

Soil Health Management in Organic Agriculture - Importance of Soil Health and Organic Management

Hem Chandra Chaudhary, Dharendra Kumar Roy, V.K. Choudhary, Amrendra Kumar

Soil health is fundamental to sustainable agriculture, particularly in organic systems that rely on natural processes to maintain productivity. A healthy soil ecosystem enhances crop yields, supports environmental sustainability, and nurtures biodiversity by maintaining essential physical, chemical, and biological functions. Organic farming emphasizes soil health management through practices such as adding organic matter, minimizing soil disturbance, and fostering biological activity. These strategies improve soil structure, nutrient cycling, and microbial diversity, while mitigating challenges like erosion, compaction, and nutrient leaching. Aligning production goals with environmental sustainability is critical in organic farming, which employs techniques like crop rotations, green manures, and composting to reduce ecological impacts. However, achieving the ideal balance between these practices and real-world constraints often requires compromises. With careful planning, ongoing monitoring, and adaptive management, farmers can effectively integrate sustainable practices, fostering both agricultural productivity and environmental stewardship. The complexity of organic farming systems highlights the need for flexibility, continuous learning, and informed decision-making, ensuring that soil health remains robust and resilient for future generations.

Keywords: *Soil health, Organic Farming, Green manures, Sustainable practices*

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Introduction

Healthy soils play a crucial role in ensuring robust crop production and sustaining our ecosystem. They enhance soil water retention, foster a variety of organisms essential for decomposition and nutrient cycling,

supply vital nutrients to crops, and help maintain carbon reserves, thereby aiding in the mitigation of global climate change. In essence, maintaining soil health is imperative for meeting the increasing demands for food, feed, fibre, and fuel. Unfortunately, unsustainable agricultural practices are leading to soil degradation across India. Organic farming techniques have the potential to halt this decline and even restore health to previously degraded soils by replenishing soil organic carbon and safeguarding underground biodiversity. Nevertheless, the precise effects of organic practices on soil health remain inadequately understood. While extensive surveys comparing soil health in organic and conventional systems consistently highlight the advantages of organic farming, there is a lack of comparative analysis of strategies within organic systems to identify the sources of these benefits and how they can be optimized. Soils represent an invaluable, non-renewable resource that plays a vital role in providing essential needs and services for both human and ecological well-being (Bordoloi, 2021). Their capacity to filter and purify vast amounts of water annually is fundamental for agricultural practices, enabling the cultivation of crops and the production of feed, fibre, and fuel. Additionally, soil acts as a significant carbon reservoir, contributing to the regulation of greenhouse gas emissions, which is crucial for climate stability. A large number of living organisms depend on soil as their primary source of mineral nutrients. Effective soil management practices ensure that sufficient nutrients enter the food chain while preventing these elements from becoming toxic or deficient for plant growth. The management of soils has a direct and indirect impact on crop yields, environmental sustainability, and human health. The primary objective in agriculture is to mitigate adverse environmental conditions while simultaneously enhancing production levels. As the global population is expected to rise, the importance of soil management will increase, necessitating a focus on intensifying food production sustainably. The challenge lies in managing soils in a way that promotes sustainability through effective nutrient management and appropriate soil conservation techniques, ensuring a reliable food supply for the future. Achieving this goal will require the implementation of sustainable practices and agricultural innovations. It is essential that agricultural methods are environmentally sound and sustainable to safeguard the natural world (Durrer et al., 2021). Protecting environmental and natural agricultural resources through sustainable systems and practices is crucial for producing adequate amounts of nutritious food at affordable prices for the growing global population. Sustainable agriculture is essential to meet present needs while ensuring that future generations can also satisfy their own requirements. Therefore, it is crucial to balance immediate economic gains with the long-term management of both natural and human resources. Given the rapid growth of the human population and the decreasing availability of arable land, the importance of sustainable agricultural practices cannot be overstated. Healthy soil is a fundamental component for optimal plant growth and is a vital indicator of high-quality food production. However, factors such as heavy metals, harmful substances, and soluble salts can adversely affect soil quality, leading to diminished soil health. Furthermore, soil degradation caused by erosion, compaction, waterlogging, toxicity, nutrient deficiencies, and improper tillage practices limits the land available for agricultural use (Giller et al., 2021). To enhance crop yields and address the global food demand, effective soil conservation and management strategies are imperative.

Soil health on organic farms

Numerous research studies indicate that organic soils generally perform better in terms of soil health metrics compared to conventional soils. For instance, organic soils exhibit enhanced biological activity, improved soil stability, increased biomass, and greater diversity than their conventionally managed counterparts. Additionally, soils managed organically often demonstrate superior water-holding capacity, porosity, and aggregate stability, which can provide yield benefits during extreme weather conditions like droughts and floods. This suggests that organic practices may be more resilient as our planet faces the challenges of climate change (Hartmann & Six, 2023).

Organic soils and climate change mitigation: Organic soils, rich in carbon and organic matter, play a pivotal role in climate change mitigation by serving as critical carbon sinks. These soils, often found in wetlands, peatlands, and undisturbed forests, store vast amounts of carbon accumulated over millennia, thereby preventing its release into the atmosphere as carbon dioxide (CO₂). Their conservation and sustainable management are essential in addressing the global challenge of climate change.

Carbon sequestration potential: Organic soils can sequester significant amounts of atmospheric CO₂ through plant photosynthesis and the subsequent accumulation of organic material in soil layers. This process is particularly effective in peatlands, which account for about 3% of Earth's land area but store approximately one-third of global soil carbon (Imadi et al., 2016).

