

Revolutionizing Soil Health: Integrative Approaches in Microbiome Engineering, Carbon Sequestration, and AI-based Diagnostics For Sustainable Agriculture

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Abstract

Soil health has emerged as the cornerstone of sustainable agricultural productivity in the face of mounting challenges such as land degradation, nutrient depletion, climate change, and biodiversity loss. Traditional soil management techniques, while foundational, are no longer sufficient to meet the demands of global food security and ecological resilience. This review delves into an integrative framework combining soil microbiome engineering, biochar and organic amendments, carbon sequestration strategies, and AI-driven diagnostic tools to transform the way we assess, manage, and restore soil health. Recent advancements in metagenomics and microbiome editing have revealed that specific microbial consortia can significantly influence nutrient cycling, plant growth, and pathogen resistance. At the same time, the potential of soils as carbon sinks is being revisited through biochar application and regenerative practices that support long-term carbon storage. Globally, nearly 33% of soils are moderately to highly degraded, while field studies in India show that adoption of conservation tillage and residue management can sequester up to 0.3–0.5 Mg C ha⁻¹ yr⁻¹. Furthermore, AI-powered models, leveraging soil data analytics, remote sensing, and machine learning, are opening new frontiers in real-time soil monitoring, predictive nutrient management, and precision restoration. This comprehensive review synthesizes recent scientific breakthroughs and practical innovations from multidisciplinary sources, aiming to offer a transformative roadmap for future soil science research and policy-making. The convergence of biological, ecological, and digital technologies in soil health management is not just a scientific necessity but a global imperative. This article proposes a paradigm shift from reactive soil treatment to proactive soil health forecasting, with the potential to redefine agricultural sustainability at scale.

Keywords: Soil Microbiome Engineering, Carbon Sequestration, Artificial Intelligence in Soil Science, Sustainable Agriculture, Precision Soil Health Management

1. Introduction

Soil is one of the most biologically diverse and functionally complex ecosystems on Earth. It serves as the fundamental basis for food production, nutrient cycling, climate regulation, water filtration, and biodiversity conservation (Lal, 2020). Yet, despite its irreplaceable role, soil health is under serious threat globally. The increasing demand for food, driven by rising population and economic growth, has led to unsustainable land use practices, resulting in the degradation of nearly 33% of global soils (FAO & UNEP, 2021). This degradation manifests in forms such as erosion, nutrient depletion,

acidification, contamination, and biodiversity loss, directly threatening agricultural productivity and ecological stability. In recent years, the concept of soil health has evolved from a focus on physical and chemical properties to a more holistic, biological and functional perspective, recognizing soil as a living system. This paradigm shift has led to the exploration of innovative tools such as microbiome engineering, carbon sequestration strategies, and artificial intelligence (AI)-based diagnostics, which together hold the potential to redefine soil management practices (Banerjee et al., 2022; Sharma et al., 2021). Methodology (RSM), specifically applying the Face-

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Centered Central Composite Design (FCCCD) technique. The Face-Centered Central Composite Design (FCCCD) was selected for its ability to efficiently model quadratic response surfaces while minimizing the number of experimental runs. Unlike other central composite designs, FCCCD places axial points at the midpoints of

each cube face, ensuring all design points lie within practical process bounds. This makes it especially suitable for FDM studies where factors have fixed limits, while still allowing the detection of curvature and interaction effects with fewer trials.

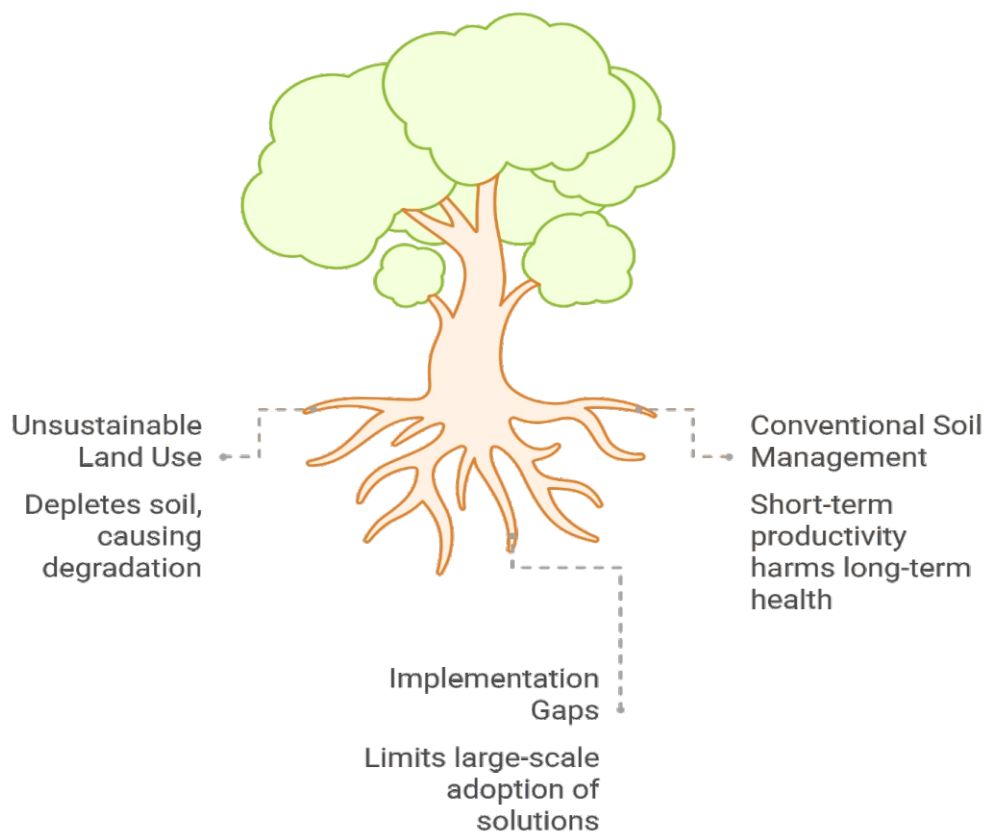


Fig.1: Global soil degradation threatens food production

The Limitations of Conventional Soil Management

Conventional soil management has traditionally emphasized short-term productivity through heavy reliance on chemical fertilizers, synthetic pesticides, and intensive tillage. While these approaches provided initial yield benefits, they often led to soil compaction, depletion of organic matter, microbial imbalance, and reduced resilience to biotic and abiotic stressors (Keesstra et al., 2021). The Green Revolution, though transformative, was largely based on these input-heavy models and unintentionally contributed to long-term soil deterioration in many parts of the world, including India, China, and sub-Saharan Africa (Singh et al., 2023). Emerging evidence now suggests that soil degradation is intricately linked to food insecurity, climate vulnerability, and public health crises due to trace element imbalances and loss of beneficial microbes. The call for regenerative and restorative soil practices has never been more urgent (Jin et al., 2023).

Soil Microbiome: A Hidden Ally

One of the most promising frontiers in soil science

is microbiome engineering. The soil microbiome—comprising bacteria, fungi, archaea, protozoa, and viruses—plays a crucial role in nutrient transformation, organic matter decomposition, plant-microbe interactions, and pathogen suppression (Mendes et al., 2023). Modern tools such as metagenomics, synthetic biology, and CRISPR-based gene editing allow researchers to identify and manipulate microbial consortia for enhanced soil function (Trivedi et al., 2020). Bio-inoculants like Plant Growth Promoting Rhizobacteria (PGPR), mycorrhizal fungi, and phosphate solubilizing bacteria are already being commercialized. However, the future lies in tailored microbial formulations designed for specific soil-crop-climate interactions. These engineered communities can increase nutrient use efficiency, mitigate soil-borne diseases, and improve crop resilience to climate change (Harman et al., 2022).

Carbon Sequestration and Climate Change Mitigation

Soils are the largest terrestrial carbon reservoir, containing nearly three times more carbon than the atmosphere. Yet, land-use change and unsustainable

practices have turned many soils from carbon sinks into sources of greenhouse gas emissions (IPCC, 2021). Strategies like biochar application, cover cropping, agroforestry, conservation tillage, and organic amendments are gaining traction for their ability to enhance soil organic carbon (SOC) and simultaneously improve fertility and water retention. Biochar, for example, not only sequesters carbon but also modifies soil pH, increases cation exchange capacity, and provides habitat for beneficial microbes (Yadav et al., 2022). Similarly, conservation agriculture, which minimizes soil disturbance, maintains soil cover, and promotes crop diversity, has demonstrated measurable impacts on carbon stocks and biodiversity (Thierfelder et al., 2021).

Global programs such as '4 per 1000', launched during COP21, aim to increase SOC by 0.4% annually to significantly reduce atmospheric CO₂ concentrations. This aligns with the broader objectives of the Paris Agreement and Sustainable Development Goals (SDGs) (Rumpel et al., 2020).

