Role of Targeted Breeding to Improve Wheat Production on the Marginal Lands of Africa

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Exploring Biotechnological Strategies in the Monitoring of Soil Quality

Linda U. Obi, Frances N. Olisaka, Christabel Ene, and Uchenna Aniakor

1 Introduction

Soil quality refers to soils' ability to promote biological productivity, preserve environmental quality, and advance fauna and flora health within the constraint of an ecosystem. The quality of soil is not limited to its agroecosystem productivity in terms of supporting plant growth; it also encompasses the natural ecosystem of sustaining biodiversity and environmental quality such as water purification, carbon sequestration, etc. (Bünemann et al. 2018). The chemical, physical and biological features of soil account for its general quality. Environmental disturbances such as drought, salinity, pollution, climate changes as well as human activities which include agriculture adversely impact soil quality which subsequently results to land degradation, loss of soil fertility, and biodiversity. Low/poor soil quality can be attributed to different physical, chemical, and biological degradation due to climate change, pollution, erosion, drought, salinity, soil compaction, decline in soil biodiversity, and different anthropogenic activities. Climate change and water erosion

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have been predicted to cause the reduction of soil organic carbon concentration through water erosion (Borrelli et al. 2020; Rust et al. 2022). Abiotic factors, such as drought and salinity, render approximately one billion hectares of global arid and semi-arid lands unproductive and infertile (Sahab et al. 2021). The accumulation of both organic and inorganic pollutants resulting from anthropogenic activities such as deforestation and environmental pollution also has an adverse effect on soil health and productivity (Zong and Lu 2019). This could also impact the microbial population and diversity of the soil and possibly lead to the deterioration of soil/land. Land deterioration is a global environmental challenge owing to its detrimental impact on about three-fourths of the global terrestrial ecosystem. Excessive anthropogenic activities have detrimental consequences on the ecosystem, manifesting in decreased soil productivity, loss of biodiversity, and potential disruptions in food production. Furthermore, these activities contribute to climate change through the release of carbon emissions into the environment. These emissions act as a heat-trapping mechanism, causing alterations in the Earth's climate system, which result in global warming and the occurrence of extreme weather events (IPBES 2019; Santini et al. 2022). Possible solutions to avert the detrimental effects of this ecosystem's degradation focus on sustainable management of lands and productivity. In accordance with the Sustainable Development Goals (SDGs) set forth by the United Nations General Assembly in the 2030 Agenda for sustainable development, protection and sustainable management of terrestrial ecosystems as well as combating climate change and its impact by reducing our carbon footprints respectively corroborates SDG 15 and 13.

Possible mitigation strategies for the effects of poor soil quality include the evaluation of soil functions and using various monitoring indicators. To evaluate soil quality, several soil monitoring indicators (Fig. 1) have been put to practical applications and have been categorized into physical chemical, and biological indicators. Physical indicators deal with water retention capacity as well such as nutrient availability in the soil ecosystem. Measuring physical indicators of soil quality, including factors like soil porosity, texture and structure, can be quickly and easily done using simple tools and techniques. By correlating these measurements with other methods of monitoring soil health, we can gain a more comprehensive understanding of soil health and identify specific management practices to improve soil quality. However, this technique has some limitations, including a lack of precise information, which may make it difficult to monitor alterations in soil quality over time and can lead to variability in measurements and unreliable data. The chemical indicators which comprise soil pH, soil organic matter, available nitrogen, phosphorus, and potassium describe the balance between soil moisture, nutrients, etc. Low soil pH reduces the availability of some nutrients such as phosphorus and calcium while soil organic matter improves water-holding capacity and nutrient retention in the soil (Feng et al. 2019; Čechmánková et al. 2021). Some biological entities which participate in the process of nutrient cycling and the breakdown of organic matter are referred to as biological indicators of soil quality (Doran et al. 1996). Additionally, assessing the activities and diversity of microbial communities in contaminated environments can be used to monitor the impact of hazardous chemicals on the

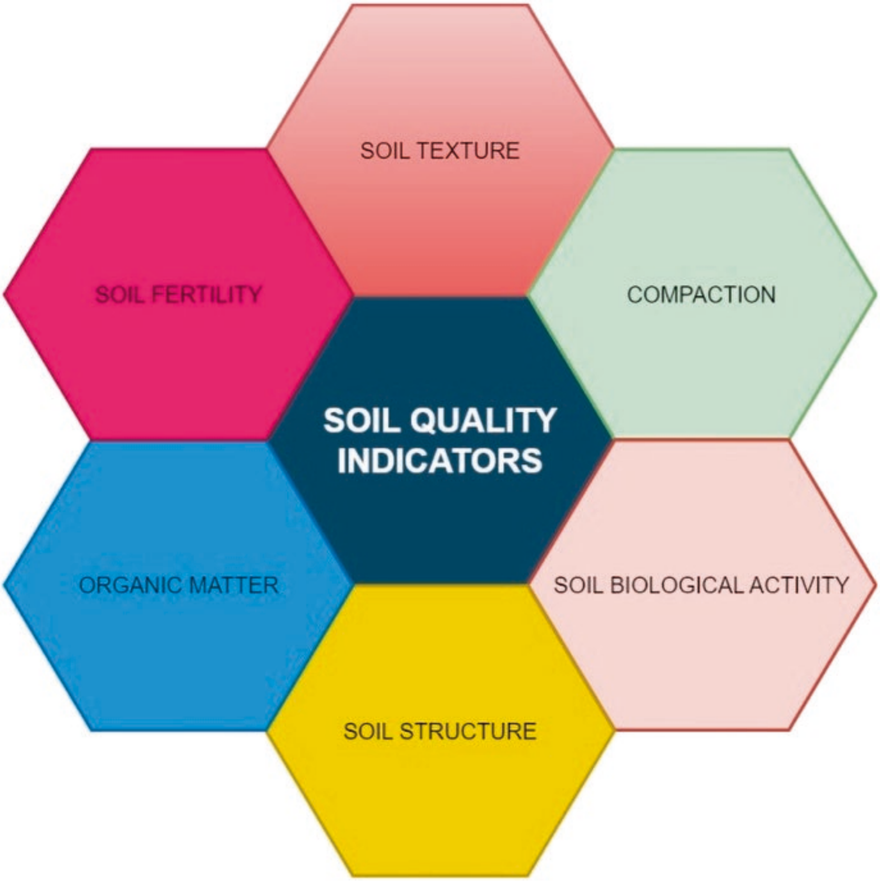

Fig. 1 Different indicators of soil quality

environment through the process of bioavailability. Bioavailability refers to the degree to which a chemical substance is accessible and can be utilized by living organisms in a particular environment.

Microbes, such as bacteria and fungi, possess unique biochemical capabilities that enable them to interact with and transform various chemical compounds in their surroundings. Microbes actively participate in the degradation, immobilization, or transformation of environmental contaminants. The presence of specific microbial species or metabolic pathways can indicate the ability of these organisms to degrade or transform particular chemicals (Pileggi et al. 2020). Changes in microbial diversity and population as well as microbial activities aid in the identification of possible signs of soil degradation. Swift response to environmental stress/changes and adaptability are some of the characteristics of microorganisms as biological indicators of environmental alterations. Over the past decade, advancements in microbial biotechnology have enabled the full genomic identification and functional analysis of soil microorganisms, which play crucial roles in various natural processes (Vieira et al. 2021). Microbial biotechnological advancements such as the 'omics' technology which includes metagenomics, metatranscriptomics, metabolomics, proteomics, etc. offer powerful tools for understanding the complex interactions between microbial communities and pollutants in contaminated environments. They provide valuable information for optimizing and enhancing phytoremediation and micro-remediation strategies, leading to more efficient and sustainable approaches for environmental remediation (George et al. 2019; Withers et al. 2020). This creates an advantage over conventional indicators for the monitoring of soil quality (Nielsen et al. 2002). A study by Bhowmik et al. (2019) deduced the potential of soil enzymes and microbial communities to indicate the degradation of soil quality in a watershed as well as their relation to the physicochemical properties of soil. The inclusion of molecular and biotechnological strategies as possible means of monitoring soil quality is essential considering recent developments in that field which include advancements in DNA sequencing technologies, the development of novel bioindicators as well as the inclusion of nano biosensors. The importance of these techniques relies on the potential of the techniques to promote productivity and sustainability. This chapter focuses on the causes of low soil quality, potential mitigation strategies, as well as an analysis of different biotechnological approaches and their effect on monitoring soil health and quality.