Climate change mitigation strategies

Preservation of existing organic soils: Preventing the drainage and degradation of organic soils is vital. When exposed to air through activities like agriculture or urbanization, these soils release stored carbon as CO₂ and methane (CH₄), potent greenhouse gases.

Rewetting and restoration: Restoring degraded peatlands and wetlands can halt carbon emissions and enhance their carbon sequestration capacity. Rewetting prevents further oxidation of organic matter and reduces CH₄ emissions.

Sustainable land use practices: Integrating organic farming practices, reduced tillage, and agroforestry systems can maintain soil organic matter, enhance biodiversity, and improve soil structure.

Challenges and considerations

Greenhouse gas emissions: While organic soils can mitigate CO₂ emissions, they may emit CH₄, especially in anaerobic conditions. Balancing these emissions is critical for achieving net climate benefits.

Land-use conflicts: Increasing demand for agriculture, infrastructure, and urbanization poses threats to the preservation of organic soils.

Monitoring and governance: Effective policies and monitoring systems are needed to protect these ecosystems and integrate them into national climate action plans.

Future directions

To enhance the role of organic soils in climate change mitigation, research and innovation are required to:

- Develop techniques for precise carbon stock measurement.
- Explore the potential of bio char and other soil amendments to stabilize organic matter.
- Strengthen global collaborations for wetland and peat land conservation efforts.

By maintaining and restoring organic soils, societies can make substantial progress in reducing greenhouse gas emissions, enhancing carbon storage, and fostering resilience to climate change. Eighty percent of the Earth's terrestrial carbon is found in soils, making it the largest carbon reservoir on the planet after the oceans.

Human activities predominantly influence soil management, and studies indicate that our practices can lead to a reduction in soil carbon stores, releasing carbon back into the atmosphere and exacerbating global climate change. Agriculture, in particular, has been associated with significant declines in soil organic carbon globally. An article in the Proceedings of the National Academy of Sciences reveals that throughout the history of agriculture, human practices have caused a loss of 133 billion metric tons of carbon from soils. It also notes that the rate of carbon loss from agricultural soils has surged over the past 200 years as more land has been converted for crops and grazing. On a positive note, several studies demonstrate that with appropriate management, certain agricultural practices can enhance the carbon content in soils, positioning healthy soils as a key element in addressing climate change (Martinez-Mena et al., 2021). A study by The Organic Center, in partnership with North-eastern University, analyzed over a thousand samples of organic and conventional soils across the United States and discovered that organic soils contained significantly higher levels of sequestered carbon compared to conventional soils. These findings reinforce previous research indicating greater total carbon levels in organic soils, underscoring the potential of organic farming to boost carbon sequestration in soils and aid in climate change mitigation.

What is Soil Fertility?

The interplay of biological, chemical, and physical characteristics goes beyond merely assessing the nutrient content of soil. The focus here is on 'interaction': increased biological activity enhances nutrient recycling and improves soil structure, while a well-structured soil supports biological processes. Organic matter plays a crucial role in effective soil fertility management. Soil fertility can be viewed as the soil's capacity to support healthy crop growth over both short and long periods. Organic farming emphasizes the importance of soil as a cornerstone of sustainable agricultural practices. Soil fertility arises from a complex set of interactions. Organic farming practices avoid the use of water-soluble nutrients that are readily available to plants. Instead, they depend on:

- The release of nutrients through the mineralization of organic residues or from natural soil sources.
- The solubilization of insoluble fertilizers, such as rock phosphate.
- Soil organisms, including bacteria, fungi, earthworms, and various other microflora and fauna, play a vital role in this system by facilitating the release and recycling of nutrients.

Organic farming employs effective crop rotations that incorporate both fertility-enhancing and fertility-depleting phases, the return of crop residues, nitrogen fixation through legumes and Rhizobium, nutrient retention via green manures, and the judicious use of manures and composts. Additionally, certain slow-release nutrient materials are allowed under various organic certification standards. The primary focus is on optimizing nutrient cycling, particularly as the importation of manure onto organic farms is increasingly scrutinized (Supangat et al., 2021). Organic matter is a cornerstone of soil fertility and agricultural productivity, playing a vital role in maintaining and enhancing soil health. Its contribution spans physical, chemical, and biological soil properties, making it indispensable for sustainable crop production.

Physical benefits

Soil structure: Organic matter promotes the formation of stable soil aggregates, improving soil porosity and reducing compaction. This enhances root penetration and seedling emergence.

Aeration: By improving soil porosity, it ensures adequate oxygen supply to roots and soil microorganisms, which is essential for plant growth and nutrient cycling.

Water holding capacity: Organic matter increases the soil's ability to retain moisture, making it particularly valuable in arid and semi-arid regions.