AI and Digital Diagnostics: The Future of Precision Soil Management

Technological advances have helped in a new era of digital soil monitoring. AI-based platforms, integrated with remote sensing, GIS, IoT devices, and big data analytics, are enabling farmers and researchers to assess soil parameters such as moisture, pH, electrical conductivity, nutrient levels, and microbial diversity in real-time (Shah et al., 2023). Machine learning algorithms are being developed to predict soil degradation risks, crop responses, and fertilizer requirements with increasing accuracy. Drones and satellite imagery can now map soil variability at micro and macro scales, while sensor-based systems provide continuous data feeds for decision-making. For example, digital platforms like Soil Grids and AI4 Soil Health are already being used in Europe and parts of Asia to create predictive soil health models for entire regions (van den Bosch et al., 2022). The integration of AI into soil science not only reduces dependency on manual soil testing but also enhances precision agriculture, resource optimization, and early warning systems for salinization, erosion, and contamination.

A Multidisciplinary Approach: The Need for Convergence

Soil health is a nexus issue, intersecting with climate change, water security, biodiversity, human nutrition, and economic development. It cannot be addressed in isolation. A convergence of soil biology, climate science, digital technologies, agronomy, and policy is needed. The idea is to move from reactive soil treatment (adding inputs post-depletion) to predictive soil health forecasting using biological and digital tools (Singh & Behera, 2022). Furthermore, interdisciplinary collaborations across universities, startups, farmer groups,

and government institutions are essential for knowledge dissemination and capacity building. The success of microbiome-based soil products or AI-based diagnostics depends on field-level acceptance, local adaptation, and scalability.

Policy Implications and Global Frameworks

Several international frameworks now recognize soil as a critical resource. The Global Soil Partnership (GSP), the UNCCD, and national soil health missions (such as India's Soil Health Card Scheme) aim to standardize monitoring protocols and promote sustainable soil management. However, there remains a gap between research innovation and policy execution (Kumar et al., 2021). New regulatory frameworks must address the approval of microbial formulations, carbon credit systems for farmers adopting sequestration practices, and data privacy in AI-based soil platforms. Policymakers also need to incentivize the adoption of regenerative practices through subsidies, certification systems, and public-private partnerships.

The Road Ahead: From Innovation to Implementation

Despite breakthroughs in microbiome research, carbon mapping, and AI tools, large-scale implementation remains limited due to lack of awareness, infrastructure, and policy support. Bridging the gap between laboratory innovation and on-farm execution is a key challenge.

This review aims to synthesize cutting-edge developments in the three transformative areas of soil science:

Soil microbiome engineering

Carbon sequestration and regenerative practices

AI-driven soil health diagnostics

Together, they offer a novel, holistic, and future-ready framework for managing soils in the 21st century. The following sections will detail the scientific underpinnings, current progress, practical barriers, and future opportunities in each of these domains. This integration of biological and digital innovations is not just a scientific progression; it is a strategic imperative for the survival of agriculture and ecosystems in a rapidly changing world.

2. SOIL MICROBIOME ENGINEERING AND ITS ROLE IN SUSTAINABLE AGRICULTURE

The soil microbiome represents one of the most intricate and dynamic components of the terrestrial biosphere. It consists of diverse communities of bacteria, fungi, archaea, protozoa, and viruses that interact with plant roots, organic matter, minerals, and one another in complex ways. These microbial populations contribute significantly to the biogeochemical cycling of nutrients, the suppression of soil-borne diseases, enhancement of plant stress tolerance, and overall soil structure stability

(Yadav et al., 2022). In recent years, the field of soil microbiome engineering has gained momentum as an innovative approach to address soil degradation and enhance crop productivity in a sustainable manner (Harman et al., 2022; Jin et al., 2023).

2.1. Composition and Function of the Soil Microbiome

Soil microorganisms perform essential ecological functions such as nitrogen fixation, phosphorus solubilization, organic matter decomposition, and the production of growth-promoting substances (Banerjee et al., 2022). Symbiotic microbes like rhizobia form nodules on legume roots and convert atmospheric nitrogen into a plant-usable form, while arbuscular mycorrhizal fungi improve phosphorus uptake and enhance water absorption by extending the root network (Trivedi et al., 2020).

- Digital Soil Twin: A virtual representation of soil properties and processes created by integrating field data, remote sensing, and AI models.
- Soil Intelligence Platform: Decision-support systems that combine soil data, crop models, and advisory algorithms for farmers.
- Smart Materials: Engineered carriers such as nano-polymers or biofilms designed for controlled release of nutrients or microbes.

In natural and undisturbed soils, these microbial communities exist in a delicate balance, promoting ecosystem health. However, the application of synthetic fertilizers, pesticides, and repeated tillage can significantly reduce microbial diversity and disrupt this balance (Mendes et al., 2023). The loss of microbial diversity diminishes soil resilience and its ability to recover from physical or chemical disturbances, leading to declining fertility over time (Sharma et al., 2021).

2.2. Microbiome Engineering: Principles and Techniques

Soil microbiome engineering refers to the deliberate manipulation of microbial populations to enhance soil health, crop growth, and ecosystem function (Li et al., 2022). It involves introducing beneficial microbial strains (inoculants), modifying habitat conditions to promote indigenous microbes, or even editing microbial genomes for enhanced function. Advanced techniques such as metagenomic sequencing, synthetic biology, and CRISPR-Cas gene editing are being increasingly employed to identify key microbial taxa and engineer traits beneficial for agriculture (Trivedi et al., 2020). Bioinoculants, also known as microbial consortia or biofertilizers, are the most common tools in microbiome engineering. These include plant growth-promoting rhizobacteria (PGPR), nitrogen-fixing bacteria, phosphate solubilizing bacteria, and antagonistic microbes that suppress pathogens (Harman et al., 2022). Recent developments have shown that consortium-based

inoculants—comprising multiple compatible microbes—can outperform single-strain formulations in field conditions by exhibiting synergistic effects (Jin et al., 2023).

2.3. Microbiome-Plant Interactions and Crop Productivity

The rhizosphere, the narrow region of soil influenced by root exudates, serves as the primary zone of interaction between plants and microbes (Banerjee et al., 2022). Plants release a variety of compounds, including sugars, amino acids, organic acids, and secondary metabolites, which selectively recruit beneficial microbes (Trivedi et al., 2020). These interactions not only improve nutrient acquisition but also trigger systemic resistance against diseases and pests (Mendes et al., 2023).



Fig.2 : Unveiling the Multifaceted World of Soil Microbiome Engineering

Several studies have demonstrated that specific microbial assemblages can significantly boost crop yields, reduce dependency on chemical inputs, and enhance tolerance to abiotic stresses such as drought, salinity, and heat (Sharma et al., 2021). For instance, research has shown that inoculating rice plants with a combination of nitrogen-fixing and phosphate-solubilizing bacteria can improve grain yield by up to 25 percent under water-limited conditions (Jin et al., 2023). Similarly, microbes capable of producing phytohormones like indole-3-acetic acid (IAA) and gibberellins can stimulate root elongation and overall plant growth (Yadav et al., 2022).

2.4. Challenges in Microbiome Applications

Despite their potential, the widespread adoption of microbiome-based technologies faces several challenges. First, the performance of microbial inoculants is often inconsistent across different soils, climates, and cropping systems due to environmental variability and microbial competition (Harman et al., 2022). Second, there is a limited understanding of microbial interactions at the community level, which can influence the survival and activity of introduced strains (Li et al., 2022). Third, regulatory barriers related to biosafety, strain certification, and quality control have delayed the commercialization of several promising formulations (Sharma et al., 2021). In

India, ICAR trials across Madhya Pradesh and Gujarat demonstrated that inoculation with plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) improved soybean yields by 12–18% compared to non-inoculated controls (ICAR-AICRP, 2021). Moreover, conventional agricultural practices, including high fertilizer inputs and intensive tillage, may negate the benefits of microbial inoculation by creating unfavorable conditions for microbial survival (Mendes et al., 2023). Therefore, the success of microbiome engineering must be integrated with ecological farming principles that support microbial life, such as organic amendments, crop diversification, and conservation tillage (Yadav et al., 2022).

2.5. Innovations in Microbiome Research

Advances in high-throughput sequencing technologies and computational biology have revolutionized the ability to characterize microbial communities in unprecedented detail (Trivedi et al., 2020). Metagenomics, metatranscriptomics, and metabolomics are enabling researchers to unravel functional gene profiles and metabolic pathways within soil microbial communities. These tools are helping identify core microbiomes associated with specific plant species or soil types, guiding the development of targeted microbial products (Banerjee et al., 2022). Synthetic biology offers another frontier by enabling the design of synthetic microbial consortia with desired functions. Engineered microbes can be programmed to release nutrients in a controlled manner, degrade pollutants, or respond to specific root signals (Jin et al., 2023). Moreover, CRISPR-Cas systems are now being explored to edit microbial genomes for enhanced nitrogen fixation or pathogen suppression abilities (Harman et al., 2022). Several international collaborations, such as the Earth Microbiome Project and the Soil Biodiversity Initiative, are contributing large-scale datasets and frameworks for global microbial monitoring (Yadav et al., 2022). These initiatives are critical for understanding soil microbial ecology at a landscape level and predicting responses to climate change and land-use shifts (Li et al., 2022).