2 Characteristics of Soil Quality

Soil quality refers to a particular type of soil's ability to promote productivity of crops and livestock, preserve or improve the quantity of the environment, including air and water, as well as promote the well-being of humans (Stivers 2017). Soil quality is the term used when referring to soils that have beneficial physical and biological attributes and are fertile. Environmental quality has three elements; these elements are water quality, air quality, and soil quality. The quality of the environment is defined by the extent of pollution in the air and water, this directly impacts natural ecosystems and human and animal consumption (Bünemann et al. 2018). In the definition of soil quality rather than being limited to the extent of soil pollution, the basic definition of soil quality is that it is the ability of soil to perform its tasks within an ecological system and the use of land to preserve environmental quality, maintain biological productivity, and promote animal and plant health (Bünemann et al. 2018). Soil quality is an external attribute of soils that changes with the desired use of that soil by humans. This could be directly associated with agricultural productivity and the ability to support wildlife, protect watersheds, or provide leisure opportunities (Tahat et al. 2020).

The cornerstone of sustainable farming practices is good soil quality. Fertile soil provides the vital nutrients that plants need to grow. Air and water can penetrate the roots of plants owing to significant physical aspects of aggregation and structure of soil. Soil quality links agricultural and soil research to policymaking, stakeholder expectations, and the management of sustainable supply chains. The soil's continuous ability to function as an essential biological ecosystem that nourishes humans, animals, and plants is soil quality. In the past, soil assessments were mainly concentrated on crop output; currently, soil quality also examines the impact of soil on human health, water quality, and climate change (Lehmann et al. 2020). Despite rising recognition of the significance of soil biodiversity, assessing soil quality continues to be dominated by chemical markers due to a lack of practical information about efficient techniques (Lehmann et al. 2020).

2.1 Different Indicators of Soil Quality

Since soil quality is a wide, integrative, and context-dependent notion, it cannot be directly measured. Instead, we examine some proxy data that, when combined, reveal information about how the soil is behaving from one or more soil-use perspectives. Indicators of soil quality are what these measurements are named. An efficient indicator set is a collection of inexpensive, easily measurable indicators that reliably predicts important soil processes. The features of soil solids, soil solutions, soil atmospheres, plants, and other soil biota are examples of soil quality indicators. They may also incorporate economic studies of land use or ecosystem services. Regardless of the approach chosen, the process of evaluating soil quality follows the same fundamental steps: identification of soil usage issues, followed by indicator selection and interpretation. To put it more precisely, one must first establish the land-use objectives before proposing, measuring, and evaluating indicators across a representative collection of lands and management approaches. These activities take place at several levels and are influenced by both natural soil properties (such as texture, OM content, pH, CEC, porosity, etc.) and external environmental (such as climate, topographical, hydrological, and biological) as well as anthropogenic (soil-use and management) factors. Some features associated with soil quality include:

2.1.1 Soil PH

The capacity of soil to provide the nourishment crop varieties require to thrive is known as soil fertility. The primary nutrients that plants take up from the soil are the following: phosphorus, potassium, calcium, nitrogen, and magnesium. Additionally, we generally need to supplement the nutrients in the soil with sustainable compost, manure, or fertilizer for optimal development of crops. The pH level of the soil is yet another vital component of fertility in the soil. The pH of the soil has an important effect on soil biogeochemical activities in the natural environment. The "master soil variable" is the soil's pH, and it influences a variety of soil chemical, biological, and physical properties as well as processes that have an impact on plant growth and biomass production (Dora 2019). PH regulates biological processes and soil biology and this results in pH and fertility of the soil having a bidirectional relationship.

Several nutrients needed by plants become significantly easier to obtain and this availability depends on the pH of the soil. Neutral soils include those which range between a pH that is slightly acidic at around 6.5 and a slightly alkaline pH level of 7.5 and this is considered to be near to the "ideal" soil pH. Within this pH range of 6.5 to 7.5, the majority of plant nutrients are optimally available to plants, and this pH range is typically very beneficial to plant development of root systems. Three main plant nutrients which include potassium (K), nitrogen (N), and sulfur (S) seems to be less significantly affected by soil pH than many other nutrients but they are affected nevertheless. However, from the three main nutrients, phosphorus (P) is the first to be affected. For instance, at alkaline pH levels higher than pH 7.5 calcium (Ca) and magnesium (Mg) typically undergo fast reactions with phosphate ions that result in less soluble compounds, also at acidic pH levels, phosphate ions undergoes reactions with iron (Fe) and aluminum (Al) to generate less soluble molecules. When soil pH surpasses 7.5, the majorities of other nutrients (especially micronutrients) are not as available and are most easily accessible at a slightly acidic pH, which ranges from 6.5 to 6.8. Molybdenum (Mo) seems to be easier to obtain at slightly alkaline pH values whereas it is less accessible at acidic pH levels (Dora 2019).

Soil pH is an important indicator of soil quality. In light of this, reliable pH sensing continues to be vital in soil quality assessment and monitoring. The application of nanoparticles (NPs) for determining pH has gained increasing attention recently, particularly for imaging and intracellular pH sensing. As a result of this, numerous nanoparticle based fluorescent pH sensors have been created for this purpose. They can be categorized into three main categories: fluorescent nanoparticles with either indirect or direct pH responses; non-fluorescent NPs utilized solely as scaffolds and recipients for pH-sensitive fluorescent dyes; and non-fluorescent nanoparticles whose pH-responsive structural modification is transformed to the fluorescence indicator associated with their attached dyes.

2.1.2 Organic Matter

Remains of plants and animals, alive and dead soil microbes, and compounds created during decomposition make up organic matter. Organic matter makes up a very small fraction of the majority of agricultural soils, but it majorly influences soil quality (Stivers 2017). Organic matter in the soil has the tendency to enhance soil biological activity, soil structure, and fertility. Cover crops, manure, compost, and crop rotation are some of the means used to add organic matter to soils. Soil organic matter can alter how bioavailable pollutants are to the soil by immobilizing or mobilizing pollutants by creating various complexes that could be either insoluble or soluble (Shrestha et al. 2019).

The impact of soil organic matter (SOM) on various properties of soil which can be either chemical, physical and biological influences soil function and directly contributes to the growth of both plants and microorganisms (Vinhal-Freitas et al. 2017). The primary source of exocellular hydrolytic enzymes involved in these cycles; nitrogen (urease) cycle, carbon (beta-glucosidase) cycle, phosphorus (phosphatase) cycle, and sulfur (arylsulphatase) cycle in soils is soil microorganisms. Exocellular hydrolytic enzymes function on the breakdown of organic materials to release micronutrients into the soil solution that are then available to microbes and for plant growth. In addition to enzymes, there are several biochemical measures that serve as indications of microbial activity, including metabolic quotient, fluorescein diacetate activity, and soil microbial respiration (qCO^2) (Vinhal-Freitas et al. 2017).

2.1.3 Soil Texture

The ratio of sand, clay, and silt in soil is used to determine its textural class. To generate soil sand, clay, and silt are normally combined together. Medium-sized particles make up the silt, sand particles are extremely huge and clay particles are smaller than sand particles. Clay and silt particles hold more fluid and plant nutrients along their surfaces than sand particles do. The fundamental characteristic of soil texture is not significantly impacted by various management strategies. The four main textural classifications of soils are loams, sands, silts, and clays. Soil texture impacts soil moisture content and drainage capacity. This is due to the fact that texture determines the soil pores, which are openings or spaces between mineral particles in clay soil. The balanced supply of both air and water in loamy soil is a result of its composition of both sand and clay and also because of its macro and micro holes.

