Review Article

Unravelling the Dynamics of Soil Health: Key Insight and Future Direction

Abstract

A healthy soil serves as a dynamic living system that provides a variety of ecosystem services, including maintaining plant production, managing the recycling and breakdown of soil nutrients, and eliminating greenhouse gases from the environment. Because soil microbial activity and variety are the primary determinants of soil health, soil health and sustainable agriculture are intimately related. Tillage and organic farming have been demonstrated to enhance soil health by raising the quantity, variety, and activity of microorganisms in the soil. While organic farming may result in exclusion of synthetic fertiliser inputs, and improve stability in environment sustainability, conservation tillage has the potential to increase growers' profitability by reducing inputs and labour costs when compared to conventional tillage. The capacity of a crop production system to consistently generate food without causing environmental damage is known as agricultural sustainability. Beneficial microbes, nematodes, cyanobacteria, and arbuscular mycorrhizal fungus (AMF) improve plant water and nutrient availability, phytohormone synthesis, soil nutrient cycling, and plant resilience to environmental challenges. Concepts related to soil health are frequently used to compare soils, analyse changes, and gauge how well land-use management is working. The external elements influencing soil health and their significance for sustainable agriculture will be covered in this review.

Keywords:soil dynamics, soil health, soil properties, environmental sustainability

1. Introduction

Environmental quality and sustainable agricultural output depend on healthy soil. Everything that humans and other species on Earth need to survive, including food, fibre, habitat, shelter, open space for enjoyment, clean air and water, and more, is based on the soil. "The capacity of a soil to function as a vital living system within ecosystem and land use boundaries to sustain plant and animal production, maintain or enhance water and air quality, and promote plant and animal health" is the definition of soil health given by Doran and Zeiss [1]. It is acknowledged as a set of traits that classify it taxonomistically and determine its state of health. On the other hand, soil quality is an external feature of soils that varies depending on how humans intend to utilise them [2]. It could have to do with how well agriculture produces goods for recreation, preserves watersheds, and supports animals.Indicators sensitive to management in soil health assessment programs have difficulties due to the large degree of geographical variability in soil and faulty agricultural practices leads to groundwater contamination [56]. The demand for agricultural goods is expected to rise due to the predicted rapid growth in global population to 8.9 billion people by 2050 [3]. “With increase inpopulation, there is shrinkage on cultivable land. Therefore, the main focus would be on increasingthe productivity by adopting improved cultivationpractices” [60].In the future, increasing crop yields using sustainable methods will be necessary due to rising food needs and a lack of fresh agricultural land.

All agricultural systems depend on effective soil management, although there is evidence of widespread soil deterioration in the form of pollution, compaction, erosion, loss of organic matter, increased salinity, and other negative effects [4]. Although naturally occurring soil deterioration is more gradual and slower than accelerated, it has a significant long-term influence on both agricultural output and the surrounding ecosystem. By adjusting and developing soil health metrics that may be used to track its state and function as a crucial component of sustainable agriculture, degradation is prevented. In addition to generating more food to feed the world's growing population, soil health management takes a comprehensive approach to preserving our soils for use by future generations [5]. These methods complement one another to determine the health of the soil. A major problem is meeting the expected demand for food production that is both sustainable and healthful. Indeed, one of the main objectives of sustainable agriculture is to increase crop output while protecting agroecosystems and reducing the effects of climate change [6].

Novel integrated strategy known as "sustainable agriculture" has been described as having the potential to address both practical and fundamental problems with food production in an environmentally responsible manner [7]. In order to create novel methods that don't hurt the environment, it incorporates biological, physical, chemical, and ecological aspects [3]. Furthermore, sustainability may be able to support global food agriculture demands [8]. The evaluation of soil health is predicated on characteristics related to soil quality that ensure the sustainability of crop production on agricultural areas [1,9]. Numerous investigations revealed that key markers of soil quality include the microbial community, abundance, variety, activity, and stability [10]. An assessment of soil health includes determining how well-suited the soil is to carry out intended tasks as well as how resilient it is to deterioration (Fig. 1). Researchers, producers, and land managers use a variety of qualitative and quantitative indices to determine the relative worth of healthy soil [11]. The restoration or improvement of soil health requires worldwide attention. It is anticipated that the evaluation of soil health indicators would further our knowledge of the underlying mechanisms promoting sustainable agriculture. The study results on soil health management techniques and their function in a sustainable environment will be covered in this review.

