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Awakening The Earth: Exploring The Power of Awareness in Soil Health and Environmental Sustainability

Moon Moon Hussain[1], Rashmi Rekha Borah[2], G. Bhuvaneswari[3]

[1]Associate Professor, School of Social Sciences and Humanities, B.S. Abdur Rahman Crescent Institute of Science and Technology, Chennai – 600048, India

[2]Assistant Professor, School of Social Sciences and Languages, Vellore Institute of Technology, Chennai-600127, India

[3]Associate Professor, School of Social Sciences and Languages, Vellore Institute of Technology, Chennai-600127, India

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ABSTRACT

Soil, humble and often unseen, is one of the most precious gifts of nature, quietly nurturing life from beneath our feet. It is the silent foundation upon which our world depends, enabling the growth of plants that feed us, clothe us, and fuel our lives. More than just a medium for roots, soil is a powerful ally in the fight against climate change, holding more carbon than all the forests on Earth combined. It breathes life into the planet through its rich and intricate ecosystems, teeming with biodiversity we barely begin to understand. Despite its immense importance, soil remains a forgotten hero in many climate conversations; perhaps because it is everywhere, we simply overlook its value. While research on soil security is steadily growing, awareness and public understanding still lag behind. To heal and preserve this essential resource amidst the growing threat of climate change, we must embrace a new way of thinking; one that honours soil as a living, breathing part of our planet. This work seeks to illuminate the path forward by exploring sustainable practices that can restore soil health on a global scale. But knowledge alone is not enough. Only through cross-disciplinary collaboration, meaningful communication, and heartfelt public engagement can we bridge the gap between science and action. Soil needs supportive policies to thrive; policies need people's voices; and those voices can only rise through awareness. This paper reviews some significant research related to soil and is a humble call to awaken to the quiet power beneath us; a reminder that the story of soil is, in many ways, the story of our own survival

Keywords: *Soil health, regenerative agriculture, sustainable agriculture, soil management, transitions, SDGs 2030, sustainable development.*

1. INTRODUCTION

Soil as a critical component of land is one of our most valuable natural resources. The life support systems comprising oxygen, drinkable water, and food that are necessary for our survival are provided by the surface of the earth, i.e., soil which is home to a complex and varied biosphere. The idea that civilizations develop and fall in direct proportion to the quality of the soils on which they are constructed is not hyperbole [1]. The health of our soils, which are the basis for many ecosystem services, our food security, and their active participation in the climate system, is essential for human survival [2]. In contrast, soil deterioration can have a negative impact on farm agricultural productivity by lowering yields while increasing the need for inputs. It causes plants to lack nutrients, which affects crop yields that are suitable for human consumption, human health (i.e. SDG 3.1, 3.2), and overall food security (i.e. SDG 2.1). When it comes to the micro elements and macro minerals that must be provided through soil with diminishing soil fertility rates, developing countries may find it challenging to achieve their nutritional needs [2]. In order to protect the ecosystem and decrease the harmful consequences of soil degradation on emerging communities and beyond, we must identify solutions to restore soil quality. Nevertheless, soil preservation cannot be successful in a vacuum; it needs a multidisciplinary strategy that takes other development aims and objectives into account [2]. The Sustainable Development Goals (SDGs) in general and in particular the SDGs 2 and 13 on climate action and SDG 15 on living on land, can change the game in terms of soil quality.

In recent years, the scientific community has increasingly recognised soil as a critical component of ecosystem services, climate change mitigation, environmental preservation, and land use planning [3] [4] [5] [6]. For many rural communities, particularly in regions of extreme poverty, soil health plays a pivotal role in determining agricultural productivity and income levels. As the foundation of food production and ecosystem services, healthy soil systems contribute to sustainable development and poverty alleviation [7] [8]. Robust soil biodiversity is essential for reducing crop diseases and pests, which directly supports efforts to eliminate hunger and poverty. Conversely, soil degradation caused by factors such as deforestation, salinization, wind erosion, and water erosion diminishes a farm's ability to produce food by lowering yields and increasing input demands] [9], [10], [11], [18]. Soil health also influences water quality, greenhouse gas emissions, and other environmental considerations linked to the Sustainable Development Goals (SDGs) [12] [13] [18] Degraded soil lacks essential nutrients, leading to lower crop yields, compromised human health (impacting SDGs 3.1 and 3.2), and reduced food security (SDG 2.1). Diminished soil fertility poses significant challenges for developing nations, making it harder to meet nutritional needs for essential microelements and macro minerals derived from the soil. Addressing soil degradation is thus crucial for achieving sustainable development and ensuring global food security [2].

Soil is a transformative force, turning death into life. An estimated 95% of the food we consume is produced by soil, a complex mixture of rock fragments, decomposing organic matter, roots, fungi, and microbes. Despite its importance, this invaluable resource is eroding at a global average rate of 13.5 tonnes per hectare per year. While soil is naturally formed over time as decaying organic materials and nutrients integrate with the underlying rock, it erodes 10–30 times faster than it is replenished. This accelerated erosion reduces global food production by an estimated 0.3% annually, and if unchecked, could lead to a 10% loss in agricultural output by 2050. In erosion-prone regions like Nigeria, 80% of the land is degraded, and in Iowa, up to 17% of land has lost nearly all its topsoil. Fertile topsoil is increasingly ending up in undesirable locations such as ditches, reservoirs, and oceans instead of sustaining crops [14] [18].