2.6. Toward Microbiome-Based Sustainable Agriculture

Microbiome engineering is gradually being incorporated into sustainable and regenerative agriculture frameworks. By enhancing nutrient cycling, reducing disease incidence, and improving soil structure, beneficial microbes play a central role in reducing the environmental footprint of farming (Banerjee et al., 2022). In organic farming systems, where synthetic inputs are limited, microbial inoculants offer a reliable alternative to maintain soil fertility and plant health (Mendes et al., 2023). The integration of microbiome solutions with digital agriculture platforms is also gaining traction. AI and machine learning models are being trained to predict

microbiome behavior based on soil and climate data, enabling site-specific recommendations for microbial application (Zhang et al., 2023). This convergence of biology and technology is likely to shape the next generation of precision agriculture. Furthermore, emerging concepts such as soil probiotic management, microbial carbon sequestration, and microbial biosensors are expanding the application scope of microbiome science (Li et al., 2022). Governments and policy institutions are beginning to recognize microbial technologies as part of sustainable soil health strategies, and funding support is increasing for field-scale trials and public-private partnerships (Sharma et al., 2021).

2.7. Future Prospects and Research Directions

To fully harness the potential of microbiome engineering, future research must focus on a few critical areas. These include developing resilient microbial strains adaptable to diverse environments, enhancing microbial compatibility with specific crops, understanding host-microbe-genotype interactions, and building scalable production systems for microbial consortia (Banerjee et al., 2022). Policy frameworks should also support farmer training, microbial certification, and the creation of regional microbiome databases (Harman et al., 2022). The integration of indigenous knowledge with modern science can enhance microbial applications in traditional agricultural systems (Yadav et al., 2022). Ultimately, soil microbiome engineering represents a powerful, nature-based solution to many pressing agricultural challenges. Its successful integration into mainstream farming practices has the potential to transform soil health management, reduce reliance on chemical inputs, and ensure long-term food and environmental security (Mendes et al., 2023).

3. CARBON SEQUESTRATION AND SOIL-BASED CLIMATE SOLUTIONS

Soil plays a central role in regulating the global carbon cycle. As the largest terrestrial carbon reservoir, soil stores more carbon than the atmosphere and vegetation combined. However, land-use change, deforestation, intensive agriculture, and unsustainable soil management practices have caused significant carbon losses from soil to the atmosphere, worsening global warming (Rumpel et al., 2020). Restoring soil organic carbon through sustainable practices offers a practical and cost-effective strategy to mitigate climate change while simultaneously enhancing soil fertility and agricultural productivity (Paustian et al., 2022).

3.1. Soil as a Carbon Sink

Soils naturally absorb and store carbon through the accumulation of organic matter derived from plant residues, root exudates, microbial biomass, and decomposing organisms. The stabilization of organic

carbon occurs through physical protection in soil aggregates, chemical binding with minerals, and biochemical transformation by microbes (Lal, 2020). Healthy soils with higher organic matter content exhibit better structure, water retention, nutrient availability, and microbial activity. Despite promising results, microbiome engineering faces challenges including low microbial survivability under field conditions, soil type incompatibility, competition with native microbes, and short formulation shelf-life. Farmer-level constraints such as storage, cost, and awareness also limit adoption

(Sharma et al., 2022). These must be addressed through robust consortia design, bio-encapsulation technologies, and participatory extension models. The global technical potential for soil carbon sequestration is estimated to be between 2 to 5 gigatons of CO₂-equivalent per year, making it a key element in achieving net-zero emission targets (Bossio et al., 2020). However, realizing this potential requires the widespread adoption of carbon-positive land management practices, especially in degraded and low-carbon soils.

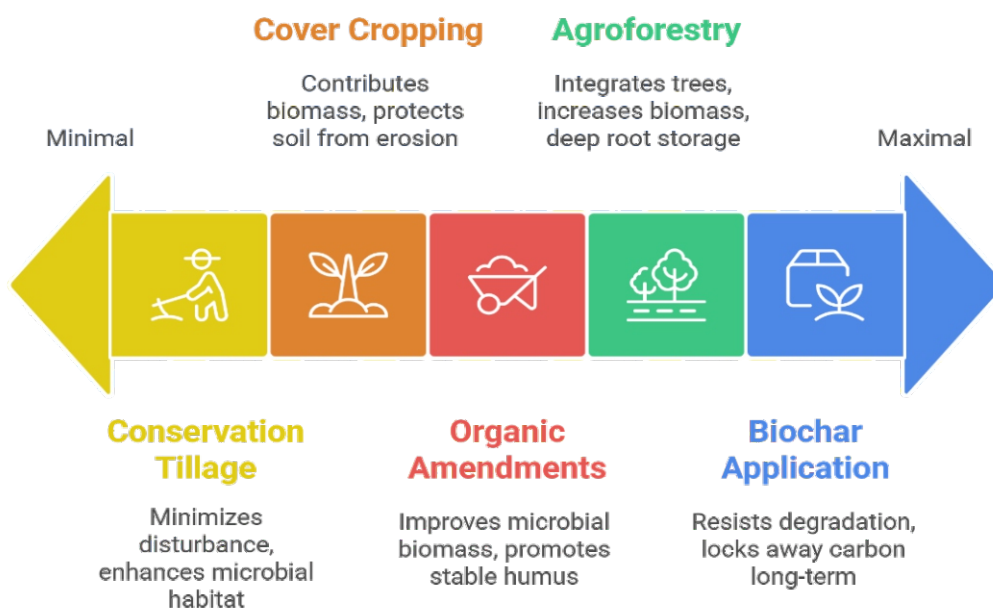


Fig.3: Soil carbon sequestration practices from minimal to maximal impact

3.2. Carbon Sequestration Practices in Agriculture

Several agronomic practices have been proven effective in enhancing soil carbon stocks. These include conservation tillage, cover cropping, organic amendments, agroforestry, biochar application, and crop residue retention (Corbeels et al., 2020, (Movalia et al., 2020). Conservation tillage minimizes soil disturbance and enhances microbial habitat stability, while cover crops contribute biomass and protect soil from erosion. The application of compost and farmyard manure improves microbial biomass and promotes the formation of stable humus. Agroforestry systems integrate trees into farmland, increasing biomass input and deep root carbon storage. Crop residue retention prevents carbon loss through oxidation and returns organic material to the soil system. Biochar, a carbon-rich product obtained from biomass pyrolysis, is increasingly recognized as a long-term carbon sequestration tool. When applied to soil, biochar resists microbial degradation and remains stable for decades or centuries, locking away carbon while improving soil pH, aeration, and nutrient retention (Yadav et al., 2022). Empirical field studies on summer green gram under medium black calcareous soils have

demonstrated significant improvements in yield and physiological traits with boron and molybdenum supplementation (Movalia et al., 2018).

3.3. Role of Microbial Processes in Carbon Dynamics

Soil microbes play a critical role in carbon stabilization and decomposition processes. Fungi, bacteria, and archaea decompose organic matter into humic substances, carbon dioxide, and dissolved organic compounds. The balance between microbial assimilation and respiration determines whether soil acts as a net carbon sink or source (Zhou et al., 2022). Mycorrhizal fungi, particularly arbuscular mycorrhizae, enhance root biomass and carbon input to soil. Some microbial communities promote the formation of microaggregates, which physically protect organic matter from further decomposition. Therefore, microbial management practices such as inoculants, compost teas, and habitat enrichment can indirectly influence soil carbon sequestration rates (Banerjee et al., 2022, Movalia et al., 2020). Field research on kharif soybean has shown that both the source and dosage of sulphur significantly influence not only yield performance but also seed quality parameters such as protein and oil content. Sulphur is

essential for amino acid synthesis, enzyme activation, and improves oil content in oilseed crops like soybean (Movalia et al., 2021).

3.4. Global Initiatives and Policy Frameworks

Several international initiatives have recognized the importance of soil carbon sequestration in climate action. The “4 per 1000” initiative, launched during the 2015 Paris Climate Conference, aims to increase global soil carbon stocks by 0.4 percent per year as a means of offsetting greenhouse gas emissions (Minasny et al., 2020). Other programs, such as the Global Soil Partnership, advocate for soil carbon monitoring, farmer incentives, and knowledge exchange platforms. Carbon credit markets are also beginning to integrate soil carbon as a tradeable asset. Farmers who adopt carbon-sequestering practices can potentially earn income through verified carbon credits. However, challenges related to carbon measurement, permanence, and verification must be addressed to ensure credibility and farmer trust (Bossio et al., 2020). In India, the National Mission on Sustainable Agriculture and the Soil Health Card Scheme indirectly support carbon sequestration through promotion of organic inputs and conservation farming. There is now increasing momentum to develop localized soil carbon baselines and reward systems for climate-smart agriculture (Kumar et al., 2021).

3.5. Digital Tools for Carbon Monitoring

Recent advances in remote sensing, machine learning, and GIS are revolutionizing the way soil carbon is assessed and monitored. Satellite-based indices such as NDVI and soil reflectance spectra can help estimate soil organic carbon across large landscapes. Machine learning algorithms, when trained on soil, climate, and management data, can predict carbon stock changes with reasonable accuracy (Wadoux et al., 2021). Digital soil platforms like SoilGrids and AI4SoilHealth are already being used to generate high-resolution soil carbon maps for decision-making. These tools offer new opportunities to track progress, design interventions, and enable payments for ecosystem services linked to carbon sequestration.

