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DECIPHERING DIVERSE FEATURES OF SOIL AND ITS MANAGEMENT FOR A SUSTAINABLE ECOSYSTEM.

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Soil is one of the most significant component of ecosystem on earth and is responsible for the homeostasis of the environment. It has a tremendous capacity to balance the water & air quality around it but also shelters some of the most significant micro-organisms under it. This virtue of soil makes it even better than other components of the ecosystem. It also harbors the organic matter in it which is crucial for the modern-day nutritional attributes in the crop. Soil management therefore is very important exercise to maintain the soil health and its quality for a sustainable ecosystem. It also is reservoir many essential micronutrients or trace elements which then becomes the part of the food chain by entering the plant system. This review provides a comprehensive analysis of its importance in a balanced ecosystem and in achieving the Sustainable Development Goals (SDGs).

Keywords: Biodiversity, Ecosystem, Microorganisms, SDG, Soil health, Sustainability.

Introduction

The topmost layer that covers the ground is called soil. It encompasses inorganic and organic constituents and provides foundation to plants that grow while serving to be a source of water and nutrients[1]. The diverse function of the soil forms the base of our ecosystem in promoting development of plant, controlling the water movement, cycling of nutrients along with maintaining a wide variety of biodiversity[2]. In addition, soils also serve as carbon (C) sinks, which is pivotal for controlling the climate and causing reduction in the production of greenhouse gases[3]. From deforestation and industrial agriculture to pollution and urbanization, human activities have caused soils to face an unprecedented range of problems in modern times[4]. These types of dangers have compromised their ability to provide essential ecosystem services by resulting in extreme soil erosion, degradation, salinization, and desertification kind of phenomena enhance the chance of soil erosion, desertification, and biodiversity loss, with adverse influences radiating through the earth's ecosystem offerings and standard climatic conditions, and threatening agricultural production and human fitness[5].

Agriculture nowadays has a double-edged challenge: on one side, we have the urgency of feeding a growing population and on the other side, we have what kind of agriculture will be sustainable in our times? Although soil sustainability and sustainable agriculture are closely related concepts, the former focuses on the preservation of soil quality and the productivity of ecosystems for future generation[6]. The concept of soil sustainability focuses on sustaining soil health, fertility, and structure through activities that limit erosion, retain organic matter, improve nutrition cycle, and support biodiversity. The capacity of a soil to serve

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environmental necessities such as ecological services is determined by its ability to function effectively in performing inherent processes that occur in all three realms under specific topographical and climate variables, as indicated by the emerging term "soil health"[7].

Soil health is an intrinsic or the integral property of a soil[8]. Soil health may be defined as its tendency to provide a viable ecosystem for living organisms along with quality water and air for the sustainable productivity[9]. Soil health is defined as a holistic characteristic that demonstrates the soil's capacity to adapt to agricultural input to continue supporting both agricultural output and the supply of ecological services[10]. Soil health is critical for accomplishing numerous Sustainable Development Goals (SDGs) (Fig. 1), because it forms the backbone of ecological resilience and sustainable agriculture. Of the seventeen Sustainable Development Goals, which was sanctioned in 2015 by the United Nations for addressing the global issues of modern times, ideally five have a direct relationship with soils, whereas other goals have a more indirect relation[11].

