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Climate change and soil health: Implications for sustainable land management

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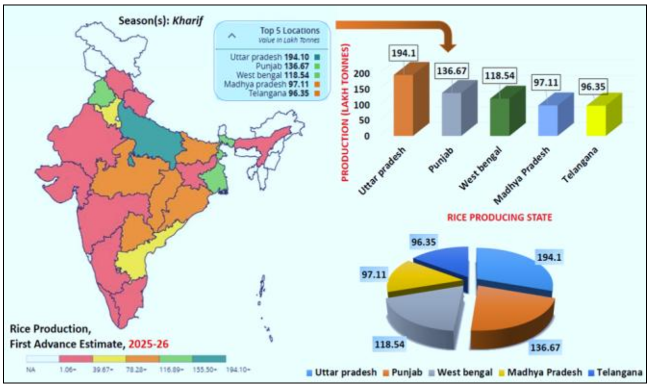
Abstract
Global scenario currently is reduced agricultural cultivable areas, increase in population growth, hence the farmer's aims to increase the productivity by applying abundant inorganic fertilizer without considering the status of Soil health. Soil health normally refers to an ecological equilibrium balance and function of soil and its vital capacity to have maintain well-balanced ecosystem with abundant biodiversity above and below the surface and productivity. The understanding and interpretation of soil health from the perspectives of soil functions, processes, and properties is summarized. Also the good soil is normally defined by the content of Soil organic carbon content, thereby strongly it impacts soil quality, functionality and health. Incorporating different approaches which tend to maximize the physical, chemical and biological property shall be encountered and practiced. This chapter gives the broad outline over soil health and key indicators, management practices, Sustainable soil management and its approaches. Enhancing and sustaining soil health is also pertinent to advancing Sustainable Development Goals of the U.N. such as alleviating poverty, reducing hunger, improving health, and promoting economic development.

Keywords: Soil health, ecosystem, soil organic carbon, sustainability, productivity

1. Introduction
Agriculture, the forerunner for sustainable food systems, plays a pivotal role in ensuring global food security, nutritional adequacy, and environmental resilience. It is the only sector in nation providing the primary essential need of every human being. India's record had protruded that evidenced food grain output for 2024-25, with rice and wheat production, total of around 332.3 Million Tonnes (LMT), despite some dry spells affecting pulses and oilseeds in the South/West part of India (Fig. 1). However, conventional agricultural practices, characterized by intensive monoculture farming, heavy reliance on synthetic inputs, and extensive soil tillage, have contributed to a range of environmental problems such as soil degradation, loss of biodiversity, and increased greenhouse gas emissions. In recent years, sustainable agriculture has emerged as a promising alternative to conventional methods, emphasizing practices that enhance environmental quality, preserve natural resources, and promote economic viability for farmers.



(Data extracted from First Advance Estimate, 2025-26 of UPAg)

Fig 1: Top Five Rice Producing State under Current Soil Health Practices

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Soil is said to be a complex system (Ladyman *et al*., 2013) [22] at the coincidence of the atmosphere (Venkatesan *et al*., 2024) [35], lithosphere (Koushal *et al*., 2025) [20], hydrosphere and biosphere (Brevik *et al*., 2015) [3] that is critical for food production system and way to key sustainability through its support of important societal and ecosystem services (Blum, 2005) [2]. Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply chain management (Gangadaran *et al*., 2024) [12]. Historically, soil assessments focused on crop production, but today soil health also includes the role of soil in water quality, climate change and human health. But for healthy food production, the soil health is to be in good quality. Hence we should abide the science involving the sustainability among the soil and equal food production for present and future generations.

On the other side, though some would sensitize the dual role in emphasizing climate change and their effect on agriculture. For the broader sake, it dwells every part of agriculture including crop production, pest population, yield dynamics and finally soil health. Climate change had become one of the most crucial term among global wide and it has to be addressed with immediate effect. According to IPCC, 2023 sixth assessment report, at present day global temperature of 1.1˚C which lies above the pre-industrial level which tend to rise up-to 1.5˚C by 2050 and there will be a projected increase in temperature by 1.8 to 4.0˚C by 2100. The major cause for climate change includes burning of fossil fuels, emission of GHGs and increase in CO_2 level in atmosphere (Kabir *et al*., 2023) [38]. The detrimental effect of climate change had altered ecosystem of environment (Abbass *et al*., 2022) [39], agriculture (Xie *et al*., 2018) [40] and most importantly the natural resources which includes soil health and fertility status (Kabato *et al*., 2025) [41].

The possession of climate change had ruined soil health which delimits agricultural production thereby rise of risk in food insecurity had been noted (Venkatesan *et al*., 2024) [35]. The critics' gap evolved between climate change pattern and agriculture production should become less and the studies should address this. The direct reflection of climate change towards every ecosystem is well noticed, and it should be minimized in precision farming (Roy and George, 2020) [43], optimisation of resource uses (Erdoğdu *et al*., 2025) [44], enhancement future through suitable management practices like climate smart agriculture (Zhao *et al*., 2023) [42], of crop resilient (Koushal *et al*., 2025; Yoselin *et al*., 2023) [20] and most importantly adjusting date of sowing towards climate.