The ability of soil to give nutrients to plants is affected by soil texture. Coarse textured soils, for example, are poor in nutrients, this is because leaching is significant in these soils and nutrients are being transported out of the soil. Burke and Hook discovered a high link between soil C and N pools and N turnover dynamics and both landscape position and soil texture (Amooh and Bonsu 2015). Since it directly impacts the water content of the soil and its temperature, the texture of soil has an impact on microbial activity (Vinhal-Freitas et al. 2017). In terms of soil porosity and its aggregation, the textural class is equally vital. Moreover, gas exchange (microbial respiration and respiration of roots) between the atmosphere and soil is significantly influenced by soil texture. Within the same soil class, heavily-textured soils exhibit higher levels of carbon stock and microbial activity than light-textured soils. The texture of soil is crucial in determining how vulnerable soil is to various land uses especially those used for agricultural purposes (Vinhal-Freitas et al. 2017). The understanding of the function of soil and its ecological processes can be enhanced by research on microbial, biochemical, and soil texture indicators.

2.1.4 Compaction

When pore spaces contract and soil particles are forced closer together, soil compaction results. When large tractors, trucks, and other machinery are driven over the soil, especially when the earth is moist, this generally happens. At the soil's surface as well as in the layer of soil immediately below the depth of tillage, soils can get compacted (subsoil compaction). Compacted soil makes it harder for plants to grow because the soil aggregates are compressed, leaving little pore space for water and air, both of which are necessary for root growth. Soil compaction can also have an effect on bigger burrowing species since burrowing in compacted soils consumes more energy than other activities like foraging and breeding (Tibbett et al. 2020). Furthermore, when there is an increase in bulk density, it often correlates with a decrease in the moisture content of soil and its organic matter. These changes can have significant implications for the community assemblages present in the soil, including burrowing species and plants (Tibbett et al. 2020).

The extent of the soil's modification during compaction can be determined by the soil's physical, physicochemical, and biological parameters such as bulk density, shear strength, penetration resistance, pH, redox potential, CO2 efflux, and microbial activity. In-situ or laboratory measurements of these qualities using soil samples are also feasible; however, this method might not always be the most effective approach to assess soil modification, particularly over vast areas of space.

A potential, albeit mostly unexplored, resource for geographically and temporally uniform examination of compaction in soil and rutting in forest systems has been provided by the latest developments in remote sensing. Across a restricted spatial extent, Cambi et al. (2018) reported that the use of high-resolution photogrammetry might potentially be used to calculate soil compaction proxies that are comparable to in-situ measurements. Similarly to this, Talbot et al. (2018) assessed the severity of soil rutting following forest cutting using unmanned aerial vehicles (UAVs) fitted with digital cameras and producing 3D images. However, a UAV-based approach like this can only be used in relatively limited spatial extents and over recently clear-cut or harvested areas. Light detection and ranging technology (LiDAR)-based terrestrial laser scanning (TLS) has been put forward as an alternative method to monitor soil compaction and rutting from beneath the protective covering (Koreň et al. 2015).

2.1.5 Soil Biological Activity

Living things such as bacteria, fungi, insects, earthworms, and others are abundant in healthy soil. These living organisms enhance soil quality by carrying out a variety of tasks as they go through their life cycles. Organic matter which include crop waste and manure from livestock farming, is broken down by soil organisms. They facilitate the bonding of soil particles into durable aggregates. They also produce humus, an organic material that doesn't further disintegrate and aids in keeping soils moist and nutrient-rich. More biologically active soils typically include fewer organisms that cause plant diseases. By digging tunnels through soils, earthworms create access points for air and water to penetrate the soil.

Soil biodiversity decrease is commonly defined as a fall in the number and variety of life living in soils (Tibbett et al. 2020). Wherever soil biodiversity decrease happens, it can have a substantial impact on the soil's functionality, its ability adapt to perturbations, and recover. Several soil hazards, such as human intense exploitation, soil organic matter decrease, and land-use change, have been shown to have a negative impact on soil biodiversity (Gardi et al. 2013).

The conventional techniques for detecting microbial communities are time-consuming and need expensive equipment. Stable isotope probing, DNA fingerprinting, 16S rRNA gene sequencing, and nanotechnology, are methods available for identification of soil microbial populations.

2.2 Possible Causes of Poor Soil Quality

Loss of soil productivity and quality is referred to as soil degradation. It might happen naturally as a result of the topography, climate, and soil's innate traits. Deforestation, excessive grazing, and improper agricultural land management are examples of human interventions that can be controlled or avoided that cause soil degradation. Human-induced deterioration occurs more quickly than natural degradation does. SOM, or soil organic matter, is often used as a measure of deterioration in soil. More organic matter in the soil improves its structure, increases water infiltration, and makes the soil more resistant to desertification, compaction, and erosion. Monitoring and evaluating soil degradation processes' using the right techniques is crucial to stop soil degradation processes from worsening soil physical, chemical, and biological properties (expert-based, remote sensing, or modeling). Below are some causes of soil degradation:

2.2.1 Erosion

Soil erosion caused by water, is the most frequent source of soil degradation worldwide which leads to loss of soil, increased pollution, and sedimentation in rivers. Putting into consideration the mechanisms of degradation of land, it has been estimated that soil and water erosion affects eighty percent of Africa's soils. Particularly, in the Sahel belt south of the Sahara, crusting of soil can increase water runoff and sheet erosion. Also water erosion is thought to be responsible for up to thirty million tons of lost soil in Nigeria (Hossain et al. 2020). Wind erosion adds significantly to soil movement and high wind speed in semi-arid and dry zones, for instance, in Burkina Faso, it has been calculated that wind erosion contributed 329 t (ha^{-1} $year^{-1}$) in soil loss, primarily from June to August prior to the advent of rain (Hossain et al. 2020).

The long-term repercussions of soil erosion on agriculture are visible. Soil erosion may diminish crop yield, and correcting it with locally available methods will be difficult. By decreasing the soil's organic matter, nitrogen, and phosphorus reserves in addition to its clay content, water-holding capacity, and soil aggregation, soil erosion lowers the productivity of crops. It is also reported that in instances involving severe soil erosion, pH, calcium, and potassium rise while iron; soil organic matter, phosphorus, nitrate-nitrogen, and zinc decrease (Chalise et al. 2019). Maintaining the condition of an outer layer of protection (trees, mulches, and crops), choosing the best land use, and building technological works (such as check dams) on the riverbed are the main methods for controlling soil erosion.

2.2.2 Organic and Inorganic Contaminants

In modern times, synthetic molecules of organic matter are present all around us. They are often found in our homes, our workplaces, in agriculture, and in public places. Organic pollutants are frequently identified far from their place of origin and can contaminate the soil, the water and the air through local contamination. Petroleum products, industrial solvents, pesticides, explosives, dioxins and furans, brominated flame retardants, and polychlorinated biphenyls (PCBs) are among the synthetic organic materials that are of concern as environmental contaminants. Various nutrients, toxic metals, and salts are examples of inorganic pollutants and these pollutants commonly occur as dissolved anions and cations. Several inorganic pollutants remain in the soil indefinitely, whereas other chemicals only degrade or change over a very brief period. Inorganic pollutants have a negative impact on the biological, physical, and fertility aspects of the soil, resulting in a decrease in productivity.

Organic and inorganic contaminants can have an adverse effect on the mechanical strength of soil, soil aggregation, and stability of soil by changing cation-exchanging capacity (CEC), soil pH, salinity, and dispersing and/or flocculating clays (Zong and Lu 2019; Salem et al. 2017). Very high soil NPK (Nitrogen, Phosphorus, and Potassium) levels improve plasticity index, bulk density, tensile strength, and coefficient of linear extensibility while drastically reducing water retention capacity, total porosity, and macro aggregate content (Zong and Lu 2019). Through volatilization and denitrification, soil contamination allows enormous amounts of nitrogen to release into the surrounding environment (Fungo et al. 2019). The interaction between pollutants in the soil and microorganisms and its interference with their regular metabolic processes reduces the production and fertility of the soil (Saxena et al. 2015; Behera and Prasad 2020).

Biological processes have proven to be the most effective way of removing synthetic organic and inorganic contaminants from polluted soils, and this method may be referred to as clean technology (Kumar 2020). Biotransformation, mycoremediation, phytoremediation, bioaugmentation, biomineralization, genoremediation, bioleaching, biostimulation, biosorption, bioadsorption, bioventing, are all examples of biological remediation methods for synthetic organic and inorganically contaminated soil.

