



Building soil resilience: pathways to sustainable agriculture in India

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Summary

Soil health forms the foundation of India's agricultural sustainability, food security, and ecological balance. However, decades of intensive, input-intensive farming have led to serious degradation, manifested in nutrient depletion, loss of organic matter, erosion, salinization, and contamination from excessive agrochemical use. As a result, widespread multi-nutrient deficiencies are now prevalent across diverse agro-ecological regions, undermining both productivity and resilience. This review examines the current status of soil health in India's varied climatic zones, with particular focus on physical, chemical, and biological indicators and their spatial variability. It further explores the major drivers of degradation, including monocropping, excessive dependence on synthetic fertilizers, inadequate recycling of organic residues, declining soil biodiversity, and the added pressures of climate change. The paper also synthesizes recent progress in sustainable management practices such as conservation agriculture, integrated nutrient management, and biofertilizer application, while highlighting emerging technological innovations like digital soil mapping, remote sensing, drone-assisted nutrient application, and AI-based decision-support systems. Finally, it identifies key research gaps and policy priorities, stressing the importance of farmer-oriented extension models and climate-smart soil management as essential pathways for restoration. A holistic, soil-centered strategy is therefore critical to ensuring India's long-term agricultural prosperity and environmental sustainability.

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Introduction

The soil health concept has emerged from a productivity-oriented concept of the soils to an understanding of a soil as a dynamic and living entity. Early concerns about soil degradation were raised by Plumptre (1940), who underlined the erosion effects and loss in productivity owing to poor soil management. The scientific pathway of soil functioning was furthered by Hans Jenny (1941), who proposed that soil formation is a function of climate, organisms, relief, parent material, and time. The term 'soil quality' came in prominence during the later part of 20th century, reflecting the capability of soil to function within ecosystem boundaries (Doran & Parkin 1994). Gradually, this transitioned into the more holistic term 'soil health,' considering greater ecological and biological role of soils in supporting soil moisture dynamics, biodiversity, and climate resilience, in addition to crop productivity (Karlen et al. 1997). The soil health is cornerstone of not only agricultural productivity, but also of the environmental sustainability, and long-term food and nutritional security (Srinivasa Rao et al. 2019; Lal 2020). As a dynamic living ecosystem, the healthy soil sustains

plant growth, ensures animal productivity, regulates water, filters pollutants, recycles nutrients, and supports a vast diversity of organisms (Choudhary et al. 2016a).

In India, where nearly 60% population is dependent on farm sector for livelihood (MoA & FW 2021a), maintaining soil health is of paramount importance (Bana et al. 2022a). India's agrarian economy is marked by smallholder-dominated farming systems, intensive land use, and growing pressure on natural resources (Bana et al. 2022b). Decades of input-intensive agricultural practices, especially since the Green Revolution, have led to widespread soil degradation, nutrient imbalances, decline in organic matter, and emergence of multi-nutrient deficiencies (Rattan et al. 2009). Soil erosion, salinity, acidity, and contamination further compound the challenge, threatening the sustainability of agricultural growth and resilience of farming communities (NBSS & LUP 2019; Jat et al. 2018).

Hence, there is an urgent need to shift from input-intensive agriculture to ecologically sound and economically viable soil management strategies. Sustainable soil health management (SSHM) involves the adoption of integrated practices that enhance soil biological activity, restore nutrient cycling, conserve moisture, and improve soil structure and fertility in a manner that supports both productivity and environmental health (Das et al. 2021).

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This review aims to critically examine the status of soil health in India, identify key challenges, explore recent scientific and technological innovations, and assess the effectiveness of existing policies and schemes aimed at promoting sustainable soil management. It also highlights the knowledge gaps and outlines a set of policy and research pathways to accelerate the transition toward soil-centric agricultural sustainability in the Indian context.

About soil health

1 Definition and indicators of soil health

Soil health, sometimes described as soil quality, is the ability of soil to consistently perform as a dynamic living system that supports plants, animals, and people. It reflects the soil's role in sustaining biological productivity, protecting environmental quality, and enhancing plant and animal well-being within specific ecosystems and land-use settings (FAO 2025).

According to FAO (2025), soil health evaluation is carried out using a comprehensive set of **physical, chemical, and biological indicators**, since no single parameter can represent the soil's overall functional capacity. These indicators, when considered together, provide insights into the ability of soil to support plant growth, regulate water and nutrient cycles, and maintain ecological balance.

a. Physical indicators

Physical attributes describe the structural condition of soil and its capacity to facilitate root development, water movement, and gaseous exchange. Key parameters include:

- **Soil texture and structure**, which govern water infiltration, retention, and ease of tillage.
- **Bulk density and porosity**, which influence root penetration and aeration.
- **Infiltration rate and water-holding capacity**, which determine the soil's effectiveness in capturing rainfall and providing moisture to crops during dry spells.

