

# SOIL HEALTH FOR SUSTAINABLE AGRICULTURE

## Abstract

Soil health refers to a balanced condition of soil to function to its full potential to sustain the physiochemical and biological processes as well as promote environment equality and prosperity of plant and animal health. The quality and vitality of soil directly influence agricultural productivity, crop resilience, water management, carbon sequestration, and overall ecosystem health. Soil health is a crucial aspect of sustainable agriculture, and it plays a significant role in ensuring food security for the ever-expanding global population. The intensification of agricultural activities to meet the growing demand has led to changes in the soil ecosystem and soil health. In order to maintain soil health, sustainable agricultural practices such as conservation tillage, Vermicomposting, Crop diversification, Crop residue management, Organic amendments, Fertilizer management, Irrigation management, Naturally Occurring Mineral Amendments, Effective Microorganisms, Use of biopesticides need to be adopted. These practices help farmers to reduce erosion, improve nutrient cycling, save money on inputs, and enhance the resiliency of their working land. This chapter aims to comprehensively assess soil health indicators, analyze their interactions, and propose sustainable agricultural practices for maintaining and enhancing soil health. Through field studies, laboratory analyses, and literature reviews, this research explores the intricate relationships between soil physical, chemical, and biological attributes, identifying key sign of soil health and their implications for sustainable farming.

**Keywords:** This chapter aims to comprehensively assess soil health .

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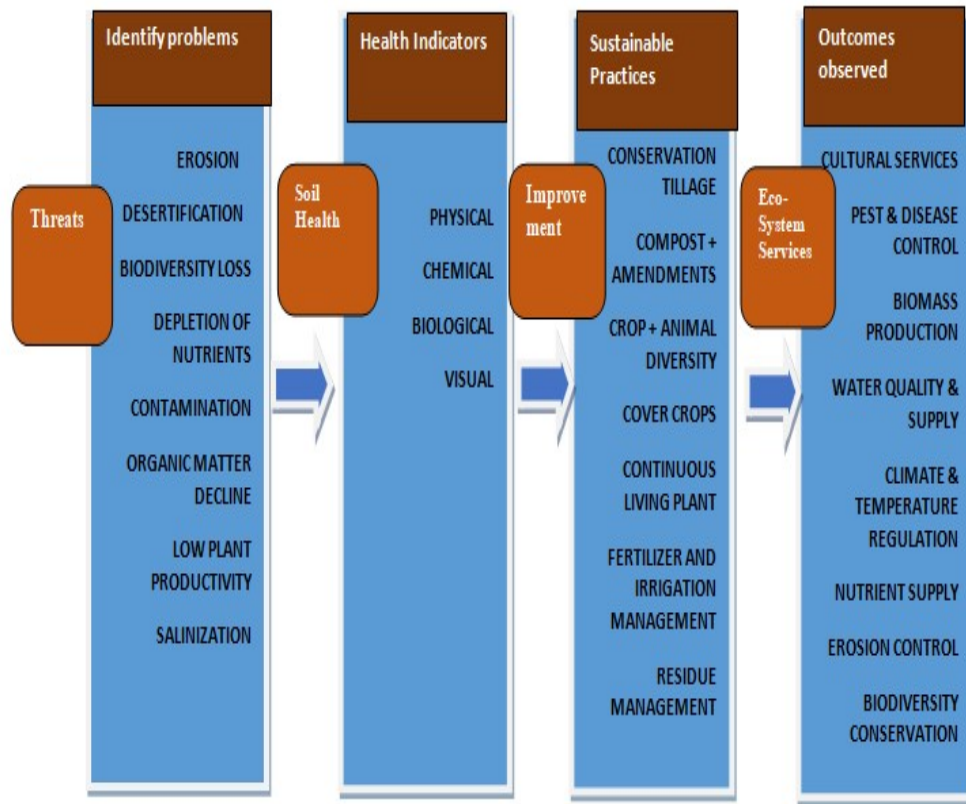
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## I. INTRODUCTION

Soil health is a fundamental component of sustainable agriculture, influencing crop productivity, environmental conservation, and overall ecosystem resilience (Tahat et al., 2020). Soil, often referred to as the "living skin of the Earth," serves as a dynamic and intricate ecosystem that supports the growth of crops, nurtures biodiversity, and plays a pivotal role in maintaining ecological balance. Human-centered practices in agricultural fields, such as biomass burning, excessive tillage of soil, excessive use of agrochemicals, over irrigation, deforestation, and extractive farming methods, are to blame for a loss in soil health. When soil health is compromised, heavy metals accumulate, essential micronutrients are deficient, the microbiome of soil gets affected and pests and pathogens contaminate food. Healthy soil can hold more water and nutrients lead to improved crop yields, reduce in utilization of synthetic chemicals, act as carbon sink and mitigate climate change as well as support a diverse community of microorganisms which helps improve soil structure and fertility. A low-cost approach to overcoming all the difficulties of sustainable agriculture is provided by healthy soil (lal, 2008). This approach may be utilised to address both theoretical and practical problems pertaining to the ecological production of food. To create new practises that are not hazardous to the environment, it incorporates biological, physical, chemical, and ecological concepts (Lichtfouse et al., 2009). Furthermore, sustainability may be able to contribute to the global food and agricultural needs (Singh et al., 2011).

Sustainable agriculture is an approach that seeks to meet the needs of the present without compromising the ability of future generations to meet their own needs. It emphasizes responsible resource management, environmental stewardship, and the well-being of farmers and their communities. It involves conservational practices that maintain or enhance health of soil, such as crop rotation, cover cropping, organic amendments, reduced tillage, and integrated pest management. These conservational practices are region-specific and site-specific. So, site-specific nutrient management and conservational strategies should be adopted (Mishra et al., 2021b). Today's agricultural technologies may increase productivity to meet world food demand, but they may also threaten agricultural ecosystems by intensifying pesticides (Mishra et al., 2021a). Certain agricultural practices like crop residue burning affect the air quality (Grover et al., 2019), soil quality and human health (Grover et al., 2015). Such faulty agricultural practices need to be managed. As humanity faces the challenges posed by a changing climate, growing population, and diminishing natural resources, understanding and prioritizing soil health has emerged as a fundamental pillar of sustainable agricultural practices. Assessment of soil health is depend on the variables of soil quality that guarantee the sustainability of crop production in agricultural lands (Doran and Zeiss, 2000; Sahu et al., 2019).



**Figure 1:** Concept of Soil Health & Sustainable Agriculture

According to Deneff and Six (2005), soil-health indicators can be broadly divided into three groups: physical, chemical, and biological. However, these divisions are not always clear-cut because many features are a result of numerous processes. For instance, chemical factors (such as the amount of organic matter), mineral types, and/or biological activity all contribute to soil aggregation (Bünemann et al. 2018). Similarly, plant-available phosphate falls under chemical indicators, but is largely a result of biological processes of microbial mineralization and plant uptake. According to several studies (Doran and Zeiss, 2000; Leskovar et al., 2016), the soil biota's microbial community, abundance, variety, activity, and stability are key indicators of the soil's quality. In order to conserve and replenish the soil ecosystem, as well as to reduce climate change and adhere to the Sustainable Development Goals, sustainable agriculture practices are becoming more and more popular. The involvement of soil microbiota in these practices is vital.

This chapter will highlight the critical role soil health plays in achieving long-term agricultural resilience and productivity. Moreover, we will explore the significance of regenerative agricultural practices, innovative technologies, and holistic management approaches in nurturing soil health. By adopting these practices, we not only ensure food security but also mitigate the environmental impacts associated with conventional farming methods.