This growing crisis highlights the need to go beyond traditional bio-geophysical studies of soil. There is an increasing recognition of the role that information management, knowledge sharing, and human behaviour play in soil health. Interdisciplinary research is essential to better understand and address the complex relationship between humans and nature to restore and maintain soil health [15] [16].

Soil health is directly tied to several Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Clean Water and Sanitation (SDG 6), Climate Action (SDG 13), and Life on Land (SDG 15). This underscores the critical importance of raising soil health awareness as a key component of sustainable development and environmental preservation efforts [17]

2. OBJECTIVES OF THE STUDY

i. To raise public awareness about the crucial role of soil in sustaining life, regulating the climate, and supporting biodiversity, emphasising its often overlooked contribution to environmental protection and climate change mitigation.

ii. To promote the adoption of sustainable soil management practices globally, by suggesting a framework for enhancing soil health and encouraging interdisciplinary collaboration to close the knowledge gap on soil health and its connection to climate resilience.

iii. To advocate for the development of supportive policies on soil health at national and international levels, underscoring the need for public support, education, and policy frameworks that recognise soil as a fundamental element in achieving environmental sustainability and combating climate change.

3. DATA AND METHODOLOGY

A review of the available literature was carried out by probing on significant electronic databases including Google Scholar, Scopus, Science Direct, PubMed, UN SDGs reports and other relevant websites of WHO, UN SDG lab, USDA and IUCN for studies focussing on soil. Keywords like soil health, regenerative agriculture, sustainable agriculture, agro-ecology, people-cantered development, SDGs 2030, sustainable development, save soil movement, etc. were used to search all the relevant materials associated with the domain of study. Also the list of references of all pertinent research papers along with reports and websites related to the topic were also explored.

4. THE CONCEPT OF SOIL HEALTH

Soil quality, or "soil health," is a vital factor in maintaining the essential functions of soil, ensuring agricultural productivity and environmental sustainability. Soil health refers to the ability of soil to function as a dynamic, living ecosystem that supports humans, animals, and plants by performing various agronomic and ecosystem roles. These include promoting biological productivity, protecting environmental quality, and fostering the health of plants and animals [19] [20].

Soil organisms play a crucial role in maintaining soil health by contributing to the formation of soil structure, transforming organic and inorganic materials, decomposing plant and animal residues, participating in the biogeochemical cycling of elements such as nitrogen fixation, and regulating the production and consumption of greenhouse gases. A biologically active soil, characterised by a diverse array of microorganisms, is a key indicator of good soil health. Biological attributes such as organic matter content, microbial biomass, respiratory activity, nitrogen mineralization, soil enzyme activity, soil fauna, and populations of suppressive organisms are all essential measures of a soil's biological vitality.

Healthy soil performs several critical functions, such as regulating water, nourishing and supporting plant life, buffering and filtering potential pollutants, detoxifying organic and inorganic materials, providing physical stability for human structures, and cycling key nutrients like carbon, nitrogen, and phosphorus. By carrying out these functions, healthy soil contributes to clean air and water, abundant crops and forests, productive grazing pastures, rich biodiversity, and picturesque landscapes [21] [22].

5. THE NEXUS BETWEEN SOIL HEALTH AND CLIMATE CHANGE

Climate variability and soil health are deeply interconnected, as climate change disrupts soil systems, leading to alterations in soil erosion, organic carbon levels, nutrient content, and alkalinity. One significant effect of climate change is the potential loss of soil organic matter, which can weaken soil structure, making it more susceptible to erosion and other forms of degradation. Factors such as heavy rainfall and rising temperatures have profound impacts on soil health. Healthy soils, which store more carbon in the form of soil organic carbon, play a vital role in mitigating climate change, but climate-induced changes can undermine this function.

Heavy rainfall, for instance, contributes to flooding, soil erosion, and landslides, all of which damage soil structure and reduce its capacity to sustain life 23]. Erosion strips away the nutrient-rich topsoil that is essential for plant growth and crop production, threatening human food security. Additionally, persistent rains lead to nutrient leaching, where minerals are washed out of the soil before plants can absorb them. This results in poor plant growth and reduced agricultural productivity. Similarly, high temperatures exacerbate soil degradation by breaking down its structure, reducing its water-holding capacity, and loosening soil particles. These changes diminish the soil's ability to remain productive and adequately support living organisms, further impairing its ecological functions [24].

6. THE EFFECT OF CLIMATE CHANGE ON SOIL AND GROUND WATER AVAILABILITY

Climate change significantly influences groundwater availability in soils, which is vital for plant growth and human survival [25] [26]. The depletion of groundwater due to climate change affects various ecosystems and food chains, including those involving humans [27]. Rising soil and groundwater temperatures may negatively impact groundwater-dependent ecosystems and could compromise critical geotechnical structures. Additionally, permafrost thawing triggered by increasing subsurface temperatures will likely alter surface and subsurface conditions, further accelerating the rate of anthropogenic climate change [28]. While long-term climate variables such as air temperature, precipitation, and evapotranspiration directly affect surface water resources, the complex and poorly understood interactions between these changing variables and groundwater are of greater significance. Increased variability in rainfall may result in prolonged and more frequent periods of extreme groundwater levels, as well as saline intrusion in coastal aquifers due to resource depletion and sea level rise. Groundwater resources are influenced by climate change both directly, through interactions with surface water systems like lakes and rivers, and indirectly, via changes in the recharge process.