2.2.3 Climate Change

Climate change can have both an indirect and direct impact on soil functions. A few examples of the direct effects of climate change on soil function and, consequently, soil quality include changes in nutrient cycling due to freeze-thaw (FT) cycles, changes in organic carbon transformations and changing soil moisture, as well as higher rates of soil erosion caused by a spike in high-intensity rainfall events. The soils' ability to successfully carry out its functions can be altered by the management of soils and climate change, which may negatively impact soil quality. Modifications in the soil's properties have an effect on how the soil performs particularly how effectively the soil transports biomass, retains water, and promotes plant growth (Ascough et al. 2019).

Functionality of soil is affected indirectly by the impacts of climate change which include those brought on by climate change mitigation techniques which include: rotation of crops, proper irrigation and tillage practices (Hamidov et al. 2018). Reduced crop yields (and subsequently debris inputs) might occur as a consequence of elevated temperatures, though this would typically be offset by the CO_2 fertilization effect, and in general, greater grass yields are anticipated. Considering the short term effect of climate change, both climate warming and increasing CO_2 levels in the atmosphere will promote tree growth (Jaihoon 2019). More studies could be done on the long-term effects of climate warming and CO_2 levels on tree growth. Through improved handling of N fertilizers, including the appropriate rate, type, and technique for application as well as soil management (avoiding soil compaction), nitrous oxide emissions can be decreased. By supplying a protective soil cover and an environment that encourages robust plant growth, sustainable agricultural strategies (minimal disturbance of the soil, cultivation of cover crops, and rotations of crops that include legumes) can restore soil organic matter (Goa and Zewude 2021).

Agricultural management can help to alleviate the consequences of climate change; one example of this is by increasing soil organic carbon sequestration (Haddaway et al. 2015). Hamidov et al. reviewed several scenario studies on climate change mitigation strategies that include agricultural adaptation options as a response to climate change. These strategies have been conducted in Europe and they include; crop rotation changes, the implementation of proper irrigation regimes in drought-prone areas, amended soil tillage practices, increased fertilization rates on cropland and the cultivation of melting permafrost soils (Hamidov et al. 2018).

2.2.4 Salinity

Soil salinization is a common cause of land degradation around the world (Rath and Rousk 2015). It has been observed to lower enzymatic activity, soil respiration, bacterial growth rate, and soil microbial biomass; all of these features affect the salinization of about 830 million ha of arable land globally and influence biogeochemical cycling (Zhang et al. 2019). Understanding the function and structure of microbial communities in saline soil is an important goal in ecology since it will aid in elucidating the biological control mechanisms for nutrient cycles in saline soil. The microbial community in the soil is well known for driving the soil nutrient cycle in a variety of land habitats, may change as a result of soil salinization.

Due to human influence, changes in land use, and soil deterioration, there is less soil organic carbon than there was previously. Through increased carbon dioxide (CO_2) emission and lower plant intake, this drop has considerably contributed to the enrichment of atmospheric CO_2 (Raj et al. 2012). Saline soils are prevalent among degraded soils and according to Lal (2001), saline soils have a significant capacity for storing carbon (C) in above-ground biomass and in the soil organic carbon, also according to Chowdhury et al. (2011), salinity primarily impacts microorganisms by lowering their osmotic potential, which in turn reduces their activity and alters the makeup of the microbial community (Raj et al. 2012). These modifications affect the decomposition of soil organic material and in turn, affect carbon fixation in the soil. The two opposing processes that affect soil organic carbon content in saline soils are reduced plant inputs, which could reduce soil organic carbon, and reduce rates of decomposition, which might increase soil organic carbon content if the carbon supply remained constant (Raj et al. 2012).

Actinobacteria, Planctomyces, and *Proteobacteria* are a few bacterial groups that could support dissolved inorganic carbon fixation (Zhang et al. 2019). The promotion of dissolved inorganic carbon fixation would in term mitigate the effects of salinity by fixing the increased soil organic carbon content in saline soils.

2.2.5 Industrial Plant Activity

For any activity, the qualities of the soil are crucial. Numerous soil contaminants have different effects on the chemical properties of the soil. According to reports by Awotoye et al. (2011); Izah et al. (2016) and Okwute and Isu (2007), absorbing effluents from soil obtained from a palm mill contains processing mill rubble and moist soil (Seiyaboh and Izah 2019). Studies have also shown that the properties of the receiving soil may change as a result of cassava processing activities (Izah et al. 2017, 2018). The flora and fauna in this area may benefit or suffer due to variations in the soil's properties. For instance, according to Izah and Aigberua (2017), absorbing effluents from soil obtained from a cassava mill reduce the quantity and variety of bacteria that exists in the receiving soil (Izah et al. 2017). This suggests that the pollutant's chemical makeup may have an impact on the soil's flora. There have also been documented cases of cassava mill effluents reducing plant productivity in literature (Izah et al. 2018). Some of the pollutants in the soil may also provide the soil with necessary nutrients, increasing productivity.

2.3 Potential Effects of Poor Soil Quality on the Economy

2.3.1 Loss of Agricultural Land

The deterioration of chemical, natural or biological traits and attributes of agricultural land is referred to as agricultural pollution of the land. It causes a negative impact on every animal, person, or plant that lives on its surface, either directly or indirectly. Pollutants of agricultural soil consists of residues from agriculture practices which includes; associated weeds, plant remains and roots left over after burning the ground, crop stalks , remains from vegetable, leaves from trees, and fruit that is unripe that has fallen to the ground (Al-Yasiri 2019). Because soil contamination is a persistent issue, it differs from other types of pollution. By addressing the disease's causes before deciding on a course of therapy, it can be entirely removed and eliminated.

Agricultural land pollution negatively impacts economic growth and development by damaging people's livelihoods, enterprises, education, and occupations. Additional negative consequences of agricultural land pollution on economic expansion and the environment include biodiversity loss and reduced food and agricultural output levels. Many locals in the Nigerian region of the Niger Delta lose their jobs, such as canoe carving, fishing, and forestry, which together account for about 70% of all employment in the area. As a result, the majority of children in those households frequently drop out of school because their parents are unable to afford their wards' school fees (Ipingbemi 2009). It is indeed obvious that agricultural land pollution lowers household income levels thereby sustaining impoverishment. As a result, agricultural land pollution and poverty have a close relationship.

2.3.2 Loss of Biodiversity

The diversity of life in soil fuels ecosystems that sustain life above ground, and promotes healthy environments, and has been mostly overlooked in global agendas despite its vital function in sustaining the well-being of humans and natural systems. The majority of the Earth's biological biomass is contributed by organisms that exist in the soil, including fungi, bacteria, nematodes, moles, earthworms, and even plant roots (Bach et al. 2020). These organisms additionally constitute over twenty-five percent of the total documented species. Several ecosystem functions, including pathogen management, the cycling of nutrients, establishing the fundamental blocks of food webs, water absorption, and the maintenance of agroecosystems, are made possible by the complex interactions and activity of soil organisms. Soils and soil biodiversity are under threat by climate change, degradation of the land, pollution, excessive usage, growing urbanization, and abuse, and similar to the vast majority of the resources on which mankind depends (Bach et al. 2020).

There are many instances that demonstrate the significance of soil biota in sustaining global food production. In China, conventional rice-fish farming involves the utilization of rice fields as fish habitats, where fish consume microorganisms that break down dead leaves of rice as food. The process of fish feeding breaks down the soil, enabling greater amounts of oxygen to penetrate. That, in turn, encourages the microbial breakdown of fish feces and plant matter, resulting in the release of nutrients that are needed by growing rice plants (Liu et al. 2013). Similar to the above, changing legumes with grain-based crops in industrial row-crop systems utilize the nitrogen-fixing bacteria associated with the legumes to create soil nitrogen that grain crops like maize subsequently utilize.

The repercussions of unsustainable resource usage at the local as well as global levels have become increasingly visible, raising questions about the connection between economic expansion and countless environmental quality initiatives (Dietz and Adger 2003). The declining level of biodiversity is also caused by of the complicated relationships between several triggers, including the equally complicated effective demand for wilderness, agricultural growth and conservation, recreational space, and conservation of genetic diversity for use in agricultural activities and production of pharmaceuticals. The advantageous effects of biodiversity are subsequently underestimated by society when weighing the manner in which they are allocated (Dietz and Adger 2003).