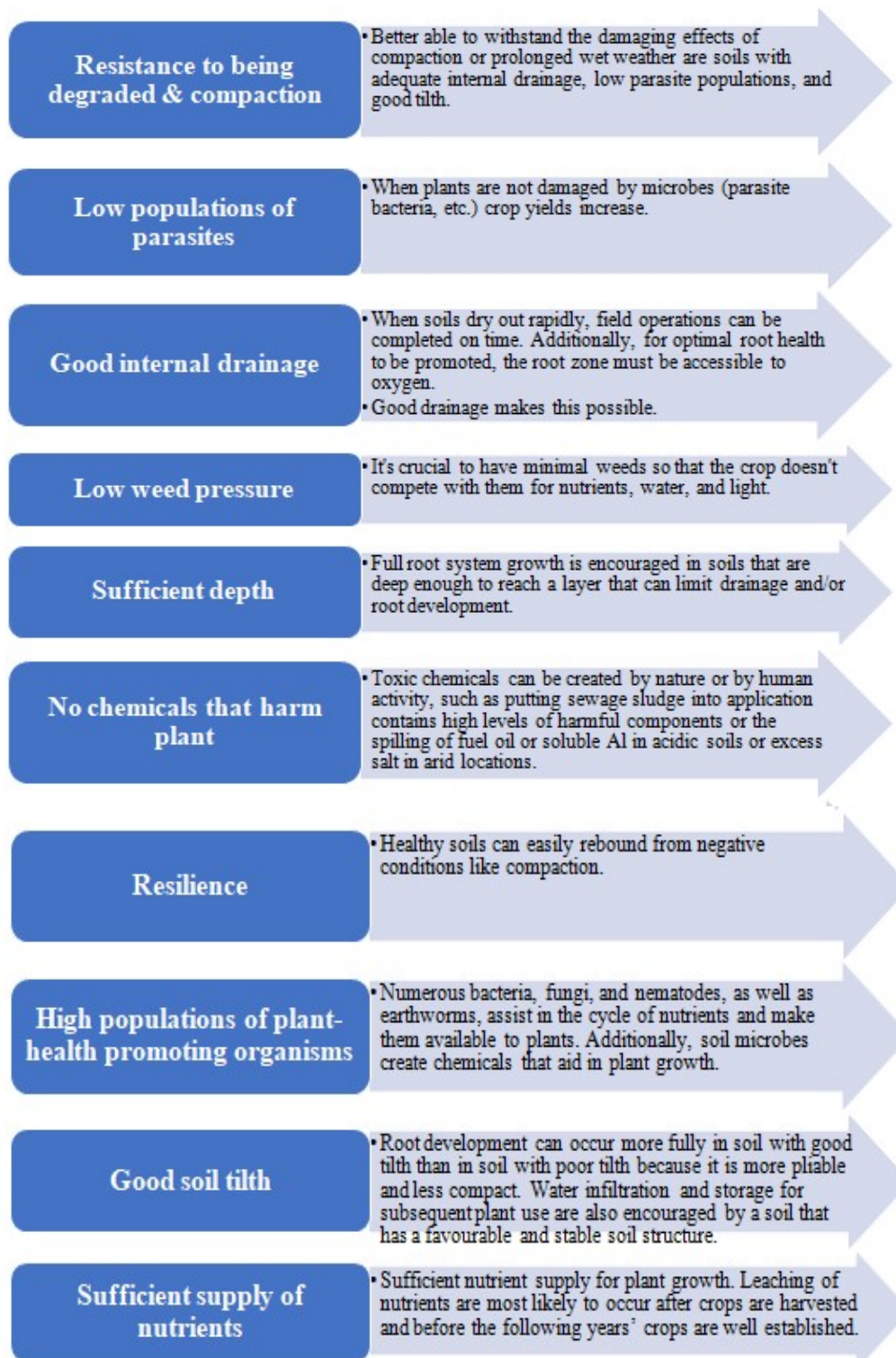
## II. CONCEPT OF SOIL HEALTH

The term "soil health" refers to the functionality of soil as a living ecosystem capable of sustaining plants, animals, and humans while also improving the environment (Doran and Zeiss, 2000). Not only is soil alive with bacteria, fungi, and other living species, but it is also composed of inert clay, silt, and sand. Only living things have "health," so in order to maintain "soil health," we must acknowledge that the soil is alive. The continuous ability of a soil to function as a vital living ecosystem that supports plants, animals, and humans is the definition of "soil health" as given by the USDA-NRCS. Soil health concept is gaining importance now a days. This concept was initiated in 1990 which received harsh criticism in its initial stage but several countries have now appreciated the concept. India has recently taken initiative for distribution of soil health cards to 100 million farmers in the launch of soil health initiatives by large corporations to manage their supply chains more sustainably. The impetus to execute proper measures for healthy soil on a worldwide scale was increased by the UNFCCC's inclusion of carbon sequestration in soils as a primary strategy for removing atmospheric carbon dioxide. The year 2015 was designated as the International Year of Soils. The motto "Healthy soils for a healthy life" emphasizes soil's significance for food security, economic development, and critical ecosystem functions. Their objectives are either directly or tangentially related to soil sustainability (Hurni et al., 2015).

All facets of soil and crop management have an impact on soil health, which includes biological, chemical, and physical components. High concentrations of residues that are still relatively fresh and serve as the organisms' food sources (referred to as particulate or light fraction organic matter in scientific literature) as well as high concentrations of humified organic matter that holds water and provides cation exchange (negatively charged) sites that hold nutrients like  $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$ , and  $\text{K}^+$  are all characteristics of a healthy soil. Living soil organisms and their roots, along with recent organic waste products and thoroughly decomposed humic components, make up soil organic matter (Magdoff, 1996). Important factors that affect soil health include salt concentration, pH, and the amounts of accessible nutrients. Low nutritional levels, excessive quantities of a hazardous element or high concentrations of salt can all have a negative impact on plant growth.

Soil health should be the centre of concern for all stakeholders such as producers, consumer, farm owners and society. The producer focuses on crop health; good health is determined when the crop is pest & disease-resistant, inputs and labour-extensive, yield is high and the shelf life is also high. The Consumers focus on the quality of food, a good quality food is determined by its high nutrition values, high flavor & aroma, free from all the toxins, and also by the shelf life of the crop. The farm owner focuses on the health of the farm, the health of the farm is determined by its high SOM, and high economic viability and it should be climate resilience. Society focuses on ecosystem health, ecosystem health can be determined by increasing biodiversity, water quality and soil carbon sequestration. Soil health is closely tied to sustainable agriculture because the main factors in maintaining healthy soil include crop rotations, no-tillage techniques, and other activities. They may improve soil quality and boost system performance. increased soil water uptake and storage, increased soil beneficial soil organisms, and improved crop output tolerance to drought and other difficult growing conditions in a variety of crop rotations. Crop rotations that include a variety of crops benefit farmers while reducing production risk and uncertainty and enhancing soil and agricultural sustainability.

## 1. Characteristics of a Healthy Soil



**Figure 2:** Characteristics of Healthy Soil

**2. Soil Health Principles:** The soil health foundation consists of five principles

- **Soil armor-** Covers the soil & provides various benefits for cropland, rangeland, gardens, & more.

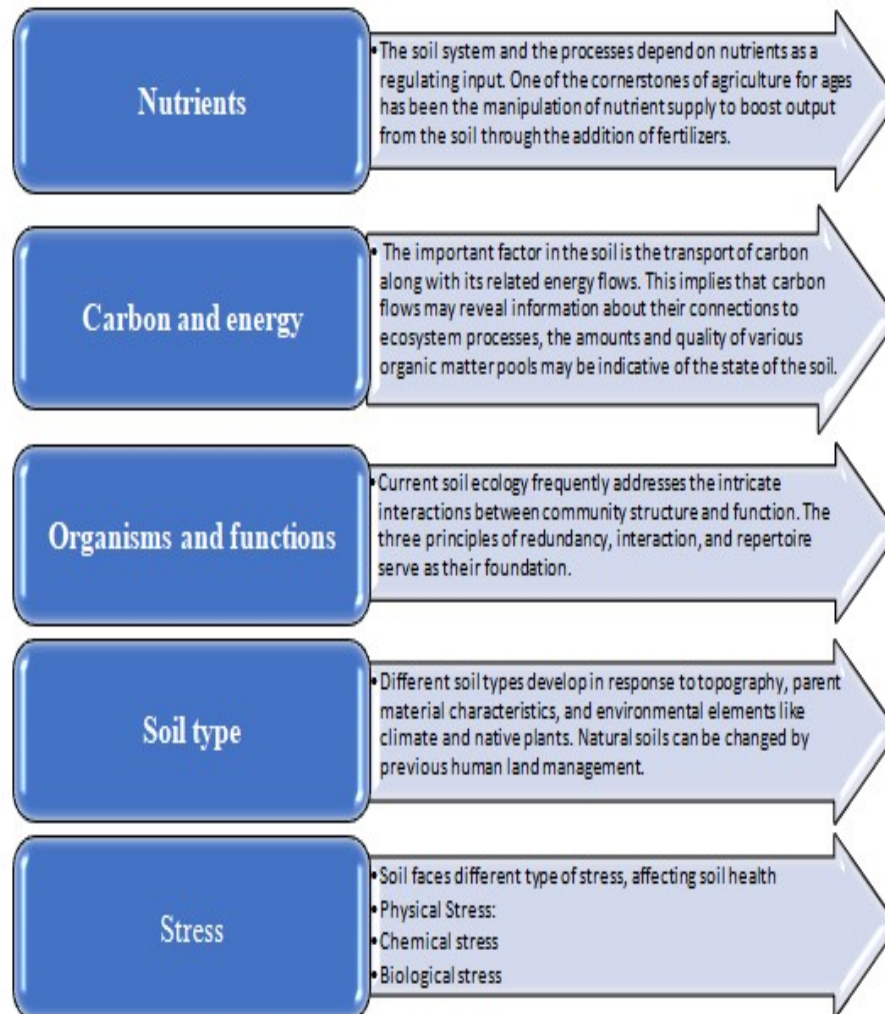
**Table 1: Benefits of Soil Armor**

<b>Benefits of soil armor:</b>	
Controlling wind and water erosion	Shields the soil's surface from wind and/or water as it passes over the soil. Holds the soil in place and preserves its beneficial nutrients and organic matter.
Evaporation rates	Lowers the rate of soil evaporation, preserving more moisture for plant usage.
Soil temperatures	Keep soil temperatures within a more moderate range, keeping soil warmer in cold weather and cooler in hot times.
Compaction	One factor in soil compaction is rain falling on bare soils. The raindrop energy is largely lost when it strikes the armor as opposed to bare ground.
Suppresses weed growth	Limits the amount of sunlight available to weed seedlings.
Habitat	Provides a protective habitat for the soil food web's surface dwellers.