To assess climate change's direct impact on groundwater supplies, it is essential to understand how groundwater recharge amounts and patterns will shift. Accurate prediction of groundwater recharge is as critical as forecasting changes in primary climate variables for evaluating the effects of climate change on groundwater resources. Consequently, it has become increasingly important for hydrogeologists to collaborate with experts from fields such as socioeconomics, agricultural modelling, and soil science to assess the potential impacts of future changes in groundwater recharge caused by both climatic and socioeconomic factors [29].

7. THE EFFECT OF CLIMATE CHANGE ON SOIL CHEMISTRY

Climate change significantly affects soil chemistry and other soil properties that are critical for crop productivity [30] [31]. The overall condition of any ecosystem is largely determined by soil characteristics, which are influenced by climate, particularly precipitation patterns [32]. Key chemical properties of soil include pH, soluble salt content (measured via electrical conductivity), nutrient and carbonate levels, their distribution within the soil profile, cation exchange capacity (CEC), and base saturation (BS) values. For instance, low pH levels enhance the mobility of harmful elements, such as heavy metals, and may lead to the loss of basic cations through leaching in well-drained, structurally stable soils that experience heavy rainfall, as seen in many upland regions of Europe [33]. In wetter climates, soil acidity could intensify if buffering reserves are depleted. Rising eustatic sea levels caused by climate change may increase flooding and salt deposition from seawater vapor along shorelines. Conversely, higher temperatures and reduced annual precipitation may limit leaching, potentially accelerating salinization and carbonate accumulation. This can lead to the formation of calcic, gypsic, or salic horizons, as well as the development of hard pans. Additionally, increased reliance on irrigation and inefficient irrigation practices may exacerbate secondary salinization [32] [34].

The loss of organic matter in soils, particularly tropical soils, is another consequence of intensive farming. This loss is primarily attributed to climate change and agricultural management practices [35] [36]. For example, studies in Finland revealed that converting acid sulfate (AS) soils for agriculture resulted in elevated levels of metal cations, potentially increasing human exposure to harmful metals. Mean concentrations of elements such as Fe, Cr, Cu, Zn, and C and N were found to be higher in AS soils compared to other soils in the same region. Since ingesting heavy metals like Cr poses risks to human health, this situation is particularly concerning [37].

8. IMPACT OF CLIMATE CHANGE ON SOIL MICRO ORGANISM INTERACTIONS

Climatic factors such as temperature, precipitation patterns, and atmospheric CO2 concentration can directly and indirectly influence soil microbial populations, though the magnitude and direction of these effects remain uncertain. Castro et al. (2010) [38] examined the effects of various climate change drivers including elevated atmospheric CO2, increased temperatures, and altered precipitation patterns on bacterial and fungal community diversity. Their findings indicated that precipitation changes had a more pronounced impact than the other factors. Notably, the shifts in microbial communities appeared to be an indirect response to alterations in plant communities rather than a direct effect of climate change. However, the biomass and species composition of plant communities were also heavily influenced by precipitation levels.

Soil microorganisms play a crucial role in regulating CO2 emissions through their physiological responses to climate change. Rising temperatures not only enhance microbial activity and soil processes but may also alter microbial community composition [39] [40] [41] [42]. Increased variability in precipitation due to climate change is expected to cause fluctuations in soil moisture, which can directly or indirectly affect microbial activity. Research suggests that uneven precipitation, leading to inconsistent soil moisture conditions, can alter microbial community composition and the bacteria-to-fungi ratio [43] [44] [45]. Drought and high temperatures, in particular, may significantly impact soil and nitrogen cycling by limiting substrate availability and reducing enzyme activity, thereby affecting soil microbial activity [46] [47] [48] [49].

9. SOIL SECURITY AND FOOD SECURITY NEXUS

Food and soil security are two critical and interconnected global challenges. Food security refers to a state where everyone has affordable access to the foods necessary to meet their dietary needs for optimal health and well-being [50] [51] [52]. Achieving food security is a universal aspiration, but it requires further research to better understand the systems and factors that make this goal attainable. Soil, being a finite resource, is at risk in many food-producing areas due to poor management practices driven by ignorance or negligence. In response to rising food demand, the world is resorting to unsustainable agricultural intensification and management, putting additional pressure on limited arable land. Addressing soil security necessitates greater awareness and care, but this cannot be accomplished without understanding the intricate connections between soil and food security. Without stable soil, producing nutrient-rich food will become increasingly challenging in the future, and how food is sourced directly impacts human and community interactions with soil. Over the past 50 years, advancements in agricultural technologies and the growing global population have placed immense strain on soils. In many regions, intensive farming practices have degraded soil health, threatening its capacity to sustain current and future food needs [53].

With the global population expected to reach 9 billion by 2050, competition for land and water resources, along with the effects of climate change, will make it imperative to enhance yields and food quality using existing soils. To maintain soil productivity while improving agro-ecosystem health, holistic production management systems must be adopted; systems that are socially, environmentally, and economically sustainable. Farmers play a pivotal role in this effort. Sustainable farming practices such as agro ecology, conservation agriculture, organic farming, zero tillage, and agroforestry are instrumental in managing soils responsibly and boosting agricultural productivity. Ultimately, fostering a deeper understanding of the interplay between soil biology, ecosystem functions, and human actions will help minimize adverse impacts and better harness the benefits of soil biological activity for more productive and sustainable agriculture [54].