These indicators together reflect the soil's ability to act as a medium for plant anchorage and its resilience against erosion and compaction.

b. Chemical indicators

Chemical characteristics highlight the fertility status of soil and its ability to provide essential nutrients (Bana et al. 2024). Important measures include:

- **Soil reaction (pH)**, which regulates nutrient availability and microbial activity.
- **Electrical conductivity**, which indicates soluble salt concentration and potential risks of salinity.
- **Cation exchange capacity (CEC)**, reflecting the soil's ability to retain and exchange nutrients.
- **Availability of macro- and micronutrients** such as nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Zn), iron (Fe), boron (B), copper (Cu), and molybdenum (Mo).

Together, these properties determine whether the soil environment can meet plant nutrient demands without causing toxicity or deficiencies.

c. Biological indicators

Biological parameters are critical for understanding soil vitality (Grover et al. 2023), as they represent the living fraction of the soil. They include:

- **Microbial biomass carbon**, a measure of the active microbial pool.
- **Soil enzymatic activities** such as dehydrogenase, phosphatases, and urease, which are directly involved in nutrient transformations.
- **Soil respiration rate**, which reflects microbial activity and organic matter turnover.
- **Soil organic carbon content**, which indicates the potential for carbon sequestration and overall soil fertility.
- **Diversity and abundance of soil biota**, including earthworms, fungi, actinomycetes, and bacteria, which play vital roles in decomposition, nutrient cycling, and soil aggregation.

By integrating these **three categories of indicators**, scientists and land managers can diagnose soil-related constraints, design corrective management practices, and monitor improvements over time. This holistic approach provides a reliable framework for promoting sustainable agricultural production while safeguarding soil as a key natural resource.

2 Status of soil health in India

India has a vast diversity of soil types, ranging from alluvial and black cotton soils to red, lateritic, desert, forest, and hill soils, distributed across 15 agro-climatic zones and 20 agro-ecological regions. This heterogeneity influences baseline soil health characteristics, nutrient dynamics, and management priorities. Despite natural fertility in several regions, many soils have shown signs of degradation due to long-term monocropping, imbalanced fertilizer use, low organic matter inputs, and inadequate soil conservation practices (Srinivasa Rao et al. 2017). Key observations include:

2.1 Nutrient imbalances

According to the Soil Health Card data (GOI 2025), a large proportion of soils exhibit low fertility status across both macro- and micronutrients (Fig. 1A and Fig. 1B). In terms of macronutrients, 77% of soils are low in available nitrogen, while phosphorus and potassium are relatively better managed, with most soils falling in the medium range (53% and 61%, respectively). Micronutrient analysis further indicates widespread deficiencies: about 38% of soils are deficient in zinc, 37% in boron, and 29% in sulphur, whereas deficiencies of iron (27%), manganese (13%), and copper (6%) are comparatively less severe. Overall, while copper and manganese remain sufficient in most soils, zinc, boron, sulphur, and nitrogen deficiencies are of serious concern, directly limiting crop productivity and soil resilience. These trends underline the urgent need for integrated nutrient management strategies that not only enhance nitrogen and organic carbon levels but also address site-specific micronutrient deficiencies for restoring soil health and ensuring sustainable agricultural growth.