- **Minimizing soil disturbance:** Soil disturbance can generally occur in different forms
  - **Biological disturbance:** The plants' capacity to absorb CO<sub>2</sub> and sunlight is constrained by overgrazing.
  - **Chemical disturbance:** Pesticide and nutrient overuse can interfere with the operations of the soil food web.
  - **Physical disturbance:** Over time, tillage lowers and eliminates soil pore spaces, which limits infiltration, destroys the organic glues holding soils together, and increases water erosion. soil organic matter loss.
- **Plant diversity:** Rotations of different crops resemble our original landscapes of plant variety. They are crucial to the everlasting security of our food supply and the sustainability of our soil resource. In addition to increasing biodiversity and the soil food web, it also enhances rainfall infiltration, nitrogen cycling, and disease and insect activity.
- **Continual live plant/root:** Cover crops can be employed as annuals, biennials, or perennials in cropping systems to address a range of resource challenges:
  - Capture sunlight and CO<sub>2</sub>, supplying carbon exudates to the soil food web.
  - Creating pore spaces and soil aggregates to increase soil infiltration
  - Inorganic fertilizers caught and released to improve water quality.
  - Salinity control.
  - Modifying the carbon/nitrogen ratio of the cover crop mixture to speed up or slow down decomposition

- **Livestock Integration**
  - **Balanced carbon/nitrogen ratio:** The carbon/nitrogen ratio is balanced and our crop rotation residue is managed for no-till sowing by fall or winter grazing to convert high-carbon annual crop residue to low-carbon organic material.
  - **Better regrowth:** Grazing annual and/or perennial plants in the spring or summer with brief exposure times and lengthy recovery times enables the plants to regenerate and harvest more sunshine and CO<sub>2</sub>.
  - **Increased nutrient intake:** By grazing crop leftovers and cover crops, we can remove cattle from perennial grasslands earlier in the fall, lengthening the time it takes the grass to recover, and improving the diet of the livestock.

### 3. Factors Affecting Soil Health

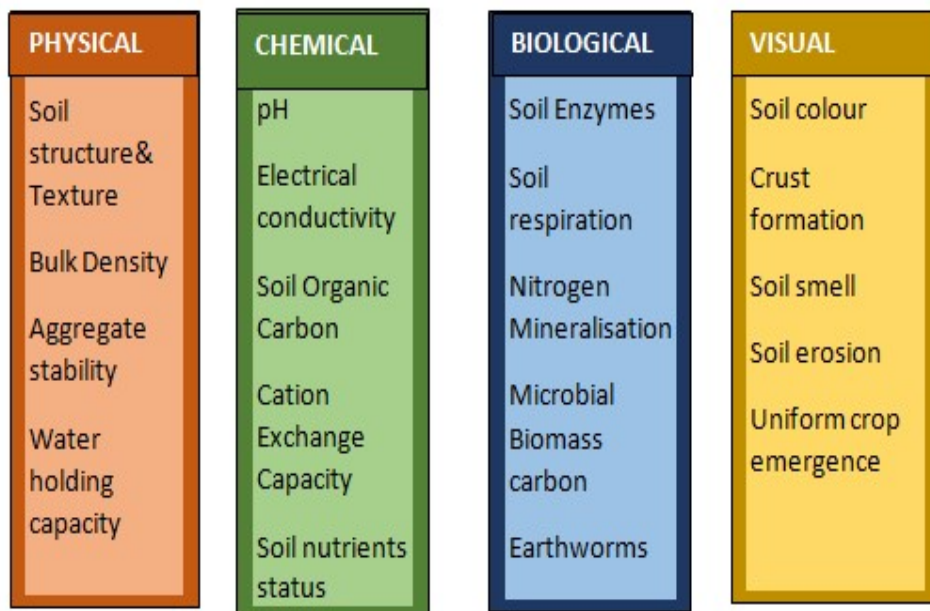


**Figure 3:** Factors Affecting Soil Health

### III. SOIL HEALTH INDICATORS

The status of soil health is assessed using soil health indicators, which are a collection of quantifiable physical, chemical, and biological characteristics related to functional soil processes. The drivers of global change (rising temperatures, increased atmospheric carbon dioxide and nitrogen deposition, growing variability in amount, intensity, and distribution of precipitation, extreme climatic events, and their interactions) must be taken into consideration when defining soil indicators. To understand soil health as a tool for sustainability, a variety of soil health indicators have been created to quantify and assess changes in soil characteristics and functioning. Good indicators of soil health are those that can alter quickly in response to anthropogenic or natural events. Bulk density, soil aggregate stability, and water holding capacity have all been determined to be the best physical markers. Chemical indicators with recognised values include pH, EC, soil organic carbon, Cation exchange capacity and soil nutrient status. In contrast to the microbiological and biochemical features, such as soil enzymes, soil respiration, mycorrhiza, lipid profile, and earthworms, which change quickly as a result of disruption brought on by various agricultural management patterns, the majority of them often respond slowly. Visual indicators includes soil colour, crust formation, soil smell, soil erosion etc.

**Integrated Approach:** Combining multiple indicators provides a holistic assessment of soil health, as no single indicator can capture its complexity. Integrating physical, chemical, and biological indicators helps identify synergies and trade-offs, aiding in sustainable land management decisions (Giller et al., 2009).

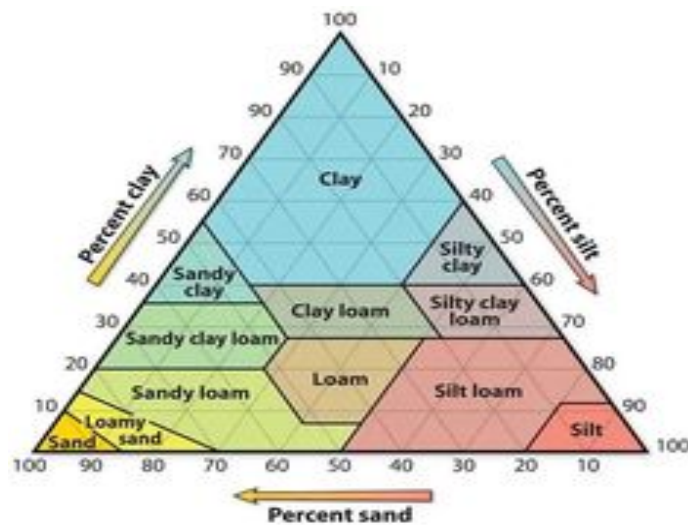


**Figure 4:** Types of Soil Indicators



## 1. Physical Indicators

- Soil Texture and Structure:** Soil texture, determined by the relative proportions of sand, silt, and clay particles, influences water holding capacity and drainage. Soil with more clay particles has a higher water holding capacity than soil with more sand particles. Soil with good structure has more pore space for water storage than soil with poor structure. Soil with more clay particles has more surface area for nutrient exchange than soil with more sand particles. Soil structure affects nutrient availability because it determines how well nutrients can move through the soil. Soil with good structure allows nutrients to move through the soil more easily than soil with poor structure. Soil structure affects root penetration and microbial activity, impacting plant growth and nutrient availability (Walkley & Black, 1934).