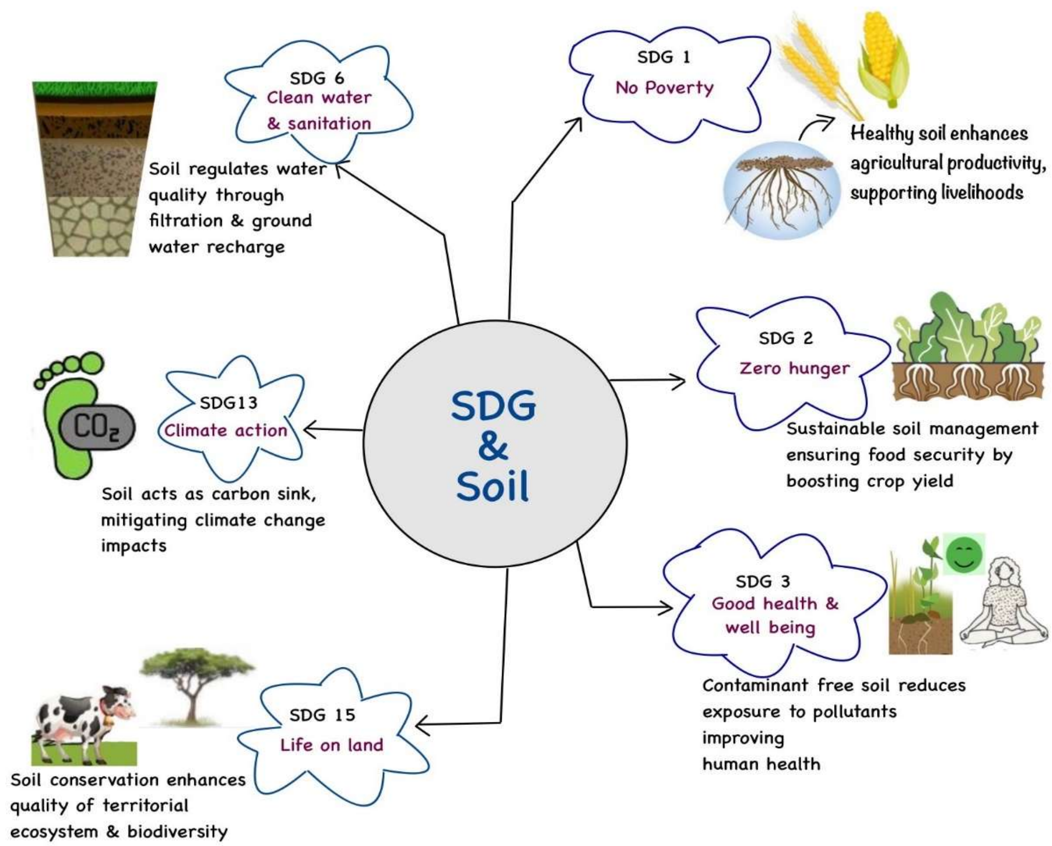

Figure 1. Significance of Soil interface with different components of the environment & ecosystem and its role in achieving Sustainable Development Goals (SDGs).

Thorough understanding about the soil health, as well as the implementation of sustainable management measures, are required to promote long-term ecological stability, productivity in agriculture, and health of the environment. This review investigates the linked roles of health of soil, quality, and sustainable methods of management for achieving environmental sustainability and comprehensive human health, stressing their joint vitality for a resilient future.

Soil: Biodiversity and Sustainability

Soils play an important role in maintaining ecosystems and human wellness, but soil biodiversity that is the richness of biological life in soil responsible for driving the ecosystems, supports the surface life and preserves pristine landscapes, has remained mostly overlooked in the overall agendas[12].

Soil biodiversity, or the vast variety of living species within the soil ecosystem, is an important component of economic agriculture operations and ecosystem conservation. The soil biodiversity described as "the variability of soil life, from genes to communities, and the complex ecological systems of which they are component, that is from soil micro-habitats to landscapes". This biodiversity is necessary for delivering an array of ecologic benefits that are crucial for wellness of humans and environs sustainability[13]. Soil biodiversity, the base for soil functions like food production, carbon sequestration, persistence of terrestrial life, and therefore key to soil restoration. Soil is a living entity teaming with a wide array of microorganisms that perform crucial functions contributing to soil health and ecosystem functioning. Soil biodiversity is the diversity of life found in soil ecosystems, encompassing bacteria, fungus, protozoa, nematodes, arthropods and earthworms. Such organisms, which make up around 30% of the species present on Earth, are well recognised by the term "biological engine of the earth"[14]. Such species combine all the critical systemic functions — cycling of nutrients, degradation of organic matter, soil structure, food production[15], detoxification and biodegradation of contaminants and purification of water[16]. A diverse array of soil biota drives fundamental soil-associated ecologic services that sustain the persistence of natural and managed ecosystems over the long-term.