2.3.3 Increased Soil Erosion

Extreme soil erosion can have both economic and environmental consequences. Loss of farm household income due to reduced agricultural and farm animal output has an economic impact, while natural water and pollution of land have an environmental impact. Additionally, both on and off-site impacts of soil erosion on productivity may occur. Off-site implications include sediment obstruction in streams, contamination of water, and damage to physical infrastructure, while on-site impacts include agricultural degradation, loss of nutrients, and loss of fertile topsoil (Posthumus et al. 2015). When topsoil depth is lost, the situation becomes severe. Tillage-induced erosion, in addition to rain and wind erosion, is responsible for the loss of topsoil in cultivated fields that are on a steep slope. It has been shown by researchers that soils lost to erosion are 1.3 to 5 times richer in soil organic matter (SOM) than soils left behind because nearly all of the SOM is found on the topsoil (Chalise et al. 2019). The reserve of SOM in the majority of agricultural soils has been diminished because of an increase in soil erosion. The functionality of soil, its ability to supply vital ecosystem services, and the health of the soil could all be adversely affected by a significant reduction of SOM content. Therefore, recovering SOM content in soils of agroecosystems could reverse the current rate of degradation, boost ecosystem services, and expand UN Sustainable Development Goals (Rattan 2020). While rehabilitating the environment, a boost in SOM content could also partially substitute for the application of chemical fertilizers and additional irrigation (Rattan 2020).

2.3.4 Anthropogenic Effect

The severity of contamination in the soil on a global scale and several restrictions which includes those caused by stress (abiotic and biotic) are the main risks to demand for food and food security given the increasing natural and anthropogenic activities, and these will likely disrupt food security in the coming years (Riaz et al. 2019). Due to reliance of agriculture on chemical fertilizers, the irrigation of wastewater, fungicides, the use pesticides as well as the quick development of industries, the concentration of toxic metal(loid)s and organic contaminants in arable land has risen and this has negative impacts on the soil-plant environmental system (Bansiwal and Maheshvari 2018). The lingering contaminants lower crop output and impairs soil productivity. The economic and social conditions around the world are being negatively impacted by this problem.

Clinical problems within biological networks (of animals and people) can arise from the accumulation of inorganic and organic pollutants in edible or inedible parts of commercially significant plants and crops grown in non-polluted soil (Li et al. 2018).

3 Different Monitoring Indicators of Soil Quality

Soil quality indicators are used to evaluate how well the soil functions and can be determined using a composite set of quantifiable physical, chemical, and biological properties related to functional soil processes. A study by Terashima and Mihara (2020), investigated the physical, chemical, and biological properties of the soil of two farms with different practices and the result indicated a significant difference between the microorganisms, but could not be identified with physical and chemical properties. This section provides an introduction to different monitoring indicators of soil qualities. The indicators for evaluating the health and quality of soil fall within three categories; this encompasses physical, chemical, and biological indicators.

3.1 Physical Indicators

The physical markers of soil quality show how well the ecosystem can absorb, store, transfer, and deliver water, oxygen, and nutrients. According to a study conducted by Ahmad et al. (2022), the soil's capacity to provide plants with a suitable environment, including moisture, air, and support, is influenced by its physical properties. To assess soil quality, various physical indicators are employed, such as pore size distribution, aggregate stability, saturated hydraulic conductivity, texture, infiltration rate, bulk density, and surface crust (Loganathan and Navendrian 2014). In a study conducted by Irmal et al. (2018), field experiments were undertaken to quantify the influence of cover cropping on soil physical properties. The properties examined in the study included Permanent Wilting Point (PWP), Field Capacity (FC), soil-water holding capacity (SWHC), bulk density (rb), saturated and unsaturated hydraulic conductivity (Ks and Kus, respectively), and infiltration rates. These properties were measured and compared across four different land cover treatments. They discovered that the soil's physical properties were unaffected by incorporating rotational cover crops into row crop cultivation, and there was no significant difference between the treatments for all seasons. They concluded by indicating that combining cover crops into various grain rotations reduced the infiltration rate but could not sufficiently determine if cover crops are responsible for altering soil physical properties. Physical indicators of soil quality include measures of:

a) **Soil bulk density**

The bulk density of soil indicates the mass of a certain volume of soil. Instead of exceeding a predetermined threshold, bulk density has been proposed as a soil quality measure for British soils in relation to trends over time. The density of the soil in large quantities influences numerous soil properties, such as infiltration, available water capacity, soil porosity, rooting depth, soil microbial activity, root proliferation, and nutrient availability (Corstanje et al. 2017). In a study conducted by Indoria et al. (2020), it was revealed that the bulk density was dependent on available macronutrients and micronutrients in the soil, with regards to organic matter, and that it decreases as the total macronutrient or total micronutrient contents in the soil increases.

b) **Soil texture**

Soil texture is determined by the proportion of three particle sizes of sand, silt, and clay. It has a significant role in the processes of soil deterioration and water transport, regulating the quality and productivity of the soil (Yu et al. 2020). It has an impact on a variety of soil characteristics; including how well the soil supplies water, how quickly water infiltrates the soil, how easily it may be cultivated, and how susceptible it is to erosion. According to Mobilian and Craft (2021), other soil properties including bulk density, water-holding capacity, permeability, and porosity are influenced by soil texture. For instance, sand-dominated soils have higher permeability and lower capacity to hold water than soils with higher concentrations of silt and clay.

c) **Soil depth**

The depth of the soil affects how much soil and how much root space the plants require to meet their hydration and nutrient requirements. Generally speaking, deeper soils can provide plants with more nutrients and water than shallower soils. Additionally, soil provides mechanical support to the majority of plants (Rajakaruna and Boyd 2008). The rooting depth and water-holding capacity of the soil are strongly influenced by its depth. In deep soils with thick topsoil and superior subsurface qualities, erosion may have little to no effect on productivity. Water availability can be influenced by soil depth in addition to soil texture and structure (Ronald 2008).

d) **Infiltration**

The capacity of the soil to permit water to enter and pass through the soil profile is known as soil infiltration. Water can temporarily be stored in the soil by infiltration, making it available to plants and other soil creatures. The main underlying factor determining infiltration is soil texture or the amount of silt and clay in the soil. Solid organic manure should be spread on the soil to increase the rate of soil infiltration (USDA 2014). One method of determining infiltration is to time how long it takes for a certain amount of water to evaporate after being sprinkled or ponded on a soil surface. The amount of water that can infiltrate into and through the soil profile is known as infiltration. Low infiltration rates in metropolitan areas brought on by compacted soil have detrimental consequences on the city's ecosystem, leading to increased flooding and poor surface water quality (Yang and Zang 2011).

e) **Water holding capacity**

The amount of water in a soil when its pore space is full with water and the drainage is constrained is referred to as its water holding capacity. The amount of water the soil can store for usage by plants' roots for a specific amount of time is known as the available water holding capacity (AWHC). Only poorly drained soils operate at their maximum water-holding capacity for an extended period in the natural environment. More water is stored in clay soil than in sandy soil (Nath et al. 2014).

f) **Colour**

The makeup of the soil is revealed by its color, which also provides insight into the conditions it is in. The amount of protein in the soil affects the color of the soil. Soils rich in humus are often dark brown to black, while those rich in iron are typically white. The color of the soil also reflects the age of the soil as well as the temperature and moisture characteristics of the climate. Cooler climates often contain topsoil that is greyish to black in color due to humus buildup. Soils in humid, warm climates tend to be more yellowish-brown to red due to the significant weathering of the soil's parent material and the hydration of ferric oxide (Amara et al. 2022). Soil color is influenced by organic matter, element concentration, moisture content, and mineral composition. Because it reflects soil characteristics and soil processes, it is a crucial diagnostic component for defining soil horizons and classifying soils (Zhang et al. 2021).

g) **Temperature**

Soil temperature plays a pivotal role in determining the direction of heat flow and has a significant impact on the transformation and uptake of nutrients by plant roots (Onwuka and Mang 2018). Elevated soil temperatures can lead to dehydration of clay and fragmentation of sand particles, resulting in a decrease in their respective proportions and an increase in silt content. Solar radiation has been acknowledged as the primary driver of soil temperature. Additionally, soil temperature affects soil moisture, aeration, and the availability of essential plant nutrients, thereby influencing soil characteristics and plant growth processes. It exerts control over the physical, chemical, and biological functions of the soil, including the rate of organic matter decomposition as well as the mineralization of various organic components (Onwuka and Mang 2018).