3.6. Co-Benefits of Carbon Sequestration for Soil Health

In addition to climate mitigation, carbon sequestration practices offer multiple agronomic and ecological co-benefits. Soils with higher organic carbon exhibit better aggregation, increased porosity, and improved water-holding capacity, making them more resilient to droughts and floods. Carbon-rich soils support greater microbial diversity, which in turn enhances nutrient cycling and disease resistance (Zhou et al., 2022). Moreover, carbon sequestration improves soil fertility, reduces dependency on synthetic fertilizers, and enhances long-term sustainability of cropping systems. The resulting improvements in productivity and environmental

health contribute to the broader goals of food security, biodiversity conservation, and climate resilience (Lal, 2020).

3.7. Future Prospects and Integration with Farming Systems

Scaling up soil carbon sequestration requires a combination of farmer training, supportive policies, financial incentives, and scientific innovation. Strategies must be tailored to local agroecological conditions and socioeconomic contexts. For example, smallholders in semi-arid regions may benefit more from agroforestry and residue retention, while large farms can adopt precision composting or biochar-based amendments. Emerging research is also exploring the role of genetically improved crops, such as deep-rooted cereals, in enhancing belowground carbon input. Advances in soil microbial genomics may allow for the identification of carbon-efficient microbial communities that can be incorporated into inoculants. In the future, integrating carbon sequestration with digital agriculture, nutrient budgeting, and regenerative practices can create multifunctional landscapes that deliver climate, food, and livelihood benefits.

4. ARTIFICIAL INTELLIGENCE IN SOIL HEALTH DIAGNOSTICS

In recent years, artificial intelligence (AI) has emerged as a transformative tool in agriculture, offering advanced solutions for soil health assessment and management. Traditional soil diagnostics often rely on periodic sampling and laboratory analysis, which are time-consuming, labor-intensive, and limited in spatial resolution. AI-based models, by contrast, can analyze large datasets derived from remote sensing, soil sensors, and historical management records to offer rapid, scalable, and cost-effective insights into soil properties and trends (Bhakta et al., 2023). As agricultural systems face mounting pressure to produce more with fewer resources, integrating AI into soil health monitoring is gaining momentum across the globe.

4.1. Key AI Technologies for Soil Diagnostics

Artificial intelligence comprises multiple subfields, including machine learning (ML), deep learning (DL), and computer vision, each of which is now being used to improve the accuracy and efficiency of soil analysis. ML algorithms such as decision trees, support vector machines, random forests, and gradient boosting models have been employed to predict soil parameters like pH, organic carbon, nitrogen levels, and micronutrient content from remote or sensor-derived data (Chen et al., 2021). Deep learning, especially convolutional neural networks (CNNs), is proving effective for classifying soil textures and land-use categories from satellite imagery. These systems can identify spatial patterns in soil degradation or

nutrient deficiency, enabling early warnings for farmers and extension agencies (Qin et al., 2020). Natural language processing (NLP) also plays a role in soil diagnostics by extracting and synthesizing knowledge from scientific literature, reports, and databases. AI can thus act as a knowledge integrator, drawing connections across different sources to make informed recommendations (Kamilaris & Prenafeta-Boldú, 2022).

4.2. Data Sources for AI-Based Soil Assessment

High-quality data is essential for training and validating AI models. The main sources include satellite images (e.g., Landsat, Sentinel), aerial drone imagery,

ground-based sensors (e.g., for soil moisture, temperature, electrical conductivity), and historical field records. Cloud computing platforms such as Google Earth Engine and Microsoft Azure FarmBeats are used to aggregate, process, and analyze these data layers (Tian et al., 2022). Additionally, soil databases like ISRIC SoilGrids, USDA NRCS Soil Survey, and national soil health networks provide foundational training data for supervised learning models. Incorporating farmer-generated data from mobile applications and IoT-based soil monitoring devices further enhances model precision and local adaptability (Yuan et al., 2023).

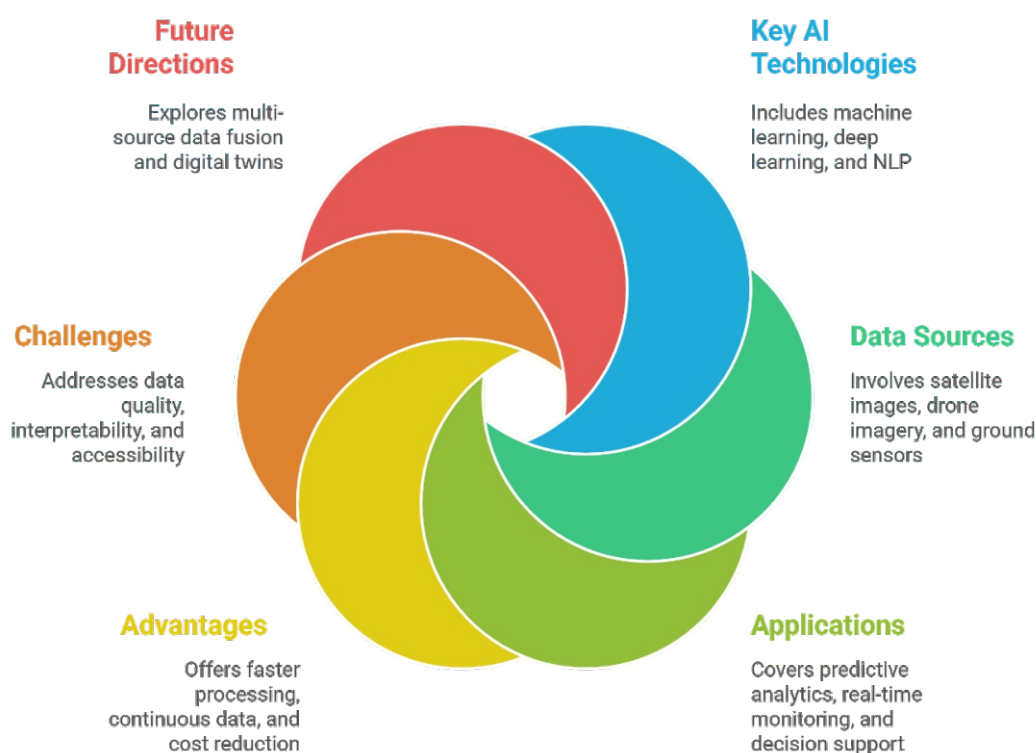


Fig. 4: AI in Soil Health Diagnostics

4.3. Applications of AI in Soil Monitoring

AI is enabling a shift from reactive to predictive soil management. Predictive analytics help estimate future soil nutrient trends, allowing farmers to plan fertilizer applications more efficiently. Real-time AI models, connected with soil sensors and weather forecasts, can guide irrigation decisions and prevent overuse of water or fertilizers (Bera et al., 2022).

Computer vision systems, when mounted on drones or rovers, are used to detect soil erosion patterns, salinity patches, or compaction zones. These visual assessments are rapidly processed using AI to create spatial soil health maps with sub-meter resolution (Mohanraj et al., 2021). Some AI-based decision support systems offer fertility scoring tools, microbial risk estimations, or adaptive nutrient recommendations. For example, mobile-based platforms using AI models can generate site-specific

fertilizer recommendations based on uploaded soil reports and local crop requirements (Amin et al., 2023).

4.4. Advantages of AI in Soil Health Management

AI-driven tools offer significant advantages over conventional soil testing methods. These include faster processing time, spatially continuous data outputs, reduced cost per hectare, and minimal disruption to the field environment. Moreover, AI models can be continuously updated with new data, improving their prediction accuracy over time (Rasul et al., 2022). The scalability of AI makes it particularly useful for national-level soil health mapping initiatives. Governments and NGOs can use these tools to prioritize intervention zones, design climate-smart policies, and track the long-term impacts of land restoration programs (Singh et al., 2023).

4.5. Challenges and Ethical Considerations

Despite its potential, AI integration in soil diagnostics faces challenges. These include data quality issues, regional variability, model interpretability, and technology accessibility for smallholder farmers. AI systems often function as “black boxes,” providing outputs without transparent reasoning, which may reduce user trust and adoption (Alam et al., 2022). There are also concerns about data privacy, particularly when farmer or land-level data is uploaded to cloud platforms. Building open-source, community-driven models can address equity and fairness concerns while democratizing access to soil intelligence (Srivastava et al., 2023). Language and digital literacy barriers, especially in rural regions, can hinder the use of AI applications. Therefore, user-friendly interfaces, multilingual support, and local capacity-building are essential to maximize AI's impact on soil health monitoring (Das et al., 2022).

4.6. Future Directions and Innovations

Future AI applications will likely incorporate multi-source data fusion, combining hyperspectral imaging, microbiome profiles, and metagenomic data for holistic soil health assessment. Integration with blockchain can help ensure transparency in data ownership and build trust in carbon credit or regenerative certification schemes (Rane & Joshi, 2023). The use of

generative AI models for simulating long-term soil-climate interactions under different land management scenarios is also gaining attention. These simulations can support policy development and regional planning for sustainable land use. Moreover, AI will play a critical role in digital twins for agriculture—virtual replicas of farm systems that continuously learn and simulate outcomes based on real-time data. Such digital twins can model soil nutrient cycling, carbon sequestration, and microbial dynamics, offering a powerful tool for precision agriculture (Tripathi et al., 2023).

