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Restoration and Improvement of Soil Health

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
September 2025

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Preface

Soil, the foundation of life on earth, is a vital resource. It sustains food production, supports biodiversity, regulates water cycles, and acts as a significant carbon sink. However, this living, wonderful gift of nature is often undervalued and subjected to widespread degradation due to unsustainable land use, intensive agriculture, pollution, and the growing pressures of climate change.

Recognizing the critical role soil plays in ensuring food security, environmental sustainability, and overall societal well-being, the Academy organized a Brainstorming Session on ‘Restoration and Improvement of Soil Health’ to take stock of the current status of the health of Indian soils, and suggest doable R&D and policy initiatives. The present document, based on the deliberations during the session, outlines strategic pathways to restore soil health through sustainable agricultural practices, conservation measures, integrated nutrient management, and robust assessment and monitoring systems.

This Policy Paper would prove useful to the policymakers, researchers, and other stakeholders committed to safeguarding soil for present and future generations. In doing so, it also makes a meaningful contribution to national goals and global commitments, such as the Sustainable Development Goals (SDGs), Land Degradation Neutrality (LDN), and the ‘One Health’ vision. I take this opportunity to thank the Convener (Dr. B.S. Dwivedi), Co-Conveners (Dr. Anil Kumar Singh & Dr. S.P. Datta), Reviewers (Dr. J.C. Katyal & Dr. C.L. Acharya) and Editors (Dr. V.K. Baranwal & Dr. R.K. Jain), whose insights and efforts have made this document possible.

September 2025
New Delhi

(Himanshu Pathak)
President, NAAS

Restoration and Improvement of Soil Health

1. INTRODUCTION

Soil, like air and water, is a fundamental natural resource that sustains diverse ecosystem goods and services, supporting mankind. It plays a pivotal role in social and economic growth by ensuring the supply of food, fibre, fodder and renewable energy to sustain human, animal, and plant life. The role of soil in food production has been recognized for a long time. However, the significance of conserving and augmenting the ecosystem services provided by soil, such as water purification, groundwater recharge, carbon sequestration, biological nitrogen fixation, pathogen control, and biodiversity conservation, has only been realized in recent years. Therefore, healthy soil is inevitable for life on earth.

In the past few decades, the terms 'soil health' and 'soil quality' gained much popularity. Although several definitions of soil health are proposed in the literature, the emphasis is laid on the services provided by soil such as crop production, water retention and infiltration, recycling of nutrients and habitat of different organisms. Scientific literature and popular press often use the terms 'soil health' and 'soil quality' interchangeably. In order to describe the soil health concept in totality, Katyal and Chaudhari (2021) suggested four indicators: (i) sustaining target growth in food grain productivity, (ii) improving provisions of environmental services like water holding and transmission characteristics, sustenance of soil organic carbon, climate regulation and soil biodiversity, (iii) maintaining efficient use of both native and added inputs and declining negative outputs in soil, air and water, and (iv) maintaining plant, animal, human and air health with quality of soil environment. Earlier, Doran and Zeiss (2000) also laid emphasis on maintenance of plant, animal, air, and human health along with the quality of soil environment to describe soil health holistically. To be practical, the basic soil health tenets should *inter alia* (i) integrate soil physical, chemical and biological parameters, (ii) be sensitive to variations in management and climate, and (iii) measurable as far as possible. The researchers often confine their efforts to the discipline(s)/areas of their interest of familiarity, thus making the soil health/quality evaluation a reductionist rather than a holistic approach (Doran and Parkin, 1994).

India, one of the fastest-growing economies in the world, is grappling with ensuring food security for its 1.4 billion population. Despite the growth in food grain production from 82 million tonnes (Mt) in 1960-61 to 353.96 Mt in 2024-25, concerns persist regarding the ability to feed the expanding population sustainably, projected to reach 1.65 billion by 2050. The nation's finite natural resources are experiencing significant strain due to various factors. Thus, a unified effort is imperative to achieve food and nutritional security through the restoration and improvement of soil health.

Soil health crisis is a worldwide issue that cuts beyond national boundaries. Over the years, soil degradation through erosion, deforestation, pollution, and unsustainable agricultural practices has become a significant global challenge. Policy frameworks are essential for directing soil restoration and management practices. International accords, such as the United Nations Convention to Combat Desertification (UNCCD), provides a global platform for advocating land degradation neutrality and promoting sustainable soil management. National governments can play a pivotal role in translating international commitments into actionable policies. The 'European Union's Common Agricultural Policy' integrates soil health into its sustainability goals, offering financial incentives to farmers who adopt practices that improve soil quality. Similarly, the 2018 Farm Bill in the United States includes soil health provisions, such as cover crop funding, conservation tillage, and other regenerative agricultural practices. These policies promote soil restoration and contribute to broader environmental objectives, including carbon sequestration and biodiversity conservation.