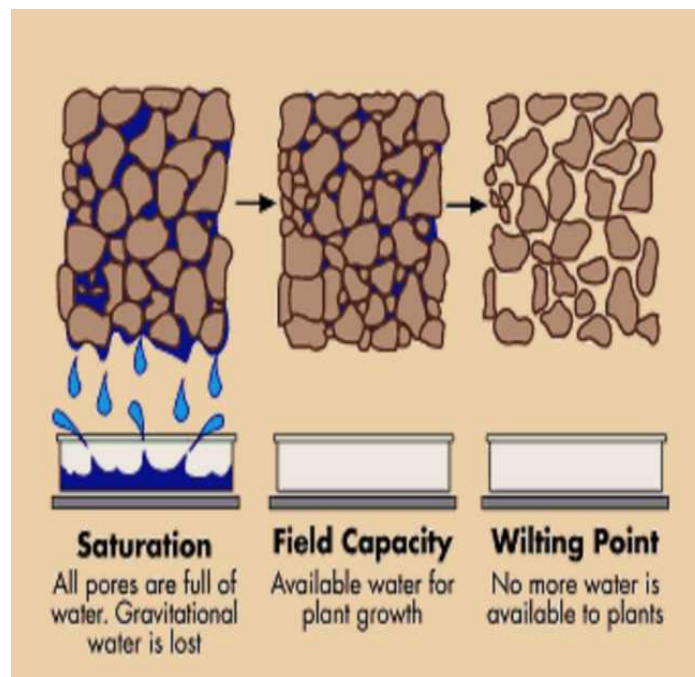


**Figure 5:** Types of Soil in Percent

- Bulk Density:** Is an indicator of how fast water is absorbed into the soil and may help in identifying the soil compaction. It is calculated as the dry weight of soil divided by its volume. Bulk density reflects the soil's ability to function for structural support, water and solute movement, and soil aeration. Bulk densities above thresholds indicate impaired function. Acc to NRCS, U. (2019). Low soil porosity and compaction are indicators of high bulk density. Root development may be hampered, and air and water may not travel through the soil as well. Compaction can reduce the amount of vegetative cover that is available to protect soil from erosion and cause shallow plant rooted and poor plant growth, which can affect agricultural productivity. Compaction can enhance runoff and erosion from sloping terrain or waterlogged soils in flat places by decreasing water uptake into the soil. Ploughing at the beginning of the growing season, for example, temporarily reduces bulk density and disturbs compacted soil layers, according to Dexter et al. (2008).
- Aggregate Stability:** Aggregate stability is the indicator which determine how well an agroecosystem will work. Well-aggregated soils have a lot of aggregates, and this condition is regarded to be particularly desirable for a variety of reasons. Better soil

health, increased agronomic productivity, reduced susceptibility to soil erosion, and potential for carbon sequestration are all characteristics of well-aggregated soils. In the development of soil structure and soil health, soil aggregates play a significant role. Excretions from soil microorganisms serve as cementing agents, holding soil particles together. Storage of air, water, and gaseous exchange are influenced by the pore spaces in soil. They enable the development and penetration of plant roots as well as provide home for soil microbes. They also aid in the transportation and cycling of nutrients. Higher aggregate stability soils are less prone to erosion. When subjected to disruptive forces like water, they maintain their shape and do not easily disintegrate. Arias (2005). **Soil aggregate stability** is an important physical indicator of soil health, which protects organic matter accumulation, improves soil porosity, drainage and water availability for plants, decreases soil compaction, supports biological activity, and nutrient cycling in the soil.

- Water Holding Capacity:** Water Capable According to Smith (2018), a soil's capacity is its ability to hold the most water between its field capacity and permanent wilting point moisture levels. This capacity is influenced by the soil's texture, organic matter content, porosity, and pore size. The amount of water a soil can store for use by crops is known as its water holding capacity. The most frequent limiting element for many crops is water. A problem with too much water is that it can cause erosion, standing water, and nutrient loss. A soil with a low capacity to retain water will have a small range of acceptable moisture levels. Poor plant development results from both situations. Soil texture and organic matter are the key components that determine soil water holding capacity. In terms of soil texture, those made up of smaller particle sizes, such as in the case of silt and clay, have larger surface area.



**Figure 6:** Stages of water holding (USDA Bulletin 462, 1960) Public Domain

## 2. Chemical Indicators

- **pH:** For farmers, the pH of the soil is a crucial factor (Pandeewari et al., 2012). A soil is described as acidic if the pH is less than 6, normal if the pH is between 6 and 8.5, and alkaline if the pH is higher than 8.5. It is a crucial factor because it ensures the availability of plant nutrients, such as Fe, Mn, Zn, and Cu, which are more readily available in acidic soils than in alkaline ones (Deshmukh 2012). It also aids in preserving soil fertility and determining the amount of amendments necessary for improvement (Daji 1996). pH is a reliable indicator of whether soil nutrients are in balance. Indicators of plant and other living organisms, nutrients that are readily available, cation exchange capacity, and organic matter concentration are also included (Foth & Ellis 1997). The pH of the soil generally rose with depth (Tale et al., 2015).
- **Electrical Conductivity:** Ion concentration in a solution is gauged by electrical conductivity. A soil solution's electrical conductivity rises as the concentration of ions does. Due to the slope of the land surface, high permeability, and heavy rainfall that caused the leaching out of alkali and alkaline bases, it changes with depth and exhibits less variance in upland profiles. It is a measurement that is related to factors in soil that influence subsurface characteristics such salinity, organic matter level, cation exchange capacity, drainage state, and soil texture (Solanki & Chavda 2012). EC is frequently employed as a measure of salinity and is used to determine the concentration of soluble salt in soil (Wagh et al., 2013). It has typically been used to test soil salinity, although it can also be used to measure soluble nutrients (Smith et al., 1996). A typical soil has an EC of less than 1 (dS/cm), 1-2 (dS/cm) is critical for germination, 2-3 (dS/cm) is critical for the growth of salt-sensitive crops, and greater than 3 (dS/cm) is detrimental to several crops. (Deshmukh 2012).
- **Soil Organic Carbon:** SOC is the carbon that is still present in soil after any substance made by living things has partially decomposed. It is found as a primary component of SOM and is essential for numerous ecological and soil activities. Soil organic matter contributes to nutrient storage, water retention, and microbial activity, supporting soil structure and fertility (Six et al., 2000). The amount of organic carbon in a soil is influenced by the local geology, climate, land use, and management. Most organic carbon is contained in the top layer of soil. In order to improve soil health and yield, farmers are interested in maintaining and growing soil organic carbon for specific fields. This also improves soil aeration, water retention capacity, drainage, and enhances microbial growth. Increasing the amount of carbon in the soil lowers the atmospheric concentration of carbon dioxide which provides a better climatic condition for plant growth.
- **Cation Exchange Capacity:** The amount of cations that are reversibly adsorbed per unit weight is known as the soil cation-exchange capacity (CEC). (Krogh et al., 2000; Yunan et al., 2018) CEC is a crucial indicator for examine the soil fertility, crop growth, partitioning and transportation of contaminants in soils. In addition, it is a significant factor that affects the adsorption of organic contaminants, including antibiotics, and heavy metals in soils. For instance, Teixido discovered that CEC was

the primary factor affecting the soil's ability to adsorb tetracycline in an acidic environment.

- **Soil Nutrient Status:** The primary source of practically all nutrients needed for plant growth is soil. It has a significant impact on how productive an agro-ecosystem can remain over time. Micronutrient insufficiency is a significant barrier to soil production, stability, and sustainability (Tale et al., 2015; Bell and Dell, 2008). Plant growth is influenced by the fertility of the soil. The presence or absence of macro- and micronutrients affects the fertility of the soil. Despite being needed in extremely small amounts, micronutrients are just as important to agriculture as macronutrients since they are essential to plant growth (Nazif et al., 2006). Boron, chlorine, sodium, copper, iron, manganese, zinc, vanadium, and molybdenum are among the important micronutrients for plants. These substances can be harmful if present at concentrations over the threshold yet are necessary at trace amounts (Islam et al., 2020). Cl, Mn, Fe, Zn, and vanadium are expected to participate in the process of photosynthesis. In terms of plant development, productivity, soil fertility, and animal nutrition, the micronutrients iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), cobalt (Co), nickel (Ni), and sulfur (S) are particularly crucial.