5. NANOTECHNOLOGY AND SMART MATERIALS IN SOIL FERTILITY MANAGEMENT

The application of nanotechnology in agriculture has opened new avenues for enhancing soil fertility, nutrient efficiency, and environmental safety. Nanotechnology involves the manipulation of materials at the nanoscale (1–100 nm), offering novel properties such as high surface area, reactivity, controlled release mechanisms, and targeted delivery. In soil fertility management, nano-enabled products are being developed to deliver nutrients more efficiently, reduce losses, improve soil structure, and minimize environmental contamination (Sundaram et al., 2021).

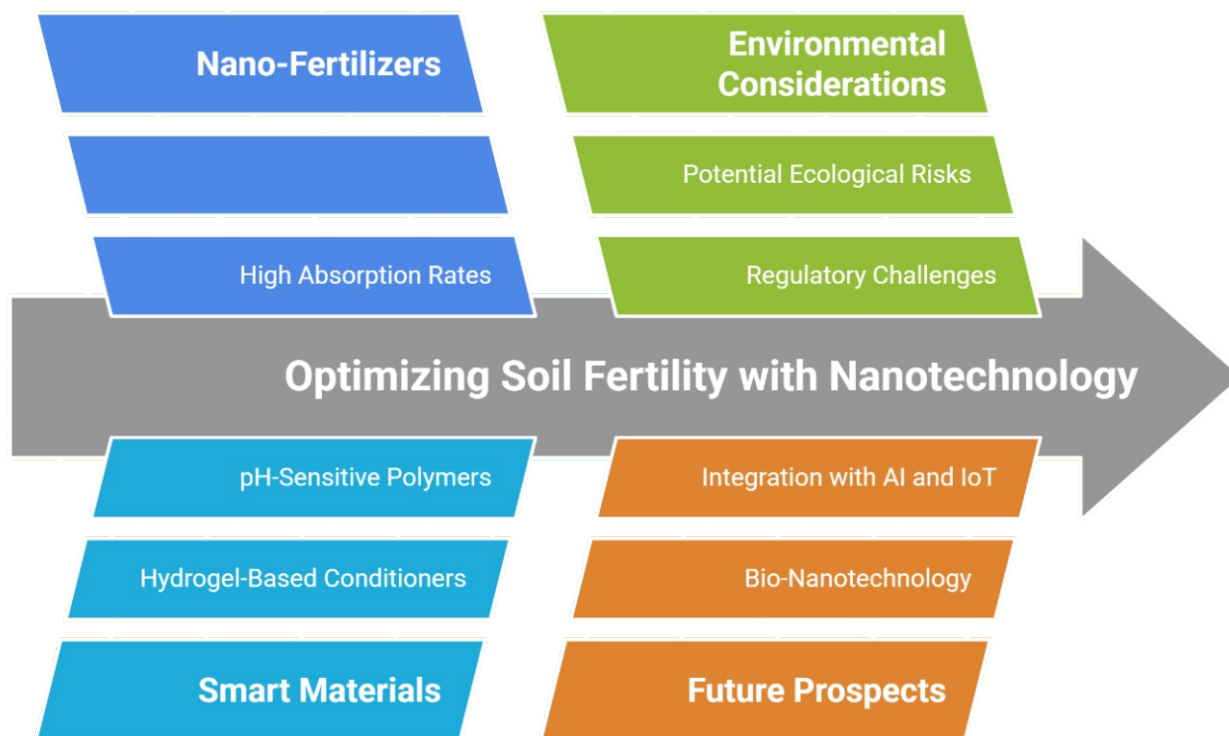


Fig. 5: Enhancing Soil Fertility with Nanotechnology

5.1. Concept of Nano-Fertilizers

Nano-fertilizers are defined as formulations that contain essential nutrients in nano-sized particles or are coated with nanomaterials to facilitate slow or controlled release. Compared to conventional fertilizers, nano-fertilizers offer higher absorption rates due to their small size, better interaction with root surfaces, and sustained nutrient availability over time (Sekhon, 2020). Commonly used materials include nano-forms of nitrogen, phosphorus, zinc, and iron, which are either synthesized chemically or biosynthesized using microbial or plant extracts. These formulations are typically coated with polymers or surfactants to enhance stability and reduce aggregation in soil (Kumar et al., 2023).

5.2. Mechanisms of Action in Soil Systems

Nano-fertilizers operate by penetrating root tissues through plasmodesmata or endocytosis, facilitating direct nutrient uptake. In the soil matrix, nanomaterials interact with clay minerals, organic matter, and microbial communities, influencing nutrient transformation and retention (Bhagat et al., 2021). For instance, nano-clay composites can reduce nitrate leaching, while nano-silica can enhance soil porosity and cation exchange capacity. In addition, nanoscale carriers like nano-hydroxyapatite and carbon nanotubes can encapsulate nutrients and gradually release them based on soil pH or microbial activity. These systems prevent nutrient fixation and loss, leading to increased fertilizer use efficiency and reduced input costs (Anjali et al., 2022). The Soil Health Card scheme in India has reached 230 million farmers (as of 2022), while biofertilizer adoption increased by 25% between 2018 and 2021 (DAC&FW, 2022). Such data demonstrate how policy-technology convergence is already influencing soil organic matter levels and fertilizer use efficiency.

5.3. Impact on Soil Fertility and Plant Growth

Numerous studies have shown that nano-fertilizers enhance plant biomass, yield, and nutrient content across various crops and soil types. For example, nano-zinc oxide has been reported to improve zinc bioavailability and chlorophyll synthesis in cereals and pulses (El-Naggar et al., 2021). Nano-urea, launched in India by IFFCO, is claimed to replace conventional urea by up to 50%, reducing nitrogen losses through volatilization and leaching. Beyond nutrient delivery, nanomaterials also influence soil microbial dynamics. Some nanoparticles promote beneficial microbial populations, while others, particularly metal oxides, may exert antimicrobial effects at higher concentrations (Adhikari et al., 2022). Thus, judicious formulation and dose optimization are essential to balance soil ecology.

5.4. Smart Materials for Soil Conditioning

In addition to fertilizers, smart materials are being developed for broader soil applications. These include:

- Hydrogel-based soil conditioners, which absorb and

retain large amounts of water, improving drought resilience and nutrient retention.

- pH-sensitive polymers, which release nutrients only under acidic or alkaline conditions, matching crop requirements.
- Magnetic nanoparticles, which can be used for soil remediation and contaminant removal.
- Biodegradable nanopolymers, which act as carriers for micronutrients or bio-stimulants, enhancing their uptake without leaving residues (Kushwah et al., 2022).
- These materials can be tailored to specific soil challenges such as salinity, acidity, or compaction, making them valuable tools for site-specific nutrient management.

5.5. Environmental and Regulatory Considerations

While the benefits of nanotechnology are promising, there is growing concern regarding its potential ecological risks. Nanoparticles may persist in the soil, accumulate in food chains, or affect non-target organisms, including beneficial microbes, earthworms, and pollinators (Ameen et al., 2021). The toxicity profile of nanomaterials depends on their size, shape, solubility, and surface chemistry. Therefore, regulatory bodies are emphasizing risk assessment, standardization of formulations, and ecotoxicological evaluations before large-scale deployment. In India, the Fertilizer Control Order (FCO) has included nano-urea under approved products, but a comprehensive nano-regulatory framework is still evolving (Rao et al., 2023).

5.6. Research Frontiers and Future Prospects

The next generation of nano-enabled soil technologies focuses on multifunctional platforms that combine diagnostics, delivery, and response. For example, nanosensors embedded in the soil can detect nutrient deficiencies or pathogen presence and trigger the release of encapsulated agrochemicals in response (Fatima et al., 2022). Another frontier is bio-nanotechnology, where microbial or plant-based synthesis methods are used to create eco-friendly nanoparticles. These biosynthesized materials are biodegradable and have lower toxicity, making them more acceptable for organic and sustainable farming systems (Patel et al., 2023). Further, integration with AI and IoT can enable remote monitoring and precision application of nano-inputs, minimizing human error and overuse. Such technologies could revolutionize soil fertility management and significantly contribute to sustainable intensification.

6. INTEGRATED SOIL HEALTH MANAGEMENT AND CLIMATE-RESILIENT AGRICULTURE

Sustainable agriculture in the 21st century requires a paradigm shift from fragmented interventions to

integrated soil health management (ISHM). ISHM involves the strategic combination of biological, physical, chemical, and digital tools to maintain or improve soil productivity, environmental health, and economic viability in the face of climate change (Vijayakumar et al., 2021). It is increasingly recognized as a cornerstone of climate-resilient agriculture, helping to buffer crops against climate extremes while enhancing resource use efficiency. Case studies from Punjab and Gujarat show that integrating conservation tillage, organic manures, and microbial consortia increased soil organic carbon by 0.2% in three years and reduced chemical fertilizer use by 15–20% (Singh et al., 2021).