10. SOIL ELEMENTS NECESSARY FOR HUMAN HEALTH

Soil contains 14 essential elements necessary for plant growth: nitrogen (N), calcium (Ca), phosphorus (P), magnesium (Mg), potassium (K), sulfur (S), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn), boron (B), chlorine (Cl), molybdenum (Mo), and sodium (Na). Additionally, some plants require other elements such as cobalt (Co), bromine (Br), vanadium (V), silicon (Si), and nickel (Ni), though these are not universally needed. Air, water, and carbon (C) also contribute essential components for plant growth by providing hydrogen (H), oxygen (O), and carbon (C). As a result, consuming plants grown in nutrient-rich soil supplies humans with most of the essential nutrients required for survival, as healthy soils foster nutrient-dense plants. However, nutrient deficiencies in soil can lead to significant health issues.

Iron deficiency is the most prevalent nutrient deficiency, potentially affecting up to 5 billion people, with 2 billion suffering from anemia. Another critical deficiency, iodine (I), can cause goiter, severe cognitive and neuromotor impairments, and other neuropsychological disorders. Recognising this, the World Health Organization has prioritised the eradication of iodine deficiency, as an estimated 1 billion people remain at risk. Iodine deficiency has been largely eradicated in many developed countries through the fortification of food products like salt and bread, but it persists in certain high-altitude, inland regions, particularly in poorer nations across South America, Africa, and Southeast Asia.

Selenium (Se) deficiencies in soils, which affect crops like wheat, are associated with low dietary selenium intake. This can lead to Keshan disease, a cardiac condition, and Kashin-Beck disease, a debilitating form of osteoarthrosis. Low selenium levels have also been linked to cancer, heart disease, reproductive issues, muscular disorders, and asthma, although further research is needed to confirm these connections. Selenium deficiencies are notably problematic in regions like northeast China, the Tibetan Plateau, parts of Africa, the Pacific Northwest, the Great Lakes, and the eastern United States.

Zinc deficiency can result in stunted growth and hypogonadism. While certain foods like whole grains may contain zinc, the bioavailability of zinc can be low, leading to deficiencies in humans. Copper deficiencies, which have been linked to heart disease, often occur in soils with specific characteristics such as alkaline sandy soils, acidic Histosols, and acidic sandy soils [55].

11. SOIL-FOOD-ENVIRONMENT-HEALTH NEXUS FOR SUSTAINABLE DEVELOPMENT

Addressing food security and achieving the Sustainable Development Goals (SDGs) requires a holistic understanding of the connections between soil, food, the environment, and human health. Sustainable soil and land management support a range of ecosystem services, including agricultural productivity, food security, climate change mitigation, and resilience. Notably, SDG 15 emphasizes the importance of preventing and reversing land degradation by 2030, highlighting the critical role soil health plays in attaining multiple SDGs [57].

Raising national and regional awareness about the functions and importance of soil is essential for meeting the UN's 2030 SDG targets. Managing soil health sustainably is pivotal to achieving various SDGs [58], such as SDG 2 (Zero Hunger), which directly links soil to food production and healthy living. Soil also provides vital ecosystem services like nutrient cycling and water regulation, which are crucial for agriculture and tie into goals like SDG 1 (No Poverty), SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation), and SDG 13 (Climate Action). Additionally, SDG 15 (Life on Land) calls for the restoration of degraded soils and land to achieve a future free from land degradation.

The importance of soil has been increasingly recognised in global initiatives. For instance, 2015 was declared the International Year of Soils by the United Nations General Assembly to raise awareness about the indispensable role of soil in supporting life. Similarly, the Save Soil Movement, spearheaded by Sadhguru Jaggi Vasudev and supported by the WHO, UN SDG Lab, and IUCN, aims to combat soil degradation and desertification. Launched at the UN in Geneva on April 5, this movement seeks to implement urgent legislative measures requiring agricultural soils to maintain an organic matter content of 3–6%. Without adequate organic matter, soil scientists warn of the risk of widespread soil degradation and potential extinction [70].

Improving soil carbon content, restoring degraded agricultural land, and maintaining organic carbon-rich soils are key strategies to address food security, adapt food systems to climate change, and mitigate anthropogenic emissions. Sustainable agricultural practices must not only enhance soil health but also be environmentally, socially, and economically viable. One of the greatest challenges to implementing sustainable practices, however, is economic feasibility. Conventional agriculture often focuses solely on maximising yield, but this approach has failed to address broader issues such as environmental sustainability and human health. To ensure a sustainable future, it is critical to adopt soil restoration strategies that are both effective and practical for farmers to implement.

12. SOIL HEALTH MANAGEMENT: THE SIGNIFICANT STEP TOWARDS SUSTAINABILITY

Soil consists of air, water, decomposed plant material, organic matter from living and deceased organisms, and mineral components such as sand, silt, and clay. Increasing organic matter often improves essential soil processes, such as water infiltration and nutrient cycling. Healthy soils are porous, allowing air and water to move freely. Such soils provide an ideal environment for plants, soil microbes, and beneficial insects to thrive. Crops grown in healthy soil are more resilient, as they can better resist pests and absorb nutrients efficiently. Managing soil health is one of the simplest and most effective ways for farmers to boost both productivity and profitability while improving the environment. By increasing organic matter and promoting soil organisms, farmers can enhance soil structure, aeration, water retention, drainage, and nutrient availability, leading to increased crop yields. Healthy soils also defend against drought, as their improved water absorption and storage capabilities provide plants with adequate water during droughts [60].