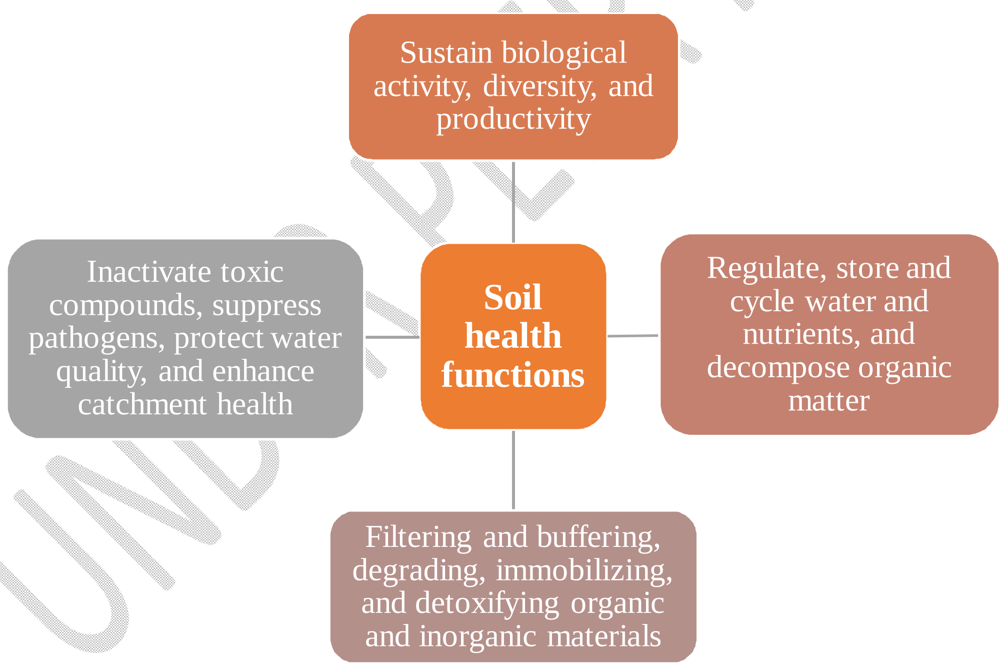

Fig. 1: Assessment of soil health function for sustainable agriculture

2. Soil Biodiversity and Sustainability

The term "soil biodiversity" describes all living things found in the soil. "The variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is, from soil micro-habitats to landscapes," is how the Convention on Biological Diversity defined soil biodiversity [12]. It has been demonstrated that factors like as growing human populations, changing global temperatures, degrading soil, and loss of arable land put more strain on natural resources and jeopardise systems that ensure the sustainability of the planet. [13]. Earth's soil biota is one of the planet's greatest repositories of biodiversity [14]. By controlling species asynchrony, aboveground net primary output, and plant diversity, soil biota influences the stability of ecosystems. Stressors on soil biodiversity included excessive grazing, declining soil organic matter, pollution, soil erosion, land degradation, intense human usage, and changes in climate [15]. Soil quality is decreased by unsuitable agricultural methods such as salinisation, acidification, compaction, crusting, lack of nutrients, decrease in soil biota biomass and biodiversity, water imbalance, and disturbance of elemental cycle [16]. The aggregate characteristics and functions of soil include population control, nitrogen cycling, and decomposition [17]. The cycling of nutrients, particularly nitrogen, and decomposition are the biological processes that occur in soil [18, 19].

A crucial agronomic technique to encourage soil biota-mediated degradation and mineralisation is the appropriate choice of organic residues, given their innate vulnerability to both enzymatic hydrolysis and physical breakdown [20]. Microbial capacities are often linked to soil health and agricultural sustainability through their functional abilities to nutrient acquisition, mobilisation, fixation, recycling, decomposition, degradation, and remediation in the soil [9]. Maintaining crop development and production requires an understanding of how soil biota mediates soil processes. Soil biota often drives both processes [15]. Soil biota often reacts quickly to soil management techniques and is linked to the squelching of pathogenic organisms, nutrient cycling, and detoxifying of water storage [21]. Plant health, soil fertility, and soil biota are closely correlated [22]. It has been acknowledged that one of the most important approaches to achieving agricultural sustainability is the function that soil biota plays in enhancing land productivity and fertility through biological processes [23]. For global agricultural sustainability, it is therefore essential to understand the risks to soil biodiversity and take appropriate action.

3. Soil Health

3.1 Concept and Background

A sustained agricultural output depends on the health of the soil, which is an essential natural resource. Increased soil water retention and availability, soil aggregation, nitrogen cycling and storage, and microbial diversity and function are just a few of the ecological services that soils perform. An assessment of soil health includes determining how well-suited the soil is to carry out intended tasks as well as how resilient it is to deterioration [24]. Compacted soil, for example, lacks structure, allows less air and water to penetrate, and stunts root growth, all of which make the soil less productive than well-structured, uncompacted soil. Here, the bulk density and penetration resistance of the soil—two indices of soil health—can be used to assess the appropriateness of the soil for healthy root development (soil function) [25]. Planting cover crops with deep roots might aid in reversing soil compaction. The following qualities should be found in a healthy soil: High soil biological activity, good soil tilth and structure, high water infiltration and retention, resistance to compaction, high organic matter content, plant nutrient availability and recycling, resistance to erosion, absence of harmful chemicals, and low weed and disease pressures are just a few of the benefits of this type of soil [26].

