categories: algae, bacteria, fungi, yeasts and actinomycetes. From all these categories, two main groups are found more often in the agricultural soils: bacteria and mycorrhizal fungi (Musbau and Ayinde, 2021).

Bacteria lives in soil in various forms. It can be found as cocci which have the form of sphere and the dimensions of 0.5 mm, bacilli with rod form and dimensions between 0.5 and 0.3 mm and spiral. Bacteria is the most predominant category of microorganisms that can be found in soil, their population decreasing with the increase of soil depth (Aislabie and Deslippe, 2013). They are one-celled organisms that constitute the highest biomass of soil organisms. Bacteria are found more abundant near plant roots, one of their main food resources because, in rhizosphere, can be found more abundant the substances secreted by roots, residues from dead plant and animal, sugars, and polysaccharides (Bakshi and Varna, 2011).

Some of the most common bacteria that can be found in soil are part of the genera *Pseudomonas*, *Arthrobacter*, *Clostridium*, *Achromobacter*, *Bacillus*, *Micrococcus*, *Flavobacterium*, *Corynebacterium*, *Sarcina*, *Azospirillum*, and *Mycobacteria* (Loper et al. 1985; Bakshi and Varna, 2011).

Soil bacteria can be classified as follows (Ingham, 2009; Aislabie and Deslippe, 2013):

- Symbiotic nitrogen-fixing bacteria that can form connections such as nodules with roots of the leguminous plants. The nodule is the spot where the atmospheric nitrogen is fixed by bacteria and transformed into ammonium which can be assimilated by the plant.
- Nitrifying bacteria which convert NH_4^+ to NO_2^- and then to NO_3^-. Nitrate is leached easier from the soil, so some farmers use nitrification inhibitors to reduce the activity of one type of nitrifying bacteria.
- Denitrifying bacteria, where nitrate is converted into nitrogen (N_2) or nitrous oxide (N_2O) gas. These types of bacteria are anaerobic, meaning that they are active in the absence of oxygen, namely in saturated soils or in the soil aggregates.
- Actinomycetes are a broad group of bacteria that grow in form of hyphae, just like fungi. In soil, actinomycetes are capable to decompose a broad spectrum of substrates, in particular the hard-to-decompose compounds (chitin and cellulose) and are active at increased levels of pH. There are some antibiotics produced by actinomycetes such as *Streptomyces*.

Fungi are microscopic cells. They make their way through soil particles, roots, and rocks with the help of hyphae. They are strongly connected with soil nutrients cycle (C, N, P) due to their capacity to decompose the organic matter (Frąc et al., 2018). Fungi are connected to water dynamics, soil nutrient cycling and biological examination against root pathogens. Furthermore, fungi assist at some processes such as, protection against drought, hormone production, and degradation of plant remaining parts (Treseder and Lennon, 2015; Jayne and Quigley, 2014; Frąc et al., 2018). Fungi have the capability to produce a great diversity of extracellular enzymes. Due to this ability, they are capable to decompose various categories of OM and soil elements and to control carbon and nutrients cycling (Žifčáková et al., 2016). Moreover, fungi can transform the OM into important elements such as biomass, CO_2, and organic acids.

According to the uptake of their energy, fungi can be found in soils under three general functional groups (Ingham, 2009, Bakshi and Varna, 2011):