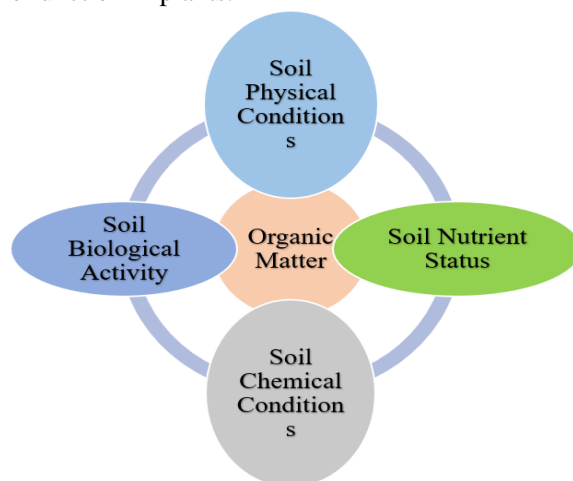
Nutrient reservoir

Organic matter serves as a significant reservoir for essential plant nutrients:

Nitrogen (N): A large proportion of soil nitrogen is stored in organic matter, released through microbial decomposition to become available to plants as nitrate (NO_3^-) or ammonium (NH_4^+).

Phosphorus (P): Organic matter contributes to the availability of phosphorus by preventing it from becoming fixed in the soil, ensuring its accessibility to plants.

Sulphur (S): Like nitrogen, sulphur is mineralized from organic matter, providing an essential nutrient for protein synthesis and enzyme function in plants.



Chemical and biological benefits

Cation exchange capacity (CEC): Organic matter enhances the soil's ability to retain and exchange nutrients, increasing its fertility.

Microbial habitat: It supports diverse soil microbial populations, which drive nutrient cycling, organic matter decomposition, and disease suppression.

Buffering capacity: Organic matter stabilizes soil pH, reducing the harmful effects of pH fluctuations on plant growth.

Management practices to enhance organic matter

- **Crop residue retention:** Leaving crop residues on fields adds organic material back to the soil.

- **Composting:** Application of compost enriches soil organic content and improves fertility.
- **Cover crops and green manures:** These practices protect the soil and contribute organic material when decomposed.
- **Minimal tillage:** Reduces organic matter oxidation, preserving soil carbon stocks.
By integrating practices that build and conserve organic matter, agricultural systems can achieve improved soil health, sustained productivity, and resilience against environmental stresses.

How organic farms are ‘different’?

Organic farming seeks to establish an agriculture system that is sustainable from economic, social, and environmental perspectives. It focuses on fostering self-sustaining biological systems instead of depending on external resources. While it is frequently characterized as merely substituting synthetic inputs with natural alternatives, organic farming encompasses much more. The International Federation of Organic Agriculture Movements (IFOAM) describes organic agriculture as a comprehensive system that relies on a series of processes aimed at creating a sustainable ecosystem, ensuring safe food, promoting good nutrition, supporting animal welfare, and advancing social justice. Thus, organic production transcends a mere method of production that selectively includes or excludes specific inputs.

Organic conversion

To achieve legal status as an organic producer, the land or processing facility utilized for production must be registered with one of the ACOS-approved Certification Bodies. For land to be recognized as 'organic,' it generally must undergo a 24-month 'conversion' period during which no prohibited substances, such as fertilizers, herbicides, or insecticides, can be used. Throughout this conversion phase, the land is managed according to organic principles and standards; however, any products harvested from this land are not certified as organic and cannot be marketed as such, though they may be labelled as 'in conversion.' It is the duty of the Certification Body to regularly monitor and inspect the producer to ensure adherence to organic standards.

Main features of organic farms

Organic farming emphasizes sustainable, holistic agricultural practices that integrate ecological principles, minimize external inputs, and enhance soil and ecosystem health. The main features of organic farms include:

Recycling and reduced reliance on external inputs: Organic farms prioritize the recycling of on-farm resources such as crop residues, animal manure, and compost, aiming to reduce dependency on synthetic fertilizers and pesticides. This aligns with the principle of creating self-sustaining farming systems.

Lower nutrient levels and timely availability: Nutrient levels in organic systems are often lower compared to conventional farming due to the absence of synthetic fertilizers. The challenge lies in ensuring that organic nutrient sources, like green manures and compost, release nutrients synchronously with crop demands.

Whole-farm system approach

Organic farming emphasizes system-level management, including:

Crop rotations: Planned sequences of diverse crops to enhance soil fertility, control pests, and reduce disease pressures.

Matching crops to fertility levels: Allocating crops within the rotation based on their nutrient requirements and soil conditions.

Diversity and mixed farming systems: Organic farms often feature a broader range of enterprises, such as integrating crop and livestock production. This diversity supports nutrient cycling, pest control, and economic resilience. However, mixed systems are not a strict requirement.

Biological activity and soil functioning: Organic farms generally demonstrate enhanced soil biological activity due to organic amendments and reduced chemical inputs. Increased populations of earthworms, beneficial microbes, and other soil organisms contribute to nutrient cycling and improved soil health.

Legislative framework: Organic farming is the only legally defined agricultural system, governed by stringent certification standards at national and international levels. These regulations ensure compliance with practices that preserve environmental integrity and promote sustainable production.

What is soil health?

Soil health refers to the soil's ability to function as a dynamic, living ecosystem that sustains plants, animals, and humans. It emphasizes the interplay of physical, chemical, and biological properties in supporting productivity, maintaining environmental quality, and promoting biodiversity.

Qualitative nature of soil health

Because of its complex and dynamic nature, soil health is often assessed using diverse indicators developed by farmers and scientists worldwide. These indicators include:

- **Visual indicators:** Soil colour, texture, and tilth (the soil's ease of cultivation).
- **Hydrological indicators:** Drainage capacity and water infiltration rates.
- **Biological indicators:** Diversity and abundance of macrofauna (earthworms, insects), microbial activity, and presence of weeds.
- **Agronomic indicators:** Crop yield and resilience to stress.