Effective conservation and restoration of soils and their supporting habitats necessitate collaboration among scientists, policymakers, society, and private partners. The intrinsic value of soils, biodiversity, and habitats surpasses simple economic factors, as an ethical obligation exists to preserve these resources for future generations. In this context, the National Academy of Agricultural Sciences (NAAS) brought out a Policy Brief in 2018 (NAAS, 2018). The present document critically analyses the existing and emerging challenges in the arena of soil health, and suggests a few pertinent recommendations for the policy makers and other stakeholders.

2. CURRENT STATE OF SOIL HEALTH

2.1. Land Degradation

Land degradation significantly threatens India's capacity for sustainable food production and adequate nutrition. Recent estimates by the Space Application Centre (SAC) for the timeframe of 2018-19 revealed that 97.85 million hectares (Mha) in the country suffers from various kinds of land degradation, which is 3.32 Mha greater than the estimates for 2003-05 timeframe (SAC, 2021). Earlier analysis by the Indian Council of Agricultural Research (ICAR) and NAAS estimated 120.7 Mha as degraded lands (NAAS, 2010). Key contributors to land degradation are water and wind erosion, vegetation degradation, soil acidity, salinity and alkalinity, and waterlogging. Soil erosion results in the detachment of soil particles, depletion of soil organic carbon (SOC) and nutrients, soil compaction, reduced soil biodiversity, and contamination with heavy metals and pesticides.

The UNCCD applies three core criteria involving changes in land productivity, soil organic C stocks and land cover density to monitor the extent of land degradation over time. As India lost 3.32 Mha area to land degradation/desertification in past one-and-a-half decade, the existing policies and their implementation need to be revisited for any need-based refinement so as to achieve the land degradation neutrality (LDN) by 2030.

The annual soil loss in India is approximately 15.35 t ha^{-1}, leading to a nutrient loss of 5.37 to 8.4 Mt, diminished agricultural productivity, increased occurrence of floods and droughts, decreased reservoir capacity by 1 to 2% annually, and a decline in biodiversity (Sharda and Ojasvi, 2016; NAAS, 2018). Erosion diminishes the productivity of the land, necessitating greater inputs like fertilizers and water to achieve equivalent yield levels, thereby raising farming costs and worsening environmental problems. TERI's (The Energy Research Institute) study on the economics of desertification, land degradation, and drought in India indicates that expenses associated with land degradation and land use change represented as much as 2.54% of India's gross domestic product (GDP) in the fiscal year 2014-15. All terrestrial biomes are affected by the problem of land degradation, which has far-reaching effects. Additionally, soil crusting and compaction result in lower soil porosity, higher bulk density, and other adverse effects such as erosion, inhibited root growth, and restricted water movement. Waterlogging affects 11.6 Mha of land, leading to further soil degradation. Using land for non-agricultural purposes and transforming productive land into low-quality wasteland worsen the situation, leading to the loss of fertile soil. Extractive farming (agricultural practices that focus on removing nutrients and other resources from the land without replenishing them), when practiced consistently, lead to fall in productivity, declining soil health and land degradation (Fig. 1).