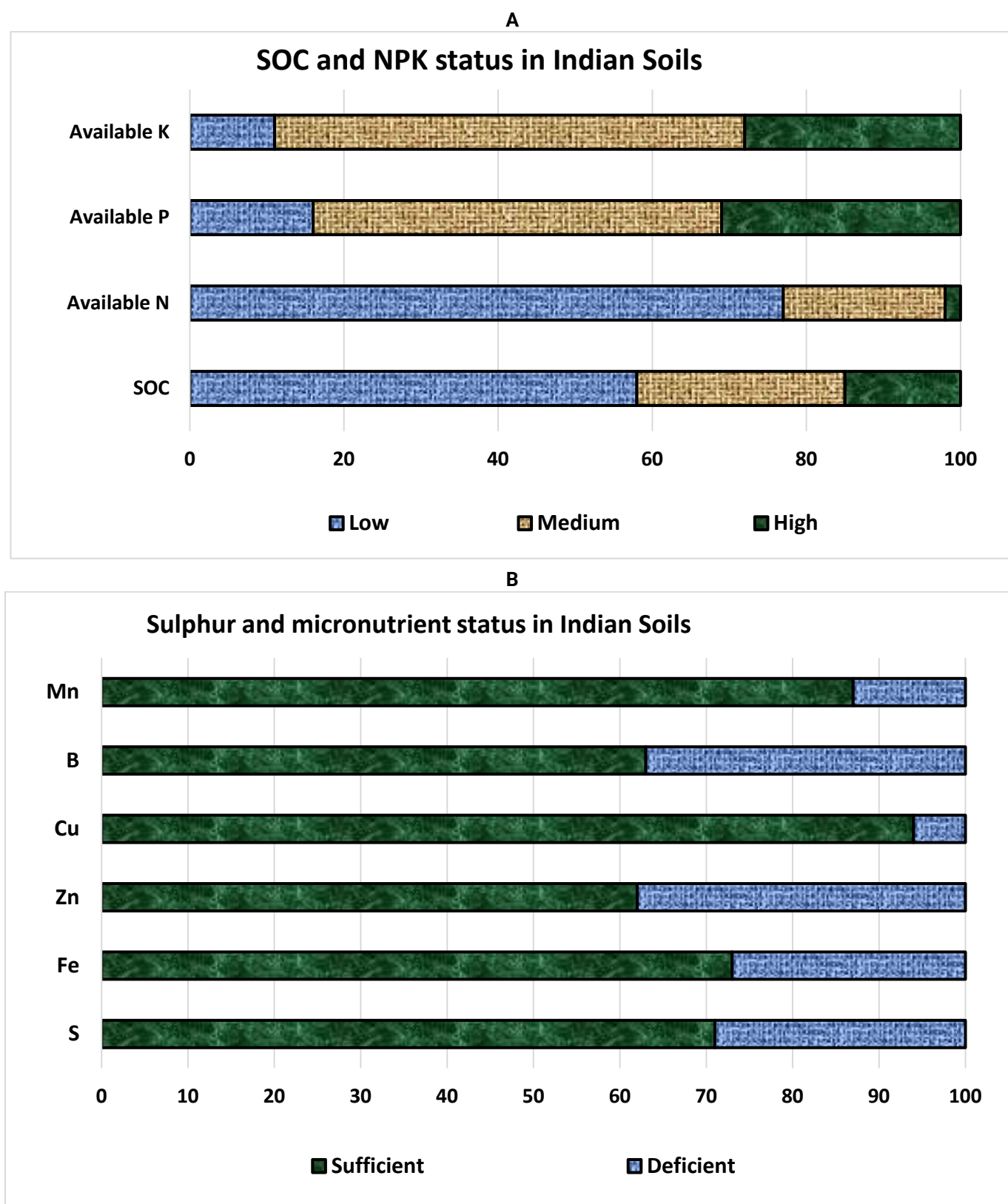


Figure 1. Extent of nutrient deficiency in Indian Soils. A: SOC and NPK; B: Sulphur and micronutrients (GOI 2025)

2.2 Decline in soil organic carbon (SOC) and biological activity

Soil Organic Carbon (SOC) is a critical determinant of soil fertility, nutrient cycling, and overall ecosystem functioning. Recent assessments indicate that about 58% of Indian soils contain low SOC levels (<0.5%), while 27% fall in the medium category (Fig. 1a). Such depletion of SOC has cascading effects, including reduced cation exchange capacity, poor soil

aggregation, diminished water-holding capacity, and weakened resilience to abiotic stress. Declining SOC also limits the energy supply for soil microbial communities, thereby impairing nutrient mineralization processes. Intensive tillage, indiscriminate use of chemical fertilizers, and narrowing of crop rotations, particularly in the Indo-Gangetic Plains and the rice-wheat belt, have further suppressed soil microbial diversity, enzymatic activities, and functional guilds

(Sahrawat 2005; Bana et al. 2023a). The synergistic decline in SOC and biological activity accelerates soil degradation, undermines nutrient-use efficiency, and threatens the long-term sustainability of Indian agroecosystems.

2.3 Acidic and alkaline soils

Soil-related chemical constraints constitute a major threat to agricultural productivity in India. About 49 million hectares (Mha) of land are affected by soil acidity, predominantly distributed across the eastern and northeastern states such as Assam, West Bengal, Odisha, Jharkhand, Chhattisgarh, and parts of Kerala and high-rainfall zones of the Western Ghats (ICAR-NBSS&LUP 2019). Acidic soils typically arise due to intense weathering, heavy rainfall, and leaching of basic cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+), resulting in dominance of exchangeable Al^{3+} and H^+ . Such conditions impair nutrient availability (particularly phosphorus, molybdenum, and calcium), reduce microbial activity, and cause aluminium and manganese toxicities, thereby constraining crop growth (Yogi et al. 2023a). Despite their widespread occurrence, acidic soils hold potential for crop intensification if managed with lime application, balanced fertilization, and use of acid-tolerant varieties.

On the other hand, salinity and alkalinity affect about 6.7 Mha of land, primarily concentrated in the arid and semi-arid tracts of Gujarat, Rajasthan, and Haryana, along with coastal regions of Andhra Pradesh, Tamil Nadu, and West Bengal (ICAR-NBSS & LUP 2019). Saline soils are characterized by high concentrations of soluble salts, mainly chlorides and sulfates of sodium, calcium, and magnesium, leading to high osmotic stress and poor water uptake by plants. In contrast, sodic/alkaline soils are dominated by excess exchangeable sodium, resulting in high pH (>8.5), poor soil structure, reduced infiltration, and restricted root proliferation. Both conditions severely limit the productivity of major food and cash crops.

The combined extent of problem soils (acidic, saline, sodic, and coastal) highlights a serious challenge for Indian agriculture, as these lands often overlap with regions of high population density and food insecurity. Effective management strategies, such as application of soil amendments (lime, gypsum, organic matter), bio-reclamation through salt-tolerant grasses and tree species, efficient irrigation and drainage systems, and adoption of stress-tolerant crop varieties, are essential to restore soil health and ensure sustainable agricultural production in these regions (Pradhan et al. 2025).

