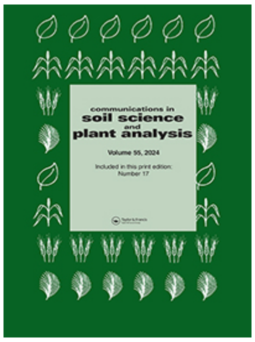


Communications in Soil Science and Plant Analysis

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/lcss20

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**To cite this article:** Elizabeth Temitope Alori, Osarenkhoe Omorefosa Osemwegie, Ayibanoa Lekoo Ibaba, Fisayo Yemisi Daramola, Faridat Temilomo Olaniyan, Francis Bayo Lewu & Olubukola Oluranti Babalola (2024) The Importance of Soil Microorganisms in Regulating Soil Health, Communications in Soil Science and Plant Analysis, 55:17, 2636-2650, DOI: 10.1080/00103624.2024.2367246

**To link to this article:** https://doi.org/10.1080/00103624.2024.2367246

Published online: 18 Jun 2024.

COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
2024, VOL. 55, NO. 17, 2636–2650
https://doi.org/10.1080/00103624.2024.2367246

# The Importance of Soil Microorganisms in Regulating Soil Health

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**ABSTRACT**

Soil is an important reservoir of innumerable natural and biological resources fundamental to the sustainability of life and the earth's functionality. The soil is complex due to changing biodiversity, physicochemical characteristics, disturbances, and pedogenesis, which are constituent indices required for the measurement of its healthiness. Hence, there is a need to concertedly protect the soil by consciously promoting practices and behaviors that optimize its priority functions in delivering ecosystem services. It is further significant for crop yield, hence the need to pay more attention to its health. Soil healthiness is also a reflection of its capacity to support biogeochemical processes, abiotic communities, and plant and animal productions. However, agronomic studies, until recently, focused more on the use of chemical indicators in determining soil health, despite the versatile ecophysiological role of microorganisms in soil formation, resource cycling, and management. These biological phenomena expressed by soil microbial communities form the basis for the conversion of diverse organic matters into bioutilizable resources for plants' healthy development. This review, therefore, explored the underlining mechanisms, particularly climate change-related, that caused divergent soil properties and how this impacted the microbial composition of healthy soil. Likewise, several pieces of agronomic literature on the physical characteristics, ecological services, and functions of a healthy soil were compared toward innovative best management practices for improving soil health.

**ARTICLE HISTORY**
Received 11 July 2022
Accepted 30 May 2024

**KEYWORDS**
Agronomy; agriculture; climate change; soil health; soil microorganisms

## Introduction

The soil is one of the most important and sensitive natural resources on earth (Alori and Babalola 2018). It plays a significant role in the growth of healthy crops, improves yield, filtration of water, nutrition for animal and human beings, and acts as a carbon sink, helping to regulate climate, hence the need for agricultural researchers and farmers to pay crucial attention to its health status. 'Quality' and 'health' are two terms used interchangeably when referring to the ability of a soil to maintain a balanced ecosystem and provide nutrients for plants. Soil quality was defined as the ability of a soil to perform its functions, which include sustaining biological productivity, promoting plant and animal health, and maintaining environmental quality within an ecosystem and land-use boundaries (Bertola, Ferrarini, and Visioli 2021). Soil quality refers to the biological, chemical, physical, and biological characteristics of soil that are paramount to long-term, sustainable agricultural productivity with

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minimal environmental impact. Healthy soil is an ecosystem with many interconnected parts, with each part functioning to sustain plant, animal, and human lives (Brevik et al. 2020). A healthy soil maintains a balance between the health of living organisms residing in or on it, environmental quality, and productivity (Khatoon et al. 2020). Healthy soil is imperative for environmentally sound, productive, and profitable systems of agriculture (Adedayo, Fadiji, and Babalola 2022b).

Microorganisms, in their diversity, have always been an integral component of the soil complex, with fundamental implications for soil ecological functions and services. The soil afforded the eco-physiological ambiance for soil microorganisms to interact inter-specifically and intra-specifically with other organisms below and above the soil. Bacteria, fungi, algae, actinomycetes, nematodes, and viruses have been reported in different soil types and pedogenesis with differential composition due to changes in biogeochemical cycling as well as plant productivity (Xiong et al. 2021). This suggests that there are spatial, temporal, demographic, ecological, and compositional variations among soil microbial communities that may constrain the use of microbial data for evaluating soil health. Although soil microbial communities still underlie the characteristic processes of disease and weed suppression, soil aggregate formation, moisture retention, and erosion control, their use in determining soil health has been strengthened by the emergence of artificial intelligence for automation and DNA sequencing technology. Consequently, microorganisms in the soil may be sensitive indicators of soil fertility, environmental change, dysbiosis, and pollution, which qualify them as one of the valuable sets of metrics used to monitor over time and assess the impacts of land-use management on soil quality (Wilhelm, Van, and Buckley 2022). Hence, the activities of the soil microbiome, even though influenced by climate factors, soil physical characteristics, soil type, and land use trends, are vital for a sustainable measure of soil health (Figure 1).