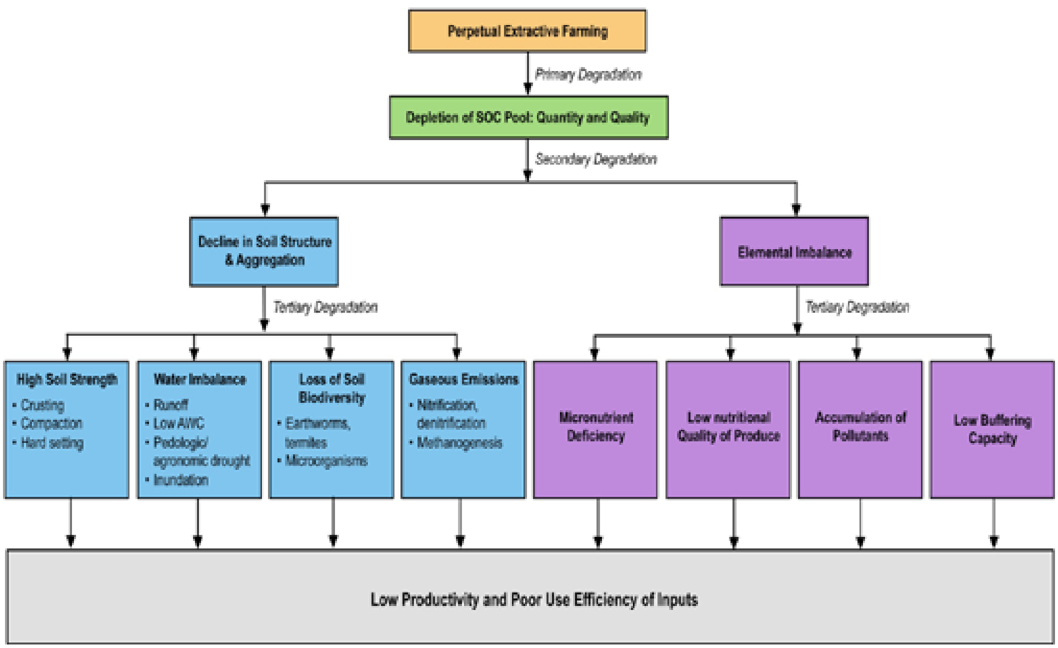

Fig. 1: Effects of perpetual extractive farming practices on soil degradation (Lal, 2017)

2.2. Soil Organic Carbon and Fertility Status

Soil organic carbon (SOC) is essential for sustaining soil health, facilitating nutrient cycling, and promoting microbial diversity. Soil type, land use, management practices, and climatic conditions influence SOC levels. The decline in SOC is mainly associated with climatic factors, conventional tillage practices, crop selection, and other farming practices. Other factors contributing to the decline of SOC include the disintegration of soil aggregates, crop residue burning, mono-cropping practices, and inadequate use of organic manure. Soils of tropical and sub-tropical regions, as those in India, have generally lower organic carbon levels than those in temperate regions, necessitating up to four times more organic inputs than temperate soils to sustain soil organic matter (SOM i.e., 1.72 times of SOC) levels. Long-term studies in India have shown a significant decline in SOC in most regions due to intensive agricultural practices and unbalanced use of plant nutrients. On the other hand, balanced nutrient input through fertilizers, especially though conjoint use of fertilizers and manure restored/improved SOC levels and overall soil health.

Analysis of about 52.7 million soil samples in the two cycles (Cycle I: 2015-16 to 2016-17 and Cycle II: 2017-18 to 2018-19) of the Soil Health Card (SHC) Scheme exhibited widespread deficiencies of nitrogen (N), phosphorus (P), and potassium (K). Across the country, 85, 97, 83 and 71 per cent samples represented low or medium levels of SOC, N, P and K, respectively, and these could be placed in deficient or fertilizer responsive category (Fig. 2), necessitating adequate NPK input for optimal crop growth.

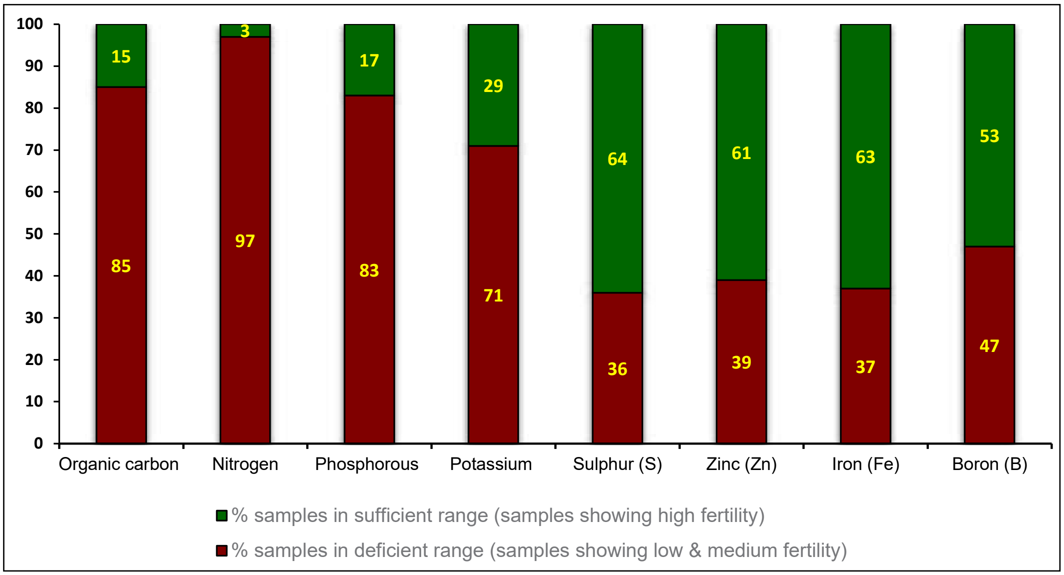

Fig. 2: Fertility status of Indian soils as evident from Soil Health Cards (adapted from Khurana and Kumar, 2022); Data Source: Soil Health Card (SHC) Scheme, Ministry of Agriculture and Farmers Welfare, Government of India