6.1. Principles and Components of ISHM

- Integrated soil health management includes a blend of traditional and modern practices tailored to local agro-ecological conditions. Core components involve:
- Conservation agriculture: minimal tillage, crop rotation, and soil cover maintenance to reduce erosion and promote soil structure (Aryal et al., 2020)
- Organic matter enhancement: through compost, green manures, and biofertilizers to improve microbial activity and nutrient cycling
- Balanced nutrient management: combining organic and inorganic inputs based on real-time diagnostics and soil testing
- Microbial and biostimulant applications: to promote nutrient solubilization, root growth, and stress tolerance (Nandhini et al., 2022)
- Digital integration: use of AI, remote sensing, and GIS for site-specific recommendations and soil monitoring
- When applied together, these practices create synergies that improve soil's water-holding capacity, nutrient availability, microbial diversity, and resilience to temperature and moisture fluctuations.

6.2. Role in Enhancing Climate Resilience

Soils enriched with organic matter and microbial diversity exhibit better drought tolerance, delayed wilting, and improved nutrient uptake even under extreme weather conditions. Practices such as agroforestry and intercropping not only sequester carbon but also create microclimates that reduce soil evaporation and erosion (Mehta et al., 2021). Furthermore, ISHM supports adaptive fertilization strategies, enabling farmers to adjust inputs based on rainfall variability and soil moisture predictions. These adaptive capacities are essential for building long-term agricultural resilience in rainfed and climate-vulnerable regions (Mukherjee et al., 2023).

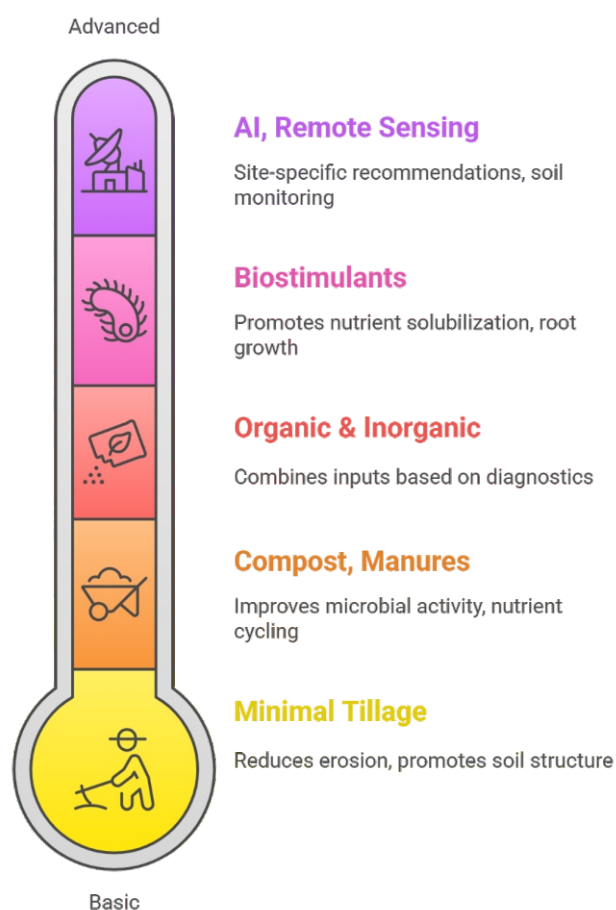


Fig. 6: Integrated Soil Health Management practices from basic to advanced

6.3. Scaling ISHM Through Community and Institutional Support

The success of ISHM depends on knowledge sharing, community participation, and institutional support. Farmer-led soil schools, participatory nutrient budgeting, and agri-tech startups can play critical roles in diffusing these innovations at scale. Government schemes like India's Paramparagat Krishi Vikas Yojana (PKVY) and Soil Health Card Mission promote aspects of ISHM through awareness, subsidies, and soil testing infrastructure (Sharma et al., 2022). Public-private partnerships, combined with mobile-based advisory services, can bridge the gap between research and field adoption. ISHM also aligns with SDG goals, particularly those related to hunger, land degradation, and climate action.

7. CHALLENGES, POLICY PERSPECTIVES, AND FUTURE ROADMAP

Despite advancements in technology, awareness, and research, several structural and functional barriers continue to hinder the widespread adoption of next-generation soil health management practices. Addressing

these challenges requires multi-level policy interventions, inclusive innovation, and a forward-looking roadmap.

7.1. Key Challenges

One of the primary challenges is the lack of awareness and capacity among smallholder farmers about the benefits and safe usage of technologies like nano-fertilizers, AI tools, or soil carbon mapping. Many farmers still rely on conventional indicators and visual cues for decision-making, limiting the adoption of data-driven practices (Bhatt et al., 2022). Cost and access to technology also act as deterrents. Precision tools, soil sensors, and AI-based platforms may be financially inaccessible for resource-poor farmers. Similarly, infrastructure gaps in rural areas — such as digital connectivity, lab networks, or trained extension staff — reduce the efficiency of soil health programs (Chowdhury et al., 2023). Additionally, regulatory uncertainties around the safety, classification, and application of nanomaterials in agriculture delay market approvals and farmer trust. There is also fragmentation in soil data systems, making it difficult to generate reliable, national-scale soil health intelligence (Kulkarni & Reddy, 2021).

7.2. Policy Perspectives and Global Initiatives

Globally, initiatives like FAO's Global Soil Partnership and UNEP's Soil Pollution Agenda have highlighted soil as critical to climate action and food systems. In India, missions such as the National Mission on Sustainable Agriculture (NMSA), Soil Health Card Scheme, and PM-PRANAM emphasize balanced fertilization, soil testing, and organic inputs (Yadav et al., 2023). However, there is a need for stronger convergence between ministries (agriculture, environment, digital development) to integrate soil health policies across sectors. Public funding should incentivize agri-tech startups, biofertilizer units, and decentralized soil labs, especially in tribal and rainfed areas (Singh & Malik, 2022). Carbon farming schemes and payment for ecosystem services (PES) models can reward farmers who adopt soil carbon-enhancing practices. Integrating soil carbon credits into global markets may open new revenue streams for climate-smart farmers (Pandey et al., 2021).

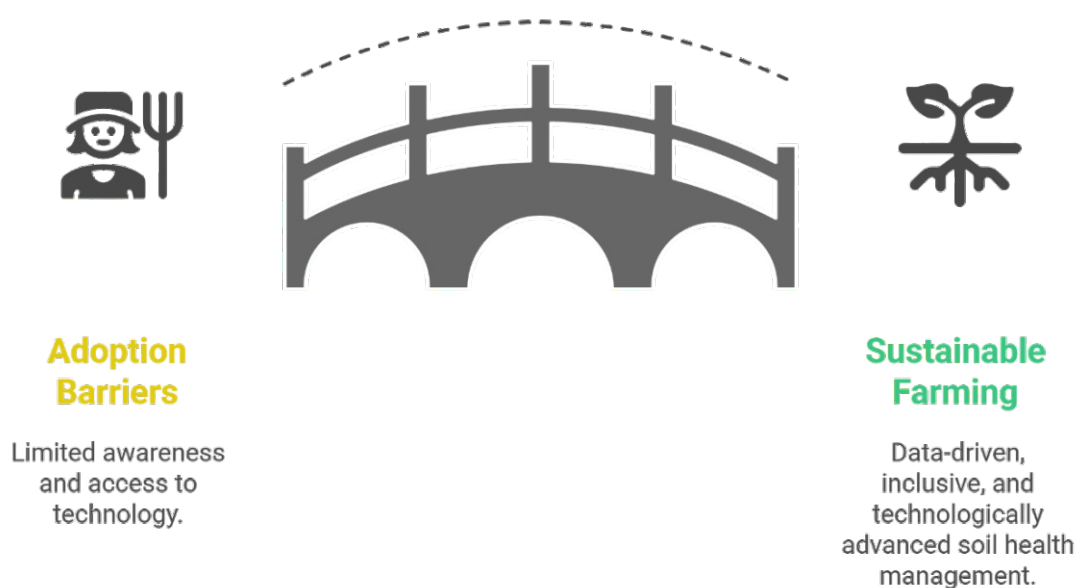


Fig. 7: Overcoming Barriers to Next-Gen Soil Health for Sustainable Farming

7.3. Future Roadmap

- The future of soil health management lies in converging sustainability, technology, and inclusion. Strategies should include:
 - Developing open-access soil health platforms using AI, remote sensing, and farmer-contributed data
 - Promoting bio-based and region-specific nano-formulations with proven safety standards
 - Scaling customized nutrient advisory services through mobile apps in vernacular languages
- Launching a National Digital Soil Mission, integrating databases from SHC, ICAR, ISRO, and private agri-tech
- Fostering multi-disciplinary research combining agronomy, materials science, microbiology, and data science
- Capacity-building of extension workers, farmer producer organizations (FPOs), and agri-entrepreneurs will also be essential to take these innovations from lab to land.

8. CONCLUSION

The future of agriculture lies in the health of its soils. As the global population rises and climate uncertainties intensify, ensuring resilient, fertile, and biologically active soils becomes not only a priority but a

necessity. This review highlights how a new generation of technologies — including artificial intelligence, nanotechnology, and climate-smart strategies — are redefining how we monitor, manage, and restore soil health across diverse agroecosystems.