Shen et al. (2022) noted that soil microbial communities interact in various ways through competition, predation, symbiosis (mutualism and protocooperation), parasitism, and amensalism, which underlie their structural and functional succession status. This is vital in the temporal structure of pathogenic, beneficial, degraders (saprophytes), prey, and endophyte succession. It suffices to say that the collective variations in soil microbial interactions are equally key to their temporal and spatial functions. The quality of soil microbiome interaction has a fundamental influence on the dynamics of soil abiotic resources and the capacity of terrestrial plants to mobilize as well as manage the resources, particularly in the rhizosphere, for optimal development (Xiong et al. 2021). Even though most literature is biased toward the reporting of specific factors (climate, pollutants, agrosystem practices, organic inputs, and irrigation) that have an effect on either microbial activity, diversity, composition, or dysbiosis of the soil, the complexity and mechanisms of the soil-microbe-plant relationships and the genetic element dynamics are still not fully understood (Xie et al. 2022). Similarly, the density and spatial variations in soil organic content (fauna, litter, root traits, minerals, and soil aggregates) also have implications for the metrics for the assessment of soil health and microbial dynamics. This was corroborated by Bhattacharyya et al. (2022) in a study that acknowledges the reversible interplay between soil microbial communities and soil organic matter dynamics in the maintenance of sustainable soil health.

It is unclear how different ecological elements interplay, transduce, and stimulate the process of attaining quality soil status. More investigation is therefore required to understand microbial resource allocation to enzymes, resource effects on microbial functional changes with a strong signature for transformation processes, and microbial response dynamics on net biogeochemical cycling.

## Relevance soil microorganisms to soil health

Soil organisms are responsible for many important functions in the soil which in turn improve soil health these include improving soil structure and soil water holding capacity. Soil microorganisms play a critical role in improving soil structure, both by breaking compacted soil and by stabilizing soil aggregates (Vadakattu and Germida 2014). Soil compaction which could be caused by the use of heavy machines and overgrazing reduces the pore space