An earlier assessment based on compilation of the data of soil testing laboratories (Table 1) also placed more than 90% soils with respect to N and P, and nearly 50% soils with respect to K in the deficient (low + medium fertility) category. The SHC estimates clearly revealed a rise in the extent of K deficiency over the years. Further, an examination of long-term nutrient balance in agricultural soils from 1970 to 2018 indicated a negative K balance, suggesting excessive mining of K from native pools obviously due to inadequate annual applications vis-à-vis crop removal.

Table 1: NPK fertility status of Indian soils

Nutrient	Per cent districts in different classes		
	Low	Medium	High
Nitrogen	59	36	5
Phosphorus	49	45	6
Potassium	9	39	52

Muralidharudu *et al*. (2011)

Among secondary and micronutrients, widespread deficiencies of sulphur (S), zinc (Zn), iron (Fe) and boron (B) to the extent of 36, 39, 37 and 47 per cent, respectively were evident during the initial two cycles of soil testing under SHC Scheme (Fig. 2). Deficiencies of manganese (Mn; 12%) and copper (Cu; 6%) were of sporadic nature.

Soils analyzed under All India Coordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants (AICRP-MSPE) revealed S, Zn and B deficiencies in 41, 36 and 23% soils, respectively (Fig. 3), besides sporadic deficiencies of Fe (13%), Mn (7%) and Cu (4%). These averaged figures masked the obvious soil fertility variations among different soil types and agro-ecologies.

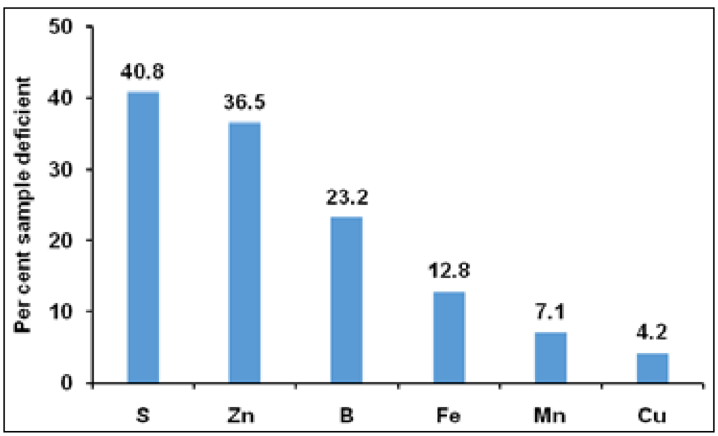

Fig. 3: Extent of secondary and micronutrient deficiencies in Indian soils (Shukla *et al*. 2021)

2.3. Soil Physical and Biological Parameters

Soil physical parameters like texture, bulk density, water holding capacity, aggregate stability, hydraulic conductivity, aeration *etc*. not only affect microbial activities, nutrient assay and movement of water and air in soil, but also have significant effect on productivity by modifying crop growth, especially seed germination and seedling emergence, and root growth. Management practices like indiscriminate tillage using heavy machinery, puddling, removal/burning of crop residues and neglect of manures result in deterioration of soil physical health. On the contrary, use of organics, balanced fertilization, minimum disturbance of soil, retention of crop residues, and crop diversification with inclusion of legumes restore and improve soil physical health. Impact of crop management practices and other natural/anthropogenic interventions like land degradation, land use change etc. on soil biological parameters has not been as frequently assessed as that on soil fertility or physical parameters, due to delayed understanding of their significance in sustenance of soil health. Long-term studies over past five decades, however, established the positive effect of balanced and integrated use of manure and fertilizers on biological parameters such as microbial population density and diversity, microbial biomass, dehydrogenase activity, soil respiration etc.