Soil productivity has been defined as the ability of a soil to support plant growth without external inputs. Increasing basic soil productivity can lead to a reduction of fertilizer application and high crop yield. The productivity of a soil can be evaluated based on crop production in unfertilized soil within the agricultural ecosystem. The productivity of the soil can also be measured by physical properties such as soil structure, rate of water infiltration, water holding capacity and hydraulic conductivity; chemical properties such as organic matter content, cation exchange capacity (CEC), and pH; and biological properties such as fauna and flora activity in the soil. Results of a past study showed that the suitable parameters for soil productivity assessment were soil available water, soil pH, clay content, and organic matter content. Climate change reduces soil productivity by increasing erosion from extreme rain, degrading structure via heat and drought, accelerating organic matter loss, altering nutrient cycles, and expanding pests/diseases, leading to decreased crop yields, water retention issues, and food insecurity, though sustainable practices like conservation tillage and cover crops can help build resilience. Keeping these points under consideration, this paper was made to highlight the significant of sustainable agriculture practices to combat climate change and to boost agriculture productivity protecting soil health for future generations.

2. Key Indicators of Soil Health: Physical, Chemical, and Biological

Soil health indicators are measurable physical, chemical, and biological properties that show how well soil functions, including physical indicators like aggregate stability, bulk density, and water infiltration; chemical indicators such as pH, organic carbon, nutrients (N, P, K), and salinity (EC); and biological indicators like earthworms, microbial biomass, and respiration, all helping in assessing soil fertility, water holding capacity, nutrient cycling, and overall ecosystem resilience. A holistic view combines these to understand soil's ability to support plants, cycle nutrients, filter water, and provide habitat (Fig. 2).

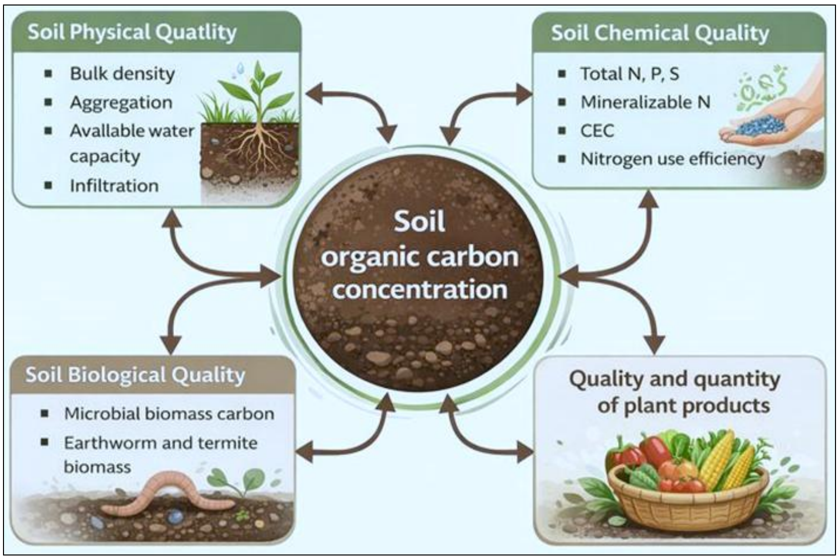

Fig 2: Key indicators of soil health

2.1. Soil Physical Properties and Health

Soil texture is an inherent properties. I.e. Sand, slit and clay (Gangadaran *et al*., 2024a) [12]. Clay forms the extreme colloidal surface as it was l ess than 0.002 mm in size and it acts as a buffering capacity in the soil. Whereas sand is a fraction which consist of quartz and silica and has no special property on soil system. Loam is contain more or less equal proportion of sand and clay. The unseen part of soil fertility management is Soil physical science. I.e. Soil structure, texture, porosity, infiltration, hydraulic conductivity etc. which will decides other part of soil health management. Soil physical property including soil structure which is a key factor in soil functioning and important factor in evaluating the sustainability in crop production system. Soil structural stability is the ability of aggregates to remain intact when exposed to different stresses (Kay *et al*., 1988) and measures of aggregate stability are useful as a means of assessing soil structural stability. Hence maintaining soil physical properties are essential for sustainable soil system.