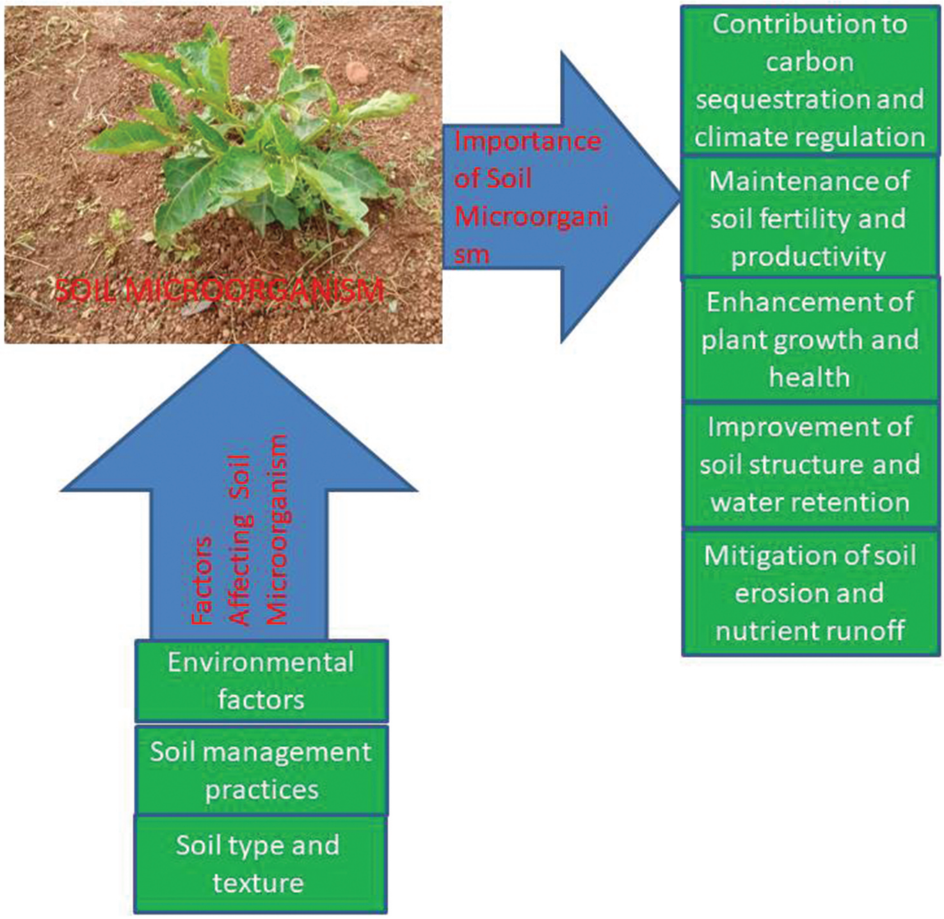


**Figure 1.** Importance of soil microorganisms and factors that affect their activities.

between soil particles, increasing bulk density and reduces soil porosity and soil hydraulic properties thereby impeding the movement of water, air, and roots through the soil. This might result in reduced soil fertility and productivity and deteriorate environmental quality (Shaheb et al. 2021). However, soil microorganisms like fungi can help to break up compacted soil by using their extra cellular hypha. Thus increasing soil porosity and improve soil aeration, which in turn reduce risks such as waterlogging and soil erosion. Soil Fungi also through their extracellular hypha and secretion of polysaccharides entwining loose soil particles there improving the soil structure and hence soil health(Wei et al. 2024).

All soil organisms help decompose nutrient rich organic material (decaying plants, animals, and animal waste), which increases soil organic matter that helps to bind soil particles together thus improving soil health (Sela 2024). Plant exudates and microbial byproducts – both considered active organic matter can be sticky substances that help hold soil particles together to form better aggregate (Gasch and DeJong-Hughes 2024).

Another way in which soil microorganisms improve soil health is by controlling pests in the soil, such as insects, nematodes, and soil-borne disease causing organisms by predation. For example, predatory nematodes and mites feed on other nematodes and soil-dwelling insects, helping to reduce their populations in the soil (Sela 2024). In addition some bacteria and fungi can compete with soil-borne pathogens for nutrients and space, limiting their growth and ability to cause disease (Lahlali et al. 2022).

Soil Microorganisms are integral component of the formation and functioning of healthy soils (Bender and van der Heijden 2021). They degrade chemical compounds in the soil and prevent these chemicals from being absorbed the crops (Alori and Fawole 2017).

## Microbial composition and properties of a healthy soil

Soil health has been described as the capacity of a soil to sustain plant productivity, maintain water and air quality, provide habitat support for biodiversity, and sustain human well-being. It affords the capacity required by the soil to optimally function within the biosphere and be tractable (Adedayo, Fadiji, and Babalola 2022a). Healthy soils are the basis for profitable, productive, and environmentally sound agricultural systems, which could be evaluated through good soil structure, resistance to compaction, high water infiltration and retention, good soil chemical properties, high organic matter content, high soil biological activity, plant nutrient recycling and availability, and low weed and disease pressures (Melakeberhan et al. 2021; Wieme et al. 2020). Healthy soil is therefore a hotspot that hosts a huge diversity of the microbial population that plays key roles in driving essential life support functions (LSF) and the sustainability of the ecosystem.

Soil microbes play a crucial role in soil formation, soil fertility, and degradation of inorganic and organic matter, nutrient cycling, and plant productivity (Krasilnikov, Taboada, and Amanullah 2022; Odelade and Babalola 2019). They carry out 80–90% of all the biogeochemical processes in the soil (Gobler et al. 2021). The main microbial groups that form an important part of the agriculture and are responsible for the soil ecosystem are bacteria, fungi, actinomycetes, protozoa, and algae (Javed et al. 2021). These diverse communities of microorganisms have implications for plant diseases, insect and weed pests' phenology, and the recruitment dynamics of beneficial symbiotic associations, particularly with plant roots (e.g. nitrogen-fixing bacteria and mycorrhizal fungi). The influence of the edaphic properties and variation of its parameters on the biogeochemical cycles, plant nutrition, soil structure, particle characteristics, and water and nutrient holding capacities cannot be overestimated (Skorobogatov et al. 2020). The soil microbial biomass is the living part of the soil organic matter, comprising fungi, bacteria, archaea, protozoa, and algae, which provide crucial ecosystem functions and services (Ayangbenro and Babalola 2018). These microbes associate with living plants and dead organic matter to maintain and regenerate healthy soil functions (Alori et al. 2020). In a healthy soil, microorganisms contribute to elements and nutrients cycling (nitrogen, carbon, phosphorus, etc.), waste and detoxification cycling, decomposition of soil organic matter, soil aggregate stability, degradation of agricultural pollutants, disease suppression, and soil fertility improvement, as well as plant health (Karlen et al. 2019; Tantawy et al. 2022). Healthy agricultural soil communities typically include a wide range of predators, parasites, and pathogens that contribute to the suppression of agricultural pests (Alori, Dare, and Babalola 2017). The richness, abundance, and composition of soil microbial communities are indicators of their quality (Alori, Adekiya, and Adegbite 2020; Hu et al. 2020). However, only a small fraction (0.05%) of the total soil volume consists of these biological components, and their activity in soil is largely concentrated in the topsoil and varies from a few to 30 cm in depth (Naylor (Naylor, Mcclure, and Jansson 2022). This small volume notwithstanding, microorganisms are involved in a variety of soil activities that collectively enhance soil health and reorient its physical or chemical markers. Microbial biomass and activities are also one of the most sensitive indicators for assessing the health of a soil, due to their rapid reactivity or alteration in the event of significant environmental change (Zaghloul et al. 2020).