When we adopt management practices that improve soil health, we ensure both present and future productivity and profitability. Healthy, functioning soils enable the production of a wide range of products at minimal costs. Therefore, maximising profitability requires prioritizing soil health. Research on soil health has identified effective methods for managing soil to enhance its functionality. A key aspect is maintaining a suitable habitat for the diverse organisms within the soil food web. This can be achieved by reducing soil disturbance, growing as many diverse plant species as possible, and keeping the soil consistently covered [61].

For soil to be agriculturally productive, it must contain at least 3–6% organic matter. However, in most regions worldwide, soil organic content is significantly below 1%. Records show that no country has soils with a minimum of 3% organic matter. Over the past 25 years, approximately 10% of the earth's land has become desert. To restore soil, the global narrative around soil must shift. It is essential to recognise that soil is a living system rather than an inert material. Unfortunately, many agricultural departments, institutions, and scientists still treat soil as merely a "material," believing it only needs small amounts of nitrogen, potassium, and phosphorus. According to United Nations agencies, the rapidly declining organic content of soil means that agricultural soils may be depleted within the next 50–60 years, leaving no viable land for cultivation. To address this crisis, land managers can adopt a range of soil health management practices to reduce risks and enhance resilience, particularly in the face of increasingly severe and unpredictable weather conditions [62]. Let's explore some of these methods:

- ***Monitor Soil Health On Farms***

For a farmer, soil is as essential as the pulse is for a doctor. It helps guide critical decisions such as when to irrigate, what and when to plant, and how to use fertilizers. While some farmers possess an innate ability to assess soil moisture and condition, this skill is not universal. In the age of climate change, making informed farming decisions based on soil health and moisture has become even more complex. As the saying goes, "if you can't measure it, you can't improve it," and this holds especially true for soil health [63]. Soil monitoring provides farmers with valuable insights into the current and potential performance of their farms. Effective monitoring involves measuring key indicators such as soil organic matter, soil life, and soil texture, alongside pH and nutrient profiles. Routine soil health assessments, like earthworm counts, infiltration tests, or lab-based analyses, empower farmers to take timely corrective actions. This ensures compliance with water usage regulations and prevents unnecessary nutrient applications.

Focusing on soil organic matter levels, especially in arable fields that may face higher risks of degradation, is particularly important [64]. Farmers can track changes over time by consistently using one lab for testing and conducting assessments frequently; ideally at least once every five years. Tools such as the Farm Carbon Cutting Toolkit, the Cool Farm Tool, or Agrecalc can help evaluate soil health and the overall farm system, improving long-term sustainability. Governments can further support soil health monitoring by establishing clear policies and providing incentives to motivate farmers to improve soil quality above their baseline soil type. Such measures would encourage widespread adoption of monitoring practices, ensuring healthier soils and more sustainable agricultural practices [65].

- ***Rotational Grazing Practices Improves Soils***

Rotational grazing enhances the return of plant and animal materials to fields, contributing to soil health and sustainability. While increasing soil organic matter is a gradual process, its benefits extend far beyond the farm. Grazing animals play a critical role in nutrient cycling, redistributing nutrients and organic matter back into the soil when managed strategically to graze at specific locations and times [66].

Grazing stimulates plants to grow deeper and more extensive root systems. These roots shed and decay over time, enriching the soil with organic matter and biomass while capturing carbon from the atmosphere. Rotational grazing also reduces soil erosion and agricultural runoff, improving soil stability. Additionally, it enhances fodder productivity, as plants often exhibit improved growth rates under this system [67].

The practice also addresses issues like soil compaction and uneven manure distribution. During rotational grazing, cattle can be removed from cool-season pastures when the remaining forage height is three to four inches. This leftover vegetation protects the soil from wind, rain, and trampling, reducing erosion and runoff. By retaining soil organic matter and nutrients, water availability for plant growth increases. Maintaining an appropriate forage height not only protects soil structure but also supports faster forage regrowth, ensuring a sustainable cycle of productivity [68].

Farmers can explore the benefits of using composts and animal manure as alternatives to synthetic nitrogen-based fertilizers. By adopting practices like growing cover crops and participating in field trials for fertility-boosting green manures, they can enhance soil health and sustainability. Additionally, introducing livestock onto farms and investing in the ecological regeneration of grasslands with the help of subsidies can further improve nutrient cycling and soil fertility.

Governments can play a pivotal role in supporting these initiatives by establishing clear goals and strategies to close nutrient loops in agriculture. This may include promoting mixed farming systems through incentives and reducing the number and size of intensive livestock operations to lower manure and slurry volumes. Policies encouraging the use of green manures and cover crops as fertility-building practices can further support sustainable farming.

Improving soil health can also be achieved by creating a hierarchy for the use of farming by-products, such as prioritizing anaerobic digestion for fibre waste and ensuring the safe recycling of all domestic and non-domestic food waste back into the soil. Increasing the safe recycling of sewage waste into soils and encouraging research to reduce contamination in recycled products can also make a significant difference. Additionally, exploring opportunities to recycle more organic matter from livestock, human, food, and crop waste both now and in the future can lead to long-term improvements in soil health and fertility [65].