2.4 Soil erosion

Nearly 147 million hectares (Mha) of land in India are affected by different degrees of soil erosion, caused primarily by water and wind action (ICAR-NBSS&LUP 2019). Water erosion, including sheet, rill, and gully erosion, is most widespread in the humid and sub-humid regions, particularly in the Himalayan foothills, Indo-Gangetic plains, and parts of central and peninsular India. This form of erosion leads to the loss of nutrient-rich topsoil, reduced soil depth, siltation of reservoirs and rivers, and increased flood risks. Wind

erosion, on the other hand, is dominant in the arid and semi-arid regions of Rajasthan, Gujarat, Haryana, and parts of the Deccan plateau, where high-velocity winds displace fine soil particles, resulting in sand deposition, nutrient depletion, and surface crusting.

Soil erosion not only diminishes soil fertility and crop productivity, but also adversely impacts rainwater-use efficiency, carbon sequestration potential, and long-term sustainability of farming systems. It accelerates the breakdown of soil aggregates, reduces infiltration, and enhances surface runoff, further aggravating drought and flood vulnerability. If unchecked, erosion processes may lead to irreversible land degradation, threatening the livelihoods of millions of farmers. To mitigate these impacts, soil and water conservation measures such as contour bunding, terracing, vegetative barriers, agroforestry, mulching, conservation tillage, and integrated watershed management have proven effective in restoring soil health and improving resource-use efficiency (Bajiya et al. 2020; Kaur et al. 2024). Thus, addressing the challenge of soil erosion is central to ensuring sustainable agricultural growth and environmental security in India. India's agro-ecological diversity results in a wide range of soil types, each with distinct fertility profiles and constraints (Choudhary et al. 2016; Shirzad et al. 2020). However, the intensification of agriculture and unsustainable land-use practices have caused widespread degradation in many regions (Table 1).

Table 1. Soil degradation types and affected areas in India

Type of Degradation	Estimated area (Mha)	Key Affected States/Regions
Water erosion	94.9	Himalayan foothills, Western Ghats, Central India
Wind erosion	12.4	Rajasthan, Gujarat, Haryana
Salinity/Alkalinity	6.7	Gujarat, Punjab, Haryana, UP
Acidification	17.9	Jharkhand, Assam, West Bengal, Odisha
Physical degradation	7.2	Indo-Gangetic Plains, Coastal regions
Total estimated degraded land	147.0	PAN India

Source: ICAR-NBSS&LUP, 2019. *Land Degradation Mapping and Assessment*; ICAR-NBSS&LUP. Annual Report 2005.

Despite the alarming extent of land degradation in the country, several policy interventions have attempted to address the crisis. Notably, the Soil Health Card (SHC) scheme, launched in 2015, has generated valuable baseline data on soil properties for more than 110 million farmers across India (GOI 2025). This large-scale initiative has facilitated more rational and site-specific recommendations for fertilizer application and

soil amendments, thereby promoting the principle of balanced nutrient management. However, the scheme has faced several challenges in practice. Constraints such as inadequate implementation at the grassroots level, limited farmer capacity to interpret technical soil data, weak extension support, and insufficient convergence with organic and biological soil health interventions have hindered its potential impact. Furthermore, the lack of strong linkages between laboratory-based soil testing and field-level advisory services reduces the scheme's effectiveness. Unless these gaps are systematically addressed through capacity building, wider use of ICT-based advisory platforms, and integration of sustainable soil management practices, the goal of restoring and maintaining soil health on a national scale will remain only partially realized (Godara et al. 2025).

3. Challenges in sustainable soil health management in India

Despite growing awareness and policy interventions, the SSHM in India faces numerous challenges. These stem largely from decades of unsustainable agricultural practices, socioeconomic pressures, and environmental changes (Table 2).

3.1 Intensive agriculture and monocropping

The Green Revolution significantly enhanced food production, but it also led to the widespread adoption of input-intensive and monoculture-based cropping systems, particularly in the Indo-Gangetic Plains (Singh et al. 2022). Continuous cultivation of rice–wheat and other cereal-based systems without sufficient crop rotation or diversification has resulted in a decline in soil fertility, organic carbon content, and biological activity (Bana et al. 2012; Choudhary et al. 2014). These practices have disrupted nutrient cycling and increased the susceptibility of soils to degradation (Langyan et al. 2025).

3.2 Indiscriminate use of agricultural chemicals

The imbalanced and excessive application of chemical fertilizers, especially nitrogenous ones, is a major cause of soil acidification, nutrient imbalance, and pollution of soil and water resources (Ranva et al. 2022). Similarly, indiscriminate use of pesticides has negatively affected soil microbial diversity, enzymatic activities, and long-term soil resilience (Sahrawat 2005; Pathak et al. 2023). According to the Ministry of Agriculture (2021), fertilizer use in India has increased from 7.6 million tonnes in 1980–81 to over 64 million tonnes in recent

years, often with N:P:K ratios far from the ideal 4:2:1 balance.

3.3 Underutilization and limitations of organic nutrient sources

Although farmyard manure (FYM), compost, green manure, and biofertilizers have proven benefits for soil health (Bana et al. 2016; Sharma et al. 2019), their adoption remains limited due to issues like bulkiness, low nutrient content, lack of timely availability, and insufficient awareness (Sahrawat 2005). Moreover, current livestock populations and biomass availability are inadequate to meet the nutrient demand organically on a national scale (Srinivasa Rao et al. 2022). Institutional support and infrastructure for large-scale organic recycling and composting are also insufficient.