The microbial composition of the soil has been extensively used as a biological indicator of soil health (Pérez-Guzmán et al. 2021). They provide early warning signs that are pointers to soil degradation or environmental stress. Because of their high surface-to-volume ratio, soil microbes are very sensitive and have close relations to their environment. They are usually the front-line recipients of the impact of climatic changes, environmental stress, and disturbances in the ecosystem (Garcia et al. 2020). Soil microorganisms are abundant and exist in large numbers in the soil. They include diverse communities of bacteria, actinomycetes, fungi, protozoa, and nematodes. There are indications that there may be more microbes in a teaspoon of soil than there are people on the earth. A healthy soil is therefore one that is rich in microbial composition and structured in such a way that there is balance and stability in the ecosystem as organisms in each trophic level perform their different roles within the food chain.

Microbial diversity and community structures are useful bio-indicators of soil and environmental health. Changes in the soil ecosystem due to extensive tillage operations and agricultural practices, including poor soil management and land use regulations, have adversely contributed to the loss of diversity and altered microbial community in most agricultural soils (Trivedi et al. 2016), thereby rendering the soil environment unhealthy for the LSF and other critical ecological roles.

Soil microbes perform various functions in the ecosystem, ranging from beneficial roles such as nutrient recycling, decomposition of organic matter, and existing in mutualistic or symbiotic relationships with plants to detrimental and harmful roles where they exist as pathogenic microbes inducing and acting as vectors of plant diseases, thereby causing poor plant growth and heavy crop losses (Jacoby et al. 2017). Bacterial communities are a major class of the soil microbial population. They are key drivers of ecosystem functions such as decomposition, nutrient cycling, and climate regulation (Jiao et al. 2019), and changes in their abundance, richness, or composition are usually considered early indicators of a change in the quality of the soil ecosystem (Delgado-Baquerizo et al. 2017). Bacteria also support important ecosystem services by improving soil structure, aggregation of nutrients, and water recycling, thereby keeping the soils healthy and productive (Enagbonma and Babalola 2019). Four major functional groups of soil bacteria – decomposers, mutualists, pathogens, and lithotrophs – were identified (Ingham, Moldenke, and Edwards 2000). Actinomycetes are single-cell organisms that are usually grouped with bacteria, but they also display some of the characteristics of fungi. They play the role of decomposers, degrading resistant organic substances in the soil such as cellulose, polysaccharides, protein fats, and organic acids. They also function in promoting soil health by enhancing soil structure, improving water retention, and breaking down humic acids in the soil into more stable forms. Fungi are also an important group of soil microorganisms that function as decomposers of lignin and organic matter. Their roles include the breakdown of hard-to-decompose organic residues that are high in cellulose, hemicellulose, lignin, or cell walls into useful forms for other microbes. They can exist in the soil as saprophytic fungi, mutualistic mycorrhizal fungi having symbiotic relationships with plants, or in their pathogenic forms, often causing root diseases of plants in many agricultural soils (Giovannini et al. 2020). Protozoa, on the other hand, are unicellular animals and are abundant near the soil surface. Their primary role in the soil is to mineralize nutrients, making them available for use by plants and other soil organisms. They include the naked and testate amoeba, ciliates, and flagellates. Protozoa are very abundant in the soil and exist in very diverse and harsh environments. They are also able to withstand tillage and soil disturbances more than other soil microorganisms. They form an essential part of all soil ecosystems and have been proposed as an early warning indicator because they react quickly to environmental changes (Muscolo, Settineri, and Attinà 2015). Their feeding activities on bacteria, organic matter, and other organisms also help to maintain microbial equilibrium in the soil. Some of the beneficial microbes that are indicators of healthy soil include *Bacillus, Agromyces, Micromonospora, Pseudonocardia, Acremonium, Lysobacter, Mesorhizobium, Microvirga, Bradyrhizobium, Acremonium, and Chaetomium*. The microbial biomass carbon, soil respiration, potential nitrogen (N) mineralization capacity, ATP content, soil fatty acid profiles, DNA characterization, and soil enzyme activities are parameters that are valuable in measuring soil health (Nikitin et al. 2022). The microbial communities contribute to sustainable soil nutrient replenishment in most agricultural soils (Brevik et al. 2020). Organic matter breakdown and nutrient cycling in soil are mediated by extracellular enzymes produced by soil microbes and plant (Brevik et al. 2020; Coonan et al. 2020).