**Table 2: Nutrient status of soil**

<b>Nutrient</b>	<b>Low</b>	<b>Medium</b>	<b>High</b>
<b>Ph</b>	< 6.5	6.5 – 7.5	> 7.5
<b>EC</b>	< 1	1-3	>3
<b>OrganicCarbon (%)</b>	< 0.50	0.50 – 0.75	> 0.75
<b>Nitrogen</b>	< 280	280– 560	>560
<b>Phosphorus</b>	< 10	10 – 25	>25
<b>Potassium</b>	< 110	110 – 280	>280
<b>Sulphur</b>	< 10	10 – 15	>15
<b>Boron</b>	< 0.5	0.5 – 1	>1
<b>Zinc</b>	< 0.60	0.60 – 1.20	>1.20
<b>Copper</b>	< 0.20	0.20 – 0.40	>0.40
<b>Chlorine</b>	< 4.80	4.80 – 8	>8
<b>Manganese</b>	< 2	2 – 4	>4

3. **Biological Indicators:** The health of the soil ecosystem is reflected by biological indicators' effects on nutrient cycling, disease prevention, and organic matter decomposition (Garland & Mills, 1991). Through their effects on the breakdown of dead organic materials, nutrient cycling, the modification and movement of soil components, and the creation and maintenance of soil structure, soil organisms have a significant influence over numerous soil processes. The biological activity of soils is primarily

focused in the uppersoil, which ranges in thickness from a few centimetres to 30 cm, although occasionally being difficult to detect. Plant roots make up 5–15% of the living component of the SOM, soil organisms make up 85%–95% of it, and their constituent macrofauna and mesofauna make up 15–30% and 60–80% of it respectively. The decomposition of organic wastes and activities that control the cycling of nutrients (such as mineralization, denitrification, nitrogen fixation, etc.) account for a large portion of biological activity. The macrofauna of the soil play a significant part in these processes because they devour dead organic matter first. Technically level and cut into small pieces the field guide to soil macrofauna. Mesofauna and bacteria can then access these tiny fragments and partially decomposed organic wastes. Soil macrofauna actively bury organic debris deep within the soil by burrowing, which also encourages the activity of microbes.

Intensive tillage, burning of residue, and environmental factors (temperature, humidity) have an impact on soil biodiversity. Therefore, its disturbance can be a serious issue for the soil Ecosystem. We must use certain techniques, including as mulching, residue management, crop rotation, crop species selection, and site-specific landscape management, in order to preserve biodiversity and the processes that are mediated by it.

- **Soil Enzymes:** Soil enzymes are biological catalysts that break down organic matter and facilitate nutrient release, serving as indicators of microbial activity and nutrient cycling (Dick et al., 2011) for plants use. Enzymes are typically produced by microorganisms and are abundant in soils with active microbial communities. For instance, the enzyme glucosidase converts the plant molecule glucoside (substrate) into glucose. They have a active sites that bind to the substrate to create a transient complex that is unique to the substrate. A result of the enzymatic process, which could be a nutrient present in the substrate, is produced. A lack of microbial activity or low enzyme activity may indicate nutrient-poor soil. On the other hand, high enzyme activity or abundance might serve as a sign of a diversified microbial population and a healthy, nutrient-rich soil.
- **Earthworms:** A source of nutrients, a suppressant of external diseases, and a decomposer of pollutants are all soil organisms (bacteria, fungi, protozoa, etc.). Earthworms improve soil structure, nutrient distribution, and water infiltration, reflecting soil vitality (Blouin et al., 2013), carbon cycle, controlling the cycling of plant nutrients and thereby their availability, blending organic and inorganic soil components and creating soil aggregates, increasing water infiltration and thereby reducing soil loss by erosion, spreading and interacting with pathogenic or beneficial microorganisms, and decomposing numerous potentially harmful pollutants in soils.
- **Microbial Biomass Carbon :** Microbial biomass carbon the term "carbon" refers to the amount of carbon (C) that living organisms such as bacteria and fungus, which make up the majority of soil organic matter, contain. By keeping track of the carbon release from the soil after chloroform fumigation (Liddle et al., 2020), it can be calculated, and it corresponds to all of the microorganisms present there (Jenkinson et al., 2004). The primary productivity of the terrestrial ecosystem is influenced by nutrient dynamics, which are controlled by MBC, which serves as a significant indicator of soil organic carbon (SOC) (Lepcha et al., 2020; Kara and Bolat, 2008).

MBC is a part of the SOC's active fraction, which also includes a fast turnover component and a passive portion of long-term stability (Alvarez et al., 2016). Conversely, when MBC is low, fine pores shield SOC from microbes and fine holes shield bacteria from animal grazers (Hassink 1992).

- **Soil Respiration:** The amount of carbon dioxide (CO<sub>2</sub>) released from the soil is measured by soil respiration. It is released as a result of the breakdown of soil organic matter (SOM) and plant litter by soil microbes, plant roots, and soil fauna. It measures the amount of microbial activity as well as the quantity and rate of SOM decomposition, making it an essential sign of soil health. When SOM decomposes, the organic nutrients it contains—like organic phosphorus, nitrogen, and sulfur—are changed into inorganic forms that vegetation may absorb. Mineralization is the name for this transformation. Carbon mineralization is another term for soil respiration.

The rate of soil respiration reveals how well the soil can support microbial life and plant growth. Low soil respiration rates signify that SOM or plant litter is not readily available to soil bacteria. Additionally, it might signify factors like soil temperature, moisture content, porosity, and quantities of accessible nitrogen that inhibit biological activity and decomposition.

- **Nitrogen Mineralisation:** The transformation of organic into inorganic nitrogen, known as soil nitrogen mineralisation (N<sub>min</sub>), is crucial for productivity and nutrient cycling. The temperature and characteristics of the soil affect the balance between mineralization and immobilization (net N<sub>min</sub>).

One of the major factors influencing the productivity of ecosystems, fertility (Elrys et al., 2021) and microbial decomposition is the availability of soil nitrogen (N), which also plays a critical role in controlling N cycling.

Plants and microorganisms fight for these N resources as organic matter is broken down and depolymerized to monomers and inorganic N. A reliable indicator of overall soil N availability is the net balance of N mineralization and immobilization, which is influenced by soil physicochemical parameters, above- and below-ground litter input, plant and microbial nutrient requirements, and climatic conditions. As a result of the influence of soil temperature and moisture & oxygen content on microbial activity, it is typically higher in well-aerated soils from more humid climates at lower latitudes.

### Conditions Affecting N Mineralization

The amount of ammonium that is released to the soil through mineralization depends on several factors:

<b>Quantity of Organic Nitrogen</b>	The total amount of organic nitrogen that can be mineralized depends on how much organic nitrogen was initially contained in the organic matter.
<b>Temperature</b>	The ideal temperature range for mineralization is 77 to 95 degrees Fahrenheit.

<b>Oxygen</b>	Since microorganisms play a role in mineralization and require oxygen to survive, there must be enough oxygen in the soil.
<b>Moisture content</b>	For optimum mineralization, water should ideally occupy between 15 and 70% of the pore space. The field capacity is similar to this.
<b>Ratio of carbon to nitrogen (C:N)</b>	The term "C:N ratio" describes the ratio of total carbon to total nitrogen present in the soil and/or organic matter. This ratio has a significant impact on the pace of mineralization that should occur for a particular type of organic matter.

When the C:N ratio is less than 20:1, net mineralization takes place because soil microorganisms require both carbon and nitrogen. Accordingly, there should be one part of nitrogen for every two parts of carbon in order to achieve net mineralization. It's critical to understand the C:N ratio if you plan to add organic amendments to your soil in order to assure N availability.

- **Microbial Diversity:** Microbes influence nutrient cycling, disease suppression, and organic matter decomposition, reflecting soil ecosystem health (Garland & Mills, 1991). Through their effects on the breakdown of dead organic materials, nutrient cycling, the modification and movement of soil components, and the creation and maintenance of soil structure, soil organisms have a significant influence over numerous soil processes. Soil biodiversity is sensitive to agricultural practices (intensive tillage, residue burning) and climatic parameters (temperature, humidity). So, its disturbance can create a significant problem with the soil ecosystem.
4. **Visual Indicators:** Farmers frequently describe the condition of the soil by describing how it feels, smells, tastes, and looks. Such morphological and visual observations of the physical properties of the soil and the development of plants can monitor the state of the soil. These observations frequently serve as a guide for later soil health evaluations. The following list includes some potential visual cues:
- **Soil Color:** Soil color can serve as a visual indicator of soil health due to its correlation with various soil properties and processes. Dark soil colors, often shades of brown or black, typically indicate higher organic matter. Well-structured soil with good pore spaces for water and air movement usually appears darker. Certain soil colors can hint at nutrient availability. For example, reddish and yellowish soils are often rich in iron and well-drained, indicating good soil aeration that promotes nutrient availability.
  - **Soil Crust Formation:** Localised soil crusting at the soil's surface causes a thin, impermeable layer that hinders seedling emergence, reduces infiltration, and favours runoff and erosion. This condition suggests unhealthy soil.
  - **Ephemeral Gullies and Runoff:** Ephemeral gullies are small, temporary channels that form in agricultural fields due to the erosion of topsoil by concentrated water flow during heavy rainfall events and transport eroded soil along with attached nutrients, pesticides, and sediments into nearby water bodies. These gullies provide

insights into soil health in the context of erosion control and sustainable land management. The presence of ephemeral gullies indicates that the soil's natural structure and stability have been compromised and transport eroded soil along with attached nutrients, pesticides, and sediments into nearby water bodies. Ephemeral gullies are the resultant of improper tillage, lack of cover crops, or inadequate vegetative cover.