3.2 Soil Health Indicators

In general, certain soil qualities are described by soil health indicators. In general, soil qualities may be divided into two categories: dynamic and stable [27]. Soil-forming elements including topography, parent material, climate, and organisms have an impact on stable soil qualities; these elements are not greatly affected by management techniques. Soil type, soil depth, and soil texture are a few examples of stable features. Soil Organic Matter (SOM), bulk density, and pH are examples of dynamic qualities that may alter quickly—typically within a human lifetime—in response to land-use and management decisions [28]. Thus, systems for evaluating the physical, chemical, and biological characteristics of soil that react to modifications in management offer insights into soil processes (Table 1). On soil health indices that apply to all agroecosystems, there is, however, disagreement. Indicators of soil health are site-specific and occasionally temporally orientated.

Table 1: Potential commonly used soil properties to assess soil health

Physical	Chemical	Biological

➢ Soil colour ➢ Aggregate stability ➢ Water infiltration ➢ Bulk density ➢ Penetration resistance ➢ Water holding capacity ➢ Runoff and ➢ erosion ➢ Rooting depth	➢ Organic C and N ➢ Particulate organic matter ➢ Active carbon ➢ pH ➢ Cation exchange capacity and base saturation ➢ Electric conductivity ➢ Heavy metals	➢ Soil respiration ➢ Potential mineralizable nitrogen ➢ Microbial biomass ➢ Soil enzymes ➢ Earthworms ➢ Crop condition, root growth ➢ Weed and disease pressure

It has been demonstrated that healthy soil inhibits infections, supports biological activity, breaks down organic matter, inactivates harmful substances, and recycles water, energy, and nutrients [9]. Biological traits and their intimate relationship with chemical and physical features make up the idea of soil quality and health, which is gaining popularity [29]. Plant health, soil fertility, and the biota of the soil are closely related [22]. An important tactic for achieving agricultural sustainability is the function that soil biota plays in enhancing land productivity and soil fertility through biological processes [23] and to understand the interrelationship of soil indicators (Table 2). In order to track the impact of past, present, and future land usage on agricultural sustainability, two metrics utilised to determine the state of the soil were soil health and soil quality.

Table 2: Interrelationship of soil indicators [61]

Selected indicator	**Other soil quality indicators**
Aggregation	Organic matter, microbial (especially, fungal) activity, texture
Water holding capacity/ infiltration	Organic matter, aggregation, electrical conductivity, exchangeable sodium percentage (ESP)
Bulk density	Organic matter, aggregation, topsoil-depth, ESP, biological activity
Microbial biomass	Organic matter, aggregation, bulk density, pH, texture, ESP, and/or respiration
Available nutrients	Organic matter, pH, topsoil-depth, texture, microbial parameters

	(mineralization and immobilization rates)

(Source: Laishram et al. [30])

4. Soil health indicators: Strategies and Management

The management of soil health indicators is contingent upon several factors, including location, climate, soil type, and land use. However, a number of broad guidelines centred on sustainable soil health management techniques may be appropriate in the majority of circumstances to result in a notable improvement in soil health indicators. These include higher levels of organic matter, lower levels of erosion, better water infiltration, greater water holding capacity, lower levels of subsoil compaction, and lower levels of agrochemical leaching into groundwater [31]. The detailed management strategies are listed in Table 3.

Table 3. Strategies of soil health management as per NRCS-USDA (2016) [32]

Management strategies	What does it do?	How does it do?
Conservation crop rotation		
Growing a diverse number of crops in a planned sequence in order to increase soil organic matter and biodiversity in the soil	✓ Increases nutrient cycling ✓ Manages plant pests (weeds, insects, and diseases) ✓ Reduces sheet, rill, and wind erosion and holds soil moisture ✓ Adds diversity so soil microbes can thrive	✓ Improves nutrient use efficiency ✓ Decreases use of pesticides ✓ Improves water quality ✓ Conserves water improves plant production
Cover crop		
An un-harvested crop grown as part of planned rotation to provide conservation benefits to the soil	✓ Increases soil organic matter ✓ Prevents soil erosion and conserves soil moisture ✓ Increases nutrient cycling	✓ Improves water quality and crop production ✓ Conserves water and improves nutrient use efficiency