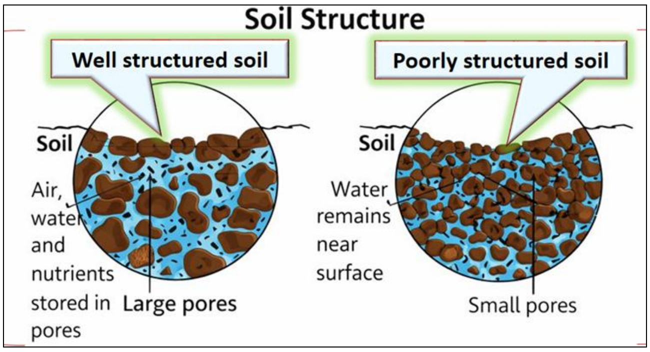

Fig. 2: Elevating the difference among the well-structured and poorly structured soil

2.2. Compaction and Its Effects on Root Growth and Water Infiltration

We know that compaction affect the different layers of horizons and it make difficult to penetrate the roots deeper into the soil system. It is mostly due to presence of trafficability and workability in field condition (Muhilan *et al*., 2025) [8]. Generally, the compaction is of two types. One is surface compaction and other is sub surface compaction. When it about to meets the compact surface, water infiltration gets reduced. The simple relation between compacted and uncompacted soil and its effect on root system is illustrated below, which was experimented by (Nannen *et al*., 2020) [28].

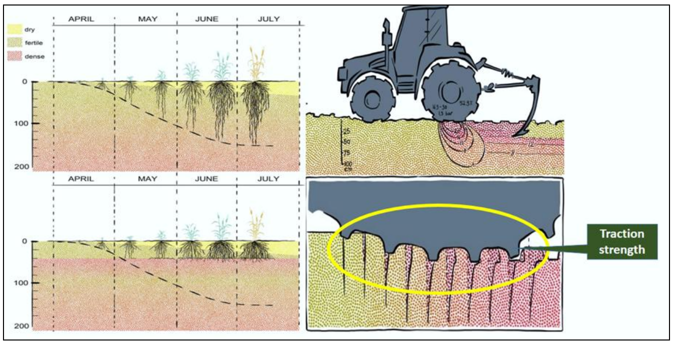

Fig 3a: The effect of soil compaction on root growth. Top

In healthy soil wheat roots utilize the soil column to a depth of 120 cm. Bottom: In compacted soil root growth is mostly limited to the plowed top soil, which dries out quickly in arid climates; 3b. The main axis of the pressure bulb under a tractor tire extends diagonally into the ground and compacts the soil below the depth of tillage (Söhne and Bolling, 1981) [32].

2.3. Soil Chemical Properties and Nutrient Management

Chemical attributes are the key promoters in performing all the chemical reaction in the soil. Soil pH, cation exchange capacity, buffering capacity of the soil, nutrient mobilization were take part in the soil system (Muhilan and Bagavathi Ammal, 2025) [9].

2.4. Soil Biology and Microbial Health

Soil microbial activity and diversity play important roles in the sustainability by keeping essential functions in soil health, involving carbon and nutrient cycling (Jeffries *et al*., 2003; Izquierdo *et al*., 2005) [19, 17]. Microbial indicators are more susceptible than physical and chemical attributes to changes imposed to the environment like soil use and management (Melo and Marchiori, 1999; Masto *et al*., 2009) [24, 23], and for this reason can early forecast any disturbance in the sustainability of an environment.

3. Role of Soil Microorganisms in Nutrient Cycling and Plant Health

Soil microorganisms have an important contribution towards the soil productivity and therefore the relationship between soil microbial populations, diversity, functions and soil management practices needs thorough understanding (Akash *et al*., 2025) [1]. Also some microorganism were capable of producing a mucilage substances that can bind the soil particles, thus promoting aggregate stability (Ilakkia *et al*., 2025). Three principal components of SOM are as follows:

1. Plant and animal residues and living microbial biomass;
2. Active or labile SOM; and
3. Relatively stable

Microorganisms are key players in the cycling of nitrogen, sulfur and phosphorus, and the decomposition of organic residues. They affect nutrient and carbon cycling on a global scale (Wani *et al*., 2015) [36].

3.1. Soil Biodiversity as an Indicator of Soil Health

Soil biota is a broad term which comprises of all the organism that spend a significant portion of their life cycle within a soil profile, or at soil – surface interface. It is also known as soil edaphon or "Soil life". Soil biota, the biologically active powerhouse of soil, include an incredible diversity of organisms. It includes micro-organisms (bacteria, fungi, and algae) and soil "animals" (protozoa, nematodes, mites, springtails, spiders, insects, and earthworms) in soil (Gangadaran *et al*., 2025) [12]. They are more diverse than the community of plants and animals on above ground. Soil biota are concentrated in plant litter, the upper few inches of soil, and along roots. Soil organisms interact with one another, with plant roots, and with their environment, forming the soil food web.

Table 1: Relative number and biomass of microbial species at 0 – 6 inches (0-15cm) depth of soil

Microorganisms	Number / g of soil	Biomass (g/m²)
Bacteria	10^8-10^9	40-500
Actinomycetes	10^7-10^8	40-500
Fungi	10^5-10^6	100-1500
Algae	10^4-10^5	1-50
Protozoa	10^3-10^4	Varies
Nematodes	10^2-10^3	Varies

3.2. Importance of Soil biota

3.2.1. Soil microbes break down organic matter

Microorganisms plays an important role in the decomposition of organic matter. Different types of microbes are specialized to different types of organic matter, between them covering just above everything (Gangadaran *et al*., 2025a) [12].