- Decomposers (saprophytic fungi) are fungi able to transform organic residues into biomass, CO_2 and organic acids. These fungi decompose the complex substrates like cellulose and lignin from wood and are essential in the process of degradation of the carbon ring structures in different pollutants.
- Mutualists (mycorrhizal fungi) are the fungi that colonize plant roots. In rhizosphere, mycorrhizal fungi are able to solubilize phosphorus and transport soil nutrients (P, N and micronutrients) to the plant. They receive in return carbon from the plant (e.g *P. indica*). There are two major categories of mycorrhizae: the *ectomycorrhizae*, and the *endomycorrhizae*. Both of them have a sleeve of external hyphae (approx. 60%) that have the role of absorbing water and ions from the soil, which the fungus gives to the plant through the internal hyphae. The differences between them occurs in the internal hyphae: *ectomycorrhizae* form Hartig's network (substance exchange between the plant and the fungus) only among the cells of the rhizoderm; while in *endomycorrhizae* some of the internal hyphae enter the cortical cells where they differentiate two types of formations: arbuscules (for the exchange of substances between the two symbiotic species) and vesicles (in which the fungus stores reserve substances in the form of glycogen).
- Pathogens or parasites, cause weakened nutrient deficient plant or death when they permeate the plant and breakdown the living tissue. There are various pathogens that increase the economic losses every year. These pathogens are part of genera

Verticillium, *Pythium*, *Phytophthora* and *Rhizoctonia*.

Protozoa are microscopic organisms with only one cell, but larger than bacteria. They are characterised taking into account the ways they move: amoebae use a pseudo (fake) foot, ciliates have cilia (short hair) and move them very fast, and flagellates have one or more flagella (whips) and move them very fast (Tugel and Lewandowski, 2001). Protozoa feed themselves with bacteria, which leads to an increase in bacteria population. In addition, they release a form of N into the soil that can be used by other soil organisms and plants which can't do this by themselves. Protozoa are important in the mineralization of nutrients, making them available plants and other soil organisms use, and help to suppress diseases by competing with or feeding on pathogens.

SOIL MICROBIOME FUNCTIONS THAT SUPPORT PLANT GROWTH

The plant root is an organ which can adapt very well to soil conditions, changing or being changed by surrounding soil parameters (physical, chemical, and biological). The soil area immediately affected by the root with altered microbial diversity, increased enzymatic activity and quantity of organisms, and complex interactions between soil microbial communities and roots is called rhizosphere (Slaughter, 2021). Rhizosphere importance is characterised by the amount of released organic matter by the presence of roots in the soil, followed by an increased number of available nutrients and plant development due to the interaction of microbial communities (Bhattacharyya and Jka, 2012; Helepciuc et al., 2019). The interactions that appear between microbial communities in the rhizosphere are known as the rhizosphere microbiome. In the rhizosphere, the composition of microbial populations, their abundance, and functional attributes are different from the bulk soil microbiome (Mendes et al., 2013).

In the rhizosphere, there are several organisms that have been studied for their beneficial influence on plant development and health: nitrogen-fixing bacteria, arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR), biocontrol microorganisms and protozoa (Mendes et al., 2013; Vorholt, 2012). On the other hand, in rhizosphere, can be found some organisms as well that are harmful for plants. This type of organisms includes the pathogenic fungi, oomycetes, bacteria, and nematodes. In addition, another important that can be found in the rhizosphere are the human pathogens (Shah et al., 2021).

For decades, in order to increase crop production was used very often soil bacteria. In soil, bacteria have various functions among which are listed: to make available the nutrients for crops, to stimulate plant development producing plant hormones, to control or inhibit the pathogens that supress plant growth, to ameliorate soil structure, bioaccumulation of inorganics and mineralization of organic pollutants (Shah et al., 2021; Hayat et al., 2010).