Challenges in defining soil health

The lack of a unified definition and standardized metrics has historically complicated efforts to compare soil health trends across different regions, farming systems, and research studies. This variability underscores the need for universal benchmarks to monitor and improve soil health consistently.

Soil Health Indicators by the Soil Health Institute (2017)

To address this challenge, the Soil Health Institute introduced Tier 1 soil health indicators, offering a standardized framework for assessing soil health. These indicators integrate:

- **Chemical metrics:** Soil pH, nutrient availability (e.g., nitrogen, phosphorus), and salinity.
- **Physical metrics:** Bulk density, soil texture, and aggregate stability.
- **Biological metrics:** Organic matter content, microbial biomass, and enzymatic activity.

Significance of soil health

A healthy soil ecosystem ensures:

- Sustainable crop production through enhanced nutrient cycling and water retention.
- Improved environmental quality by reducing erosion, runoff, and greenhouse gas emissions.
- Greater biodiversity by providing a habitat for microorganisms and fauna.
- Resilience to environmental stresses, such as drought and heavy rainfall.

Table 1. Soil health indicators used in this study

Soil health indicators		
Physical health	Chemical health	Biological health
Aggregate stability (how the soil sticks together) <ul style="list-style-type: none"> • Water-holding capacity • Infiltration and porosity • Susceptibility to runoff and erosion 	Levels of <ul style="list-style-type: none"> • Nitrogen • Phosphorus • Potassium • Sulphur 	<ul style="list-style-type: none"> • Organic matter • Microbial biomass • Earthworm abundance • Weed pressure and diversity

Managing nutrient supply to soil through organic sources

Nutrient management presents a significant challenge for organic farmers.

- In the short term, the key issue is providing adequate nutrients to crops at the right stages of growth to ensure economically sustainable yields.
- In the long term, the focus shifts to maintaining a balance between nutrient inputs and outputs to prevent depletion and minimize environmental impact.
- Achieving both objectives largely relies on effective organic matter management.

In most organic farming systems, nutrient management encompasses two primary components:

- A fertility-building ley that includes legumes to enhance nitrogen levels in the soil.
- The use of manures to effectively redistribute nutrients across the farm.
- Other nutrients, aside from nitrogen, are typically brought onto the farm through purchased feed and animal bedding, along with additional sources like green waste compost.

Fertility building leys

The fertility building ley serves as a fundamental element in most organic farming rotations. When managed effectively, a ley can supply nitrogen to cash crops, provide forage for livestock, and assist in managing weeds, pests, and diseases. Despite its critical role in nitrogen fixation from the atmosphere, there remains a significant lack of understanding among both farmers and researchers regarding the amount of nitrogen a ley can fix and how this nitrogen is released after being incorporated into the soil, a process known as mineralization. Improving the accuracy of predictions related to these two factors could help mitigate

nitrogen losses from excess applications and prevent crop failures caused by insufficient nitrogen. Determining nitrogen fixation and mineralization is complex due to the influence of various factors, including legume species, soil type, climate, and the presence of pests and diseases. However, for specific legume species, there tends to be a strong correlation between total nitrogen content and yield. Effective management practices can enhance the amount of nitrogen fixed, rather than that which is absorbed from the soil, thereby increasing nitrogen input to the farm (Swami, 2020). It is crucial to note that legumes will only fix substantial amounts of nitrogen when they are unable to source it from the soil. Therefore, any addition of nitrogen to the ley can potentially diminish fixation, while any removal of nitrogen can enhance it. This consideration is vital when planning ley management strategies. For example, adding manure to the ley is a common practice due to favourable ground conditions for spreading and its provision of phosphorus and potassium, which are particularly beneficial if the ley is harvested for silage. However, the nitrogen present in manure may inhibit fixation, and repeated applications could lead to a decrease in the proportion of legumes within the ley. One alternative approach is to integrate manure into different segments of the crop rotation. This will enhance the yield of cash crops through nitrogen (N) while ensuring that phosphorus (P) and potassium (K) remain accessible to the ley. Utilizing manure that has a high concentration of readily available N, such as slurry or poultry manure, can significantly hinder nitrogen fixation. In contrast, composted farmyard manure (FYM) is less harmful, as it contains a limited amount of available N while still providing good levels of P and K. Additionally, cutting and removing plant material, like silage, can facilitate nitrogen fixation more effectively than grazing or simply cutting and mulching, since it extracts N from the field. Although this process reduces the nitrogen available for subsequent cash crops, the removed nitrogen can be reintroduced to the field through manure. Leaving cut leguminous plants in the field as mulch will return nitrogen-rich material to the soil but may limit the overall nitrogen fixation. Nonetheless, this method can be crucial for managing weeds (see Figure 1).