3.4 Soil erosion, salinization, and nutrient depletion

Soil erosion caused by water and wind affects nearly 30–40% of India's land area, stripping away fertile topsoil and diminishing productivity. In irrigated regions, mismanaged water application has led to secondary salinization, particularly in parts of Punjab, Haryana, and Gujarat. Nutrient depletion due to over-cultivation without replenishment is another persistent issue, especially in rainfed and tribal areas where fertilizer use is limited (Bana 2014).

3.5 Land degradation and climate change impacts

India is home to nearly 30% of the world's degraded land (MoEF & CC 2020), with degradation processes driven by both anthropogenic and natural causes. Land degradation hurts soil structure, water retention, and nutrient cycling. Moreover, climate change (manifesting as increased frequency of droughts, floods, and heatwaves) intensifies land degradation and adversely affects soil biological processes and organic carbon sequestration (Srinivasa Rao et al. 2025).

3.6 Miscellaneous factor

Several emerging challenges are contributing to localised yet critical soil degradation.

These include:

- Rapid urbanization** leading to soil sealing, construction debris dumping, and loss of arable land.
- Industrial and solid waste pollution**, with toxic heavy metals entering peri-urban agricultural lands.
- Mining activities**, which lead to the physical destruction of soil profiles.
- Landfills and dump yards**, especially in city fringes, which contaminate soils with plastics, pharmaceuticals, and persistent organic pollutants.

Table 2. Key challenges to soil health in India and their consequences

Challenge	Description	Key Consequences	Sources
Monocropping and intensive farming	Lack of crop diversity and high external input dependence	Nutrient imbalance, reduced SOC, loss of microbial diversity	Ghosh et al. 2012; Jat et al. 2018; Aggarwal et al. 2020
Excessive fertilizer use	Imbalanced NPK application and overreliance on urea	Acidification, nitrate leaching, eutrophication	Tandon 2020; MoA & FW 2021a; Pathak et al. 2023
Low organic input use	Inadequate application of compost, FYM, or green manures	Reduced soil biological activity, low carbon sequestration	Sahrawat 2005; Ramesh et al. 2010; Sharma et al. 2019; Ranva et al. 2022
Soil erosion and	Caused by poor land	Loss of topsoil,	NBSS&LUP 2019; ICAR-CSSRI

salinity	management and over-irrigation	decreased water productivity	2020
Climate change and land degradation	Increased weather extremes, land misuse, and water stress	SOC depletion, reduced resilience, desertification	MoEF & CC 2020; Aggarwal et al. 2022; Lal 2022; Srinivasa Rao et al. 2025
Pollution and urban sprawl	Soil contamination from urban, industrial, and landfill sources	Heavy metal toxicity, disruption of soil food web	CPCB 2019; Kumar et al. 2022; Singh & Mishra 2023

4. Innovations and technologies for sustainable soil health management in India

India's diverse agro-ecological regions require location-specific, integrated, and sustainable strategies to restore and maintain soil health (Arora et al. 2022). Over the past two decades, multiple innovative technologies, scientific practices, and digital tools have been developed to mitigate physical, chemical, and biological forms of soil degradation (Figure 2). These innovations are vital not only for enhancing resource-use efficiency and adaptive capacity under climate variability but also for ensuring long-term agricultural productivity, ecological balance, and improved livelihoods for farming communities (Table 3).



Figure 2. Sustainable strategies for soil health management

4.1 Conservation Agriculture (CA) and Resource Conservation Technologies (RCTs)

The CA is built on three fundamental principles: minimum soil disturbance, permanent soil cover, and diversified crop rotations. These practices not only conserve natural resources but also contribute to long-term sustainability of farming systems (Bana et al. 2023b). Evidence from field experiments and long-term trials in the Indo-Gangetic Plains (IGP) has demonstrated that CA practices significantly improve soil organic carbon (SOC) stocks, reduce bulk density, and stimulate microbial biomass and activity, thereby enhancing soil health and biological functioning (Jat et al. 2019; Sapkota et al. 2021). Improved SOC and better soil aggregation under CA further aid in moderating soil temperature, reducing erosion, and increasing nutrient cycling efficiency (Yogi et al. 2023b).

Moreover, CA-based approaches and a range of RCTs such as zero tillage, residue retention, precision nutrient management, and direct-seeded rice have been shown to improve soil water retention capacity, enhance infiltration rates, and reduce surface runoff losses (Meena et al. 2025). These benefits directly contribute to improved nutrient-use efficiency, reduced dependence on external inputs, and greater stability of crop yields under climatic stresses (Pradhan et al. 2025; Bana et al. 2023b). Importantly, CA has been found particularly suitable for semi-arid and rainfed regions, where efficient utilization of limited rainfall and improved soil moisture storage play a crucial role in sustaining crop productivity (Ankit et al. 2022). In such fragile ecosystems, the adoption of CA helps mitigate risks from erratic rainfall and temperature variability, supports climate resilience, and improves overall system profitability while ensuring environmental sustainability (Yogi et al. 2023b).