Nitrogen fixing bacteria are microorganisms important in the increase of nutrients availability, notably nitrogen. Nitrogen has an essential role in the increase of food and feed production and in the improvement of plant development (Pandey et al., 2020). In addition, nitrogen it is also required for cellular synthesis of enzymes, proteins, chlorophyll, DNA and RNA. Bacteria commonly named as "*Rhizobia*" are considered contributes to the formation of nodosis/bacteriorrhiza/symbioses between nitrogen-fixing bacteria and the roots of leguminous plants. Species of *Rhizobium* (*Rhizobium*, *Mesorhizobium*, *Bradyrhizobium*, *Azorhizobium*, *Allorhizobium* and *Sinorhizobium*) have been used globally to allow the nitrogen-fixing symbiosis with leguminous crop plants (Hayat et al., 2010). Over time, the amount of PGPR identified has increased, due to the fact that rhizosphere as an ecosystem has acquired importance in the functioning of the biosphere (Saharan et al., 2011). Rhizobia, which live inside the nodular structures on host roots and assume the form of bacteroides, have a symbiotic relationship with legumes. The rhizobial bacteria transform atmospheric nitrogen into a form that the plant may use in exchange for carbon nutrients from the host, enabling the plant to meet its own nitrogen needs. Nitrogenase enzymes transform atmospheric nitrogen into NH_3 using

ATP as energy source. Biological nitrogen fixation is an essential growth parameter which influences development and yield of the crops. Various species of microorganisms from different genera have capacity of biological nitrogen fixation such as *Bacillus*, *Azospirillum*, *Pseudomonas*, *Klebsiella, Enterobacter*, *Flavobacterium*, *Erwinia*, and *Rhizobium* (Silva et al., 2016). Nowadays, in agriculture is utilised 65% of the nitrogen through the process of biological nitrogen fixation and will continue to be essential for a sustainable crop production (Shah et al., 2021).

Azospirillum colonize the surface and inside of roots. They are known for their capacity to promote plants, stimulating root development and increase the rate of water and mineral intake per root, and maintain soil quality.

Actinomycetes have a critical role in the decomposition of more resistant organic materials such as chitin and in the inhibition of several plant pathogens in the rhizosphere. Furthermore, they are able to decay complex mixtures of polymer in dead plant, animal and fungal material. Through this process can result many extracellular enzymes which are important to crop production (Bhatti et al., 2017). Actinomycetes can be found in the rhizosphere of agricultural crops. In the rhizosphere, they are able to increase soil fertility through organic matter conversion and solubilizing phosphate (Hozzein et al., 2019). Such interactions have made possible to characterize them as plant growth-promoting rhizobacteria (PGPR).

Bacillus is the most abundant genus in the rhizosphere, and the PGPR activity of some of these strains has been known for many years. They are important in the increase of availability of the nutrients that crops need for their development. In addition, *Bacillus* species are known as phosphate-solubilizing bacteria. In rhizosphere, near the roots, *B. subtilis* is capable to maintain stable contact with higher plants and positively influence their growth. *Bacillus subtilis* is also used as a biocontrol agent due to its ability to form endospores and produce different biologically active compounds. In 2004, Garcia et al. have noticed, after the inoculation with *Bacillus licheniformis* on tomato and pepper fields, a considerable colonisation in the rhizosphere. They concluded that this strain can be used as a biofertilizer without affecting normal management in greenhouses (Garcia et al., 2004). *Bacillus* is also found to have potential to increase the yield, growth, and nutrition of raspberry plant under organic growing conditions (Orhan et al., 2006).

Rhizobacteria also play a critical function in increasing soil structure and the growth and stabilization of mineral phosphates.

Arbuscular mycorrhizal fungi (AMF) are plant symbionts associated with the roots of 90% of the plant species, including most important crops, such as cereals, legumes, and members of Solanaceae (Zhu et al., 2010).