3.2.2. Recycling nutrients

Soil microbes plays a crucial role in returning nutrients to their mineral forms, which plants can take up again. This process is known as mineralization. (Eg. Plant can take nitrogen in the form of Ammonical and nitrate).

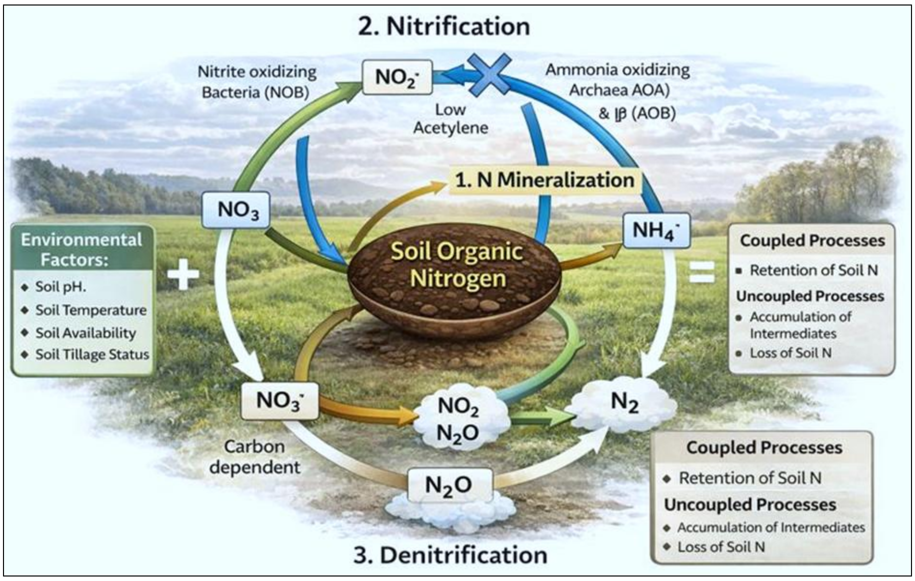

Fig 4: Soil N cycling and various losses

3.3. Techniques to Enhance Soil Microbial Health (e.g., Bio-fertilizers)

Biofertilizer is the microbial inoculants that contain the culture of dormant or live cells of the effective strains of N-fixing, P-solubilizing/ mobilizing, K-solubilizing. Microorganisms at their cellular level which is often applied to seeds, soils, or compost material to accelerate the microbial activities by such organisms through their multiplication and enhance the nutrient's availability, which can be easily accessible by the plants. Very often microorganisms are not as efficient in natural surroundings as one would expect them to be and therefore artificially multiplied cultures of efficient selected microorganisms play a vital role in accelerating the microbial processes in soil. Use of bio fertilizers is one of the important components of integrated nutrient management, as they are cost effective and renewable source of plant nutrients to supplement the chemical fertilizers for sustainable agriculture. Several microorganisms and their association with crop plants are being exploited in the production of biofertilizers. They can be grouped in different ways based on their nature and function.

Table 2: Different groups of biofertilizers with example

S. No.	Groups	Examples
N2 fixing Biofertilizers		
1.	Free-living	*Azotobacter, Beijerinkia, Clostridium, Klebsiella, Anabaena, Nostoc,*
2.	Symbiotic	*Rhizobium, Frankia, Anabaena azollae*
3.	Associative Symbiotic	*Azospirillum*
P Solubilizing Biofertilizers		
1.	Bacteria	*Bacillus megaterium* var. *phosphaticum, Bacillus subtilis, Bacillus circulans, Pseudomonas striata*
2.	Fungi	*Penicillium sp, Aspergillus awamori*
P Mobilizing Biofertilizers		
1.	Arbuscular mycorrhiza	*Glomus sp.,Gigaspora sp.,Acaulospora sp., Scutellospora sp. & Sclerocystis sp.*
2.	Ectomycorrhiza	*Laccaria sp., Pisolithus sp., Boletus sp., Amanita sp.*
3.	Ericoid mycorrhizae	*Pezizella ericae*
4.	Orchid mycorrhiza	*Rhizoctonia solani*
Biofertilizers for Micro nutrients		
1.	Silicate and Zinc solubilizers	*Bacillus* sp.
Plant Growth Promoting Rhizobacteria		
1.	Pseudomonas	*Pseudomonas fluorescens*

3.4. Conservation Agriculture and Reduced Tillage

Conservation tillage is a widely-used terminology to denote soil management systems that result in at least 30% of the soil surface being covered with crop residues after seeding of the subsequent crop (Jarecki and Lal, 2003) [18]. Conservation agriculture removes the emphasis from the tillage component alone and addresses a more enhanced concept of the complete agricultural system. To withhold food security concern and to improve the degrading soil quality status, conservation tillage acts as a beneficial agriculture practices where soil were minimally disturbed and maintaining surface soil through retaining crop residues coupled with achieving zero tillage functional ensuring minimal soil disturbances Derpsch (2003) [56].