4.2 Integrated Nutrient Management (INM)

Integrated Nutrient Management (INM) emphasizes a holistic approach to plant nutrition by combining chemical fertilizers with organic manures, crop residues, green manures, and biofertilizers in order to achieve a balanced nutrient supply and sustain soil fertility over the long term (Wani et al. 2009). Unlike reliance on chemical fertilizers alone, INM seeks to optimize the efficiency of all nutrient sources, thereby improving nutrient cycling and reducing environmental risks. Long-term experiments conducted at multiple sites by ICAR have consistently shown that INM practices not only enhance crop productivity but also help in maintaining soil pH, electrical conductivity, organic matter content, and available macro- and micronutrient pools, ensuring the long-term sustainability of production systems (Ramesh et al. 2010; Das et al. 2021).

Another critical component of INM is the integration of legumes in cropping systems, which plays a dual role (Bana et al. 2016). Firstly, legumes biologically fix atmospheric nitrogen through symbiotic associations with *Rhizobium* bacteria, thereby enriching soil nitrogen pools naturally and reducing dependence on synthetic N fertilizers (Yogi et al. 2023b). Secondly, legumes contribute substantial amounts of residues and root biomass, which improve soil organic carbon levels, aggregation, and overall soil structure (Ankit et al. 2022). Over time, these processes enhance soil porosity, water-holding capacity, and microbial activity, creating a favorable environment for subsequent crops (Wani et al. 2009). Additionally, INM approaches improve the synchronization between nutrient release and crop demand, reduce nutrient losses through

leaching or volatilization, and promote the efficient use of scarce resources. Thus, integrated nutrient management not only sustains high yields but also strengthens soil health, ecosystem services, and resilience to climate variability, making it a cornerstone of modern sustainable agriculture (Bana et al. 2016).

4.3 Use of biofertilizers and microbial consortia

Microbial-based inputs such as *Rhizobium*, *Azotobacter*, Phosphate Solubilizing Bacteria (PSB), and arbuscular mycorrhizal fungi (AMF) are increasingly gaining importance as SSHM strategies. These bioinoculants play a crucial role in enhancing nutrient solubilization, mobilization, and biological availability in the rhizosphere, thereby supporting better nutrient uptake by crops (Jain et al. 2022). For example, *Rhizobium* establishes symbiotic associations with legumes and contributes to biological nitrogen fixation, while *Azotobacter* improves free-living nitrogen fixation in non-leguminous crops. Similarly, PSBs convert insoluble forms of phosphorus into plant-available forms, and mycorrhizae extend root surface area through hyphal networks, facilitating improved uptake of phosphorus, zinc, and other micronutrients (Naragund et al. 2022). Collectively, these inputs not only improve root growth, plant vigor, and nutrient-use efficiency but also enhance soil biological activity and microbial diversity, contributing to the restoration of soil ecological balance (Meena et al. 2017; Jain et al. 2022; Sinha et al. 2023).

Recent advances have expanded the scope of microbial inputs beyond single-strain inoculants. The development of microbial consortia, where multiple beneficial microbes are combined to provide synergistic effects, has demonstrated higher reliability across variable soils and climatic conditions (Naragund et al. 2022). These consortia can simultaneously address nitrogen fixation, phosphorus solubilization, potassium mobilization, and biocontrol of pathogens, making them more robust than single-microbe applications. In parallel, innovations in nano-biofertilizers have further improved the efficiency, stability, and shelf life of microbial products. By encapsulating microbial formulations or nutrients within nanomaterials, controlled release and better protection of microbial viability can be achieved, ensuring longer field effectiveness and reducing application rates (Ali et al. 2021). Such innovations highlight the transition from traditional biofertilizers to next-generation microbial technologies that are capable of supporting climate-resilient, resource-efficient, and environmentally friendly farming systems.

4.4 Soil Organic Carbon Management

Rebuilding soil organic carbon (SOC) has emerged as a global priority for restoring soil health, improving agricultural productivity, and mitigating climate change (Srinivasa Rao et al. 2017). A wide range of carbon-conserving and carbon-enhancing practices are now promoted, including composting, residue recycling, agroforestry interventions, and reduced tillage systems (Jat et al. 2019). These practices contribute to increasing the stable organic matter fraction in soils,

improving aggregation, and enhancing the soil's role as a long-term carbon sink (Srinivasa Rao et al. 2025). In particular, the return of crop residues and the application of compost provide a continuous supply of organic substrates, which improve soil structure, water retention, and nutrient availability while reducing soil erosion and degradation risks (Yogi et al. 2023b). Agroforestry systems, by integrating trees with crops or pastures, not only add above- and below-ground biomass but also diversify carbon inputs and strengthen the resilience of farming systems to climatic stresses (Lal 2020).