	✓ Provides nitrogen for plant use, suppresses weeds, and reduces compaction	✓ Decreases use of pesticides ✓ Improves water efficiency
No till		
A way of growing crops without disturbing the soil through tillage	✓ Increases organic matter and improves water holding capacity of soils ✓ Reduces soil erosion and energy use ✓ Decreases soil compaction	✓ Conserves water and improves water quality and efficiency ✓ Improves air quality and crop production ✓ Saves renewable resources ✓ Increases productivity
Mulch tillage		
Using tillage methods where the soil surface is disturbed but maintains a high level of crop residue on the surface	✓ Reduces soil erosion from wind and rain ✓ Increases soil organic matter, moisture and reduces energy use	✓ Improves water quality ✓ Conserves water ✓ Saves renewable resources ✓ Improves air quality and crop production
Mulching		
Applying plant residues or other suitable materials to the soil surface to compensate for loss of residue due to excessive tillage	✓ Reduces erosion from wind and rain and moderates soil temperatures ✓ Increases soil organic matter and conserve soil moisture ✓ Reduces dust and control weeds	✓ Conserves water, improves air and water quality ✓ Improves crop productivity ✓ Increases crop production ✓ Reduces pesticide usage
Nutrient management		
Managing soil nutrients to meet crop needs while minimizing the impact on	✓ Increases plant nutrient uptake ✓ Improves physical,	✓ Improves water quality ✓ Improves plant production ✓ Improves air quality

the environment and the soil	chemical, and biological properties of soil ✓ Budgets, supplies, and conserves nutrients for plant production	

4. Soil as a dynamic interface for soil health and quality

The lithosphere (rock), atmosphere (air), hydrosphere (water), and biosphere (living organisms) all interact dynamically with soil. It is the area where interactions occur between rocks and living things as well as the air and water that pass through and around them. In addition to its constituent physical components, soil is also the result of dynamic interactions between these constituent physical, biological, and chemical components [33]. The properties of a soil define how that soil, whether natural or artificially cultivated, works as the basis of the ecosystem to which it belongs. The interacting mechanisms involved in this functioning and how human management affects these processes are our main concerns when we talk about soil health. Sustainable agriculture requires healthy soils which are vital components for environment sustainability.

Farmers frequently use the sight, feel, smell, and taste of the soil to convey its health. Soil health may be monitored by visual and morphological assessments of plant development and soil physical conditions. These observations frequently direct later evaluations of soil health. Some possible visible markers include changes in soil colour, the creation of soil crusts, ephemeral gullies, runoff, physical structure and aggregation, soil depth, root growth, crop emergence, and weed density. Reduced aggregation, surface sealing, and crusting of the soil are signs of surface compaction and SOM loss. Good soil health and management are shown by uniform crop emergence and healthy growth. Deep soils support root development, SOM, nutrients, and water retention.

4.1 Characteristics of a Healthy Soil

Good soil tilth and depth: Suitability for crop production is determined by the general physical characteristics of the soil, which are referred to as good soil tilth and depth.

Excellent microbial population: Numerous beneficial soil organisms contribute to the decomposition of organic matter, cycling of nutrients, preservation of soil structure, biological control of plant pests, and other processes. A robust, well-aggregated soil that is home to a wide variety of living things is more resilient and resistant [34, 53, 54]. A healthy soil will recover from adverse events more rapidly and develop resilience when unfavourable conditions arise.

4.2 Soil Health an Integral Approach

Without a doubt, soil is a tremendously complicated system. It is defined as a multifunctional system with several constituent parts, distinct working boundaries, and a distinctive spatial arrangement that establishes the predominate physical and chemical characteristics. Agricultural interventions have, however, frequently changed this. Most of the internal processes of the agricultural soil system, which is a subsystem of the agro-ecosystem, interact in different ways at different geographical and temporal scales [35]. Biological fertilisers, composts, ground coverings, mulches, and biological inoculants are examples of management techniques that are used to improve and control soil ecological processes. Recycled organic matter is highly encouraged in "alternative" agricultural production and is a crucial component of sustainable agricultural systems. This lessens the deterioration of the land, improves food safety, and undermines the trust that people have in "conventional" agricultural methods.

5. Enhancing the Soil Health

A growing number of people around the world are becoming interested in organic farming as the most sustainable agricultural system because it not only improves soil nutrient mineralisation, microbial activity, abundance, and diversity, as well as physical, biological, and environmental resources like groundwater quality (lower nitrate concentrations), yield, and product quality [36–38]. When compared to mineral fertilisation, it has been shown that legume crops, such as lucerne and *Sesbania* spp., may increase soil organic matter by about 50% and improve soil N supply capability and sequestration [39]. Organic farming can improve soil's chemical and physical properties. For example, in a clay soil, organic systems increased soil water content (15%) and retention capacity (10%) and decreased soil bulk density (8%) in the top 20 cm soil layer compared to conventional systems [40]. Moreover, organic farming offers a superior source of macronutrients. For example, in a long-term (18-year) study using chemical and organic fertilisation regimes, the N storage of soil treated with organic manure was much larger (by 50%)