3.2 Chemical Indicators

The ability of the soil to provide plants with nutrition is determined by its chemical conditions (Surya et al. 2018). The primary chemical markers for soil are pH, electrical conductivity, adsorption capacity, Cation exchange capacity, available Phosphorous and potassium, total Nitrogen, and soil organic matter (Thakur and Sharma 2019).

a) **Soil reaction (pH)**: The pH (acidity or alkalinity) level of the soil directly influences its chemical and biological characteristics and plays a crucial role in regulating various chemical and biological processes within the soil. The United States Department of Agriculture's National Resources Conservation Service has categorized soil pH values into different ranges: acidic (3.5), very acidic (3.5–4.4), strongly acidic (5.1–5.5), moderately acidic (5.6–6.0), slightly acidic (6.1–6.5), neutral (6.6–7.3), slightly alkaline (7.4–7.8), moderately alkaline (7.5–8.4), strongly alkaline (8.5–9.0), and very strongly alkaline (>9.0) (Oshunsanya 2019).
b) **Cation exchange capacity**: Cation exchange capacity (CEC) is a crucial chemical characteristic of agricultural soil. Soil nutrients exist as positively charged ions when dissolved. The positively charged ions are known as cations. The nutrients which exist as cations are Sodium (Na+), ammonium (NH4+), potassium (K+), calcium (Ca2+), magnesium (Mg2+), hydrogen (H+), iron (Fe2+), aluminum (Al3+), copper (Cu2+), zinc (Zn2+) and manganese (Mn2+) (Arit 2016). CEC is a crucial indicator for assessing soil fertility, crop growth, and the partitioning and transportation of contaminants in the soil (Dai et al. 2018). Sharma et al. (2013) used the cation exchange capacity of the soil as well as other soil factors to successfully forecast the production of maize and soybeans.
c) **Available Nitrogen**: Nitrogen has a positive impact on the quality of agricultural soils, due to its ability to improve soil fertility and crop-growing conditions; however, because it alters plant variety, it typically has a negative impact on the soil quality of natural soils. By changing the solubility of phosphorus in the soil, nitrogen salts may have an impact on how much phosphorus plants can absorb (He et al. 2022).
d) **Available Phosphorous**: Between 30 and 65 percent of the total soil phosphorus is present in organic forms that are unavailable to plants, while between 35 and 70 percent is present in inorganic forms. Microorganisms in the soil and the leftovers of deceased plants and animals are sources of organic phosphorus. These organic forms of phosphorus are transformed into forms that are beneficial to plants by soil bacteria (Prasad and Chakraborty 2019).

e) **Available Potassium**: Potassium, being the third essential macronutrient for plant growth and metabolism, plays a crucial role in various plant processes, following nitrogen and phosphorus. Insufficient potassium in plants leads to underdeveloped roots, slow growth, reduced disease resistance, delayed maturity, low seed output, and decreased yields. Potassium in the soil originates from four distinct sources. The majority of soil potassium (90 to 98%) is present in soil minerals such as feldspar and mica; however, this form of potassium is not readily available for plant uptake. The second source of potassium is non-exchangeable potassium, which accounts for 1 to 10% and is associated with clay minerals having a 2:1 ratio. Non-exchangeable potassium serves as a reserve source in the soil. The third source of potassium, making up 1 to 2% of the total, is found in the soil solution or cation exchange sites. This form of potassium is easily absorbed by plant roots and replenished by the potassium present at the exchange sites. The fourth and fifth sources of potassium in the soil are organic matter and the soil's microbial community, respectively. However, these sources contribute only a small portion of the required potassium for plant growth (Prajapati and Modi 2012).
f) **Electrical conductivity**: The electrical conductivity (EC) of soil refers to its ability to conduct an electrical current. EC is a crucial indicator of soil fertility and nutrient availability. The presence of negatively charged sites in the soil, such as clay and organic particles, and the accumulation of cations with a positive charge determine the EC. The higher the number of cations stored in the soil, the higher the EC value. These beneficial cations for plant growth include sodium (Na+), ammonium (NH4+), potassium (K+), calcium (Ca2+), magnesium (Mg2+), hydrogen (H+), iron (Fe2+), aluminum (Al3+), copper (Cu2+), zinc (Zn2+), and manganese (Arit 2016).
g) **Soil organic matter**: This has an impact on various soil properties, including its water-holding capacity, rate of water penetration, aeration, fertility, ease of cultivation, and susceptibility to erosion. Soil organic matter encompasses a wide range of materials, from the original tissues of plants and animals to the well-decomposed mixture called humus. The organic matter present in the soil serves multiple functions. It plays a crucial role as a "nutrient reservoir" and also contributes to improving soil structure, maintaining soil quality, and reducing erosion. When plant residues are returned to the soil, different organic substances undergo decomposition. Additionally, organic matter exhibits a strong affinity for moisture (Nath et al. 2014).

3.3 Biological Indicators

Biological indicators of soil quality refer to the measurement or assessment of specific organisms or their activities within the soil ecosystem to gauge its overall health and functionality. These indicators provide valuable insights into the biological processes occurring in the soil and can be used to evaluate the impact of management practices, pollution, or environmental changes on soil quality. In the last fourteen years, soil biological indicators have been given more weight in soil quality monitoring and assessment programs (Krüger et al. 2018). Due to their correlation with soil activities including microbial respiration and enzyme synthesis as well as organic matter content, terrestrial arthropod fauna, lichen, and microbial community, biological characteristics have been employed as markers of soil quality. Examples of biological indicators of soil health include microbial biomass, carbon and nitrogen, soil respiration, water content, soil enzyme, and Potential mineralization nitrogen (anaerobic incubation) (Dupont et al. 2021). Biological indicators include:

a) **Nematodes**: Saprophytic nematodes serve as bio-indicators of soil health because they utilize a variety of advantageous strategies to improve soil functions, including ecosystem management, nitrogen enrichment through ingestion of nitrogen and the release of additional nitrogen in the form of NH4, which is easily assimilated, putrefaction and the distribution of bacteria and fungi to recently available organic residues (Khanum et al. 2021). According to Al-Maliki et al. (2021) *Acrobeles* and *Rhabditis* nematodes are said to have greatly increased soil fertility or nitrogen in soil. It is generally known that soil nematodes dramatically increase bacterial populations and soil nutrients.
b) **Earthworms**: They can be utilized as bio-indicators of soil quality, since they are more sensitive to temperature changes than to impacts of moisture content. However, they found that these species (*Namalycastis indica, Helodrilus oculatu, Aporectodea caliginosa*) improved soil quality when the temperature was above 35 °C, whereas *Lumbricus terrestrissh* owed an inconsistent response at a temperature of a more than 35 °C. As the soil quality improved at 48 °C, it was also discovered that *Namalycastis indica* exhibited a high tolerance to temperature. They came to the conclusion that soil parameters like moisture content and pH were also affected by temperature, in addition to the earthworm community (Al-Maliki et al. 2021).
c) **Soil enzymes**: They have been used successfully as indicators of soil quality in a variety of agricultural settings. Soil enzyme activities are important biological soil quality indicators because they are operationally realistic, incredibly sensitive, integrative, and easy to measure and because they are more responsive to soil tillage and structure than other soil variables (Adetunji et al. 2017). Dehydrogenase is one of many soil enzymes that may serve as a sign of active soil microbial biomass. It is, nevertheless, extremely susceptible to seasonal variation. Beta-glucosidase, urease, amidase, phosphatase, aryl-sulphatase, and fluorescein diacetate hydrolyzing enzymes are some potential markers of soil quality. They have been suggested as prospective soil quality indicators due to their sensitivity, connection to biological activity, and quick responsiveness to changes in the soil (Al-Maliki et al. 2021).
d) **Soil Respiration**: The rate of soil respiration reveals how well the soil can support soil life, such as plants, soil animals, and microorganisms. In the global C cycle, soil respiration is crucial for controlling the levels of atmospheric CO_2,

dissolved CO_2, and climate dynamics. However, soil respiration is extremely susceptible to environmental changes and is closely linked to nutrient activities like mineralization and decomposition (Luo and Zhou 2006).