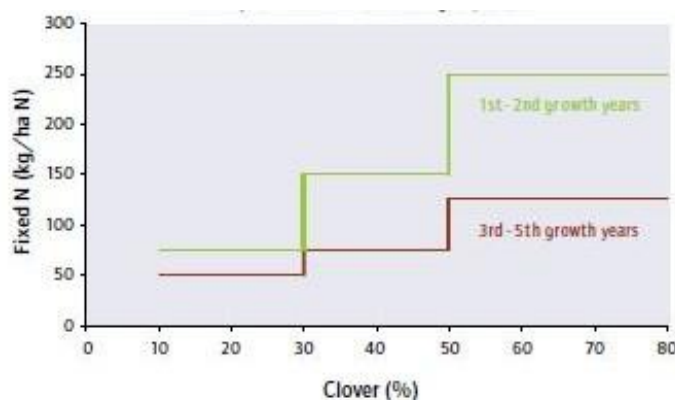


Figure 1. Example of Nitrogen accumulation under grass/clover

While effective ley management can enhance nitrogen fixation, soil nitrogen levels will eventually accumulate, leading to a decline in the fixation rate. For a grass/white clover ley, the ideal duration is likely around three years, after which net fixation diminishes, making incorporation advisable. Predicting nitrogen fixation is challenging, but forecasting mineralization is even more complex. This microbial process is affected by factors such as temperature, moisture, soil type, and the characteristics of the incorporated material. However, it can be anticipated that there will be a significant surge in nitrogen availability shortly after ley incorporation, followed by progressively smaller releases in the following years (see Figure 2).

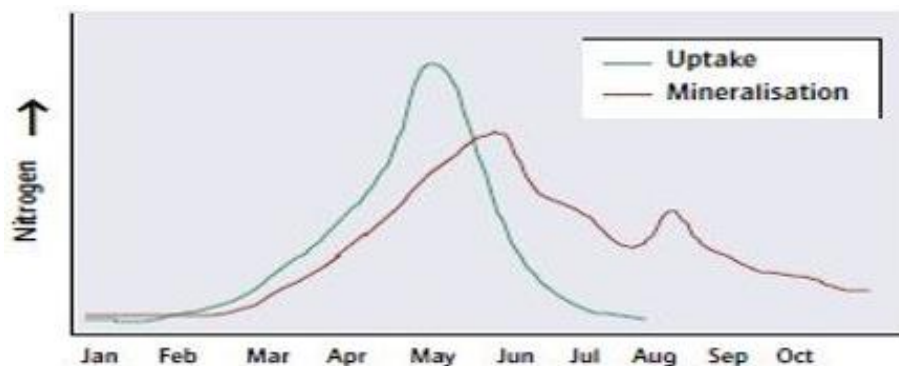


Figure 2. Mineralisation and Uptake of Nitrogen

Manure management

The primary way nutrients enter a farm is typically through animal feed and bedding. Animal manure plays a crucial role in redistributing essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulphur (S), and magnesium (Mg) across the farm. Additionally, manure contributes valuable organic matter. It is important to note that certain nutrients in manure can be easily lost, leading to both a waste of a vital resource and potential environmental pollution. While manure is undeniably significant for organic farmers, there remains considerable opportunity for enhanced management practices on many organic farms. Fresh manure, particularly in the form of slurry and poultry manure, contains a significant amount of nitrogen in readily available forms, mainly ammonium-N, which can be quickly lost to the atmosphere. Furthermore, rainwater can wash away nutrients, especially nitrogen and potassium. The loss of ammonia and nitrate not only contributes to environmental pollution but also represents a missed opportunity for crops to utilize nitrogen. Implementing effective manure management strategies can help reduce nutrient losses and optimize the benefits for crops. There are two primary treatment methods: actively composting and stacking solid manure, as well as aerating slurries. For slurry, mechanical separation is an additional option that can decrease the volume of material needing transport and facilitate the irrigation of the separated liquid. While organic standards promote the active composting of manure and aeration of slurry, these practices are not consistently applied on many farms. Each method of manure management presents its own advantages and challenges regarding nutrient management.

Composting

The effective composting of solid manures and the aeration of slurry offer several advantages, including:

- Decreased odours.
- Elimination of weed seeds and pathogens.
- Reduction in material volume.
- Creation of a more consistent product.
- Stabilization of nitrogen in an organic form (in solid manure).

However, the process of turning solid manure during composting can lead to significant nitrogen loss as ammonia. Similarly, aerating slurry may also result in increased nitrogen losses, especially if the aeration is either excessively vigorous or insufficient. Additionally, carbon is lost in the form of carbon dioxide. It is

important to note that the nitrogen present in composted solid manures tends to be less accessible to subsequent crops in the short term. The choice to engage in composting or aerating slurry is fundamentally influenced by the specific goals of the farming operation. While effective composting can be a labour-intensive and costly endeavour, it may lead to increased nitrogen losses and a temporary decrease in nitrogen availability for crops immediately following application. However, the benefits include a reduction in the volume of material that needs to be spread and the creation of a more uniform, sterile medium, which supports long-term soil health, helps manage harmful pathogens, and decreases the presence of weed seeds. Similarly, slurry aeration, though also costly and challenging to implement effectively, can yield significant advantages when performed correctly. It can lower weed seed counts, mitigate odours particularly problematic in liquid manure systems and result in a more consistent material. Ultimately, the optimal approach for any given farm will hinge on its specific objectives and the resources at its disposal. To minimize the gaseous losses of ammonia, the most efficient approach is to incorporate it quickly into the soil. Additionally, refraining from spreading during hot or windy conditions can further decrease these losses. The table 2, below illustrates how postponing the incorporation of manure into the soil impacts nitrogen losses.

Table 2. Proportion of available Nitrogen retained by manures

Manure type	Proportion of available Nitrogen retained	
	90%	50%
Slurry	Immediate	6 hours
FYM	1 hours	24 hours
Poultry Manure	6 hours	48 hours

Green manures and cover: Green manures and cover crops play a significant role in various organic farming systems, yet many farmers may not be utilizing them to their full potential. Research indicates that incorporating green manures and cover crops into crop rotations for short durations, typically less than six months between cash crops, can effectively maintain soil nitrogen levels and yields, comparable to long-term (three-year) leys.