Arbuscular mycorrhizal fungi (AMF) are part of *phylum Mucoromycota* and *subphylum Glomeromycotina* (Khaliq et al., 2022). These soil fungi form a complex hyphal network which is productive in mineral and water absorption from a larger surface area. Moreover, the growth of arbuscules occur in cortical cells of roots that empower the fungi with bidirectional resource exchange with the plant (Choi et al., 2018). This type of association can be found at the roots area of about 90% of terrestrial plants, because fungi can supply plants with phosphorous (P) and other mineral nutrients, increase the ability to absorb water and ameliorate leaf photosynthesis (Porcel et al., 2015). This type of fungi leads to several benefits for the plant. Among these benefits are listed: facilitate plant nutrition in providing soil nutrients (phosphorus and nitrogen), protect plant roots against soil pathogen, increases crop yield and mitigate abiotic stresses (Buczkowska and Sałata, 2020; Séry et al., 2016; Floc'h et al., 2022). In rhizosphere, AMF are important in nutrient cycling and in structuring the microbial communities. In addition, the hyphal networks that AMF form in the rhizosphere ameliorate soil parameters such as soil particle aggregation, making the soil more resistant to erosion by wind and water. Finally, AMF decrease nutrient leaching from the soil, having an important contribution in the retention of nutrients in the soil and decreasing the risks of contamination of ground water (Chen et al., 2018). These multiple benefits of AMF make them essential into ecological services in natural circumstances. These fungi are the crucial players of the interactions that appear between soil rhizosphere-Plant-Bacteria-AMF. Furthermore, AMF are used in agriculture as bio-inoculants, and researchers motivate their use as bio-fertilizers in sustainable crop production (Barrow, 2012).

In rhizosphere can be found two major groups of mycorrhizal fungi based on their relational anatomy with host plant roots. The first ones are called septate fungi, which are *Basidiomycota* and *Ascomycota* and are part of the group ectomycorrhizas. Their internal hyphae never penetrate the cells; but they develop among rhizoderm cells and surround the root tips of host plants (Khaliq et al., 2022). The second group contain arbuscular mycorrhizas, ericoid, and orchid, which are considered endomycorrhizas. Their internal hyphae enter and develop in the cells of plant roots (Mbodj et al., 2018).

In various studies, there were highlighted the effect of AMF and PGPR in increasing plant development and protection against pathogens. The process of nitrogen (N) fixation in soil is conducted by *Rhizobia*. Various researchers pointed out that AMF and *Rhizobia* have the same signalling pathway, which stimulates their association with plants (Primieri et al., 2021). In addition, the studies have shown a positive correlation between colonization of plant roots with AMF and the soil microbial diversity (Ferreira et al., 2021).

ABUNDANCE OF MICROBIAL COMMUNITIES IN SOILS WITH DIFFERENT MANAGEMENT SYSTEMS

The agricultural management systems that farmers choose for tillage can influence the physical and chemical parameters of soil and the activity of the microbial communities. Modern agricultural mechanisms, such as the usage of chemical products for plant protection (fertilizers, insecticides, fungicides, and herbicides) allow the defense of crop plants for pathogens and provide better efficiency. These compounds present in conventional agriculture accumulate in soil and can negatively influence the environment and led to soil, atmosphere, and water pollution. On the other hand, organic agricultural management is more environmentally friendly compared to the conventional system. Organic system is characterised by a higher amount of soil organic matter, better soil quality and structure and better protection of the soils against erosion. Moreover, organic managed soils are characterized by a higher biodiversity of plants, animals (pollinators, soil fauna, birds) and soil microbial communities and a greater landscape diversity compared to conventional farms.

In 2008, Birkhofer et al., have noticed that the soils intensively managed frequently contain less fungi biomass. Furthermore, when plant residues are left on the soil surface without being plowed, the quantity of pathogenic fungi to plants may rise (*Fusarium* sp.). Meanwhile, a long-term economy without plowing results in a profound diversification of microbial communities and increases fungal biomass in the soil's top layer. In addition, the number of distinct groups of soil microorganisms is influenced by nitrogen fertilization of the soil. Excessive nitrogen doses used in conventional agriculture, may cause accumulation of toxic compounds, such as ammonia, which is not good for *Actinobacteria* (Natywa et al., 2010).