in the 20 cm topsoil than that of normal chemical fertilisers [41]. Thus it is evident that organic farming improves soil health and enhance sustainability. In *vrikshayurveda*,herbal based kunapajala is used to enhance the bio-logical efficiency of crop as well as soil. The liquidmanure kunapajala (jala=water) or kunapambu, isderived from the Sanskrit word 'kunapa' meaning"stinking" and it is a fermentedorgani liquid manures prepared from flesh, animal urine, marrow to enhance crop and soil health[58]. Farmers today mostly rely on outside inputs for their farming operations, which seriously harms theenvironment. Using locally available resources, this subject led the current inquiry to concentrate on old (ortraditional) methods that improve agricultural growth and development without harming the environment [59]."Soil can be supplemented with microbial inoculums like *Panchagavya*, *Beejamruth*, *Jeevamruth*and *Kunapajala* to hasten the soil micro flora propagation and as soil enrichment. These indigenous concoctions are very significant to nurture the growth of soil microorganisms without adding external inputs.Researchers found that seed priming with either 10% or 25% organickunapajala is an effective method to bring about improvement in germination of wheat and predictits field performance" [57]."Natural farming is an environmentally friendly practice similar to organic farming, developed in Japan during 1935. Unlike conventional farming, natural farming improve soil health by altering soil microbial diversity and also act as defence to plant pathogens" [55].

"It has been demonstrated that tillage practices affect the chemical and physical properties of the soil" [42]. "Adopting efficient tillage techniques is necessary to maintain the health of the soil" [43]. "It has been demonstrated that the conservation tillage methods (no-tillage, reduced, and strip) increase soil microbial activity, soil moisture, organic matter, aggregate stability, cation exchange capacity, and crop production while simultaneously significantly lowering soil macro- and micro-aggregate stability" [44–46]. "Conservation tillage approaches increased soil accessible P in the topsoil (0–20 cm) by 3.8%, K by 13.6%, and soil organic matter by 0.17% when compared to conventional tillage methods" [47].

Keeping crop leftovers on the top layer of the soil (full cover, no till; partial cover, strip tillage) is another way to decrease soil erosion and increase soil moisture content [48]. Conservation tillage boosts the number of earthworms, nematodes, gram-positive bacteria, and bacteria and fungus in comparison to traditional approaches [49,50]. The goal of cultivating cover crops is to improve soil quality, nutrient availability, water retention, protection and enrichment of the soil, and soil fertility. Cover crops have the potential to promote and preserve soil microbial biodiversity and sustainable agriculture [51,52]. The primary goal of cover crop planting is to lessen soil erosion. Crop rotation offers a number of benefits, both economic and ecological. More specifically, it aids in soil management and long-term agriculture. Crop rotation affects the formation and spread of biopores, the cycling of nutrients in the soil, and the proliferation of beneficial bacteria in various types of soil. These practices reduce compaction and improve the condition of the soil. Even in highland areas, crop rotation planning and the use of a range of perennial grass species can assist minimise erosion. The following agricultural practices are some of the essential approaches for maintaining soil health.

6. Future perspectives and directions

By highlighting the importance of soil in contemporary society, the soil-health concept addresses a critical stakeholder demand in sustainable development and is growing into a compelling and useful tool for farmers, land managers, communities, and legislators. Because of the concept's adaptability, a wide range of stakeholders may embrace soil health and make it work for them. Soil health is widely accepted as a goal to strive for by the public since it offers an illustrative connection to more general sustainability objectives that can inspire creative soil management. Researchers are coming to a consensus on what constitutes healthy soil and are creating or improving techniques to measure its many aspects, but primarily in relation to its role in crop yield and with insufficient attention to biotic and abiotic variety. Rather than viewing soil health as only a measurable attribute, researchers should embrace it as an underlying concept to which they may add information. This would strengthen the case for soil health as a scientific subject to which a wide range of disciplines may contribute. One method to do this would be to put each discipline's research under the term "soil health" among other fields. All parties engaged must be involved in order for the soil-health concept to fully realise its potential as a unifying idea that combines soil functions. In particular, stakeholders and scientists must have a common understanding. Given the many roles that soil plays in the environment and in society, soil health need to be officially acknowledged as a common benefit. Governmental or intergovernmental organisations like the Global Soil Partnership should take the lead in developing soil health measurement criteria. It is necessary to create international standards for the right kinds of indicators, their methodological specifications, and how they should be included into indexes.

Then, in order to support sustainability goals, local, regional, or national jurisdictions and organisations should refer to such a thorough soil-health index when making choices that affect the soil and its functions.

7. Conclusion

This review evaluated the function of soil health and found variables to take into account when evaluating soil health elements in sustainable farming systems. The soil biota, which includes microbial variety, activity, abundance, and community stability, is a factor in soil health. The indicators of soil health are dynamic in nature; some, such the biological and chemical ones, are more likely to change quickly, while the physical ones may take longer to alter as a result of management activities. Optimising sustainable crop production may be achieved by creating sustainable soil health indicators management techniques using a methodical approach that incorporates physical, chemical, and biological principles of the soil. Critical values must be established for several of the soil health indicators for which there is insufficient data. To investigate soil health indicators for diversity of edaphic, climatic, and management situations, systematic research is required. Conservation agriculture techniques have been demonstrated to enhance soil health indicators. These techniques include zero tillage, residue recycling, managing soil cover, implementing suitable crop rotations, and adding organic amendments. To further improve our understanding of how production strategies and environmental factors affect the physical, biological, and chemical stability and dynamics of the soil-rhizosphere-plant systems and their impact to short- or long-term sustainability, improved assessment of soil health indicators is required.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