- ***Crop Rotation***

Crop rotation is a sustainable agricultural practice that helps replenish essential nutrients in the soil without relying on synthetic inputs. This approach disrupts the cycles of pests and diseases, enhances soil health by increasing biomass through diverse root structures, and promotes biodiversity in both cash crops and cover crops. Diversity in plant species not only supports soil life but also attracts beneficial insects and pollinators, further boosting ecosystem health [71].

By incorporating diverse crop rotations, farmers can reduce crop-specific pests and diseases, improve soil microorganism health, and ultimately achieve better yields. For high-value crops such as potatoes and carrots, insufficient crop rotations can make sustainable production challenging. To address this, farmers can design rotations with more variety and longer intervals between planting the same crop. Incorporating cover crops and increasing soil organic matter are particularly effective when spring crops are included in the rotation [66].

Crop rotation systems that include leguminous crops are especially beneficial, as they reduce the need for synthetic fertilizers and help minimize nitrate leaching into groundwater. While crop rotations do not guarantee yield increases in all scenarios, they contribute to long-term soil health and sustainability.

Governments can support these practices by assisting farmers in transitioning to specialty and protein crops and funding research into alternative crops with a focus on climate resilience. Such measures can encourage broader adoption of diverse crop rotations while addressing environmental and economic challenges [65].

- ***No-till/Conservation Tillage***

Traditional or intensive agriculture often degrades soil both physically and chemically, resulting in the loss of organic matter, reduced biological activity, and declining crop productivity [73] [74]. While the plough is historically celebrated as one of the greatest agricultural innovations, it can significantly harm the soil. Tilling disrupts soil structure, dries out the topsoil, and accelerates erosion, even though it serves to break up compacted surfaces, control weeds, and incorporate organic matter. Similarly, excessive irrigation; another traditional practice; can harm soil by degrading its biodiversity, lowering water quality, and diminishing its productivity. In Europe alone, approximately 70% of soil is considered unhealthy due to these detrimental practices.

Soil disturbances can arise from physical, chemical, or biological activities. Physical disturbances, like tillage, leave soil bare or compacted, creating an inhospitable environment for soil microbes. Improper use of agricultural inputs can disrupt the symbiotic relationships between fungi, other microorganisms, and plant roots, negatively affecting soil health. Overgrazing, a form of biological disturbance, influences soil temperature, increases runoff, and reduces root mass, further degrading the habitat for soil microbes and destabilizing the soil food web [72]. Sustainable agriculture offers an alternative approach, founded on three core principles: crop rotation, soil-free farming techniques, and maintaining continuous soil coverage with vegetation or plant detritus. These practices aim to restore and preserve soil health, ensuring long-term productivity and ecological balance [73] [74].

Farmers can reduce nitrogen fertilizer inputs by conducting a Farm Gate Nutrient Balance of Nitrogen, which assesses the overall farm operation. This process helps identify potential financial losses, environmental damage caused by nitrogen surplus, and opportunities to transition to using recycled nitrogen produced on the farm. Such measures can help address these challenges effectively. To further reduce dependency on chemical inputs, farmers can increase habitat for natural predators, thereby reducing the need for insecticides. Leaving certain areas unsprayed can also help determine whether fungicides are necessary, as improved soil health may naturally decrease the risk of fungal diseases, making routine fungicide applications less essential. Farmers can explore practices like reduced tillage or no-tillage systems, observe farms that successfully utilise these methods, participate in farm trials, or connect with innovative farmers for knowledge sharing. If local resources are unavailable, reaching out to organizations like the Soil Association can provide additional guidance. The government can support these efforts by promoting minimum and no-tillage systems as part of whole-farm approaches. This can be achieved by funding research and development focused on the benefits of soil biology, addressing regulatory gaps to protect soils, establishing statutory pesticide reduction targets (covering both usage and associated risks), enforcing the polluter-pays principle for pesticide and fertilizer use, and offering financial incentives and rewards for adopting low-tillage practices [65].

- ***Reduce Soil Compaction from Machinery and Livestock***

Soil compaction is one of the most significant yet relatively simple issues to address. It can lead to increased surface runoff, drought stress, reduced grazing days, weak root growth, and lower yields [75]. While awareness of the dangers of soil compaction is growing, the solutions have been inconsistent. The trend toward larger tractors and equipment continues to exacerbate the problem. Some farmers are adopting measures to combat soil compaction, such as reduced or no-till farming methods when appropriate, utilizing satellite navigation technology to minimize soil travel, and implementing Controlled Traffic Farming (CTF) systems. CTF confines machinery movement to designated tracks in the field, reducing the area exposed to compaction. These practices are more commonly used by arable farmers raising crops for market. In England, enforcement efforts have increased due to the 2018 farming rule requiring farmers to take reasonable measures to reduce agricultural diffuse pollution, including addressing soil compaction [76].

Several mitigation strategies can help minimize compaction risks. These include using lighter equipment, properly managing tyre pressure, reducing the number of passes over the field, avoiding over-grazing, and refraining from driving on or grazing wet soils. Other practices include adopting reduced-till or no-till methods, avoiding late harvesting on vulnerable soils, and implementing Controlled Traffic Farming. Governments can play a critical role by raising public awareness about the impact of soil compaction on productivity and promoting its prevention, detection, and management. Clear baseline regulations that include compaction prevention should be established, enforced with unambiguous penalties, and supported with adequate funding to ensure compliance [65].