In response to changes in the composition of organic fertilizers, populations of microorganisms that breakdown cellulose and hemicellulose vary their composition. When organic manure was used as a fertilizer in rice fields, microbial activity increased, but it decreased when chemical fertilizers were used (Mahajan et al., 2016). Moreover, in fields where organic farming was practiced, the populations of *Actinomycetes*, free N-fixing bacteria, and *Azotobacter* spp. increased dramatically compared to conventional system.

In a field experiment involving conventional and organic managements with various tillage intensities (no-tillage, reduced-tillage, and intensive tillage), Hartmann et al. (2015) evaluated soil and winter wheat root-associated microbiomes. Their findings demonstrated that organic farming with intensive tillage for soil and root communities had the maximum diversity of bacteria and fungi. Moreover, the impact of more than 30 years of conventional, no-till, and organic management systems on the soil and soybean-associated microbiomes (roots, stems, and leaves) throughout the plant development stages has also recently been examined by Longley et al. (2020). They added that *Bradyrhizobium* and *Glomeromycotina*, which are known as beneficial organisms for plants, were more prevalent in the roots due to no-till management. Schmidt et al. (2019) demonstrated that there was greater bacterial and fungal diversity in the rhizospheres of organically managed plants compared to conventionally managed plants after using six paired tomato farms in northern California with conventional and organic approaches. Moreover, organic managed farms found to have a higher relative abundance of certain microorganisms that promote plant growth, such as *Pseudomonas*. In a recent thorough study, Ricono et al. (2022) examined the long-term impact of organic and conventional farming on the bacterial and fungal communities linked to the winter wheat roots throughout 40 agricultural areas. According to their findings, compared to conventional farming, the organic one increased the variety of the root microbiomes and increased the abundance of symbiotic fungi (such as *Glomeromycota*) and bacteria that prevent disease, such as *Pseudomonadaceae*, *Burkholderiaceae*, and *Xanthomonadales*, *Gammaproteobacteria*.

Another management practice used in organic agriculture in order to increase the soil organic matter and microbial biomass are the cover crops. Organic fertilizers that replace mineral fertilizers that are known to improve soil organic matter content are typically used in organic agriculture to add significant amounts of C to the soil (Martínez-García et al., 2018). The study conducted by Gattinger et al., in 2012 has demonstrated that (cover) crop residue decomposability variables, such as leaf C: N, greatly influence the rise of soil organic crops stocks in organic versus conventional agriculture. Other studies have shown that the major elements that enhance soil water holding capacity, soil microbial abundance and structure, and weed suppression are cover crop production and its residues management strategies. In a recent study, organic farming has a higher soil organic matter content than conventional farming (Cagnini et al., 2019). The addition of cover crops increased the amount of soil organic carbon and enhanced the organization of the microbial community, soil organic matter, and microbial biomass carbon (Finney et al., 2017). In essence, these alterations are based on the cover crops chemistry and the biotic interactions between plants and soil. Due to rhizobia boosting soil mineralization and the N pool, leguminous cover crops are able to fix an increased amount of atmospheric N (Muhammad et al., 2022).

CONCLUSIONS

For the development and growth of plants, the fertility and health of the soil are crucial. Microbial communities help plants develop more by delivering vital nutrients and minerals that they are unable to use on their own. They breakdown the organic residues so that it can be easily absorbed by plants. In this regard, soil microbes are the primary factor responsible for numerous soil processes influencing the change of nutrients and subsequently affecting the availability of these nutrients to plant roots. The potential of microorganisms to solubilize and mineralize nutrients from inorganic and organic pools is now well understood, and their use could create a new horizon for more profitable and beneficial crop production. One of the major challenges in the current situation is to boost soil productivity by introducing advantageous microorganisms and enzymes without altering the organic structure of the soil. This is because various anthropogenic activities that contribute to environmental concerns have risen.

The presented review indicates that soil is a complex ecosystem, and that cultivation practices have an effect on a variety of soil characteristics (biological, chemical, and physical), as well as the species that live there. Plant growth and consequently yields may be impacted by changes in the populations of soil organisms.

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