In addition to these broad strategies, more specialized practices such as vermicomposting, green manuring, and mulching play an equally important role in SOC restoration (Bana et al. 2016). Vermicomposting accelerates the decomposition of organic wastes through earthworm activity, producing nutrient-rich organic amendments that are highly effective in building SOC pools (Wani et al. 2009). Green manuring, through the incorporation of legumes and other cover crops, not only contributes organic matter but also enhances biological nitrogen fixation, thereby improving soil fertility alongside carbon sequestration. Mulching with crop residues or biomass protects the soil surface, reduces evaporation losses, suppresses weed growth, and gradually releases carbon into the soil profile (Ankit et al. 2022; Sharma et al. 2022; Mevada & Makwana 2023). Together, these practices not only improve SOC concentration and stability but also stimulate soil enzyme activity, microbial biomass, and overall biological functioning, which are vital for nutrient cycling and soil ecosystem services (Lal 2020; Sharma et al. 2022). Over time, the cumulative effect of such practices leads to healthier soils, greater resilience to climate variability, and a more sustainable agricultural production base (Bana et al. 2023a).

4.5 Precision Soil Mapping and Digital Tools

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) has played a pivotal role in modernizing soil resource assessment through the development of digital soil maps that integrate GIS and remote sensing technologies. These high-resolution maps provide valuable information on soil type, texture, depth, nutrient status, and constraints, which can be effectively used to design location-specific soil and land management strategies. By enabling site-specific recommendations, such mapping helps optimize fertilizer use, conserve resources, and mitigate land degradation. Complementing these efforts, the Government of India launched the Soil Health Card (SHC) scheme in 2015 intending to promote balanced nutrient use and improve soil fertility management. Since its inception, the scheme has generated a massive dataset of more than 250 million soil samples across the country, creating one of the world's largest repositories of soil fertility information (GOI 2025). This database has been instrumental in providing tailored nutrient recommendations to farmers, thereby supporting judicious fertilizer application, reducing nutrient imbalances, and enhancing input-use efficiency.

(MoA&FW 2021a; ICAR 2022). Beyond its immediate benefits for farmers, the SHC program also contributes to national-level planning by supplying policymakers and researchers with region-specific insights on soil

health trends, enabling long-term strategies for sustainable land use, productivity enhancement, and environmental protection.

Table 4. Key technological interventions for Sustainable Soil Health Management in India

Technology/Innovation	Core Feature	Soil Health Benefit	References
Conservation Agriculture	No-till, residue retention, crop rotation	Enhances SOC, reduces erosion and compaction	Jat et al. 2019; Sapkota et al. 2021
Integrated Nutrient Management	Use of organic + inorganic + biological sources	Balances nutrient supply, improves soil microbial biomass	Ramesh et al. 2010; Das et al. 2021
Biofertilizers	Beneficial microbes for N fixation, P solubilization	Improves nutrient availability and soil life	Jain et al. 2022; Meena et al. 2017
Organic matter recycling	Compost, vermicompost, green manures	Increases SOC, improves aggregation and soil enzymes	Lal 2020; Sharma et al. 2022
Digital soil mapping & SHC	GIS mapping, soil sampling, lab-based diagnostics	Site-specific nutrient management	MoA & FW 2021b; ICAR 2022

4.6 Use of Remote Sensing, AI and IoT in soil health monitoring

Recent advances in digital agriculture are transforming the way soil resources are monitored, managed, and restored. The integration of remote sensing, artificial intelligence (AI), Internet of Things (IoT) sensors, and smartphone-based diagnostic tools now allows for near real-time tracking of key soil health parameters, including soil moisture dynamics, nutrient availability, salinity, and early signs of land degradation (Aggarwal et al. 2022; Mishra et al. 2023). Remote sensing technologies, supported by satellite imagery and drones, enable large-scale assessment of soil and land conditions, helping identify spatial variability and degradation hotspots with high accuracy. IoT-enabled soil sensors, on the other hand, provide continuous in-situ data on moisture and nutrient fluctuations, allowing for more efficient irrigation scheduling and fertilizer application (Aggarwal et al. 2022; Kavadi et al. 2023). Artificial intelligence and machine learning models further enhance these capabilities by processing vast

datasets to predict soil fertility trends, crop responses, and degradation risks, thereby enabling data-driven decision-making (Godara et al. 2024). Smartphone-based diagnostic applications and portable soil testing kits make these advanced technologies accessible to farmers at the grassroots level, bridging the gap between research and practice. Together, these innovations contribute to precision agriculture, ensuring that interventions are not only timely but also tailored to the specific needs of each field (Table 5). By empowering farmers with real-time advisories, early warning systems, and site-specific nutrient recommendations, digital agriculture strengthens the resilience of farming systems, reduces input costs, and minimizes environmental externalities (Godara et al. 2025). Over time, the widespread adoption of such tools holds the potential to significantly accelerate progress toward sustainable soil management and climate-smart agriculture.