Bacteria aid in the decomposition of organic matter in the soil and constitute a part of several nutrient cycling processes. Some bacteria like *Azotobacter vinelandii, Bacillus megaterium, Chlamydomonas sajao*, and *Rhizobium* sp have been reported to produce various extracellular compounds like polysaccharides and amino acids, which help in binding soil particles to form aggregates, thus improving soil structure (Mengual et al. 2014; Ortíz et al. 2015). More so, certain bacteria in the rhizosphere produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase that transforms the ACC precursor of ethylene to metabolizable ammonia and α-ketobutyrate (Adeleke and Babalola 2021; Chukwuneme, Ayangbenro, and Babalola 2021). The action enables plant-associated bacteria to support plant growth under biotic and abiotic stress by decreasing the levels of stress ethylene (Adedayo (Adedayo et al. 2022). Actinomycetes are important in forming stable humus, which enhances soil structure, improves nutrient storage, and increases water retention. Fungi can either be single or multicellular organisms, and they are also responsible for some decomposition and nutrient cycling processes in soil. Arbuscular Mycorrhizal and other fungi form hyphae and mycelium, filaments with a large surface area that spread throughout the soil to entangle and bind soil particles together (Begum et al. 2019). Algae are instrumental in liberating large quantities of oxygen via photosynthesis, binding soil together by acting as cementing agents, and increasing soil organic carbon upon their death and decomposition.

Soil micro-organisms are also fundamental to establishing soil health. Macro-organisms in the soil are responsible for soil mixing and the formation of micropores, and due to their sensitivity, they are also important indicators of soil disturbances, microbial community composition, microbial respiration and biomass, and agro-economics (Brevik et al. 2020). Many ecological processes, such as pedogenesis, sustainable soil nutrient heterogeneity, soil respiration, microbial activity, water infiltration, and storage, are influenced by some soil microorganisms (Aponte et al. 2021). Soil organisms such as earthworms, ants, mites, termites, etc. importantly contribute to carbon and nutrient cycling, improving soil structure, facilitating soil mineralization, increasing nutrient availability, bioaccumulating oil and heavy metal contaminants. Hence, both their abundance and diversity are used as bioindicators of soil health (Ramadass et al. 2015).

Another group of soil microorganisms is soil nematodes, which are invertebrate roundworms that exist in the soil environment either as plant parasitic, enthomopathogenic, or free-living nematodes. Most nematodes are microscopic in size and not visible to the naked eye, but they have a significant impact on agricultural soils. Plant parasitic nematodes have been implicated in causing plant diseases that lead to huge economic losses and reductions in crop yields (Coyne et al. 2018; Daramola, Lewu, and Malan 2021). Entomopathogenic nematodes function as biological control agents of insect pests, while free-living nematodes perform key roles in ecological balance and serve as useful indicators of soil health. Nematodes are ubiquitous in distribution, occupy a wide range of habitats, and can help to measure changes in the function and status of the soil because of their ability to reflect changes in terrestrial habitats due to their rapid response to environmental and anthropogenic disturbances (Du Preez et al. 2022; Zhang et al. 2020). Nematode functions are based on their feeding groups, which have been placed into five main categories to include herbivores or plant feeders, bacterivores, fungivores, predators, and omnivores (Laasli et al. 2022). Just like protozoans, the beneficial roles of nematodes include nutrient recycling and maintaining a balance of the soil food web, and they can also serve as biological agents for pest and disease control.

The microbial composition of the soil in terms of the diversity, richness, and abundance of bacterial communities, fungi, protozoa, and nematode assemblages can thus be a major factor that determines the ability of plants to obtain important soil nutrients such as nitrogen, phosphorus, and micronutrients and, by implication, the soil health, quality, the suitability of such soil for agricultural and related life support functions. They also determine nutrient and carbon cycling on a global scale and can affect the soil's physical properties, such as soil aggregate, water holding capacity, and susceptibility to compaction (Amoo et al. 2021). The microbial community structure is also key in determining the health status of the soil. For instance, the ratio of fungi to bacteria can help to evaluate soil health and fertility because the soil microbial community with a higher ratio of fungi to bacteria (F:B) promotes the mineralization of soil endogenous carbon substrate and tends to be more persistent and stable (Naylor, Mcclure, and Jansson 2022). Also, the proportion of bacterial-feeding and fungal-feeding nematodes in the soil, which is determined by the F:B ratio, indicates the level of disturbance in the soil.