- **Crop Emergence:** Crop emergence refers to the initial growth stage of plants when they emerge from the soil after germination. It can indeed serve as a visual indicator of soil health. Healthy soil conditions, including proper structure, adequate moisture, nutrient availability, and minimal compaction, contribute to timely and uniform crop emergence. Monitoring emergence can provide insights into the effectiveness of soil management practices and guide adjustments to optimize soil health and crop productivity. Prompt and uniform crop emergence indicates healthy soil while Uneven or delayed emergence can signal nutrient deficiencies or imbalances in the soil.
- **Weed Density:** Weed density can serve as a visual indicator of soil health and management practices. High weed density can indicate soil disturbance, imbalances in soil nutrients, inappropriate soil moisture conditions and management practices. So, weed density can provide insights into soil health, management practices, and the conditions that favor weed growth. Monitoring and assessing weed density can guide decisions regarding soil management, nutrient application, tillage practices, and other strategies to improve soil health and crop productivity.
- **Integrated Approach:** Combining multiple indicators provides a holistic assessment of soil health, as no single indicator can capture its complexity. Integrating physical, chemical, and biological indicators helps identify synergies and trade-offs, aiding in sustainable land management decisions (Giller et al., 2009).

## 5. Sustainable Agricultural Practices to Enhance Soil Health

- **No tillage/Conservation Tillage:** According to research by Sun et al. (2011) and van Groenigen et al. (2011), conservation tillage techniques like no-till and limited tillage have the potential to reduce soil carbon loss through decomposition and increase soil organic carbon (SOC) storage. SOC plays a significant part in preserving soil fertility, and changes in SOC can be utilised as a gauge of soil health (Veronika et al., 2020).

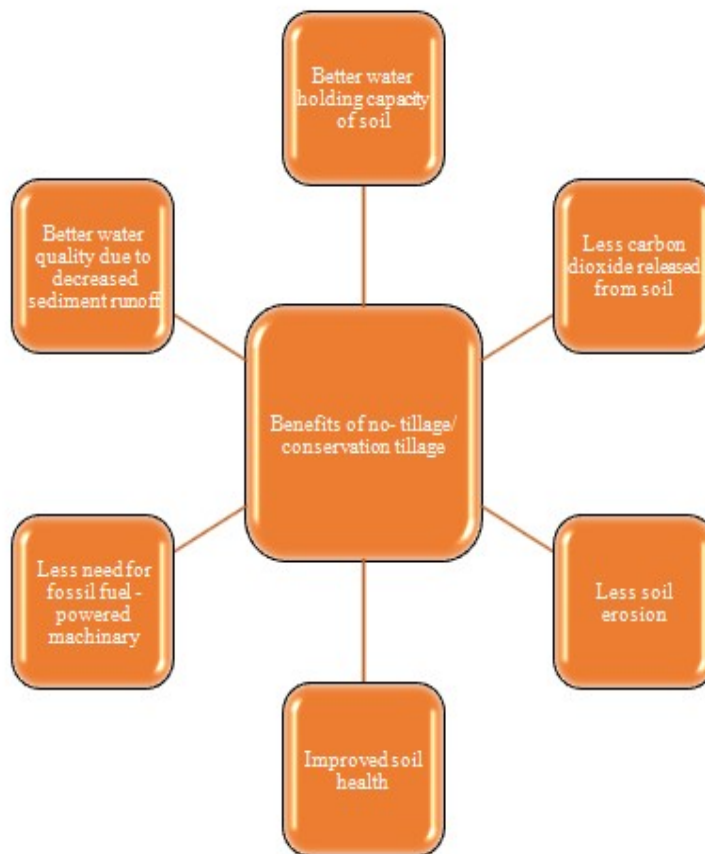
On 9% to 15% of the world's arable land, no-tillage has been widely embraced (Prestele et al., 2018). Conservation tillage has the capacity to sequester carbon, which would ultimately mitigate climate change (Kassam et al., 2019; Lal, 2004). According to Hobbs et al. (2008), it is regarded as a sustainable and environmentally benign approach for crop farming. By minimising soil disturbance and maintaining the surface soil residue layer, no-tillage can change the physical attributes of the soil (Blanco-Canqui and Ruis, 2018).

Conservation tillage could lessen soil erosion (Barton et al., 2004, Pramanick et al., 2022) and greenhouse gas emissions (Zhao et al., 2016). It could also increase



soil water-holding capacity and water usage efficiency (Liu, 2013). Energy can be saved as a result (Moitzi et al., 2019). More importantly, conservation tillage improves soil quality by encouraging the formation of stable aggregates in the soil (Choudhury et al., 2014), increasing the sequestration of total nitrogen (TN) and soil organic carbon (SOC) (Lal, 2004), and increasing the amount of nutrients that are available in the soil right away (Zhao et al., 2012).

### Benefits of no-tillage/ Conservation Tillage



**Figure 7:** Benefits of Conservation Tillage

- Vermicomposting:** The solid waste produced by earthworms after they have digested organic material in an aerobic environment is known as vermicompost. As a result of interactions between microorganisms and earthworms, vermicompost is a byproduct of the bio-degradation of organic materials using a non-thermophilic method. This vermicomposting byproduct is abundant in macro and microelements as well as humus and has a wide range of active microorganisms. High porosity, aeration, drainage, water holding capacity, and microbial activity distinguish vermicompost from other types of compost. (Edwards and Burrows, 1988; Atiyeh et al., 1999, 2000). Vermicompost boosts crop yield by enhancing soil health and soil physical characteristics including structure, texture, and tilth, which influence a land's

agronomical potential. The physical properties of the soil have a big impact on plant root penetration, potential rooting volume, nutrient mobility and uptake, water availability, and aeration. Soil texture has a significant impact on soil moisture content and chemical properties like cation exchange capacity. Sandy soils benefit especially from vermicomposting because it increases the organic matter content of the soil, which in turn improves soil aeration, maintains excellent soil aggregation, prevents soil erosion, and increases nutrient availability. Vermicompost also includes a variety of plant nutrients, such as nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, iron, manganese, zinc, copper, and boron, that improve the nutrient content of plants (Tammam et al., 2023).

- **Crop Diversification:** Crop diversification practises improve agroecosystem biodiversity, which can improve resource use effectiveness and the long-term stability of agroecosystem output (Cardinale et al., 2012; Wagg et al., 2014; Renard and Tilman, 2019). In this sense, crop diversity is an effective way to manage the land sustainably in order to prevent soil erosion and degradation, reduce climate change, and guarantee food security.

Crop rotation and intercropping have both been shown to increase grain yield through temporal and spatial diversification (Li et al. 2020a; Zhao et al. 2020). It offers numerous ecological advantages while removing ongoing barriers to monocropping. According to Jian et al. (2020), the addition of cover crops to crop rotations enhances soil organic carbon (C) by a considerable 15.5%, and long-term intercropping may increase soil organic C and total nitrogen (N) by 4% and 11%, respectively (Cong et al. 2015). According to Jia et al. (2021) and Lange et al. (2015), microbial diversity and activity have a direct impact on soil C and N.

- **Mulching/ crop residue management:** By retaining soil organic matter, crop residue management through conservation agriculture can increase soil productivity and crop production. Crop residue management/mulching has two key advantages: increased nutrient cycling and improved soil organic matter close to the soil surface. A significant amount of microbial biomass activity close to the soil surface serves as a reservoir for nutrients important for crop production and improves structural stability for greater infiltration (Singh et al., 2019). For agricultural soils, crop residue is regarded as "the greatest source of soil organic matter" (Tisdale et al., 1985). Remaining crop residue on the soil surface or incorporating it is known to have a number of positive effects on soil quality (Wilhelm et al., 2007; Blanco-Canqui and Lal, 2009).

The effects of residue management on several important physical, chemical, and biological characteristics of soil, including soil temperature, moisture content, and soil temperature variability, as well as soil organic carbon, soil pH, and cation exchange capacity.