Vital microorganisms of soil

Soil health is supported by a large variety of microbes that fix nitrogen, decompose organic materials, and suppress pathogens[61]. Microorganisms, nematodes, and earthworms are key to such things as nutrient cycling[62], humus production, organic matter decomposition, soil assembly, and different forms of symbiosis and parasitism with plants[17;18;19]. Some examples of bacteria associated with nitrogen fixation and organic matter decomposition include Rhizobium, Azotobacter, and Bacillus, which also contributes to soil fertility[70]. Fungus-Mycorrhizal fungus, such Glomus and Rhizophagus, create symbiotic associations with plant roots, assisting them in absorbing nutrients and water. Fungi such as Penicillium and Trichoderma help to break down organic materials and control pathogens. Protozoa and Nematodes-Protozoa recycle nutrients and regulate bacterial populations, while nematodes devour bacteria and fungi, which further aids nutrient cycling (Table 1).

Table-1 Role of different microorganisms in various biological events of the environment.

Processes	Microorganism
Nitrogen fixation[68-70,73]	*Burkholderia, Azorhizobium, Bacillus safencis, Rhizobium, Aminobacter*
Nitrification[81-83]	*Nitrosomonas, Nitrobacter, Nitrosolobus, Nitrosovibrio*
Potassium solubilization[71-73]	*Bacillus megaterium, Paenibacillus glucanolyticus*
Phosphate solubilization[74-77]	*Burkholderia tropica, Methylobacterium sp. 2A, Streptomyces sp., Apergillus niger 9-p*
Zinc solubilization[78-80]	*Acinetobacter sp. RSC9, Lecanicillium psalliotae*

Earth's soils biological diversity is important for ecological efficiency and resilience because it promotes plant health, regulates water infiltration, and increases carbon storage. This complicated web of life not only supports ground-level biodiversity[20;21] but it also helps with agricultural efficiency, weather regulation, and ecological sustainability by maintaining an equilibrium in soil environment. In addition, soil biodiversity is expected to be more sophisticated and resilient to change than aboveground organisms, making it a key defender of food stability and sustainability given the threat of global warming[16]. Modern Human activities that are known to degrade ecosystems, harm the diversity of soil and associated biological processes. Restoring soil biodiversity is essential for global health, and it presents numerous problems and opportunities[22].

Health and Quality of the Soil

Soil health and quality are terms cited simultaneously in scientific literature, and some argue that they are functionally equivalent. However, experts use the phrase soil quality, but farmers prefer soil health[23]**.** The phrases soil quality and soil health are used interchangeably in the literature. However, they may be separated in terms of timeline; "soil health" is used for shorter durations and for longer durations ‘soil quality’ is used[24]. Soil is an essential aspect of the earth's biosphere, working not just to produce food and fiber, but also to maintain local, regional, and global environmental quality[25]. The formal notion of soil quality (SQ) was created in the 2nd part of the 20th century, consequently to the necessity to examine soil degradation concerns from an integrated viewpoint[26;27;33].

Soil quality can be defined as- the soil virtue to balance the biodiversity along with quality of water and air present in its proximity for a sustainable ecosystem[28;29]. SQ is a multidimensional concept influenced by a variety of physical, chemical, and biological variables[30]. Soil quality is heavily influenced by its inherent features, including texture, structure, and mineral composition. Climate, parent material, and terrain all contribute to soil formation and development, influencing its intrinsic properties[31]. The foundation for Soil quality and sustainability evaluation was built by defining a common framework to assess soil functions, degradation threats, and soil-use choices[32]. The SQ index is also well defined and has got many parameters for calculation of soil quality[33].