Through adopting such tillage practices, various crop residues including (stalks, leaves, husks, straws) left after harvest, like rice straw, wheat straw, corn stover, and sugarcane bagasse which covers the surface soil scale where it protects directly from sunlight and rainfall drop ensuring minimal soil disturbances and regulating soil biological function like microbial activity (Ma *et al*., 2025) [57]. Conservation tillage such as no-till, strip-till, and mulch-till retains around 30% of crop residue on the soil surface, significantly improving soil structure, reducing erosion, and enhancing water infiltration (Dang *et al*., 2020) [58].

Study conducted by Deleon *et al*. (2020) [59] in Colorado's irrigated maize systems found conservation tillage increased aggregate stability, reduced bulk density, and enhanced earthworm populations leading to improved infiltration and profitability within five years. Similarly, a long-term study of maize-wheat systems under zero-tillage and permanent beds reported SOC gains of 31–33%, improved soil biological status, a 13–18% yield increase, and net economic benefits (Govaerts *et al*., 2006) [60]. Conservation tillage protects and restore soil moisture status by 20-40% than conventional methods (Handiso *et al*., 2023) [61]. These interactive benefits soil biodiversity, water retention, nutrient cycling, lower fuel use, reduced runoff make conservation tillage a cornerstone of sustainable soil management (Behera *et al*., 2023) [62].

Jacobs *et al*. (2011) [63] observed that through minimal tillage (MT), not only aggregate stability of soil gets increased, but also organic carbon level and nitrogen were high enhanced by 30 and 25% especially in top 5 cm of surface soil after 40 years of tillage implemented. Soil chemical properties including soil pH, cation exchange capacity (CEC), anion exchange capacity (AEC), and total nitrogen content were severely affected by tillage operation (Murugan *et al*., 2014) [64]. Yu *et al*. (2026) [65] observed increased wheat yield by 9.19 % and 7.88 % and improvement of SQI in topsoil (0–5 cm) through amending no-till straw mulch (NTS) with greater residue segmentation in soil. Also, it was noted that, no-till farming practices reduces surface runoff which limits the exposure of ground water contamination where interaction between residual agro-chemical leachate and soil sediments interaction with ground water is highly reduced (Kukal *et al*., 1991) [66]. It combines the following basic principles:

1. Reduction in tillage: The objective is to achieve zero tillage, but the system may involve controlled tillage seeding systems that normally do not disturb more than 20-25% of the soil surface;

2. Retention of adequate levels of crop residues and soil surface cover: The objective is the retention of sufficient residue on the soil to protect the soil from water and wind erosion; to reduce water run-off and evaporation; to improve water productivity and to enhance soil physical, chemical and biological properties associated with long term sustainable productivity. The amount of residues necessary to achieve these ends will vary depending on the biophysical conditions and cropping system.

3. Use of crop rotations: Crop rotation refers to the planting of sequential rotation of crops in the same cultivated land in order to improve soil health and boost soil physical properties. By adopting crop rotation practices, different root system exhibited among different crops penetrate at different depth making well aerated by increased pore space across different horizons resulting in better water infiltration rate and oxygen diffusion rate (ODR) in soil (Struijk *et al*., 2026) [49]. It was consider as a less ubiquitous farming practice where soil ecological diversity gets flourished over time. Cover cropping refers to the planting or growing non cash crops like legumes or grasses which covers the entire soil surface soil leaving no sunlight or rainfall to enter and disturb soil structure resulting in reduction of top fertile soil loss (erosion), boost organic matter level, control weeds, which is often utilized with conjunction with crop rotation practices.

Most of the southern part of Tamil Nadu farmers integrate to adopt both rotation and cover cropping simultaneously (Santhi *et al*., 2025) [50]. Crop rotation and cover cropping are integral part of conservative agriculture and sustainable farming. Incorporating diversified crop rotations will breaks pest and disease cycles, enhances nutrient availability, and promotes soil organic matter accumulation (Al-Musawi *et al*., 2025) [51]. A study in the southeastern United States found that combining cover crops with conservation tillage increased root activity, microbial diversity, aggregate stability, and organic carbon than either practice alone (Farmaha *et al*., 2022) [52]. Cover crops help retain soil cover year-round, reducing erosion and improving water retention while inhibiting weeds and reducing the need for spraying herbicides as it reduces cost input for chemical herbicides. Together with diversification, these practices build resilient, healthy soil systems that diminish chemical dependency.

On the other side following crop rotation practice boost microbial population in soil especially at (A) horizon (Weisberger *et al*., 2023) [53]. Chamberlain *et al*. (2020) [54] observed increased bacterial population when soil follows through corn-soybean rotation system and notable, soil properties including pH and organic matter levels influences the soil bacterial communities significantly. Yin *et al*. (2025) [55] evaluated long-term no-till crop rotation in controlling soil borne pathogens adopting different cropping rotation practices and among which corn-pea–winter wheat-soybean (CPWwS) found to be more effective and had a consistently lower *M. phaseolina* population. Zero tillage with residue retention improves dry aggregate size distribution compared to conventional tillage (Govaerts *et al*., 2009a) [13]. Hence minimizing the tillage operation will enhance the aggregate stability.