4 Various Biotechnological Methods of Monitoring Soil Quality and Their Application

Monitoring of soil quality is aimed at improving agricultural productivity as well as environmental protection and sustainability. Recent biotechnology advancements have prompted the need to investigate the possibility of integrating microbial biotechnology into soil quality monitoring. The main objective of using biotechnology methods in the field of soil management is to enhance water infiltration, increase the carbon content, reduce erosion, ensure the availability of water at plant-root zone, and boost useful organisms. The following are several biotechnological methods used for monitoring soil quality, along with their respective applications:

a) **Metagenomics**: This offers a fresh perspective on the microbial world that will not only alter modern microbiology but also have an impact on our understanding of all living things and their roles in various ecosystems. Metagenomics data can reveal a wealth of information on the genetic capacity of soil-based microbial communities to digest pollutants. Systems biology, bioinformatics, and genomics are combined to create metagenomics. By simultaneously studying the genomes of numerous creatures, it is innovative in its operation (Shrinivas et al. 2019). Nevertheless, the development of 'omic'-based technologies aimed at the global detection of genes (genomics), mRNA (transcriptomics), proteins (proteomics), and metabolites (metabolomics) presents new approaches to assess soil biological functioning. An evaluation of the mostly untapped genetic pool of soil microbial communities can be made using soil metagenomics, which entails the isolation of soil DNA, and the creation and screening of clone libraries. New biomolecules have already been discovered as a result of this strategy. The most diverse microbial communities can be found on Earth in soil habitats. The genomic, metabolic, and phylogenetic diversity that is stored in the soil metagenome has so far only been partially explored by metagenomic techniques. The development of techniques that capture the heterogeneity and dynamism of complex soil microbial communities, both over time and space, represents one of the main difficulties for soil metagenomics. Although there has been significant progress in the characterization of microbial communities by random sequencing, it is still necessary to enhance sequencing technology, lower the cost of sequencing, and develop bioinformatic tools for analyzing the massive amount of data collected. Through the application of metagenomic technology, soil microbes will continue to serve as the primary source of innovative natural products (Rolf 2005).

b) **Metabolomics**: Metabolomics is the systematic identification and quantitation of all metabolites in a given organism or biological sample. The environmental sciences have used metabolomics for a variety of purposes, including phenotypic characterization of organisms, evaluation of plant and soil organismal assemblage responses to biotic and abiotic factors, characterization of different microbial community structures (Graham et al. 2018), and the discovery of biomarkers. Metabolomics, when applied to the soil microbiome, may offer a technique to characterize the varying activity of microbial communities, reflecting microbial genome-environment interactions and thus a cutting-edge method to evaluate soil health. By doing so, we can gain a better understanding of how communities and cells respond to abiotic and biotic stressors and gain new perspectives on how basic soil biochemical processes work (Withers et al. 2020).
c) **Bioremediation**: Compared to the chemical and physical methods, bioremediation may remove significant portions of petroleum hydrocarbons for a relatively low cost and with far less environmental impact. In bioremediation, toxins are removed from the environment by using microorganisms like bacteria and fungi, frequently in conjunction with plants (Wu et al. 2021). The identification of novel bacterial species and genes for bioremediation is made possible by recent advancements in molecular techniques and gene mining. For the bioremediation of mercury pollution, transgenic bacteria expressing *mer* genes have been employed. JM109, a genetically modified strain of *Escherichia coli*, can extract mercury from contaminated sediment or soil. They are environmentally friendly and present an efficient method for the detoxification and removal of chemicals and heavy metals in contaminated locations (Azad et al. 2014).
d) **Microbiome engineering**: This entails employing synthetic biology to produce microbes, plants, inhibitors, and enhancers to change the components of root exudates both qualitatively and quantitatively to transform the rhizosphere microbiome (Barkha et al. 2022). Ecological equilibrium can be restored through engineering microbiomes to change the microbiota's structural makeup. For better soil health and plant fertility, it is possible to engineer the soil microbiome to create more diversified and well-balanced microbial populations (Jee et al. 2017).
e) **Molecular markers**: Numerous biotechnology methods have become accessible in recent years and the current benchmarks for measuring microbial community and diversity in soil are the 16S rRNA gene sequence in prokaryotes and the 18S rRNA gene and intergenic transcribed spacer region between the ribosomal genes in eukaryotes. Additionally, the broad distribution of Mesophilic archaea in soil has been demonstrated by the 16S rRNA gene sequencing of soils. According to Huera-Lucero et al. (2020), it was revealed that primers created from the 16S and 18S rDNA genes, molecular markers distinguished between fungal microbial biomass. These methods provide accurate information on the soil's condition and the environmental factors that affect microorganisms. When there is some sort of influence on the soil, the genome of bacteria sends out signals. Currently, the DNA and RNA of the many species of soil organisms are used to determine the markers of soil quality. It offers more accurate measurements of the biota, moves quickly, and has a lot of potential. By sequencing

16S rRNA genes, the composition and diversity of soil bacterial populations were evaluated. The results showed that the debris with shallow plough less tillage and treated with farmyard manure contained the maximum biodiversity. The two most common bacterial species were actinobacteria and proteobacteria (Vilkiene et al. 2021).

f) **Biostimulants**: They are microorganisms and other substances applied to plants, the rhizosphere, seeds, soil, or other growing media with the goal of improving plant uptake of nutrients and promoting benefits to plant development, such as tolerance to abiotic stress (Kremer 2017). Environmental preservation has greatly benefited in recent years from the use of biostimulants to enhance soil quality and promote plant growth. Due to their ability to promote plant growth and increase stress tolerance, biostimulants made from seaweed extracts are highly well-liked. According to a study by Yousfi et al. (2021), the application of a rhizogenic biostimulant, made from fulvic acids, probiotics, and prebiotics, increased microbial activity, organic matter, and enzymatic activity in both types of sandy and sandy loam soils, hence increasing their fertility. With the application of the biostimulant, the soil's calcium, potassium, magnesium, and phosphorus content increased while its pH and electrical conductivity fell.

g) **Biofertilizer**: This is a blend of dormant or active cells from beneficial strains of microorganisms such as fungi, bacteria, and blue-green algae (Aravind et al. 2021). Biofertilizers, which are microbial or soil inoculants, can enhance the fertility and productivity of plants and soil. Examples of unique microorganisms found in biofertilizers include nitrogen-fixing *Azospirillium* and phosphate-solubilizing bacteria, which make phosphorus available to plants from soil and fertilizers. Demir (2020) conducted a study to investigate the impact of microbial biofertilizer application, including *Azotobacter chroococum* and *Azotobacter vinelandii*, on the physicochemical properties of sandy-clay-loam soil in greenhouse-grown eggplant. The results demonstrated that biofertilizers could effectively improve the soil's physical and chemical characteristics, even under different irrigation levels, enhancing the overall physicochemical attributes of the soil.

h) **Soil conditioners**: These are many kinds of organic materials, gypsum, natural deposits, and various water-soluble polymers that hold water in the soil, living plants, and microbes, which makes the soil more functional. Different types of soil conditioners include: organic soil conditioner which is made of materials from living things that increases infiltration and soil water retention, provides the substrate for biological activity, and improve aeration. Farmyard manure improves the soil's biological, chemical, and physical properties. Crop residues enhance nutrient cycling and soil conservation (Shinde et al. 2019). In a study by Ejaz et al. (2022) Potassium polyacrylamide (KPAM) (30 kg/ha), was used on wheat under water stress conditions, and it was revealed that KPAM significantly reduced the negative effect of drought stress on the wheat plant used, which lead to the conclusion that the use of soil conditioners is a promising technique for dealing with negative consequences of drought stress for achieving high crop yield. Another study by Deshesh et al. (2019), on the effect of using some crop residues as natural conditioners on some physical and chemical properties and compared it with available N, P, and K on maize. It was revealed that the studied physical and chemical properties of the sandy soil were improved significantly with the application of all conditioners (sawdust, rice straw, and maize stalk).

i) **Compost tea**: a container or commercial "tea brewer" that contains composted material inside a permeable bag suspended in flowing water with the goal of preserving an oxygenated environment. The fermented end product has low nutrient levels, living microbes that were cultured from the compost, and microbial metabolites that suppress plant diseases or promote plant development (Kremer 2017). The increase in organic matter and microbial diversity in compost tea-treated soils, as well as the advantages this brings, are essential features. Regardless of the usage of compost tea, its benefits for crop growth and soil fertility, while also preventing insect and disease outbreaks, make it a modern, sustainable tool compatible with organic agriculture (Eudoxie and Martin 2019).