There are two main categories of these crops:

- Those that capture nitrogen, thereby preventing its leaching.
- Those that fix nitrogen, enhancing soil fertility.

Both types contribute fresh organic matter to the soil, which boosts microbial activity, protects against erosion, and some can serve as forage. The selection of crops depends on their intended purpose. For example, grazing rye is effective for nitrogen capture, while vetch excels in nitrogen fixation, and crops like rape and stubble turnips are valuable for forage. Additional considerations include the season (as some species may not withstand frost), soil type, climate conditions, growth rate, persistence, potential for becoming volunteer weeds, and seed costs. Disease implications are also important; for instance, rotating mustard with brassica crops may heighten the risk of clubroot, whereas legumes from the *Trifolium* family can help mitigate the occurrence of take-all disease in wheat.

Crop residues: Crop residues serve as a significant source of nutrients and organic matter, with both the quantity and composition varying across different crop types. For instance, cereal straw typically contains approximately 35 kg of nitrogen per hectare and exhibits a high carbon-to-nitrogen (C: N) ratio. In contrast, certain vegetable residues can provide over 150 kg of nitrogen per hectare and have a much lower C:N ratio.

This lower C:N ratio in green leafy residues facilitates a quicker release of nitrogen compared to cereal straw. Consequently, effective management strategies must be tailored to the specific type of residue to maximize benefits. When green leafy residues are incorporated into the soil, a swift increase in soil nitrogen levels is likely to occur. Promptly establishing the subsequent crop can help capitalize on this nitrogen availability. If immediate planting is not feasible, utilizing a cover crop may be an effective strategy to retain the nitrogen. On the other hand, incorporating low nitrogen residues, such as cereal straw, can lead to nitrogen immobilization in the soil, which may hinder nutrient availability for subsequent crops.

Organic amendments: In organic farming, the application of synthetic nutrients is prohibited, necessitating that farmers utilize naturally occurring fertilizers like compost and manure to improve soil nutrient levels. Research indicates that organic amendments can enhance soil carbon sequestration, potentially aiding in the fight against climate change by sequestering carbon that might otherwise contribute to greenhouse gas emissions. Nonetheless, the nutrient content, carbon-to-nitrogen ratios, and nutrient release timing of organic soil amendments can vary significantly, leading to inconsistent effects on soil health. This variability in the types and treatments of organic amendments complicates the comparison of different studies; however, this project has identified some overarching trends. Notably, the combination of various organic amendments, such as vermicompost paired with manure, tends to promote better soil health than the use of a single type of organic fertilizer.

Supplementary nutrients: Over time, all organic systems will necessitate the addition of supplementary nutrients to compensate for those extracted from the land through crops and livestock or lost to the environment. While some soil reserves may provide nutrients for extended periods, certain soils and systems, particularly intensive vegetable production, will require regular supplementation to prevent nutrient depletion. Organic standards acknowledge this necessity and permit the use of a limited selection of nutrient supplements, including rock phosphate, potassium sulfate, and green waste compost. Some of these may require a derogation and necessitate the demonstration of need through soil and/or crop foliar analysis. The most appropriate supplement will vary based on specific circumstances. Green waste compost serves as a valuable source of phosphorus, potassium, and organic matter; however, its availability can be limited, and costs may be high. When a particular deficiency is identified, such as low soil phosphorus levels, opting for a targeted product like rock phosphate is advisable. It is crucial to note that many of these supplementary nutrient sources have relatively low availability and should be considered as part of a long-term nutrient management strategy rather than a quick fix for immediate yield enhancement.

Soil pH: Soil pH is a critical factor in ensuring that crops receive adequate nutrients. Even if all essential nutrients are present in the soil in sufficient amounts, an improper pH level (ideally between 6.0 and 7.0) can lead to visible nutrient deficiency symptoms in crops, preventing them from reaching their full yield potential. This issue arises because acidic conditions (with a pH below 5.5) diminish soil biological activity, which in turn hampers the release of nutrients. Additionally, at both extremes of the pH spectrum, certain major and minor nutrients may become inaccessible to plants. Other consequences of low pH include compromised soil structure, diminished crop quality, decreased fertilizer effectiveness, increased nutrient loss, and the degradation of grass swards.

Rotation diversity and length: Crop rotation, which refers to the systematic sequence of different crops cultivated on the same land over time, plays a vital role in sustaining healthy soil ecosystems. This practice disrupts the cycles of pests and weeds, facilitates nutrient cycling, and mitigates the financial risks linked to monoculture farming. Organic farms typically implement longer crop rotations compared to conventional

farms, resulting in greater on-farm biodiversity. Research predominantly examines the implications of rotation length, complexity, and the differences between grain and forage rotations. The inclusion of diverse crops, particularly perennials like alfalfa, is crucial for improving soil health indicators such as soil carbon content, nitrogen levels, and aggregate stability (Martinez-Mena et al., 2021).

Tillage: In terms of tillage, organic farms may utilize tillage as a method for weed management; however, excessive tillage can compromise soil structure and lead to a decline in soil organic carbon. There is an increasing interest in organic practices that minimize tillage. Evidence suggests that reduced tillage can enhance soil carbon levels, yet the inconsistent definitions of "reduced tillage" complicate the identification of broader trends. It is important to note that organic no-till practices may result in lower yields, prompting the need for future studies to explore methods that decrease tillage while maintaining yield levels. Alternatively, shallow non-inversion tillage, also known as "vertical tillage" or "strip-tillage," may provide a balance between optimizing yields and enhancing soil carbon storage. Further investigation into various tillage techniques, ranging from chisel ploughing to shallow inversion tillage, would be beneficial in developing strategies that support multiple aspects of soil health without adversely affecting crop yields on organic farms.