3.5. Organic formulation Practices for Soil Health

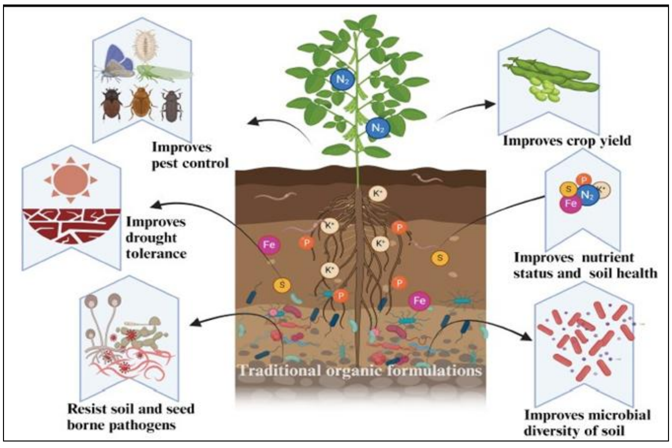

Fig 5: Beneficial effect of Traditional organic formulation on soil properties

Table. 3: Benefits of Traditional organic formulation and its effect on plant and soil properties

Sl. No	Traditional organic formulations	Benefits	References
1.	Amritpani	Induce biotic and abiotic stress tolerance in crops and improve crop growth and yield.	(Kumar and Singh, 2021) [21]
2.	Beejamurtha	Provide macro and micronutrients and control soil and seed-borne pathogens.	(Shyamsunder and Menon, 2021) [31]
3.	Egg amino acid	Promotes plant growth	(Nandhini and Somasundaram, 2023) [27]
4.	Fish amino acid	Provides nutrition to plants	(Nandhini and Somasundaram, 2023) [27]
5.	Five leaves extract	Works against sucking pests	(Nandhini and Somasundaram, 2023) [27]
6.	Jeevamurtha	Improves soil health and nutrition	(Nandhini and Somasundaram, 2023) [27]
7.	Panchagavya	Boosts crops, promotes growth, induces biotic and abiotic stress tolerance in crops	(Kumar and Singh, 2021) [21]
8.	Sanjivak	Promotes growth and induces biotic and abiotic stress tolerance in crops.	(Mathukiya *et al.*, 2023)
9.	Biological Extract (Thailand)	Soil health improvement enriches microbial sources in soil and promotes plant growth.	(Chunsathit and Kaenla, 2014) [5]
10.	VESTA (Europe)	Improves soil health, plant growth, and bacterial community composition, diversity, and function	(Deng *et al.*, 2019) [7]

3.6. Agroforestry and Perennial Crops for Soil Stability

Although every cropping pattern and sequence maintains the soil structural form in same situation. To overcome that, growing of trees and perennial crops can be encourage for soil health stability and build in structural stability in soil ecosystem. The influence of agroforestry on soil quality through changes in ecosystem functions and services caused by direct and indirect effects of trees varies depending on the crop type, climate, and geography. When integrating trees in the farm land, will definitely increases the field capacity and organic matter content (Chatterjee *et al.*, 2018) [4], available potassium, available phosphorus, soil carbon stocks (Surki *et al.*, 2020) [33], and lower bulk density (BD) (Hailu, 2015) [15], which retain water by increasing the water holding capacity (WHC) and release the water to plants gradually like a sponge (Schroth *et al.*, 2003) [29]. Agroforestry also leads to higher soil C-sequestration rates; moisture contents; and levels of available soil K, N, and P, the residues of which are available for subsequent crops, allowing more sustainable farming in the upcoming seasons and reducing the use of chemical fertilizers (Surki *et al.*, 2020) [33]. And there are many ways or processes by which agro – forestry helps the soil to regain health and quality. They are listed below;

1. Photosynthetic fixation of carbon and its transfer to the soil via litter and root decay,
2. Nitrogen fixation by all leguminous trees and in few non-leguminous species (e.g., Alder and Casuarinas),
3. Improved nutrient retrieval by tree roots, including through mycorrhiza and from lower horizon,
4. Providing favourable conditions for the input of nutrients from rainfall and dust
5. Control of erosion by combination of cover and barrier effect, especially the former,
6. Root uptake of nutrients that would otherwise have been lost by leaching,
7. Soils under trees have favourable structure and water holding capacity, through organic matter maintenance and root action,
8. Provision of a range of qualities of plant litter, woody, and herbaceous,
9. Growth promoting substances,
10. The potential through management of pruning and relative synchronization of timing of release to nutrients from litter with demand for their uptake by crops, and
11. Effects of tree shading on microclimate.

Perennial crops like herbaceous perennial legume crops, such as alfalfa or clover, can suppress weeds via competition and multiple defoliations, and require no N fertilization. Perennial legumes have been a popular option for the transition period. Perennial crops also contribute to all or most of the soil health principles and are considered a promising option for improving soil health and fertility (Pimentel *et al.*, 2012) [6].