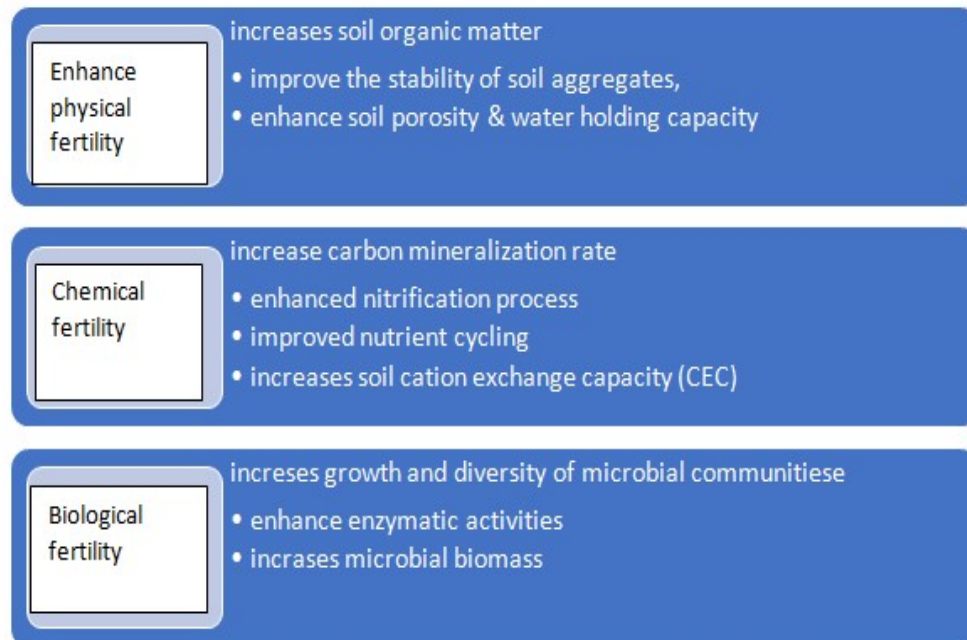
Crop residue retention can improve soil structure in a variety of ways, such as: (1) increasing soil aggregation by incorporating organic matter into the top soil; (2) protecting soil aggregates from raindrop contact; and (3) protecting soil from

compaction caused by raindrop impact. Jacobs et al. (2009); Six et al. (2006); Havlin et al. (1990).

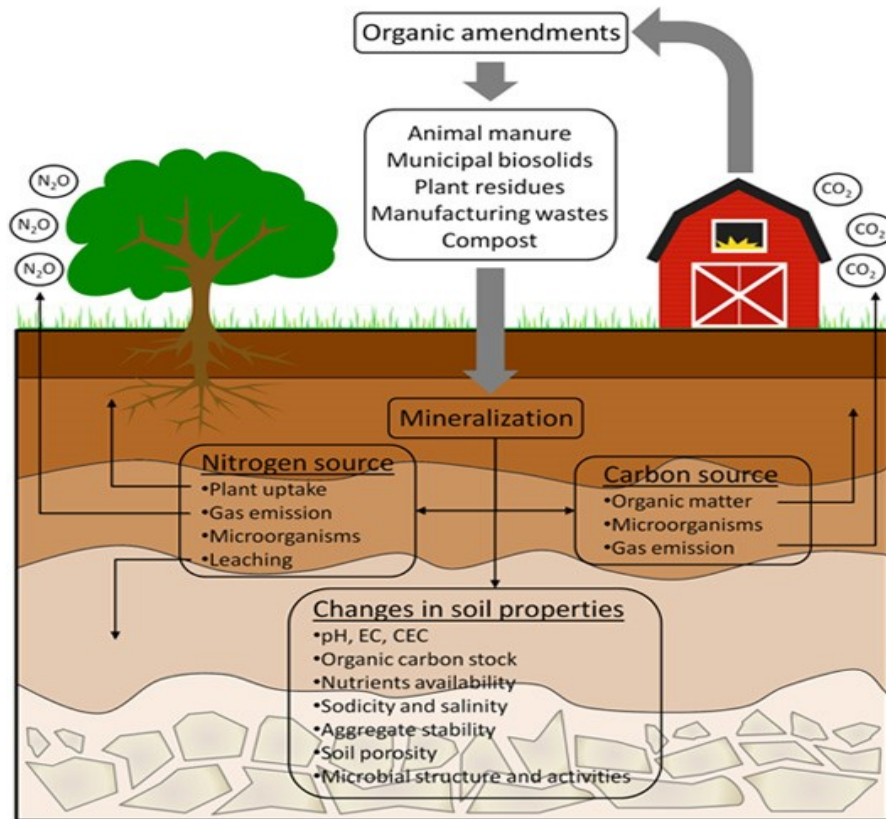
- **Organic Amendments:** The main barrier to crop sustainability and human existence is soil degradation. Farmers, environmentalists, and the general public face a major issue as a result of the intensifying consequences of climate change, including irregular rainfall patterns, unexpected increases in rainfall intensity, and temperature fluctuations around the world. (Glaesner et al 2014).

Genetic manipulation, increased fertiliser doses, improper irrigation techniques, pesticides, weedicides, and other agricultural management tactics are typically used to improve crop growth and output (Costantini et al.2022). Due to low soil organic matter, micronutrient or particular nutrient deficit, loss of biodiversity, persistence of pollutants in the soil system, etc., only a few management strategies prevented the worsening of soil health. These elements contribute to soil and land degradation, a significant issue for decreased agricultural output.

Due to their ability to raise crop yield and improve soil health, organic amendments are frequently used in agricultural practises. According to Urra et al. (2019), organic amendments of various origins and compositions, such as animal slurry, manure, compost, sewage sludge, etc., can provide the soil with essential nutrients and increase the amount of organic matter in the soil. These effects are beneficial for soil health.



**Figure 8:** Benefits of Organic Amendments



Source: Organic amendments as sustainable tool to recovery fertility in intensive agricultural systems, Scotti(2015)

- 6. Fertilizer Management:** Since different soils have different nutrient contents and plants essentially take all nutrients from the soil through their roots. For the soil to operate, it needs to contain minimum amounts of all important elements, including the N and P that are available to plants. However, an excess of reactive N and P compromises the quality of the soil. (Velthof et al., 2011). When a lot of fertiliser P is applied, for example, the soil accumulates P until it reaches a point where it can no longer take in more nutrients without becoming "saturated." P losses to surface waterways through overland flow, erosion, subsurface leaching, and drainage may increase when soil P concentrations rise.

But by specifying a dependable process for spreading compost that is both appropriate and timely, productivity can be raised. The usage of compost in the IGP in RWS is a significant element since the mean application of N + P<sub>2</sub>O<sub>5</sub> + K<sub>2</sub>O increased from 258 kg ha<sup>-1</sup> in the LGP to 444 kg ha<sup>-1</sup> in the TGP. Numerous composts, like as vermicompost, chicken manure, and Homestead yard fertiliser, can enhance crop systems based on rice and wheat. Several chemicals, including Panchagavya, an ancient traditional organic source of plant nutrients used in India, were used to fertilise rice fields. When applied to rice fields, various materials, such as Panchagavya, a deeply ingrained organic source of plant nutrients in India, increased grain productivity with RDF (suggested dose of RDF (recommended dose of fertilizers)).

- 7. Irrigation Management:** The management of irrigation must be adjusted to prevent unnecessary water waste. The amount of water supplied for irrigation during the growing season must not be larger than the effective crop water requirements in order to increase the efficiency of water use in agriculture. The crop water demand is the amount of water required to replace the water lost through evapotranspiration from a planted area. A crop's water requirements must be satisfied in order to provide the potential yields (Saccon 2018). It comprises providing water at rates commensurate with the soil's ability to absorb it and the erosion risk of the location, in levels that can be held in the soil and made available to crops, in line with crop needs.

The difference between the crop's water requirements and effective precipitation is known as the net irrigation requirement, and it is used to calculate how much water is needed to refill the soil's water content in the root zone. Utilising the soil's hydraulic qualities, the crop's characteristics, and the local temperature, the daily crop water requirement will be calculated (Saccon, 2018). You can create field channels to control water flow into and out of your field, prepare the land to limit water loss, and use other suitable water management techniques to effectively and efficiently use water and optimise rice harvests.