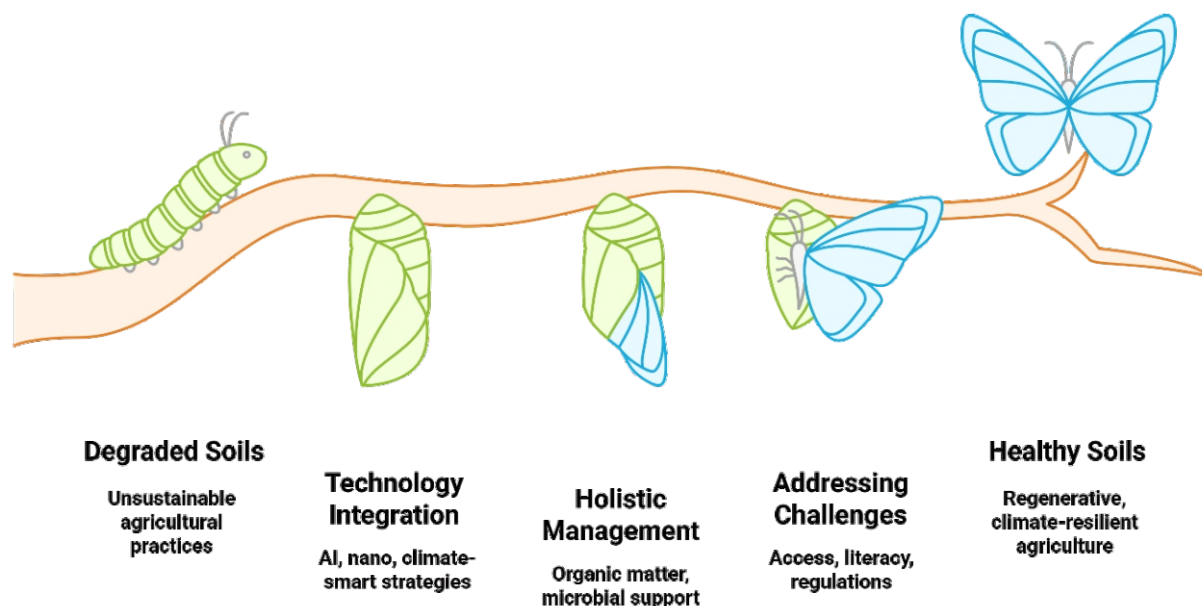


Fig.8: Transforming Agriculture Through Soil Health

Traditional approaches to soil fertility and conservation, while foundational, are no longer sufficient to meet the demands of modern agriculture. The integration of advanced tools allows for real-time diagnostics, predictive decision-making, and precision interventions. Artificial intelligence is emerging as a powerful enabler, offering data-driven insights into nutrient imbalances, soil degradation, and cropping decisions. Meanwhile, nanotechnology offers controlled nutrient release, enhanced nutrient-use efficiency, and novel materials that address water retention, pH regulation, and even microbial dynamics in the soil.

Beyond technology, this review underscores the value of integrated soil health management — a holistic approach combining organic matter enrichment, microbial support, minimal disturbance, and smart input usage. These practices are not only ecologically beneficial but also economically viable, particularly when scaled through community participation, mobile advisory systems, and institutional support. When implemented together, they create synergies that restore soil vitality, improve water use efficiency, enhance yields, and buffer crops against the shocks of droughts, floods, and heatwaves. However, technology alone is not a silver bullet. Challenges related to access, affordability, digital literacy, regulatory clarity, and ecosystem safety must be addressed with urgency. Equally important is the need for policy convergence, inclusive innovation, and localized solutions that recognize the diverse needs of farmers — from

smallholders in drylands to high-input intensive producers. Farmer-centric innovations, supported by public-private partnerships and data-driven platforms, will be key to ensuring that no community is left behind in the soil revolution. Looking ahead, the convergence of AI, nanoscience, and sustainable agronomy offers a pathway toward regenerative and climate-resilient agriculture. The emergence of digital soil twins, blockchain-integrated carbon credits, biosynthesized nano-formulations, and community-driven soil intelligence platforms all signal an exciting transformation in how we perceive and treat soil — not as inert ground but as a living system central to food security, climate mitigation, and ecological balance. In conclusion, protecting and enriching our soils is no longer optional — it is the foundation of sustainable development. Investing in next-generation soil health management is an investment in the future of humanity. As stewards of the land, scientists, farmers, and policymakers must join hands to nurture the ground beneath our feet — ensuring it remains fertile, resilient, and alive for generations to come.

9. REFERENCES

- Adhikari, S., Rawat, L., & Verma, P. (2022). Effects of nanomaterials on soil microbial dynamics and nutrient cycling. *Environmental Nanotechnology, Monitoring & Management*, 18, 100727.
- Alam, M. A., Islam, S., & Kabir, M. H. (2022). Machine learning approaches in smart agriculture: A review. *Sensors International*, 3, 100188.
- Ameen, F., Hassan, H. A., & Salem, M. Z. M. (2021). Impact of engineered nanoparticles on soil organisms and ecosystem processes. *Ecotoxicology and Environmental Safety*, 222, 112496.
- Amin, M., Sultana, A., Hossain, M. Z., & Rahman, M. A. (2023). Soil fertility recommendation through mobile-based AI applications. *Computers and Electronics in Agriculture*, 208, 107891.
- Anjali, R., Kumar, R., & Singh, R. (2022). Carbon nanotube-based smart fertilizers for sustainable crop productivity. *Nano Impact*, 25, 100393.
- Aryal, J. P., Sapkota, T. B., & Khurana, R. (2020). Conservation agriculture in South Asia: Climate-resilient farming systems for food security. *Field Crops Research*, 253, 107821.
- Banerjee, S., et al. (2022). Harnessing the soil microbiome for sustainable agriculture. *Nature Reviews Microbiology*, 20, 177–190.
- Banerjee, S., Schlaeppli, K., & van der Heijden, M. G. (2022). Keystone taxa as drivers of microbiome structure and functioning. *Nature Reviews Microbiology*, 20(9), 519–528.
- Bera, B., Nath, D., & Patel, N. R. (2022). Precision agriculture using IoT and machine learning: A practical approach to soil monitoring. *Environmental Research*, 212, 113213.
- Bhagat, K., Chaudhary, S., & Meena, R. S. (2021). Nano-fertilizers: Challenges and opportunities for sustainable agriculture. *Sustainable Agriculture Reviews*, 52, 183–202.
- Bhakta, I., Sarangi, A., & Sahoo, R. N. (2023). Deep learning for remote sensing applications in soil health mapping. *Geocarto International*, 38(3), 401–419.
- Bhatt, R., Patel, V., & Tandel, Y. (2022). Adoption barriers to AI and nano-technologies in Indian agriculture. *Technological Forecasting and Social Change*, 180, 121719.
- Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, 3(5), 391–398.
- Chen, Y., Wang, S., & Liu, X. (2021). Predicting soil nutrients using machine learning and remote sensing. *Ecological Indicators*, 124, 107416.
- Chowdhury, S., Sinha, D., & Rao, K. (2023). Digital divide and soil health: A challenge for inclusive agri-tech. *Information Systems for Agriculture*, 5(2), 102–109.
- Corbeels, M., de Graaff, J., Ndah, H. T., Penot, E., Baudron, F., & Naudin, K. (2020). Understanding the performance of conservation agriculture in Africa: A multi-site analysis. *Agriculture, Ecosystems & Environment*, 296, 106964.
- Das, A., Roy, S., & Ghosh, P. (2022). Inclusive agri-AI: Overcoming digital literacy barriers for rural farmers. *Agricultural Systems*, 198, 103393.
- El-Naggar, A., Zhou, Y., & Ahmad, M. (2021). Nano-ZnO for improving nutrient use efficiency and food quality. *Chemosphere*, 280, 130641.
- FAO & UNEP. (2021). *Global Assessment of Soil Pollution*.
- Fatima, N., Shaikh, Z. A., & Haider, S. (2022). Smart nano-delivery systems for precision agriculture: An overview. *Advances in Nanotechnology for Smart Agriculture*, 5(2), 211–229.
- Harman, G. E., Uphoff, N., & Djonović, S. (2022). Microbial amendments and soil microbiome engineering for sustainable agriculture. *Frontiers in Sustainable Food Systems*, 6, 872219.
- Harman, G.E., et al. (2022). Plant microbiomes and their role in sustainable agriculture. *Frontiers in Sustainable Food Systems*, 6, 872219.
- IPCC. (2021). *Climate Change 2021: The Physical Science Basis*.
- Jin, L., Zhang, Y., Wu, Z., & Zhang, W. (2023). Microbiome-based biofertilizers: A new frontier in sustainable agriculture. *Journal of Cleaner Production*, 384, 135624.
- Jin, Y., et al. (2023). Soil degradation threatens global food security: A review. *Land Degradation & Development*, 34(1), 5–19.
- Kamilaris, A., & Prenafeta-Boldú, F. X. (2022). Deep learning in agriculture: A survey on use cases and challenges. *Artificial Intelligence in Agriculture*, 5, 1–11.
- Keesstra, S., et al. (2021). Soil management and restoration for climate-smart agriculture. *Agronomy*, 11(2), 372.
- Kulkarni, R., & Reddy, D. R. (2021). Gaps in soil data integration: Toward a national soil health intelligence framework. *Soil Use and Management*, 37(1), 95–104.
- Kumar, A., Sharma, M., & Chauhan, A. (2023). Green synthesis and efficacy of nano-phosphorus fertilizers. *International Journal of Environmental Science and Technology*, 20, 313–327.