3.7. Crop Rotation and Diversification for Soil Fertility Management

Crop rotation and diversification are the one of the important crucial strategies adopted and followed which will helps the farmers, environment and most important is soil fertility management. Since, the way of protruding different types of crops, their root system are also getting different. This make the way for increase in soil aeration porosity. Crop rotation, a beneficial approach, an agricultural practice, which involves growing of different crops in a definite sequence over a period of time in a definite area (Zhao *et al.*, 2013) [37]. By adopting crop rotation practices, the incidence of pests, diseases and most important weed can be reduced simultaneously (Guinet *et al.*, 2023; Garland *et al.*, 2023) [14,]. In addition to crop rotation, the diversification of agricultural landscapes also plays a crucial role in enhancing the sustainability and resilience of farming systems (Tamburini *et al.*, 2020) [34]. When a farmer only focused on continuous monocropping system, the crop may subject to severe pest and disease and therefore, adopting diversified cropping system or sequence will make soil more fertile and sustainable one. The benefits of Diversified cropping rotation when compared with monocropping is illustrated in Fig. 6.

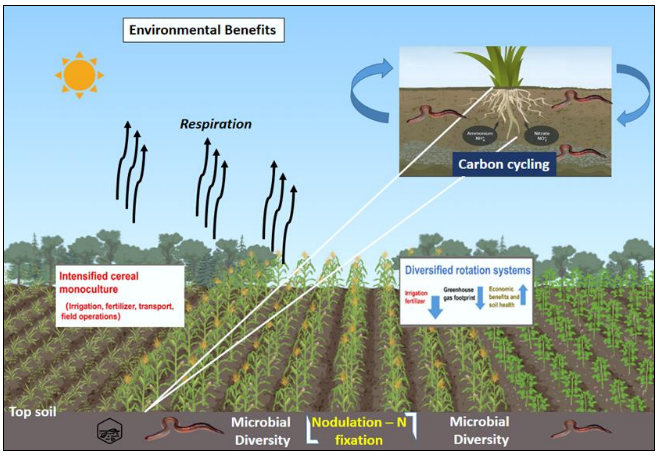

Fig 6: Social economic and environmental benefit of practicing diversified cropping rotation than monocropping system (created in biorender.com)

3.8. Significance of Rhizosphere in nutrient cycling

The rhizosphere is a thin layer of soil that surrounds plant roots and is a central place for microbial activity. It's made up of soil particles, organic matter, plant roots, and a diverse community of microbes. The rhizosphere is a micro ecosystem where complex interactions take place between the plant roots and the microorganisms.

3.8.1. Plant - microbe interaction

On the basis of our current knowledge, plant–microbial interactions can be classified into three basic groups: (i) negative (pathogenic) interactions; (ii) positive interactions, in which either both partners derive benefits from close association (symbiosis), both partners derive benefits from loose association or only one partner derives benefits without harming the other (associative); and (iii) neutral interactions, where none of the partners derives a direct benefit from interaction and in which neither is harmed. Symbiotic and pathogenic interactions have attracted the most scientific attention (Hirsch *et al*., 2003) [46].

3.8.2. Rhizosphere and nutrient cycling

Next to water and temperature, nutrients are the environmental factor that most strongly constrains terrestrial plant growth. Rhizosphere generally acts as a biodiversity hotspot area since it was abundant with numerous microorganisms. The zone of root exudation has clearly shown in progress with increase the mass and activity of soil microbes and fauna found in the rhizosphere (Butler *et al*., 2003) [47]. Most of the studies in which plants were grown in pots as a monoculture revealed that specific groups of microorganisms were associated with the rhizosphere (Baudoin *et al*., 2003) [48]. Soil microorganisms depend upon plant C and, in turn, provide plants with nitrogen (N), phosphorus (P) and other minerals through decomposition of soil organic matter. There are some microbial plant growth promoting substance which was released by the microbes and their role in plant growth and development which was tabulated in Table. 3.

Table 3: Effect of Plant growth promoting micro-organism influencing plant growth regulation

Sl. No.	Plant growth promoting microbes	Sources / plants	Plant growth regulation
1.	*Erwinia* species and P. *chlororaphis*	*Coffea rhizosp* L	Efficient uptake of insoluble phosphate from the soil
2.	Pseudomonas aeruginosa FP6	Chili	Siderophore produced by biocontrol strain for *Rhizoctonia solani* and *Colletotrichum gloeosporioides*
3.	*Bacillus amyloliquefaciens* 5113 and *Azospirillum brasilense* NO 40	Wheat	Promote plant growth under drought condition, increase enzyme activity in wheat plant
4.	*Bacillus amyloliquefaciens* HK34	Panax	Induction of systemic resistance against *Phytophthora cactorum*
5.	*Bacillus thuringiensis* AZP2	Wheat	Decrease volatile emissions and increase photosynthesis
6.	*Bacillus thuringiensis* GDB-1	Lavandula dentate	Enhanced phytoremediation of heavy metals (Pb, Zn, As, Cd, etc.)
7.	*Pseudomonas putida* H-2-3	Soybean	Improve plant growth under saline and drought condition. Increase leaf length and chlorophyll content
8.	*Aeromonas hydrophila* QS74 and *A. hydrophila* QSRB5	Maize	Enhanced soil aggregation and nutrient cycling
9.	*Bacillus subtilis, and Bacillus amyloliquefaciens*	Tomato	Increased thickness of the upper epidermis, lower epidermis, palisade tissue, spongy tissue, and vascular bundles and improved photosynthetic efficiency
10.	*FJS-3(Burkholderia pyromania), FJS-7(Pseudomonas rhodesiae), and FJS-16(Pseudomonas baetica)*	Tea plant, Tobacco, and Chili pepper	Increased plant biomass, enhanced chlorophyll content and carotenoid content