The microbial properties of the soil include microbial community characteristics that reflect the biological activities expressed or taking place within the soil ecosystem. Such microbial processes and parameters are useful indicators for monitoring soil quality and soil health. Soil microbial activities are complex and controlled by an interplay of different factors such as nitrogen content, oxygen level, soil pH, temperature, and moisture (Alori, Adekiya, and Adegbite 2020). An optimum level of biological activity is essentially dependent on the combination of these factors within an ideal range that is suitable to sustain ecosystem functions. Soil respiration, microbial biomass of C and N, acid phosphatase, asparaginase, and density of ammonifying and ammonium-oxidizing microorganisms are also some of the frequently measured microbial and biochemical indicators of soil health (Sahu et al. 2019).

To determine the microbial properties of the soil, several parameters and techniques have been extensively used for soil microbial analysis (Naylor, Mcclure, and Jansson 2022). The techniques for analyzing the microbial properties ranged from the traditional parameters such as microbial biomass and global or potential microbial activity patterns or assays that indicate potential enzymatic activities (Schloter et al. 2018) to the more advanced molecular-based methods, which include DNA-based techniques and the development of some'state-of-the-art' molecular markers, such as the more recent methods that determine the abundance of the targeted gene sequence of microbes with qPCR using soil microbiome DNA. Schloter et al. (2018) gave a comprehensive review of several parameters that have been useful as bioindicators of soil microbial activities and proposed the need to implement new trait-based indicators that monitor the life-support functions of the soil ecosystem. Some of the microbial bioindicators frequently used include microbial biomass (direct microscopy, dilution plating, chloroform fumigation/extraction, SIR-substrate-induced respiration), FISH (fluorescence in situ hybridization), PCR/qPCR, microbiome fingerprinting (DGGE/TGGE), microbial enzyme activities, microbial activity patterns, phospholipid fatty acid analysis (PLFA), phylochip/geochip microarrays, and high-throughput sequencing (Schloter et al. 2018). More recently, the study of soil microbiome has been accelerated with the advent of metagenomics (Vieira, Moura, and Silva 2021), which has proved useful in the determination of the microbial community found in an environment and enabled the study of the microbial diversity and function. This has opened a new frontier and ever-expanding opportunities to explore microbial communities in soil samples.

## Physical characteristics of a healthy soil

Physical indicators of soil health include moisture content, porosity, bulk density, aggregate stability, texture, and temperature. According to De Mendonça et al. (2022), soil that shows low rates of water infiltration, enhanced surface runoff, poor cohesion, low aeration, and root density, and proves difficult for mechanization can generally be physically poor soil. The soil physical attributes affecting water availability and aeration will also affect the soil microbial activity since the inverse correlation between water availability and microbial activity has been described before (Chang et al. 2021).

Soil texture is an important factor that may determine the properties of other soil physical factors, even though it remains relatively unchanged over time, irrespective of management practices. It plays an essential role in water movement and retention in soil, which is dependent on pore space. Soils with coarse textures will have higher permeability and provide more rooting space for plants to take up nutrients and water compared to clay soil, but they will have poor water holding capacity and a high temperature because of the large pore spaces. Fine textured soils will have lower permeability due to fewer pore spaces. Soil biodiversity is also a function of soil texture. Suboptimal conditions such as low moisture content in coarse-textured soils will lead to a reduction in the population of macro- and microfauna (Fiorentino et al. 2018; Tibbett, Fraser, and Duddigan 2020). The texture could also affect organic matter content in the soil since coarse-textured soils have a reduced capacity for stabilizing soil carbon.

Bulk density and total porosity are good indexes for soil health assessment as they can easily be altered by soil use and management (He et al. 2021). Decreased soil porosity promotes anaerobic microsites, which may lead to changes in soil microbial communities that affect soil nutrient cycling (Bhattacharyya et al. 2022; He et al. 2021). A high bulk density is an indicator that the soil is low in porosity and therefore compacted. Compaction lowers the aggregate stability index of the soil and inhibits air and water circulation. Root growth is also inhibited, resulting in low crop performance. Reduced plant cover makes the soil more vulnerable to erosion (Elemike et al. 2019; Shah et al. 2017). Compaction can also lead to increased runoff and erosion due to the impedance of water infiltration. A soil that will allow the optimal flow of air, water, and uptake of nutrients by plants should have a bulk density of $1.10\,g/cm^3 - 1.60\,g/cm^3$, depending on the soil texture and position in the profile (Liang et al. 2021). Soils undisturbed by anthropogenic activities, such as native forest soils, typically show lower bulk densities (Semy et al. 2022).

## Ecological services and functions of a healthy soil

Healthy, well-functioning soils provide several benefits to humans and the environment as a result of complex interactions between physical, chemical, and biological processes in the soil (Vogel et al. 2018). Various soil functions are achieved through the interaction of several mechanisms, and any one of the mechanisms may contribute to several soil functions (He et al. 2019). Soil contributes to the provision of food, wood, fiber, fodder, and other organic materials by providing anchorage for plants. Soil also plays a crucial role in the provision of shade and shelter by nourishing and maintaining vegetation. Healthy soils with porosity and aeration are conducive and provide rooting space for plants to absorb water and nutrients, whereas compacted soils will cause inhibition of root growth and lead to poor crop yields.