Managing soil structure

Soil structure is a crucial aspect that is often overlooked. Understanding soil texture is vital, as it guides effective management practices. To enhance soil structure, consider the following actions:

- Implement timely cultivation.
- Add organic matter.
- Prevent livestock from compacting the soil.
- Regularly assess soil conditions to identify structural issues and determine necessary restorative measures.

The structure of the soil influences the size and distribution of soil pores, which are essential for air and water movement as well as root growth. Poor soil structure can result in inadequate root penetration, limited nutrient access, hindered drainage, diminished microbial activity, increased soil erosion, and ultimately, crop failure. Additionally, cultivation may require more energy, and animal health in grassland systems could be adversely affected. Soil structure is partially influenced by soil texture, which refers to the ratios of sand, silt, and clay particles (Martinez-Mena et al., 2021). These particles, along with organic matter, form clusters called aggregates. The arrangement and type of these aggregates play a significant role in determining soil structure.

Due to the strong impact of soil texture on structure, the type of soil can impose limitations on what can be achieved. For instance:

- Sand grains that interact weakly are unable to form aggregates.
- Clay minerals that interact strongly can create stable aggregates that withstand trampling, cultivation, machinery weight, and rainfall.

Maintaining good biological activity is essential for preserving soil structure. Plant roots and fungal filaments help bind aggregates, while substances produced by bacteria that feed on organic matter assist in adhering sand, silt, and clay particles together. It is important to note that, within the limits set by soil texture, soil

structure can be managed effectively through a combination of organic matter additions and careful cultivation, supported by a basic understanding and simple observations.

Managing soil biology

Biological activity is fundamental to organic farming and positively impacts all agricultural systems. This activity encompasses a wide range of organisms, from earthworms to bacteria, with microorganisms playing crucial roles in nutrient cycling, soil structure development, and the management of pests and diseases.

To promote biological diversity and activity in soils, it is essential to:

- Maintain good soil structure.
- Incorporate fresh organic matter.

Specialized microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, offer significant advantages to organic systems; therefore, it is important to design crop rotations and management practices that support their growth. The living organisms within the soil are integral to the principles of organic farming. While earthworms are the most noticeable soil inhabitants and contribute significantly to the decomposition of organic matter, it is the microscopic organisms that are the true key players. In agricultural soils, bacteria represent the largest group in terms of both numbers and biomass, followed by fungi, protozoa, and nematodes. In a typical grassland ecosystem, the total biomass of these microorganisms far surpasses that of the grazing animals (Supangat et al., 2021). The challenges associated with studying microscopic soil organisms have resulted in considerable gaps in our understanding. However, it is evident that not only are there vast numbers of these organisms, but there is also remarkable diversity among the various groups. This leads to a highly intricate 'food web' within the soil, where different organisms interact with soil organic matter and with one another.

Improving biological activity in soils

Enhancing soil biological activity is essential for fostering a productive and sustainable agricultural system. Soil microorganisms drive critical processes such as nutrient cycling, organic matter decomposition, and disease suppression. Simple and effective measures can be taken to stimulate microbial activity and maximize its benefits:

Key strategies for improving biological activity

Provide comfortable living conditions

Good soil structure: Ensures adequate pore space for air and water movement, which are essential for microbial respiration and activity. Maintaining proper soil aggregation helps create a stable habitat for microbes.

Proper moisture and aeration: Avoid waterlogging and compaction to maintain a balance of oxygen and moisture in the soil.

Supply a food (energy) source

Fresh organic matter: Crop residues, green manures, and farmyard manure (FYM) provide an easily accessible carbon source, stimulating microbial populations in the short term.

Composted organic matter: Offers a more stable and long-lasting energy source, contributing to sustained microbial activity over time.

Diverse inputs: Incorporating different types of organic matter promotes a broader range of microbial communities, enhancing functional diversity in the soil.

Avoid antagonistic materials

- Refrain from using substances harmful to microorganisms, such as excessive synthetic fertilizers, pesticides, or herbicides.
- Minimize soil disturbance through reduced tillage practices to preserve microbial habitats.

Microbial activity and soil health

The breakdown of organic matter by soil microorganisms has cascading benefits:

Improved soil fertility: Nutrients are mineralized and made available to plants.

Enhanced soil structure: Microbial by-products, such as gums and polysaccharides, bind soil particles, forming stable aggregates.

Disease suppression: Beneficial microbes outcompete harmful pathogens, reducing disease incidence.

Carbon sequestration: Stabilized organic matter contributes to long-term soil carbon storage, mitigating climate change impacts.

By maintaining favourable conditions and providing abundant organic matter, farmers can stimulate soil biological activity, fostering resilient and productive ecosystems that support sustainable agricultural practices.