- 8. Naturally Occurring Mineral Amendments:** The Alimentarius Commission (Codex) permits the use of several naturally occurring alkaline-earth mineral additions because they improve quality of soil and plant production, especially in nutrient-poor and badly weathered acidic soil (Jones and Handreck, 1965; Mitani and Ma, 2005). Rock phosphate, potassium, sulphate, gypsum (calcium sulphate), etc., are some of these additions. Alkaline-earth mineral soil additives can increase soil fertility by changing the chemical makeup of the soil and promoting the synthesis of inorganic carbon in the soil (and hence CO<sub>2</sub> sequestration). Van Straaten (2006) has investigated how fertilisers made of multi-nutrient silicate rocks impact biochemical processes and nutrient movement across the root surface. He found that these fertilisers had the ability to add macronutrients like N, P, and K, as well as micronutrients like Ca and Mg, to soil. The addition of wollastonite to the soils improved the growth of soybean and lucerne plants, indicating that wollastonite has a positive impact on agricultural crops and has the potential to be used as a soil amendment in the agricultural sector, according to the biomass dry weight yield data (Haque et al., 2020). Farmers would be persuaded to use wollastonite as a soil supplement judiciously in order to reduce climate change without compromising crop quality because of these extra benefits.
- 9. Effective Organisms:** Effective microorganisms are both aerobic and anaerobic and are beneficial in a variety of ways (Bhat et al., 2021; Baldotto et al., 2010), such as increasing the beneficial microbial population in the soil for sustainable crop production, accelerating the natural composition of organic matter, and promoting the balance of microbial flora contributing to plant development (de Araujo Avila et al., 2021). They mostly comprise of photosynthesizing bacteria, lactic acid bacteria, yeasts, actinomycetes, and fermenting fungi. According to Iriti et al. 2019, EM will enhance the activities of native microorganisms, improve the structure and fertility of the soil, suppress soilborne pathogens, fix nitrogen in the soil and improve nutrient uptake, increase beneficial minerals in organic compounds, increase plant strength, and increase crop yield.

#### IV. BIOPESTICIDES

In comparison to conventional pesticides, biopesticides are a revolutionary technique for controlling or eradicating pest species such as weeds, plant diseases, and insects (Saxena and Pandey, 2001). A type of insecticides known as "biopesticides" uses non-toxic manufacturing techniques to manage pests in a way that is good to the environment. Biopesticides are made from a variety of living and extinct organisms, including plants (*Chrysanthemum* and *Azadirachta*), animals (nematodes), and microbes (*Bacillus thuringiensis*, Nucleopolyhedrosis virus), as well as their byproducts (microbial products and phytochemicals) and live species (natural enemies) (Leahy et al., 2014). The three main categories of biopesticides are: microorganisms that control pests (microbial pesticides), naturally occurring substances that control pests (biochemical pesticides), and plant-controlled pesticides including genetically modified organisms (GMOs). The use of each type of biopesticide has increased by about 10%. Bacterial biopesticides make up 74% of the pesticides on the market for a range of crops, followed by fungal biopesticides, 10% viral biopesticides, 10% fungus biopesticides, 8% predator biopesticides, and 3% other biopesticides. By generating hazardous metabolites or by using a variety of other processes, microbial insecticides can manage a range of target pests. (Bellinger, 2007).

New fungal biopesticides are employed to eradicate mites, weeds, nematodes, insects, and other fungus. They create toxins, much like bacteria, that outcompete the diseases they are meant to kill. By attacking them, they can also immobilize insects or plant diseases. Another fungicide that targets *Pythium*, *Rhizoctonia*, and *Fusarium* is *Trichoderma harzianum* (Langewald, 1999). There are several fungi that are employed to manage insects, including *Paecilomyces fumosoroseus*, *Beauveria bassiana*, etc. (Lacey and Neven, 2006). A mosquito larva-active peptide called beauverin was identified from *Beauveria bassiana* (Uribe and Khachatourians, 2004) causes intestinal cells to lyse (Jisha et al., 2013). Because of their effectiveness and safety, spore formers including *Pseudomonas aeruginosa*, *Bacillus thuringiensis*, etc. are employed commercially.

**1. Rhizobium Inoculants:** According to Ahemad and Kibret (2014), Gopalakrishnan et al. (2015), Khan et al. (2017), and Volpiano et al. (2019), rhizobial inoculants are used as biocontrol agents against plant diseases because they give plants resistance against disease-causing pathogens. The production of growth hormones, antibiotics, enzymes, siderophores, and hydrogen cyanide (HCN) are just a few of the mechanisms that Rhizobia can employ for biocontrol and disease suppression, in addition to the competition for infection sites and resources, the activation of induced systemic resistance (ISR), and the production of these substances (Deshwal et al., 2003; Ahemad and Kibret, 2014; Tariq et al., 2020).

Deshwal et al.'s 2003 study found that while fast-growing rhizobial strains were able to stop the growth of the pathogenic organisms, 20 rhizobial strains were able to limit the growth of seven soybean pathogenic bacteria. Rhizobial strains can be used as biocontrol agents in agricultural production, which is an eco-friendly strategy and a chance to use fewer pesticides. The marketability of rhizobial inoculants has also significantly increased the productivity of agricultural systems across all countries. This component of the study addresses the current understanding of the utilisation of rhizobial strains as biocontrol agents and mechanisms of action for control and suppression of

illnesses caused by plant pathogens, with a primary focus on fungi, bacteria, viruses, and nematodes.

- 2. Phosphate solubilising microbes:** Large phosphorus (P) reserves are typically present in agricultural soils, but they are generally in forms that are inaccessible to plants, needing ongoing P fertiliser applications. There is growing interest in better managing the pool of P already present in soil using P-solubilizing microorganisms due to current concerns regarding supply security, the cost of extraction, processing, and shipping of P, as well as the environmental effects of P fertilisers on water quality (Richardson, 2001; Richardson & Simpson, 2011). The biogeochemical cycle of inorganic and organic P in the plant rhizosphere has been demonstrated to involve a diverse spectrum of microorganisms, and the commercial development of inoculants based on P-solubilizing bacteria is anticipated (Parnell et al., 2016; Rafi et al., 2019).

With wheat and canola, *Penicillium bilaii*, a P-solubilizing fungus that has developed and been well studied, is advised. In the United States, maize trials were undertaken from 2005 to 2011. A meta-analysis of these trials indicated that using these fungi generally increases yields by 1.8% to 3.5%, with just two of the six years showing significant differences in treated vs. non-treated comparisons. There was no evidence of a pH decrease despite the fact that inoculation functioned better in low-P soils, indicating that the major process was probably not the production of organic ions or proton outflow.

- 3. Mycorrhiza:** Mycorrhizal fungi are "biotic fertilisers" that can replace large volumes of some fertilisers, enhancing the efficiency of fertiliser use. Many products with claims of P-solubilizing capacity are based on arbuscular mycorrhizal fungi (AMF), which increase plant P uptake by either physically extending the root systems through soil extension of the hyphae (Richardson et al., 2009) or by their capacity to absorb orthophosphate from soil solution at lower concentrations than roots. Regarding whether AMF inoculants consistently benefit crops, experts disagree (Ryan & Graham, 2018; Zhang, Lehmann et al., 2019). It has been demonstrated that AMF aid plant survival in challenging conditions. Additional barriers to their economic feasibility include the technological difficulties of mass manufacture and short shelf lives, as well as the fact that they are obligate symbionts and must colonise a host plant to finish their life cycle. They could have unanticipated effects on natural systems, which is a worry. They are challenging to monitor and, if invasive, may endanger soil and plant biodiversity (Hart et al., 2018).

## V. CONCLUSIONS

In conclusion, the concept of soil health has emerged as a fundamental pillar in the pursuit of sustainable agriculture. In a world where the pressures of climate change, biodiversity loss, and resource scarcity intensify, prioritizing soil health transcends being a choice; it becomes an ethical and strategic necessity. Recognizing soil health as an integral component of sustainable agriculture equips us with the tools to strike a balance between food production, ecological resilience, and responsible land management. This chapter has delved into the critical importance of soil health, explored key indicators for its assessment, and highlighted sustainable management practices that contribute to its enhancement. The significance of soil health lies in its profound impact on agricultural productivity, environmental resilience, and human well-being. Healthy soils are not only the foundation for

successful crop growth but also play a vital role in water filtration, carbon sequestration, and biodiversity support. Recognizing the intricate relationships between soil health, ecosystem services, and sustainable food production is essential for shaping resilient agricultural systems.

Sustainable management practices are at the heart of nurturing soil health. Conservation tillage, cover cropping, integrated pest management, agroforestry, and precision agriculture are just a few examples of strategies that promote soil health while minimizing environmental impact. These practices underscore the need for a holistic approach to land management that considers the interconnectedness of soil, water, air, and biodiversity. The dynamic relationship between soil health indicators empowers us to make informed decisions that enhance agricultural productivity while minimizing negative environmental impacts. An understanding of soil health's multidimensional aspects enables the formulation of strategies that enhance agricultural productivity while preserving vital ecosystems.

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