Soil, in general, serves key environmental activities such as providing habitat for wildlife, providing ecosystem services, and supporting biodiversity[34]. Thus, to ensure the quality of the soil that is responsible for various ecological functions, it is important to first understand the various factors in all three realms (physical, chemical and biological) that affect quality of the soil[61].

Soil quality determinants

Soil quality is an evolving attribute that is affected by both natural and manmade sources. Understanding these elements is crucial for monitoring and maintaining soil quality.

Soil organic matter (SOM) enriches the soil health as it contains decomposed plant and animal wastes that improve the foundation of the soil, fertility, and biological functioning[36]. SOM enhances soil structure by promoting aggregation, water retention, and nutrient cycling. It also provides a home for soil microbes, which play an important role in nutrient cycling[35]. It plays an important role in regulating several environmental aspects such as reducing Na^+ concentration, holding water, its filtration and electrical insulation[40;41;62].

Soil Texture and Structure is governed by the ratio of sand, silt, and clay, affects the physical qualities of soil[39] including aeration, drainage nutrient retention, etc. Soil structure describes how particles combine into bigger units (aggregates), which influence water infiltration, root penetration, and microbial habitat. Sandy soils have strong drainage but little nutrient and water retention, whereas clay soils retain nutrients but have poor oxygenation and drainage. Loam soils are frequently regarded as the best for farming due to their equilibrium of features.

Climate affects soil moisture, temperature, and general microbial activity. Soil moisture is important in microbial operation because most microorganisms are sensitive to variations in water supply[37]. Higher temperatures boost microbial growth, which can improve nutrient cycling but can also hasten organic matter decomposition, resulting in a breakdown of SOM and hence affecting soil's quality[38]. High rainfall causes erosion and leaching, whilst low rainfall can produce drought stress, each of which affect soil health.

Microbial activity affects soil quality in variety of terms. The microbial decay converts organic waste into plant-available forms, preserving soil fertility and structure[35]. Microbial exudates improve soil structure by enhancing aggregation and porosity, allowing for improved water infiltration and root growth[36].

Some soil microorganisms have tolerance to contaminants like heavy metals and insecticides. The microbes are able to break down pollutants but prolonged exposure may exacerbate microbial diversification and have an adverse impact on ecosystem services[39].

Soil quality is influenced by various factors including land use, climate, vegetation cover, soil organism diversity, etc. Unsustainable agricultural practices, forest destruction, excessive grazing and urbanization can all damage soil structure and nutrients, reducing fertility and resilience. Developing upon the concepts that affect soil quality, the various classes of pollutants that impact the soil are diverse and frequently anthropogenic. Organic elements such as pesticides and hydrocarbons disrupt microbial activity; inorganic contaminants (heavy metals, salts, excessive nutrients) alter soil chemistry and structure. Moreover, soil pollution is caused largely due to industrial remains, plastic remains and drug waste. Comprehension of such pollutants is imperative for developing niche remediation strategies and for maintaining the ecological balance needed for soil health.

Categorization of Soil Contaminants

Soil contamination due to anthropogenic activity is responsible for a wide range of ecological and economic problems. How do contaminants affect soil structure, biomass of microorganisms/biota and health quality of water? Recognizing few of the influential factors of soil quality enlightens the path to find suitable management practices[36].

Heavy metals

Lead, cadmium, arsenic and mercury are one the most persistent and dangerous of all soil contaminants: heavy metals. They arrive in soil through mining, industry and contaminated cropping irrigation water. These metals have the potential to change soil chemistry, inhibit microbial processes and bioaccumulate in food webs. This impedes microbial diversity at high levels[37] lowering microbial functions such as nitrogen fixation and consequently impacting soil fertility[35]. Sources of toxic accumulation include mining, industrial discharges, agricultural runoff, sewage sludge and application of pesticides. Soil biota are important for nitrogen cycling and the ability of soil to break down compounds; however, toxic metals can compromise their roles.