Soils store and provide essential nutrients to plants in needed quantities and ionic forms; they also store mobile nutrients within the root zone to avoid losses by leaching and gaseous emissions. Pore spaces in the soil absorb water from precipitation and store it for plant use, creating a pool of available water for plants to take up in intervals between precipitation. Infiltration of water into the soil also contributes to flooding mitigation and prevents surface run-off. Soils filter, adsorb, and transform potentially harmful elements and compounds, such as heavy metals and pesticides, by various, chemical and biological means (Daniel et al. 2022).

Soil contributes to biodiversity by serving as a habitat for a diverse array of macro- and micro-organisms that perform several functions; visible soil roots and animals such as earthworms and ants improve soil structure and moisture through flora and faunal turbation, and insect pollinators that pupate, nest, or raise larvae underground are equally present in the soil. The soil is a host to microorganisms that fix nitrogen and decompose organic matter into simpler mineral forms that are utilized by plants, animals, and microorganisms to create new living tissues and create humus, an amorphous substance that binds soil particles together and improves soil structure (Nielsen, Wall, and Six 2015).

The soil maintains the balance of the global carbon cycle by absorbing atmospheric carbon and storing it in the soil carbon pool and soil organic carbon. This process, known as carbon sequestration, is primarily mediated by plants through photosynthesis. Active organic carbon remains in organic matter for decades or even centuries. Insect pests in the soil may be regulated by sophisticated biological processes in the soil. Depending on soil fertility and plant nutrition, airborne pests may be promoted or discouraged (Gougoulias, Clark, and Shaw 2014).

## Factors affecting soil health

Agricultural intensification could result in the breakdown of soil structure, an increase in bulk density, the depletion of soil organic matter and essential nutrients, and a change in soil pH, all of which affect the abundance, species richness, and diversity of soil biota((Topa, Cara, and Jităreanu 2021). In the long run, the current conventional system of agriculture to meet the fiber, food, and fuel demand of the ever-increasing population, detrimentally affects the soil's potential and capacity to perform its functions. This most of the time, results in soil and ecosystem degradation and loss of productivity (Baude, Meyer, and Schindewolf 2019). Overharvesting without returning organic residues and mineral nutrients to the soil will also cause a depletion in soil fertility and productivity. Nutrient depletion can also be caused by erosion. Indiscriminate deforestation and bush burning will also adversely affect microbial communities and cause the release of greenhouse gases into the atmosphere.

Improper irrigation, particularly in arid regions, may lead to the salinization of the soil, affecting its chemical properties and biodiversity. Salinization is the accumulation of soluble salts of sodium, magnesium, and calcium in soil to the extent that soil fertility is adversely affected. Increased salinity caused by high salt concentration irrigation water resulted in increased bulk density and reduced porosity, which was attributed to the collapse of small, aggregates, and deposits in the spaces within the groupings, which led to the formation of semi-compressed layers (Hassan, Al-Bustany, and Mohammed 2018). It also increases the penetration resistance of the soil to tillage because of the effect of salty water, which separates and deposits the soil particles in the spaces, making up adhesive material (Ossai et al. 2020). This process will lead to gathering the salts at the surface layer to make a solid shell, increasing penetration resistance.

The use of heavy machinery, as well as a strong concentration of livestock on a piece of land, can lead to compaction of the soil, which will cause an increase in bulk density and a reduction in porosity, infiltration, and nutrient uptake. This consequently causes deterioration of soil structure, water storage capacity, and biological activity. It also makes the soil difficult to cultivate and causes water-logging due to the slow rate of infiltration.

Exposure of soil to toxic substances because of industrial processes or chemical spills can severely damage the ability of soil to perform its ecosystem functions. Varjani and Upasani (2019) reported that in the event of crude oil spills in soil, nitrogen and phosphorus are made less available due to an increased carbon content of the soil, which results in a larger C/N ratio. Soil physicochemical properties such as temperature, structure, nutrient status, and pH are also affected (Ayangbenro and Babalola 2021). It also causes a reduction in size and number of pores due to blockage of pore spaces, which results in increased bulk density and impairs soil aeration and water infiltration (Talukder et al. 2022). This results in the breakdown of the soil structure and, consequently, disaggregation. The availability of mineral elements to plants is also limited, as crude oil forms a hydrophobic layer over the plant root, thus negatively affecting the absorption of water and nutrients.

Indiscriminate application of agrochemicals such as pesticides and herbicides affects biodiversity in the soil.