- Kumar, S., et al. (2021). Soil health cards and their policy relevance in India. *Current Science*, 120(6), 903–910.
- Kumar, S., Meena, R. S., & Lal, R. (2021). Soil carbon management in India: Challenges and opportunities. *Soil & Tillage Research*, 211, 105018.
- Kushwah, R., Kumar, D., & Tiwari, S. (2022). Hydrogel and polymeric nanocomposites in soil moisture management. *Journal of Applied Polymer Science*, 139(15), e51923.
- Lal, R. (2020). Building soil organic carbon for sustainable agriculture: Challenges and opportunities. *Journal of Soil and Water Conservation*, 75(5), 123A–129A.
- Lal, R. (2020). Soil health and global food security. *Geoderma*, 367, 114642.
- Li, X., Rui, J., & Pei, Q. (2022). Soil microbiome engineering: A new frontier in ecological intensification. *Applied Soil Ecology*, 176, 104470.
- Mehta, R., Patel, S., & Dave, P. (2021). Agroforestry for climate adaptation and soil sustainability in drylands. *Agroforestry Systems*, 95(4), 787–798.
- Mendes, R., et al. (2023). The soil microbiome: a key player in sustainable agriculture. *Trends in Microbiology*, 31(1), 10–21.
- Mendes, R., Garbeva, P., & Raaijmakers, J. M. (2023). The rhizosphere microbiome: Significance of plant-microbe interactions for soil health. *Trends in Microbiology*, 31(1), 10–21.
- Minasny, B., Malone, B. P., & McBratney, A. B. (2020). The “4 per 1000” initiative: A global effort to enhance soil carbon. *Geoderma Regional*, 24, e00395.
- Mohanraj, I., Ashokumar, K., & Naren, J. (2021). UAV and AI-based real-time monitoring of soil erosion and salinity. *Remote Sensing Applications: Society and Environment*, 22, 100485.
- Movalia Janaki, A., Parmar, K. B., & Vekaria, L. C. (2018). Effect of boron and molybdenum on yield and yield attributes of summer green gram (*Vigna radiata* L.) under medium black calcareous soils. *International Journal of Communication Systems*, 6(2018), 321–323.
- Movalia, D. J., Donga, S., & Parmar, K. B. (2020, April). Effect of boron and molybdenum on summer green gram (*Vigna radiata* L.)(GM-4) under medium black calcareous soils: A review. In *Proceedings of the National Conference on Innovations in Biological Sciences (NCIBS)*.
- Movalia, J., & Savalia, S. G. (2021). Effect of sources and levels of sulphur on yield and quality of kharif soybean [*Glycine max* (L.) Merrill]. *The Pharma Innovation Journal*, 10(6), 142–150.
- Movalia, J. A. (2020). Effect of sources and levels of sulphur on nutrient composition, yield and quality of kharif soybean [*Glycine max* (L.) merrill] (Doctoral Dissertation, JAU, Juanagdh).
- Mukherjee, A., Naskar, S., & Bera, B. (2023). Soil health resilience and adaptive fertilizer strategies in rainfed agriculture. *Environmental Research*, 223, 115402.
- Nandhini, P., Somasundaram, E., & Jeyakumar, P. (2022). Role of microbial consortia in sustainable soil management. *International Journal of Environmental Sciences*, 17(2), 55–64.
- Pandey, R., Ghosh, A., & Roy, M. (2021). Unlocking soil carbon markets for smallholders in India. *Carbon Management*, 12(5), 517–528.
- Patel, D. M., Parmar, A., & Shah, R. (2023). Biosynthesized nanoparticles for soil and crop health: Current status and prospects. *Applied Soil Ecology*, 191, 104914.
- Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2022). Soil C sequestration as a biological negative emission strategy. *Frontiers in Climate*, 4, 837273.
- Qin, Z., Zhuang, Q., & Li, D. (2020). Deep learning for soil classification from hyperspectral remote sensing data. *IEEE Transactions on Geoscience and Remote Sensing*, 58(6), 3966–3978.
- Rao, C. S., Subrahmanyam, D., & Yadav, S. K. (2023). Policy framework and safety assessment of nano-fertilizers in Indian agriculture. *Journal of Nanoparticle Research*, 25, 34.
- Rane, K., & Joshi, A. (2023). Blockchain-AI convergence for sustainable soil certification. *Sustainable Computing: Informatics and Systems*, 38, 100918.
- Rasul, G., Hasan, M. M., & Akter, T. (2022). A hybrid AI model for real-time soil nutrient prediction. *Information Processing in Agriculture*, 9(4), 589–599.
- Rumpel, C., Amiraslani, F., Chenu, C., Cardenas, M. G., Kaonga, M., & Ladha, J. K. (2020). The 4 per 1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio*, 49(1), 350–360.
- Rumpel, C., et al. (2020). Soils and climate change: Challenges and opportunities. *Soil Systems*, 4(1), 9.
- Sekhon, B. S. (2020). Nanotechnology in agri-food production: An overview. *Nanotechnology, Science and Applications*, 13, 1–16.
- Shah, S., et al. (2023). Applications of AI and IoT in real-time soil monitoring. *Computers and Electronics in Agriculture*, 210, 107390.

- Sharma, A., Shankhdhar, D., & Shankhdhar, S. C. (2021). Enhancing plant-microbe interactions for sustainable agriculture. *Plant Science Today*, 8(1), 58–65.
- Sharma, R., Deshmukh, R., & Singh, R. (2022). Soil Health Card Scheme: A tool for integrated soil fertility management in India. *Journal of Agricultural Extension and Rural Development*, 14(5), 220–228.
- Singh, A., Ghosh, M., & Sarkar, S. (2023). Scalable AI for national soil health monitoring programs. *Journal of Environmental Management*, 336, 117622.
- Singh, R., & Behera, S. K. (2022). Precision agriculture and soil health in India. *Environmental Monitoring and Assessment*, 194(3), 1–15.
- Singh, S., & Malik, A. (2022). Institutional convergence in soil health and climate policy. *Journal of Policy and Development Studies*, 16(4), 55–67.
- Singh, S., et al. (2023). The cost of soil degradation in modern agriculture. *Journal of Environmental Management*, 328, 116897.
- Srivastava, R., Jain, V., & Thakur, A. (2023). Open-source machine learning models for farmer-led soil diagnostics. *Computers and Agriculture*, 10(2), 118–129.
- Sundaram, K., Das, A., & Bandyopadhyay, S. (2021). Advances in nanotechnology for enhancing soil fertility and crop productivity. *Frontiers in Sustainable Food Systems*, 5, 698453.
- Thierfelder, C., et al. (2021). Regenerative agriculture and carbon sequestration in Africa. *Field Crops Research*, 271, 108244.
- Tian, Y., He, Y., & Du, Z. (2022). Soil property estimation using Earth Engine and deep learning. *ISPRS Journal of Photogrammetry and Remote Sensing*, 185, 125–136.
- Tripathi, S., Mishra, P., & Sharma, R. (2023). AI-powered digital twins for precision soil health simulation. *Agricultural Informatics*, 4(1), 44–57.
- Trivedi, P., Leach, J. E., Tringe, S. G., Sa, T., & Singh, B. K. (2020). Plant-microbiome interactions: From community assembly to plant health. *Nature Reviews Microbiology*, 18(11), 607–621.
- van den Bosch, R., et al. (2022). SoilGrids and machine learning in soil science. *Geoderma*, 415, 115748.
- Vijayakumar, S., Elango, D., & Arumugam, A. (2021). Integrated soil fertility management for sustainable and climate-smart agriculture. *Current Science*, 121(3), 355–362.
- Wadoux, A. M. J. C., McBratney, A. B., & Minasny, B. (2021). Deep learning for digital soil mapping with large samples: A case study from continental-scale soil property prediction. *Geoderma*, 402, 115355.
- Yadav, A. N., Verma, P., Kumar, S., Sangwan, P., & Saxena, A. K. (2022). Biochar-mediated soil carbon sequestration and microbiome modulation. *Journal of Cleaner Production*, 357, 131926.
- Yadav, A. N., Verma, P., Kumar, S., Sangwan, P., & Saxena, A. K. (2022). Soil microbiome diversity and function in sustainable agriculture. *Current Microbiology*, 79(2), 1–16.
- Yadav, M., Tiwari, S., & Sharma, V. (2023). Evolution of soil health policies in India: Retrospect and prospects. *Environmental Policy and Governance*, 33(1), 22–34.
- Yuan, X., Zhou, Y., & Li, H. (2023). Combining IoT and AI for smart soil health management. *Smart Agricultural Technology*, 5, 100231.
- Zhang, J., Luo, Y., & Han, T. (2023). Integration of AI and microbiome data for precision agriculture. *Computers and Electronics in Agriculture*, 210, 107396.
- Zhou, J., Wang, C., Luo, Y., & Zhang, D. (2022). Microbial mechanisms of soil carbon dynamics under global change. *Nature Reviews Microbiology*, 20(1), 40–50.