Table 5. Digital and AI-based innovations for soil health management

Technology	Description	Benefits	Source
Soil Health Card Mobile App	App providing nutrient status and fertilizer advice	Farmer-friendly interface, localized info	MoA & FW 2021b
Remote Sensing + GIS	Satellite imagery + spatial mapping	Degradation hotspot identification	NBSS & LUP 2019; Mishra et al. 2023
AI-driven advisory tools	Machine learning models on soil/crop data	Decision support for sustainable inputs	Aggarwal et al. 2022
IoT-based soil sensors	Real-time soil moisture and EC monitoring	Precision irrigation and fertilization	Godara et al. 2025; Aggarwal et al. 2022

5. Research gaps and funding challenges

India’s soil research ecosystem, though extensive and supported by institutions such as ICAR, faces several critical limitations. Foremost among these is the scarcity of long-term soil health data across diverse agro-climatic zones, particularly in ecologically fragile drylands and uplands, hindering assessment of trends over time (ICAR 2022). Reliable real-time soil monitoring systems that measure chemical, physical, and biological indicators remain insufficient, delaying

corrective interventions (Sen et al. 2025). Further, interdisciplinary linkages between soil biology, carbon dynamics, socio-economics, and climate adaptation are underdeveloped, impeding integrated soil management. The private sector’s role is limited, with weak commercialization of innovations such as nano-biofertilizers, sensor-based diagnostics, and microbial consortia, stalling scalability (Narayana et al. 2025). Finally, funding constraints for on-farm participatory trials persist, despite their value for validating and

scaling locally adapted soil health innovations (FICCI 2022). Overcoming these gaps will be essential to create a responsive, innovation-driven soil health management ecosystem in India.

6. Climate-smart soil management strategies

With increasing climate variability, future soil management in India must be resilient, adaptive, and resource-efficient (Srinivasa Rao et al. 2020; Bana et al. 2023a). Priority actions include mainstreaming climate-smart practices like mulching, cover cropping, residue retention, and minimum tillage, which have been shown to enhance soil organic carbon storage and soil moisture conservation, especially in fragile dryland areas (Bana et al. 2023a; Das 2024). Complementary strategies such as agroforestry and silvopastoral systems not only improve soil fertility but also sequester carbon and diversify farmer income sources, with substantial carbon stocks evident under agrosilvopastoral systems (Das 2024). Another key direction is the development of AI- and IoT-enabled soil health decision support systems, capable of providing real-time advisories and stress prediction—emerging technologies that hold promise for data-driven soil restoration (Narayana et al. 2025; Pandey et al. 2025). Additionally, payment for ecosystem services models are increasingly advocated as mechanisms to incentivize farmers adopting soil-conserving and regenerative practices, such as watershed-based ecosystem services valuation (Meena et al. 2022). Finally, strengthening climate–soil–crop simulation models is essential for scenario planning and risk assessment, helping anticipate and manage the impacts of changing rainfall and temperature patterns (Bana et al. 2023b). To realize these strategies on the ground, a multi-layered governance framework that integrates local Panchayats, FPOs, and district-level soil missions is crucial for operationalizing climate-smart soil health approaches in diverse agricultural landscapes.

Table 7. Summary of major gaps and recommended future interventions

Domain	Key Gaps/Constraints	Future Directions
Farmer Adoption	Low awareness, input access issues, limited incentives	Strengthen extension, FPO-based models, incentivize soil services
Research and Development	Poor data integration, funding bottlenecks	Invest in digital labs, long-term trials, PPPs in soil innovation
Climate Resilience	Soil vulnerability to droughts and heat waves	Promote CA, agroforestry, smart irrigation, carbon farming
Institutional Linkages	Scheme fragmentation and limited convergence	Soil Health Missions at state/district levels with convergence

7. Conclusion

Soil health stands at the heart of India's agricultural sustainability, food security, and ecological resilience. Decades of intensive agriculture, coupled with imbalanced fertilizer use, organic matter depletion, and land degradation, have critically impaired soil quality across various agro-ecological zones. While policy frameworks like the Soil Health Card Scheme, *Paramparagat Krishi Vikas Yojana*, and National Mission on Sustainable Agriculture have initiated corrective measures, the pace and scale of implementation remain uneven. Simultaneously, emerging innovations—from conservation agriculture and integrated nutrient management to AI-powered soil diagnostics and drone-based nutrient applications offer new opportunities to reverse degradation and enhance long-term soil productivity. However, realizing these opportunities requires addressing significant gaps in farmer adoption, input accessibility, long-term field data, and inter-institutional coordination. The limited awareness among small and marginal farmers, weak integration of soil biological indicators in assessment protocols, and fragmented efforts across government schemes continue to pose major hurdles. There is also a need to transition from short-term yield maximization to long-term soil ecosystem restoration, anchored in participatory, decentralized, and climate-resilient approaches.

Going forward, a multi-pronged strategy is vital for strengthening soil health management in India. This requires enhancing extension systems through KVKs, FPOs, and digital platforms to provide farmer-centric training and timely input delivery. At the same time, climate-smart practices such as crop diversification, agroforestry, and conservation agriculture must be mainstreamed, particularly in rainfed and degraded areas. Greater investment in real-time soil monitoring tools powered by AI, IoT, and geospatial data will enable dynamic, site-specific management, while stronger convergence across government schemes and linkages with MGNREGA can support land improvement and agroecological restoration. Finally, incentivizing farmers as soil stewards through mechanisms like Payment for Ecosystem Services, carbon credits, and green financing will be crucial to sustain long-term adoption of soil-conserving practices.

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