2.4. Impacts of Poor Soil Health

Deterioration of soil health has grave implications on agriculture, especially (i) widespread and acute nutrient deficiencies; (ii) fall in nutrient use efficiencies and return from the investments; (iii) inability to sustain high yield levels; and (iv) higher remedial costs for restoring degraded soils. The financial and ecological impacts of inadequate soil health are considerable. Decreased agricultural yields can result in higher food costs, making it increasingly difficult for low-income individuals to access nutritious food, which worsens poverty and inequality, especially in rural regions. Additionally, poor soil quality leads to a greater dependence on inorganic fertilizers and other inputs, which further harms the environment and poses long-term sustainability challenges, besides raising the cost of production. Enhancing soil health is crucial for achieving climate objectives, particularly in nations like India, where agriculture significantly contributes to greenhouse gas emissions. To tackle the issues related to poor soil health, it is vital to implement a comprehensive strategy that includes constant monitoring of soil health, advocating sustainable farming methods, and public policies that promote soil health restoration. It is equally important to educate farmers on the significance of healthy soil and equip them with the necessary tools and knowledge to enhance their land management strategies to bring-in an improvement in soil health.

3. SOIL HEALTH EVALUATION: INFRASTRUCTURE

The present infrastructure for evaluation of soil health comprises a network of soil testing laboratories (STLs) mostly owned by State Governments, and All India Coordinated Research Projects (AICRPs), besides other short- to medium-term research projects operating at agricultural universities (AUs) and ICAR institutes. In India, soil health monitoring and evaluation is often synonymous to soil fertility appraisal using soil testing. Soil biological and physical parameters are seldom tested in the STLs.

3.1. Soil Testing Service

Soil testing service in India began in 1955-56 with the establishment of 16 STLs under the 'Indo-US Operational Agreement for Determination of Soil Fertility and Fertilizer Use'. Thereafter, the STL network expanded continuously. At present (2023-24), a total of 1663 STLs (1389 static + 274 mobile STLs) are functioning in different states. Of these, about 75% belong to the State Departments of Agriculture, and remaining to fertilizer industry, public sector undertakings and private sector. The annual soil analyzing capacity of these STLs is 13.53 million samples, though the capacity utilization varies in different states. In addition, nearly half of the *Krishi Vigyan Kendras* (KVKs) have soil testing facilities. The AUs and a few ICAR institutes also impart soil testing services to the farmers on a limited scale.

3.2. Research Support to Soil Health Evaluation

Of the ongoing AICRPs of the ICAR, at least five are dedicated to studying soil health-related issues *i.e.,* delineation of soil fertility status, impact of management practices on long-term changes in soil physical, chemical and biological parameters, and formulation of judicious fertilizer prescriptions for targeted yield. These are: (i) AICRP on Long-Term Fertilizer Experiments (LTFE); (ii) AICRP-MSPE; (iii) AICRP on Soil Test Crop Response Correlations (STCR); (iv) AICRP on Integrated Farming Systems; and (v) AICRP on Dryland Agriculture. Besides, several other studies are being taken-up outside these AICRPs in the ICAR institutes (mainly NBSS&LUP, IISS, CSSRI, IISWC and IARI) and AUs to develop and improve soil test methodology, soil resource characterization and mapping, and soil test-based balanced and integrated nutrient recommendations. Nonetheless, poor coordination between service and research components of soil testing continues one of the major constraints in strengthening soil testing service.

Despite large network of STLs, the demand for soil testing is relatively low. This is often due to unawareness regarding benefits of soil testing, and occasionally due to lack of trust in the services offered by STLs. Hence, soil testing in India is more a government-driven programme rather than a farmer demand-driven one. Some specific reasons responsible for this situation are: lack of farmers' participation in soil sampling, problems associated with soil test methods, inadequate analytical facilities, incomplete fertilizer prescription, poor human resource, and weak linkage with research institutions. Whereas the infrastructure of STLs necessitates revamping, soil testing research needs to be simultaneously strengthened. This necessitates desired convergence among the stakeholders. A few specific suggestions for strengthening the service are: (i) establishment of state-of-the-art STLs with high output; (ii) creation of a dedicated service cadre in the states for soil health monitoring; (iii) deployment of trained manpower in the STLs; (iv) assessment of irrigation water quality; (v) establishment of quality control mechanism; (vi) refinement of soil test methods (especially for N, K, S and B); and (vii) revisiting fertilizer recommendations using site-specific nutrient management approaches.

The holistic assessment of soil health, however, requires identification and quantification of critical soil parameters (especially soil physical and biological ones), specific to soil and farming situations. There is need to enumerate indicators for monitoring the changes in soil health on spatio-temporal scale.