j) **Nanobiosensors** have also been used to find pesticides in soil samples that have been contaminated (Garba and Kumar 2020). When applied to soil quality assessment, nano biosensors have the potential to serve as innovative biological indicators by detecting and quantifying key biomarkers or indicators associated with soil health. Metals including As, Cr, Cd, Mn, and Pb may be extracted from contaminated soils using nano-materials (NMs). More recently, new avenues for pollution removal from soils have been made possible by the cooperative application of NMs and biotechnology to environmental concerns. First, the interaction between NMs and pollutants may create ideal conditions for biotechnology-based soil remediation. For instance, the addition of fullerene and graphene oxide (GO) nanoparticles increased the transport of pollutants in saturated soils, potentially increasing the effectiveness of contaminant removal by plants or microbes (Gong et al. 2018). The use of nano biosensors as biological indicators of soil quality offers several advantages, including high sensitivity, real-time monitoring capabilities, and the potential for on-site or in-field measurements.

k) **Soil Health and Genetically Modified Crops**: Plants that are genetically modified, indirectly affect the structure, function, and diversity of soil and rhizosphere microbial communities. Genetically modified microorganisms have the potential to bio-remediate soil by more effectively degrading a variety of chemical pollutants. One of the most promising new technologies for the remediation of contaminated environmental sites is the genetic engineering of endophytic and rhizospheric bacteria for use in the plant-associated degradation of toxic compounds in soil (Joutey et al. 2013). Heavy metal removal processes have employed genetically engineered (GE) bacteria to remove Cd, Hg, Ni, Cu, and Fe. Studies have demonstrated that genetically modified crops indirectly affect the composition, diversity, and structure of microbial communities in the soil and rhizosphere. The gene *CrylAb* from the bacterium *Bacillus thuringiensis*, which produces an insecticidal protein that is released into the soil by root exudation, is engineered into transgenic crops like cotton and maize to improve the soil quality (Li et al. 2022).

5 Potential Challenges of Application of Microbial Biotechnology as Bioindicators of Soil Quality

To monitor and evaluate soil quality, appropriate indicators are needed. These indicators are expected to be in line with soil management, ecological activities, climate change, merging of soil biological, physical, and chemical properties, and must be useable by different users (Lehmann et al. 2020). The existence and actions of microorganisms within the soil cannot be over-emphasized as they play a crucial role in the decomposition of organic matter and the cycling of nutrients (Brookes et al. 2008). Their activities, along with other physical and chemical factors are frequently used to qualify a healthy soil (Bossolani et al. 2021). In connecting experimental facts to the biology of soil, various indices have been used to group soil microbial populations and their activities, as measures for soil quality. Microbial diversity, activities, biomass, and soil enzymes are potential microbial biotechnological applications which are been employed as markers for assessing soil quality (Fierer et al. 2021). Notwithstanding the fact that these indices have long existed, and have proven to be very useful in most conditions, the science in which these indices are built is usually inadequate to give a clear understanding of the purpose of management implementation and policies. Kuzyakov and Blagodatskaya (2015), stated that soil microbiome activities are specific to the environmental conditions of the soil, leading to the concept of "hot spots" next to "hot moments" in the soil. "Hot spots" refer to localized areas in the soil where microbial activity is particularly intense or concentrated. Within these hot spots, microbial communities may exhibit increased enzymatic activity, nutrient cycling, and organic matter decomposition, leading to enhanced ecosystem processes. On the other hand, "hot moments" represent short periods of intense microbial activity in response to temporal changes or events. Hot moments are characterized by rapid turnover rates of nutrients, increased microbial respiration, and dynamic changes in soil processes. Quantifying soil microbial biomass, or evaluating the diversity ratio of microbes, may not provide a clear perspective for the assessment of soil quality, due to various abiotic and biotic soil factors that affect the limited involvement of microorganisms in the soil. For example, in a study by Isobe et al. (2020), a constant change in microbial populations was observed, in relation to a change in the moisture levels of the soil. Similarly, in different studies carried out by Delgado-Baquerizo et al. (2018) and Hermans et al. (2020), it was discovered that there was a steady change in the microbial population of soil, in relation to changes in the soil pH and available phosphorus in the soil correspondingly.

Also, most methods used for the estimation of microbial biomass tend to evaluate the total microbial biomass, instead of estimating the active and potentially active biomass, which is the most important fraction that contributes to the entire biogeochemical process (Blagodatskaya and Kuzyakov 2013). In the use of microbial enzymes as indicators, enzyme activity in soils is influenced by modifications resulting from agricultural management techniques such as rotating crops, performing tillage, applying fertilizers, and managing residues or some ecological factors. The impact of these modifications was observable within practical time intervals; from a month to 12 or 24 months, far earlier than alterations in the organic matter content of the soil (Alkorta et al. 2003). The challenges involved are that the Enzyme activities related to carbon/nitrogen/phosphorus (C/N/P) metabolism may not consistently indicate the actual limiting nutrient. Increased enzyme activities can be deduced as either higher nutrient availability or decreased nutrient availability and enzyme assays of this kind measure potential activities rather than in situ activities (Nannipieri et al. 2012). Assays involving soil enzyme activity, do not always define the activities of microbes in soil samples. This complicates the interpretation of soil enzyme activities when trying to distinguish the activities of enzymes that are soil-bound, from the microbial community in the soil and those found in the root of plants (Nannipieri 1994). Similarly, the measured enzymes represent only a small fraction of enzymes with potential significance in the soil (Fierer et al. 2021). In the case of microbial diversity and biomass, different soil types have been shown to be the main determining factor when extracting the nucleic acid component of microbial communities in the soil. The presence of humic or fluvic acid, which is an enzyme-inhibiting compound is known to impede nucleic acid extraction (Thies 2007). The inability to culture most soil microbes has hindered research into the discovery of the relationships between the structure and function of intricate soil microbial communities. With the advent of next-generation sequencing (NGS), in-depth study of the composition and roles of entire microbial communities and metagenomic studies have become possible (Escobar-Zepeda et al. 2015). Nonetheless, its use and application in the understanding of indicators of soil quality, has shown potential challenges. These limitations were thought to have been circumvented by the use of serial molecular methods that allow the identification, quantification, and classification of soil microbes without the necessity of cultivation (Saleem et al. 2019). Unfortunately, these methods have failed to provide a proper understanding and connection, of the link between microbial presence, capacities, and soil functions, making the use of metagenomics in the soil a complex one. This is because the results are subject to different factors which include analysis of data, nucleic acid extraction, and sequencing (Leite et al. 2022), thereby distorting its ability to correctly identify these microbes as indicators of soil quality (Lahlali et al. 2021). Precise microbes or functional genes associated with some biological processes such as production of methane, biodegradation of cellulose, denitrification and nitrification could be identified using molecular tools. In the use of these tools in the study of microbial population and their activities based on the richness of the taxa in soil, some fundamental characteristics of the soil could hinder getting a correct result. This is well known to arise when carrying out DNA extraction or amplification of targeted genes during the PCR cycle (Sipos et al. 2010). More challenges seem to arise in the presentation of data using metagenomics. This is based on the fact that microbial populations and their role in soil are determined greatly by certain physical and chemical factors present in that soil. The effect of these factors, on the population and activities of the microorganisms in the soil, is completely ignored (Kuramae et al. 2012). To have a better understanding of the impact of environmental factors on the microbial population and activities, proper measures and regulations are essential and should be taken into consideration by the use of independent research to determine overall trends using already available public data. In the effective study of microbial populations in soil, strict standardized procedures should be set up. Also, the frequency of sampling and the ideal sample size should be put into consideration and adopted in other for them to effectively serve as bioindicators of soil quality.

In conclusion, biotechnological strategies offer a promising avenue for the monitoring of soil quality. The identification and utilization of genetically engineered/novel microbial species to evaluate soil quality/health is proposed to be a more effective and eco-friendly means of monitoring soil quality. Incorporation of a hybrid of the 'omics' technology will enhance the efficiency of the biotechnological strategies that aim to improve possible soil biodiversity, soil productivity, as well as sustainable land management practices. Further research is needed to develop new soil monitoring tools that can be used in the field by farmers and land managers.

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