➢ ***Bring More Trees onto Farmland***

Trees play a multifaceted role in the landscape, offering more than just aesthetic value. They contribute to soil stabilization, carbon sequestration, and nutrient cycling, while also providing habitats for a wide range of insects, birds, and animals. Strategically placed trees can enhance agricultural operations by improving water management, reducing the risk of flooding, and supporting overall ecosystem health. Integrating trees into farming systems; whether as hedgerows, individual trees, farm woodlands, or agroforestry systems can also boost agricultural productivity. These benefits include protecting crops and livestock from extreme temperatures, cold, and wind, along with offering long-term market opportunities through the production of fruit, nuts, or lumber.

Farmers have several options for incorporating trees into their land, such as allowing natural regeneration, planting trees on vulnerable or steeply sloped fields, or adopting agroforestry strategies. These approaches may involve establishing shelterbelts, riparian plantings, extending existing woodlands, connecting woodlands with corridors, or planting trees in unused field corners. Other methods include replacing or enhancing old hedges or creating alley cropping systems, where trees provide additional income from products like fruit, nuts, or timber while complementing ongoing agricultural activities.

Government support plays a critical role in enabling farmers to adopt such practices. Initiatives could include providing funding for capacity-building programs and training to equip farmers with the skills needed to manage trees and woodlands effectively. Governments can also invest in research and knowledge transfer on agroforestry practices, offer capital subsidies to encourage tree-planting projects, and develop infrastructure and supply chains to support woodland-based industries. Such efforts ensure that farm woodlands and agroforestry systems are integrated seamlessly into agricultural operations, promoting both sustainability and productivity [65].

➢ ***The Contribution of Nuclear and Isotopic Techniques***

Nitrogen-15 and phosphorus-32 isotopes are valuable tools for tracking the movement of labelled nitrogen and phosphorus fertilizers within soils, crops, and water systems. They provide quantitative data on fertilizer efficiency, mobility, residual effects, and transformations, which is crucial for developing improved fertilizer application techniques. Additionally, the nitrogen-15 isotope method measures the amount of atmospheric nitrogen fixed by leguminous plants through biological nitrogen fixation.

The carbon-13 isotope signature is another useful tool, enabling the quantification of agricultural residue integration for enhanced soil fertility and stabilization. For instance, by analysing crop residue incorporation, this technique assesses the impact of conservation practices on soil moisture and quality. This information helps identify the sources and relative contributions of different crop types to soil organic matter, offering valuable insights for sustainable soil management [77].

Recognising specific climate threats and the importance of agricultural planning to address them is essential. However, the level of understanding about these risks varies widely among stakeholders. Individuals with high awareness, such as researchers and local input suppliers or off-takers, often operate within institutional silos, reflecting the persistent gap between theory and practice. Meanwhile, transnational corporations and international NGOs, which are beginning to raise awareness, struggle to fully understand the practical implications of these threats. They often neglect long-term crop suitability and spatial planning concerns from the perspective of smallholder farmers.

At the grassroots level, awareness is lowest among smallholder farmers and local planners, who frequently lack access to critical information about anticipated climate changes and their effects on crop suitability thresholds. This knowledge gap makes it challenging for those directly impacted to make informed decisions or adapt effectively to changing climatic conditions [77].

13. THE WAY FORWARD FOR SOIL HEALTH AWARENESS TO CREATE A SUSTAINABLE WORLD

The development, formulation and implementation of widely accepted environmental protection and climate mitigation policies at both global and regional levels are essential for ensuring the sustainable use of soil in today's world [78] [79] [80]. These policies must gain broad acceptance and adoption to be truly effective. It is crucial to demonstrate that everyone can benefit from the transition to healthier soils, ensuring no one is excluded or left behind. Open dialogue among farmers, policymakers, consumers, and the scientific community is necessary to address the needs and interests of all parties equitably. Such direct interactions foster mutual understanding and shed light on the challenges to taking specific actions. For a successful transition to healthy soils, every stakeholder needs appropriate tools and support.

Farmers: Farmers require fair pricing and incentives to invest in soil health and produce high-quality products, along with financial security to manage their expenses and loans. They may also need further education, access to unbiased advisors, and recognition for their hard work in supplying food to society [81].

Consumers: Consumers seek food that is affordable, nutritious, and healthy. By supporting environmentally responsible food production, they can help sustain a robust market that promotes minimal environmental harm. A well-informed consumer base that understands the importance of soil health can make thoughtful choices that contribute to a healthier planet by prioritizing soil, climate, and human well-being. However, consumers often lack sufficient knowledge about how soil and people are treated within food production systems. Frequently, they overlook or deny the environmental impacts of their purchasing habits, especially those affecting distant regions. If consumers were fully informed about the realities of food production, they might develop a strong aversion to the existing systems and demand more sustainable alternatives [81].

Certification and Labelling: A society that understands the impact of its consumption habits demonstrates greater awareness and cognizance than those that do not. Consumers can accelerate the shift to sustainable food systems by prioritizing the purchase of locally and seasonally produced foods that improve soil health and directly support farmers. Farmers who adopt sustainable practices to maintain soil health or openly communicate their environmentally friendly methods may either receive formal certification based on a structured framework such as a supply chain with defined criteria tied to management practices and measurable soil health indicators; or gain informal recognition through direct sales to customers. To promote soil health and local, seasonal food production, the food industry can also support farmers by offering fair price premiums and accepting lower profit margins for certified products.