References

1. Doran, J.W.; Zeiss, M.R. Soil health and sustainability: Managing the biotic component of soil quality. Appl. Soil Ecol. 2000, 15, 3–11.
2. Kiran Doggali G, Tiwari U, Pandey PK, Devi OR, Gireesha D, Laishram B and Patel A. Discovering new frontiers in plant breeding: The fascinating world of advancements shaping future growth. International Journal of Research in Agronomy. 2024; 7(1):441–445. https://doi.org/10.33545/2618060x.2024.v7.i1f.262.

3. Lichtfouse, E.; Navarrete, M.; Debaeke, P.; Souchere, V.; Alberola, C.; Menassieu, J. Agronomy for sustainable agriculture. A review. Agron. Sustain. Dev. 2009, 29, 1–6.
4. European Commission (2006) Thematic Strategy for Soil Protection. Commission of the European Communities, p. 12.
5. Devi OR, Sarma A, Borah K, Prathibha RS, Tamuly G, Maniratnam K and Laishram B. Importance of zinc and molybdenum for sustainable pulse production in India. Environment and Ecology. 2023; 41(3C): 1853–1859. https://doi.org/10.60151/envec/lcch4556.
6. Timsina, J. Can organic sources of nutrients increase crop yields to meet global food demand? Agronomy 2018, 8, 214.
7. Lal, R. Soils and sustainable agriculture. A review. Agron. Sustain. Dev. 2008, 28, 57–64.
8. Singh, J.S.; Pandey, V.C.; Singh, D.P. Efficient soil microorganisms: A new dimension for sustainable agriculture and environmental development. Agric. Ecosyst. Environ. 2011, 140, 339–353.
9. Sahu, P.; Singh, D.; Prabha, R.; Meena, K.; Abhilash, P. Connecting microbial capabilities with the soil and plant health: Options for agricultural sustainability. Ecol. Indic. 2019, 105, 601–612.
10. Leskovar, D.; Othman, Y.; Dong, X. Strip tillage improves soil biological activity, fruit yield and sugar content of triploid watermelon. Soil Tillage Res. 2016, 163, 266–273.
11. Devi OR, Ojha N, Laishram B and Devi OB. Opportunities and Challenges of Soil Fertility Management in Organic Agriculture. Vigyan Varta. 2023; 4(8): 228-232.
12. Turbé, A.; De Toni, A.; Benito, P.; Lavelle, P.; Lavelle, P.; Ruiz, N.; Van der Putten, W.; Labouze, E.; Mudgal, S. Soil Biodiversity: Functions, Threats and Tools for Policy Makers. Report for European Commission, DG Environment. 2010. Available online: https://ec.europa.eu/environment/archives/soil/pdf/biodiversity_report.pdf (accessed on 8 June 2020).
13. Gomiero, T. Soil degradation, land scarcity and food security: Reviewing a complex challenge. Sustainability 2016, 8, 281.
14. Yang, G.; Wagg, C.; Veresoglou, S.; Hempel, S.; Rillig, M. How soil biota drive ecosystem stability. Trends Plant Sci. 2018, 23, 1057–1067.
15. Orgiazzi, A.; Bardgett, R.D.; Barrios, E.; Behan-Pelletier, V.; Briones, M.J.I.; Chotte, J.L.; De Deyn, G.B.; Eggleton, P.; Fierer, N.; Fraser, T.; et al. Global Soil Biodiversity Atlas; European Commission, Publications Office of the European Union: Luxembourg, 2016; p. 176; Available online: https://esdac.jrc.ec.europa.eu/content/global-soil-biodiversity-maps-0 (accessed on 11 June 2020).
16. Lal, R. Restoring soil quality to mitigate soil degradation. Sustainability 2015, 7, 5875–5895.