## Management practices to improve soil health

Soil health management systems are one way to try to offset the effects of these projected climate changes on crops and cropland and to improve short-term drought tolerance and, potentially, groundwater recharge. These systems can increase infiltration, reduce evaporation, moderate soil temperature changes, increase rooting depth, increase nutrient uptake, and improve the water-holding capacity of most soils. These improvements lead to better crop resilience during droughts. In some circumstances, they also provide for groundwater recharge. Additionally, increased infiltration rates decrease runoff, thereby reducing sediment and nutrient loading to streams as well as flood volumes.

## Conservation tillage

Implementing a conservation tillage system that could either involve no-till or minimal tillage minimizes soil disturbance and can, over time, improve biological diversity, soil structure, porosity, and infiltration, thereby improving soil health (Hassan et al. 2022). Minimal tillage prevents the disintegration of soil and makes soil less susceptible to being washed away by precipitation or blown away by the wind. Mineralization is also slower under conservation tillage practices because exposure to organic matter because of the breaking up of soil particles is minimized (Jahangir et al. 2021). In the absence of excessive tillage, which leads to the death of various soil macro- and microorganisms, biological diversity in the soil also flourishes. Choudhary et al. (2018) reported an increase in bacterial diversity in zero tillage systems as compared to conventional tillage. Similary, Ma et al. (2022) noted an increase in earthworm abundance and other faunal activities under a conservation tillage system. A comparative increase in mycorrhizal activities was also noted in the study.

## Cover cropping

Cultivation of cover crops contributes numerous benefits to soil health (Scavo et al. 2022). Roots of cover crops create macropores in soil, which alleviate compaction and improve porosity and infiltration. Cover cropping also helps to keep the soil covered and prevent erosion. Fibrous-rooted cover crops can improve soil aggregation. Cover crop species that host mycorrhizal fungi can help to maintain their abundance in the soil (Arruda et al. 2021). Leguminous cover crops can also improve soil nitrogen via nitrogen fixation. Cover crops can help to retain nitrate and other nutrients that would otherwise be lost through leaching. The biomass produced by cover crops can be used as mulch, which contributes to soil organic matter content. Mulch lowers the temperature of the soils to a certain extent and slows decomposition processes, causing the accumulation of SOM (Meyer et al. 2021). It also helps in promoting more stable aggregates and biotic diversity as a result of increased microbial activity and better protection of the soil surface (Sarker et al. 2022). Therefore, it provides a niche for different soil biota, including earthworms, which burrow the soil and improve its aeration.

## Crop rotation

Consistent and diverse crop rotation can reduce the incidence of pests and diseases that are specific to a particular crop by breaking up soil borne pest and disease life cycles. It also helps in nutrient use efficiency and recycling in the soil, as different crops have different nutrient requirements and some crops, like legumes, add nutrients to the soil. Soil workability is also improved, while erosion and sedimentation, as well as soil crusting, are reduced (Morvan et al. 2018).

## Use of multiple organic manure sources

Incorporation of crop residues and manures into soil increases the soil's organic carbon concentration, which means a relative increase in organic matter content as well (Ozlu et al. 2019). It also improves biodiversity in soil, as carbon and other nutrients added to the soil because of the incorporation of residues serve as substrates for microorganisms. Several studies have noted an increase in microbial abundance in the soil after the addition of various types of organic matter (Li et al. 2019). Improved soil organic matter content also means improved soil texture and water holding capacity. The addition of manure also contributes to the maintenance of the soil pH at a level that is conducive to crop growth.

### *Challenges of the use of soil microorganisms in regulating soil health*

The complexity of soil microbial communities and their dynamic responses to both biotic and abiotic factors present significant hurdles in fully grasping their interactions and behaviors. These barriers stem from the vast species diversity within microbial populations and their adaptable functions within intricate soil environments (Ge et al. 2023). Furthermore, the lack of standardized protocols for microbial analysis and interpretation of results poses a serious challenge to the understanding of the metabolic, physiological, and ecological roles of soil microorganisms and hence their manipulation for use in regulating soil health (Bharti and Grimm 2021).

### Future directions/recommendation

The exploration of inventive strategies for managing soil health and promoting sustainable agricultural practices requires advanced studies in molecular techniques for high-throughput microbial analysis. Integration of soil microbiome data into precision agriculture practices and the development of microbial-based biostimulants and biofertilizers for sustainable soil management are recommended.

## Summary

Anthropogenic threats to the soil, such as intensive agriculture and climatic changes, to a large extent determine the microbial composition present in the soil, their community structure, and the biological activities that take place, which in turn affect the physical and chemical properties of the soil and, in the long run, the quality and health status of the soil and its ability to support agriculture and other important ecological processes.

## Acknowledgements

OOB acknowledges the National Research Foundation, South Africa grants (UID123634 and UID132595) that support research in our laboratory.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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