Labelling and certification systems that highlight soil health-focused production methods can encourage consumers to make more sustainable choices. Supermarket labels can simplify decision-making for shoppers, enabling them to choose environmentally friendly products without investing extra time in research. These certifications and labels not only help consumers identify sustainable options but also raise awareness about the importance of soil health. Increasing the visibility of certified products, for example, by positioning them prominently on supermarket shelves without added costs, can further motivate shoppers to choose sustainable options [81].

Education: Although there is ample information available about soil health, it has not yet reached or effectively raised awareness among a wider audience. For instance, while World Soil Day is observed annually on December 5th with a unique theme each year, its impact remains limited. A new strategy is needed to educate society about the importance of soil health. Educational efforts should target all age groups, from young children to adults. Schoolchildren can be encouraged to understand and appreciate soil health by growing vegetables in school gardens. Activities such as exploring soil layers and learning about earthworms could be organised during a designated soil awareness week, perhaps aligned with World Soil Day [81].

Young farmers: Training programs for young farmers should be revised to place a stronger emphasis on soil health. By receiving in-depth education on practices that enhance soil health and learning about updated, sustainable regulations, young farmers can manage soil better than previous generations. Immediate updates to educational programs are critical; otherwise, achieving significant progress in soil management may require waiting for another generation.

Adults: Education about soil health should not stop when people enter the workforce. Instead, awareness should be expanded through the promotion of educational videos on platforms like YouTube, Facebook, and television, making soil health as prominent an issue as climate change. Beyond digital outreach, initiatives like open farm days can foster connections between farmers and consumers, enabling discussions about farming challenges and goals. Public education efforts, including product labelling and widespread awareness campaigns, must also receive consistent support to ensure long-term engagement [81].

14. CONCLUSIONS

This study was aimed to give all the readers and stakeholders a deeper understanding of what we can do to help accomplish the SDGs connected to land and soil while minimising quid pro quo with other SDGs. It is an effort to share successful illustrations of land and soil management with other scientists, policymakers, practitioners, end users, and people. There will surely be major repercussions for humanity if the value of soil in increasingly intensive agricultural systems is not recognised. Consideration of intergenerational justice would also be a failure of contemporary civilization [82] [83].

There is a necessity to establish the narrative that soils are becoming a scarce resource, and that the degradation of soils causes a demonstrable economic and monetary loss of services. UNESCO has raised alarms about widespread soil degradation, emphasising soil's critical role in sustaining life on Earth. Director General Audrey Azoulay called for prioritising soil protection and rehabilitation, estimating that 75% of the world's land is already degraded, potentially rising to 90% by 2050. Soils are fundamental for food production, water filtration, climate regulation, and biodiversity. Erosion caused by water, wind, and ploughing are major threats, exacerbated by deforestation and intensive farming practices. Experts recommend adding organic matter, maintaining permanent soil cover, and reducing ploughing to combat soil degradation. Initiatives promoting soil-conserving agriculture face resistance from conventional agricultural practices and insufficient legislation [84]. As such, the significance of soils in our lives must be unambiguously considered in economic agendas and policy making. Raising awareness of the importance of soil and land can change our world into one that is sustainable for our well-being and the wellbeing of future generations as well. The Food and Agriculture Organization (FAO) offers thematic infographics and factsheets to educate the public on various aspects of soil health, including its role in water filtration, climate change mitigation, and biodiversity support. These resources are available in multiple languages to reach a broad audience. Raising awareness about soil health is crucial for implementing sustainable practices that ensure long-term ecological balance and human well-being [85]. The most effective strategy is to highlight the robust association of soil and land to the challenges such as biodiversity, food and water supply, climate change, migration and peace that are considered significant on the social and political forefront.

Soil is recognised as one of the most essential natural resources on Earth, playing a critical role in maintaining life and environmental stability. It supports vegetation growth for food, fibre, and fuel, thereby forming the foundation of human food production systems (FAO, 2015) [86]. Beyond its role in climate regulation, soil also supports a complex and diverse ecosystem that contributes to biodiversity and ecological health [87]. Despite these critical functions, soil is frequently omitted from climate change discussions, possibly due to its pervasive nature and the tendency to take it for granted [88]. As such, there is an urgent need to elevate the significance of soil health in both environmental policy and public consciousness. Although there has been extensive research on soil degradation and soil security, public awareness of soil health remains limited. Awareness is crucial, as supportive policies require public endorsement, and such support is grounded in understanding and education [89]. The marginalisation of soil in climate and environmental discourse has contributed to a gap between scientific knowledge and societal action. To address this gap, a collaborative, interdisciplinary approach is necessary to promote sustainable soil management practices [90]. Educating the public about the ecological importance of soil and its vulnerability to climate change can foster greater engagement and advocacy. Raising awareness not only promotes behavioural change at the individual and community levels but also provides a foundation for policymaking that prioritises soil health. A global shift toward recognising soil as a vital component of environmental protection is imperative. This requires structured awareness programs, policy interventions, and academic initiatives that emphasize the central role of soil in sustaining ecosystems and human livelihoods

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