Chemical agents

Herbicides & pesticides are the tools which industrial farming uses to kill weeds and pests. Soil pesticide residue is a soil contamination effect due to overdose or misapplication of pesticides, with negative consequences for soil health and micro-biotechnology[36]. Glyphosate, neonicotinoid insecticides and chlorothalonil fungicides lower the diversity of soil microbes[37]. Pesticides also affect the community composition (bacteria, fungus, and earthworms) of your soil. Plant-dependent water and nutrient delivery is halted due to the disruption of microbial populations in the rhizosphere[39;8].

Nutrient pollution

Nutrient contamination is a primary cause of soil degradation, primarily due to the overuse of synthetic fertilizers including nitrogen (N) and phosphorus (P). This influence affects not just soil, but also aquatic bodies, causing eutrophication and oxygen deprivation[35]. High nitrogen levels cause pH imbalances and leaching of nutrients. Excess phosphorus may become less soluble and hence inaccessible to plants[39]. Nutrient pollution affects microbial diversity, particularly among nitrogen-fixing bacteria. Salinization of the soil also promotes the growth of opportunistic organisms that are detrimental to the soil ecology[36].

Salinization

The salinization of soil occurs when water-soluble salts accumulate, which is commonly caused by poor irrigation practices, particularly in dry locations. Salinity is one of the harmful characteristics of soil quality, generating rising agricultural difficulties all over the world[43;44]. High salt concentrations inhibit plant growth, induce soil compaction, and decrease water infiltration[37;42]. Salt accumulation reduces soil moisture-holding capabilities, agricultural yield, and microbial activity[35]. Most plants and microorganisms do not thrive in salinized soils[39].

Soil contamination from industrial activity, inappropriate waste management, overuse of pesticides and fertilizers, and heavy metals all represent serious concerns. These toxins affect microbial communities, change soil chemistry, and can cause long-term environmental and health problems, emphasizing the importance of integrated management methods for soil health. Soil biota's function in improving land productivity and fertility through natural mechanisms has been acknowledged as a crucial technique for agricultural sustainability[44]. New methodologies and sustainable tactics are necessary to offset the decline in soil quality[45]. SQ is a changing attribute impacted by a variety of natural and manmade influences. Understanding these elements is critical to good soil management and sustainability.

Management of Soil

Soil management, the foundation of successful agriculture for millennia, has undergone dramatic evolution from traditional practices to modern scientific methodologies. Historically, methods such as crop rotation, fallowing, and basic tillage with animal power intended to maintain soil fertility and control weeds, demonstrating a thorough awareness of local conditions[46].

Instead, for contemporary soil management these scientific advances help inform practices that use conservation tillage, precision agriculture and data driven nutrient management to increase resource efficiency while decreasing environmental consequence[47]. This shift displays a growing recognition of the interrelated nature of soil health, environmental sustainability, and food security in an evolving global landscape. Soils physical, chemical and biological characteristics are influenced by agricultural operations[48], which in turn lead to environmental problems like soil degradation[49], waterlogging[50] salinization /alkalization[51] and pollution[52;53]. Such environmental challenges are affecting soil and crop productivity thereby restricting food production as well as security. Soil management approaches that are sustainable, promote soil health, are productive and have low environmental impact. These approaches aim to preserve resources and promote soil quality[37].

Organic farming

Organic farming prevents the use of artificial chemicals and fertilisers in favour of crop rotation, composting, and organic additives like manure and biochar. This technique results in enhanced biodiversity, higher SOM content, and better soil structure.

Conservation tillage

Conservation tillage reduces soil disturbance while protecting soil structure, avoiding erosion, and improving water retention. These measures enable microorganisms to thrive and increase soil organic matter content. This strategy preserves soil structure by limiting plowing and leaving plant remains on the soil surface[63].