3.9. Future Directives

3.9.1. Development of Climate-Resilient Soil Management Practices: Future research should prioritize the design and validation of soil management strategies that enhance resilience to climate-induced stresses such as drought, flooding, salinity, and temperature extremes. Conservation agriculture, regenerative practices, and nature-based solutions need long-term, location-specific evaluation under changing climatic scenarios.

3.9.2. Integration of Advanced Monitoring Tools: The application of remote sensing, GIS, proximal soil sensing, and IoT-based soil sensors should be expanded to enable real-time monitoring of soil health indicators. Integrating these tools with climate models will improve prediction accuracy and decision support for sustainable land management.

3.9.3. Soil Carbon Sequestration and Greenhouse Gas Mitigation: Future studies must focus on quantifying soil carbon stabilization mechanisms and trade-offs among carbon sequestration, nutrient cycling, and greenhouse gas emissions. Innovative practices such as biochar application, cover cropping, and organic amendments require standardized assessment frameworks.

3.9.4. Microbial and Biological Indicators of Soil Health: There is a need to advance understanding of soil microbial dynamics under climate stress. Future directives should emphasize the use of microbial functional diversity, enzyme activity, and soil biodiversity as sensitive indicators of soil health and ecosystem resilience.

3.9.5. Climate-Smart Nutrient and Water Management: Research should move toward precision-based nutrient and water management approaches that minimize losses and enhance efficiency under variable climates. The role of nano-fertilizers, slow-release formulations, and isotope-based tracing techniques warrants deeper investigation.

3.9.6. Modelling, Forecasting, and Scenario Analysis: Process-based and machine learning models integrating soil, crop, and climate data should be refined to assess long-term impacts of climate change on soil health. Scenario-based assessments will aid policymakers in designing adaptive land-use strategies.

3.9.7. Socioeconomic and Policy-Oriented Research: Future work must bridge biophysical soil research with socioeconomic dimensions, including farmer adoption, cost–benefit analysis, and policy incentives. Strengthening soil governance frameworks and mainstreaming soil health into climate policies are critical.

3.9.8. Standardization of Soil Health Metrics: Global harmonization of soil health indicators and thresholds is essential for comparative assessment across regions. Developing universally accepted soil health indices that account for climate variability will enhance monitoring and reporting.

3.9.9. Long-Term and Multi-Scale Experiments: Establishing long-term field experiments across agro-ecological zones is necessary to capture cumulative climate effects on soil systems. Multi-scale studies from micro-aggregates to landscapes should be encouraged.

3.9.10. Capacity Building and Knowledge Transfer: Future directives should emphasize farmer-centric extension, digital platforms, and participatory approaches to translate scientific findings into practical land management solutions, ensuring sustainable soil stewardship under climate change.

4. Conclusion

Productive soil is fundamental to achieving higher crop yields and sustaining global food security. In the 21st century, ensuring soil quality and health has become increasingly critical to withstand rapidly changing climate scenarios, including rising temperatures, erratic and uneven rainfall patterns, delayed onset of sowing, accelerated erosion of fertile topsoil, and the progressive decline of soil fertility. These challenges collectively render soils unproductive, ultimately leading to poor crop performance and reduced agricultural output. To balance sustainable food production with future food security, agriculture occupies a pivotal role in addressing these emerging constraints. Healthy soils are the cornerstone of resilient agro-ecosystems, as they enhance nutrient cycling, water retention, microbial activity, and overall crop productivity, thereby ensuring the production of safe and nutritious food. Agriculture, as a shared global responsibility, requires collective participation and equitable contributions from all stakeholders to achieve long-term sustainability.

However, unsustainable agricultural practices such as excessive and indiscriminate use of synthetic fertilizers, systematic deforestation, intensive and improper tillage, and the combined action of wind and water erosion have severely degraded soil resources. Additionally, the loss of soil organic matter, increasing soil salinization, and widespread land degradation have accelerated desertification, resulting in the loss of millions of tonnes of fertile topsoil each year. These processes indirectly contribute to siltation of rivers and reservoirs, disruption of hydrological cycles, climate change amplification, and significant loss of biodiversity. Therefore, restoring and maintaining soil health is not merely an agronomic necessity but a global imperative for climate resilience, environmental sustainability, and long-term food and nutritional security.

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