17. Ritz, K.; Black, H.I.J.; Campbell, C.D.; Harris, J.A.;Wood, C. Selecting the biological indicators for monitoring soils: A framework for balancing scientific and technical opinion to assist policy development. Ecol. Indic. 2009, 9, 1212–1221.
18. Bardgett, R.; van der Putten, W. Belowground biodiversity and ecosystem functioning. Nature 2014, 515, 505–511.
19. Handa, I.T.; Aerts, R.; Berendse, F.; Berg, M.P.; Bruder, A.; Butenschoen, O.; Chauvet, E.; Gessner, M.O.; Jabiol, J.; Makkonen, M. Consequences of biodiversity loss for litter decomposition across biomes. Nature 2014, 509, 218–221.
20. Whalen, J. Managing soil biota-mediated decomposition and nutrient mineralization in sustainable agroecosystems. Adv. Agric. 2014, 1–13.
21. Harris, J. Soil microbial communities and restoration ecology: Facilitators or followers? Science 2009, 325, 573–574.
22. Altieri, M.A.; Nicholls, C.I. Soil fertility management and insect pests: Harmonizing soil and plant health in agroecosystems. Soil Tillage Res. 2003, 72, 203–211.
23. Giller, K.; Bignell, D.; Lavelle, P.; Swift, M.; Barrios, E.; Moreia, F.; van Noordwijk, M.; Barois, I.; Karanja, N.; Huising, J. Soil Biodiversity in Rapidly Changing Tropical Landscapes: Scaling down and Scaling up. In Biological Diversity and Function in Soils (Ecological Reviews); Bardgett, R., Usher, M., Hopkins, D., Eds.; Cambridge University Press: Cambridge, UK, 2005; pp. 295–318.
24. Singh, J.S. Cyanobacteria: A vital bio-agent in eco-restoration of degraded lands and sustainable agriculture. Clim. Chang. Environ. Sustain. 2014, 2, 133–137.
25. Van der Heijden, M.; Bardgett, R.; van Straalen, N. The unseen majority: Soil microbes as drivers of plant diversity and productivity in terrestrial Ecosystems. Ecol. Lett. 2008, 11, 296–310.
26. Eickhorst, T., and R. Tippkoetter. 2016. The Hidden World of Soils. University of Bremen, Germany. http://www.microped.uni-bremen.de.
27. Awale, R., Machado, S., Ghimire, R., Oregon State University, & Bista, P. (n.d.). Soil Health. In Advances in Dryland Farming in the Inland Pacific Northwest. http://files.extension.wsu.edu/em108-ch2.pdf.
28. Reardon, C., and S. Wuest. 2016. Soil Amendments Yield Persisting Effects on the Microbial Communities: A 7-year Study. Applied Soil Ecology 101: 107–116.
29. Chaussod, R. La qualitébiologique des sols: Des concepts aux applications. ComptesRendus de l'Académied'Agriculture de France 2002, 88, 61–68.
30. Laishram B, Devi OR and Ngairangbam H. Insight into Microbes for Climate Smart Agriculture. Vigyan Varta. 2023; 4(4):53-56.
31. Rosa DDL, Sobral R (2008) Soil quality and methods for its assessment. In: Braimoh AK, Vlek PLG (eds) Land use and soil resources. Springer, Dordrecht.
32. NRCS-USDA (2016) Natural resources conservation service-United States Department of Agriculture. Healthy, productive soils checklist for growers. www.nrcs.usda.gov.

33. Stirling, G.; Hayden, H.; Pattison, T.; Stirling, M. Soil health, soil biology, soil borne diseases and sustainable agriculture: A guide. Australas. Plant Pathol. 2017, 46, 387.
34. Mäder, P.; Fließbach, A.; Dubois, D.; Gunst, L.; Fried, P.; Niggli, U. Soil fertility and biodiversity in organic farming. Science 2002, 296, 1694–1697.
35. Othman, Y.; Leskovar, D. Organic soil amendments influence soil health, yield, and phytochemicals of globe artichoke heads. Biol. Agric. Hortic. 2018, 34, 258–267.
36. Fernandes, V.C.; Domingues, V.F.; de Freitas, V.; Delerue-Matos, C.; Mateus, N. Strawberries from integrated pest management and organic farming: Phenolic composition and antioxidant properties. Food Chem. 2012, 134, 1926–1931.
37. Gong, W.; Yan, X.; Wang, J.; Hu, T.; Gong, Y. Long-term application of chemical and organic fertilizers on plant-available nitrogen pools and nitrogen management index. Biol. Fertil. Soils 2011, 47, 767–775.
38. Mäder, P.; Fließbach, A.; Dubois, D.; Gunst, L.; Fried, P.; Niggli, U. Soil fertility and biodiversity in organic farming. Science 2002, 296, 1694–1697.
39. Schrama, M.; de Haan, J.; Kroonen, M.; Verstegen, H.; Van der Putten, W. Crop yield gap and stability in organic and conventional farming systems. Agric. Ecosyst. Environ. 2018, 256, 123–130.
40. Matoh, T.; Saraswati, R.; Phupaibul, P.; Sekiya, J. Growth characteristics of Sesbania species under adverse edaphic conditions in relation to use as green manure in Japan. J. Soil Sci. Plant Nutr. 1992, 38, 741–747.
41. Bassouny, M.; Chen, J. Effect of long-term organic and mineral fertilizer on physical properties in root zone of a clayey Ultisol. Arch. Agron. Soil Sci. 2016, 62, 819–828.
42. Gong, W.; Yan, X.; Wang, J.; Hu, T.; Gong, Y. Long-term application of chemical and organic fertilizers on plant-available nitrogen pools and nitrogen management index. Biol. Fertil. Soils 2011, 47, 767–775.
43. Gathala, M.K.; Timsina, J.; Islam, M.S.; Rahman, M.M.; Hossain, M.I.; Harun-Ar-Rashid, M.; Ghosh, A.K.; Krupnik, T.J.; Tiwari, T.P.; McDonald, A. Conservation agriculture based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice–maize systems: Evidence from Bangladesh. Field Crops Res. 2015, 172, 85–98.
44. Jabro, J.D.; Stevens, W.B.; Evans, R.G.; Iversen, W.M. Tillage effects on physical properties in two soils of the Northern Great Plains. Appl. Eng. Agric. 2009, 25, 377–382.