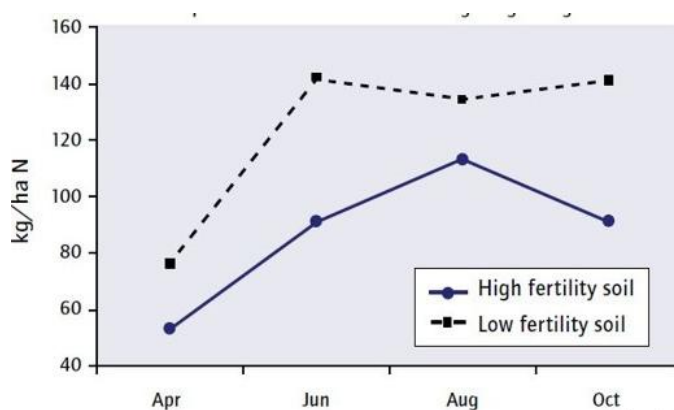
Specialised micro-organisms: Specialized microorganisms play a crucial role in soil health. The addition of organic matter rich in readily available nitrogen can inhibit nitrogen fixation, whereas incorporating phosphorus and potassium tends to promote nitrogen-fixing organisms. Conversely, while phosphorus can hinder the activity of mycorrhizal fungi organisms that establish beneficial relationships with various crops to enhance nutrient uptake nitrogen can enhance their function.

There are specific amendments, such as compost teas, designed to encourage particular groups of soil microorganisms, but research on their efficacy remains limited. Table 3, depicts the crops dependency on micro-organisms and figure 3 represents the available nutrient in cropping seasons.

Table 3. Crops dependency on micro-organisms

Non-mycorrhizal crops	High dependency crops
Brassicas	Maize
Sugar beet	Alliums
Leaf beets	Linseed
Lupins	Soyabean
	Sunflower
	Cereals
	Pulses

When considering soil microbiology, it is also essential to take into account the type of crops and cultivation practices. For example, although many crops benefit from mycorrhizal associations, certain plants like brassicas and sugar beets do not. Planting a non-mycorrhizal crop can diminish the mycorrhizal potential of the soil, which may adversely affect the yield of crops that rely heavily on mycorrhizae. Consequently, it is generally not advisable to follow a non-mycorrhizal crop, such as a mustard cover crop, with a crop that is highly dependent on mycorrhizae, like maize. The accompanying table outlines temperate crops that are either highly reliant on mycorrhizae or non-mycorrhizal.

**Figure 3. Examples of soil mineral levels during the growing season**

Pitfalls and problems

Organic farming requires a nuanced approach to managing resources while meeting both production and environmental goals. Striking this balance often presents challenges, as conflicts may arise between ideal practices and practical realities.

Key challenges and considerations

Conflicts between best practices and practicality

- In some cases, implementing environmentally optimal practices may not align with immediate production needs or available resources. For example, delaying harvest to protect wildlife habitats might conflict with optimal crop maturity timing.

- Farmers must strive to minimize these conflicts by planning and integrating practices that mitigate environmental harm without significantly compromising productivity.

Understanding and managing consequences

- When compromises are unavoidable, it is crucial to understand their potential consequences. For instance, choosing less labour-intensive soil preparation methods might lead to temporary declines in soil health or biodiversity.
- Awareness of trade-offs allows farmers to implement restorative measures later or adjust practices to minimize long-term impacts.

Skilful integration into the farming system

Successful management of organic systems demands high levels of skill and adaptability. Farmers must integrate various practices such as crop rotations, organic matter amendments, and pest control into a cohesive system that balances ecological and economic goals.

Approaches to minimize environmental impacts

- **Proactive planning:** Anticipate potential conflicts and design farming schedules and resource use to avoid or mitigate them.
- **Monitoring and adaptation:** Regularly assess the impacts of farming activities on soil, water, and biodiversity, and adapt strategies based on observations and outcomes.
- **Diversified practices:** Employ diverse crops, livestock, and soil management techniques to distribute environmental pressures and enhance system resilience.
- **Community and expert collaboration:** Work with agricultural advisors, environmental experts, and local communities to identify best practices and innovate practical solutions.

No simple solutions

The inherent complexity of organic systems means there is no universal answer to conflicts between production and environmental objectives. Farmers must remain flexible, informed, and committed to continuous learning and improvement. By prioritizing sustainable practices and maintaining an awareness of the trade-offs, it is possible to navigate these challenges while supporting both agricultural productivity and environmental stewardship.

Conclusion

Soil health is the cornerstone of sustainable agriculture, particularly in organic systems, where the reliance on natural processes is paramount. A healthy soil ecosystem enhances crop productivity, ensures environmental sustainability, and supports biodiversity by maintaining essential physical, chemical, and biological functions. Effective soil health management in organic farming integrates practices like the

addition of organic matter, careful soil cultivation, and the promotion of biological activity. These measures collectively improve soil structure, nutrient cycling, and microbial diversity while mitigating risks like erosion, compaction, and nutrient leaching. The importance of balancing production objectives with environmental sustainability cannot be overstated. Organic farming systems prioritize reducing environmental impacts by employing diverse strategies such as crop rotations, green manures, and composting. While challenges and trade-offs between ideal practices and practical realities are inevitable, thoughtful planning, regular monitoring, and adaptive management can help minimize conflicts. Ultimately, the success of soil health management in organic agriculture depends on the skilful integration of sustainable practices into the farming system. By focusing on long-term ecological benefits, farmers can not only maintain productive soils but also contribute to broader environmental goals, ensuring resilience and sustainability for future generations.

Conflicts of interest

Authors of Directorate of Seed, Dr. Rajendra Prasad Central Agricultural University (RPCAU), Pusa, Samastipur, Bihar (India) have no conflicts among author for publications.

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