Cover cropping

Cover crops, including legumes (e.g., clover, vetch) and grasses (e.g., rye, oats), protect the soil against erosion, improve soil fertility, and promote soil structure by providing organic matter[64].

Integrated pest management

IPM minimizes dependency on chemical pesticides[65] by using biological control measures, crop rotation, and resistant plant cultivars, therefore enhancing soil health and biodiversity[66].

Agroforestry

Agroforestry, or the technique of incorporating trees into agricultural landscapes, plays an essential role in maintaining soil wellness by enhancing soil structure, increasing organic matter, and lowering soil erosion[54]. Agroforestry systems can enhance soil structure, water retention, and biodiversity. Integrating trees into agricultural systems helps to minimize soil erosion by stabilizing the soil and adding organic matter. There are certain agroforestry practices such as alley cropping that is Crops grown between rows of trees increase soil fertility while decreasing wind and water erosion. Integrating vegetation and livestock improves soil fertility and avoids overgrazing[55].

Mitigation strategies

Soil management methods, as increasing soil organic matter content and implementing water-saving practices, can help to reduce the effects of climate change on soil quality[67]. Increasing SOM boosts the soil's composition, preservation of water, and microbial diversity. Mulching, drip irrigation, and rainwater collection are among techniques that can help keep soil moisture levels stable[68].

Daily life practices- certain daily life practices can also help in improving soil health and its quality. Practices of sweeping off all the dried leaves off the ground and not letting it sit in the soil itself is one of the main problems in modern lifestyle. Certain kitchen waste if managed properly and returned to soil can help maintain the soil biodiversity and help in improving the soil health.

Integrated nutrient management

To maintain a balanced nutrient supply and increase soil health, NM uses both organic (manure and compost) and inorganic fertilizers. Fertigation in which Fertilizers are applied more precisely through irrigation systems, minimizing waste and environmental impact.

Erosion is a significant danger to soil health, and numerous approaches can help decrease its impact. erosion control practices such as terracing and wind breaks helps in this scenario. Creating steps on slopes decreases water flow and improves soil retention and Planting trees and shrubs around fields to decrease wind erosion and keep soil from blowing away[56].

Aero-ecological approaches emphasize employing natural processes to preserve soil health, such as integrated pest management (IPM), encouraging biodiversity, and lowering chemical inputs. Crop rotation entails planting various crops in a certain order to preserve soil fertility and decrease pest and disease infestation. It also contributes to minimizing soil depletion caused by monoculture[57].

Conclusion

Ensuring the sustainability of soil resources is a key task that necessitates a diverse strategy. Soil quality, a notion that incorporates soil's capacity to function within ecological and land-use constraints, is an important aspect in evaluating the sustainability of land management methods[58]. Soil quality is becoming more acknowledged as a comprehensive indication of environmental quality, food security, and economic viability, and it is inextricably tied to the concept of sustainable land management[59]. Soil quality evaluations often integrate soil attributes, topography and climate to assess the suitability of a soil for specific purposes. The inherent variability of soils and their site specificity as well as trade-offs between different supported ecosystem services makes the interpretation of soil quality measures not so straightforward, though[60]. Researchers recognized several commonly used soil quality indicators, considered either physical, chemical, or biological aspects of soil as well as landscape-scale factors to aid in overcoming these complicating issues. Soil sustainability is an important feature of environmental quality, agricultural productivity, and require a delicately balanced series of biological, physical and chemical benedictions. This review highlighted the many interactions between soil biodiversity and management practices, as well as broader scale issues like pollution and climate change. Long-term land use, pollution reduction and soil biodiversity conservation should be the focus of all good plans. By merging research-based policy and smart technology, we can secure soil health down the line, driving food security, ecosystem resilience and wider sustainable development goals.

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Conflict of Interest

The authors declare that they have no conflict of interest for this work.

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