45. Gozubuyuk, Z.; Sahin, U.; Ozturk, I.; Celik, A.; Adiguzel, M.C. Tillage effects on certain physical and hydraulic properties of a loamy soil under a crop rotation in a semi-arid region with a cool climate. CATENA 2014, 118, 195–205.
46. Cannell, R.; Hawes, J. Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Field Crops Res. 1994, 30, 245–282.
47. Al-Kaisi, M.; Douelle, A.; Kwaw-Mensah, D. Soil microaggregate and macroaggregate decay over time and soil carbon change as influenced by different tillage systems. J. Soil Water Conserv. 2014, 69, 574–580.
48. Shao, Y.; Xie, Y.; Wang, C.; Yue, J.; Yao, Y.; Liu, W. Effects of different soil conservation tillage approaches on soil nutrients, water use and wheat-maize yield in rainfed dry-land regions of North China. Eur. J. Agron. 2016, 81, 37–45.
49. Celik, A.; Altikat, S.; Way, T. Strip tillage width effects on sunflower seed emergence and yield. Soil Tillage Res. 2013, 131, 20–27.
50. Sengupta, A.; Dick, W. Bacterial community diversity in soil under two tillage practices as determined by pyrosequencing. Microb. Ecol. 2015, 70, 853–859.
51. Laishram B, Singh TB, Kalpana A, Wangkheirakpam M, Chongtham SK and Singh W. Effect of Salicylic Acid and Potassium Nitrate on Growth and Yield of Lentil (Lens culinaris L.) under Rainfed Condition. International Journal of Current Microbiology and Applied Sciences. 2020; 9(11):2779–2791. https://doi.org/10.20546/ijcmas.2020.911.337.
52. Yang, S.; Kim, M.; Seo, Y.; Choi, K.; Lee, S.; Kwak, Y.; Lee, Y. Soil microbial community analysis of between no-till and tillage in a controlled horticultural field. World J. Microbiol. Biotechnol. 2012, 28, 1797–1801.
53. Bach, D. (2022). Importance of Soil Biodiversity and it's contribution. Bio Bulletin. Netherlands.
54. Singh, S. Chaudhary, D. Verma, S. (2023). Soil Microorganism and their Role. Agriculture Magazine.
55. Devi, O. R., & Laishram, B. (2023). Natural farming: An ecological approach for improving soil health. *VigyanVarta*. 2023b, 4(4), 20-22.
56. Devi, O. R., Laishram, B., Debnath, A., Doggalli, G., Ojha, N., Agrawal, S., & Dutta, S. (2024). Mitigation of arsenic toxicity in rice grain through soil-water-plant continuum. *Plant, Soil and Environment.* 70, 2024 (7): 395–406. https://doi.org/10.17221/470/2023-PSE.

57. Devi, O. R., Verma, O., Laishram, B., Raj, A., Singh, S., & Gaurav, K. (2023). Influence of Seed Invigoration with Organic Kunapajala on Seed Quality and Biochemical Activity in Late Sown Wheat. *International Journal of Environment and Climate Change*, 13(9), 900-906.
58. Devi, O. R., Halder, R., Pandey, S. T., Verma, O., &Chaturvedi, P. (2022). Effect of seed priming with liquid organic on germination, seedling development and enzymatic activity of wheat (*Triticum aestivum* L.). *Environment and Ecology* 40 (3C) : 1720—1725, July—September 2022.
59. Devi, O. R., Harish, B. M., Doggalli, G., Laishram, B., Verma, O., Sharma, A., & Ojha, N. Effect of liquid fermented organic manure concoctions and their foliar spray under different dose of nutrients on chlorophyll content of late sown wheat. Plant Archives Vol. 24, No. 1, 2024 pp. 1244-1248. doi.org/10.51470/*PLANTARCHIVES*.2024.v24.no.1.173
60. Devi OR, Verma OP, Pandey ST, Laishram B, Bhatnagar A and Chaturvedi P. Correlation of germination, seedling vigour indices and enzyme activities in response to liquid organic kunapajala to predict field emergence in late sown wheat. *Environment and Ecology*. 2023; 41(3B): 1694–1698. https://doi.org/10.60151/envec/wegd5962.
61. Raghavendra M, Sharma MP, Ramesh A, Richa A, Billore SD, Verma RK. Soil health indicators: Methods and applications. Soil Analysis: Recent Trends and Applications. 2020:221-53.