4. STRATEGIES FOR SOIL HEALTH RESTORATION AND IMPROVEMENT

A poor soil will not be able to perform different soil functions at the desired pace, and will cease to support sustained high productivity. Any yield gains achieved on such soil, except judicious soil management, would encourage further deterioration in terms of depletion of SOC and native nutrient reserves. Nevertheless, soil health issues are often reversible in nature, and could be effectively addressed with proper management.

4.1. Promoting Sustainable Agricultural Practices

Modern global agriculture is marked by a heavy reliance on inputs and soil cultivation, which, along with practices like stubble removal and burning, lead to nutrient depletion, soil erosion, and a decline in SOM. Several countries have initiated programs to address this detrimental trend, and encourage farmers to adopt sustainable agriculture, encompassing economic incentives and specific technological solutions. The innovations in sustainable agricultural practices would enhance resource efficiency, mitigate environmental consequences, and boost productivity. Since 2014-15, Ministry of Agriculture and Farmers Welfare (MoA&FW) initiated a National Mission for Sustainable Agriculture (NMSA) that encompasses multiple programs targeting agroforestry, rainfed areas, water and soil health management, and climate impact mitigation and adaptation. The *Pradhan Mantri Krishi Sinchai Yojana* (PMKSY) promotes precision farming including micro-irrigation, alongside the Integrated Watershed Management Programme, which supports rainwater harvesting initiatives.

4.2. Implementing Soil Conservation Measures

Land degradation is a complex issue that requires ongoing and sustained efforts to effectively manage and protect soil resources. Soil conservation measures can achieve this objective. Soil conservation primarily addresses land degradation, more so, the accelerated erosion of soil. Accelerated erosion results from the physical forces of wind and water impacting soil that has become vulnerable owing to indiscriminate anthropogenic activities. Two approaches – mechanical and agronomic, are most commonly used for restoring degraded lands. Some commonly employed mechanical approaches are: bunding (for agricultural land with a slope of 1-6%), terracing (which shortens the slope length; constructed on slopes up to 10%), contour ploughing (ploughing the field at right angles to the natural slope while marking the elevation contour lines), grassed waterways (which allow water to flow down the centre of a designated grass strip), water harvesting ponds, check dams, and retaining walls (structures built to hold soil on unnatural slopes). Agronomic approaches involve crop rotation, green manuring, use of cover crops, reduced tillage, strip cropping, and alley cropping systems, among others.

4.3. Encouraging Agroforestry Systems

Agroforestry, through processes like litterfall and fine root dynamics, nutrient pumping and rhizodeposition, can improve soil fertility and soil physical conditions. Well-managed agroforestry systems may reduce overall erosion losses. In a global meta-analysis, Kuyah *et al*. (2019) noted that agroforestry practices decreased runoff and soil loss, and increased infiltration rate and soil moisture content. Trees as windbreaks and shelterbelts on the farms also reduce wind speed and protect crops and soils. Planting suitable biodrainage species/trees under proper configuration and management could bring-in gradual reclamation of waterlogged and saline soils by removing excess soil water through evapo-transpiration, besides providing economic returns. Under the Kyoto Protocol (1997) and later in the Paris Agreement, agroforestry was recognized as one of the best management practices for restoration of the C lost over decades due to cultivation. Though agroforestry systems are known for C sequestration and climate-change mitigation, a uniform set of methods and procedures has not yet been developed for measuring C sequestration in these systems. Consequently, wide variations exist in sampling procedures, analytical methods, computations, data interpretation, and presentation.

4.4. Integrated Nutrient Management

Integrated nutrient management (INM) is an age-old concept. Terminology variants viz., IPNS (integrated plant nutrient supply) and INSAM (integrated nutrient supply and management) also connote almost similar meaning as that of INM. A large number of studies revealed that consistent adoption of INM led to restoration/improvement of soil health, sustenance of crop productivity, prevention of nutrient deficiencies in soils and plants, and improvement in nutrient use-efficiency (NUE). One of the major lessons learnt from the AICRP-LTFE is that the balanced fertilization, in general, was not detrimental to SOC, though the INM raised the SOC in different soils and cropping systems (Fig. 4).

Analyzing multi-location long-term experiments, Katyal and Chaudhari (2021) concluded that integrated use of organic manures plus fertilizers, irrespective of initial SOC content, raised annual productivity and level of SOC. This practice also minimized the effect of groundwater pollution, improved NUE helping thereby reducing fertilizer

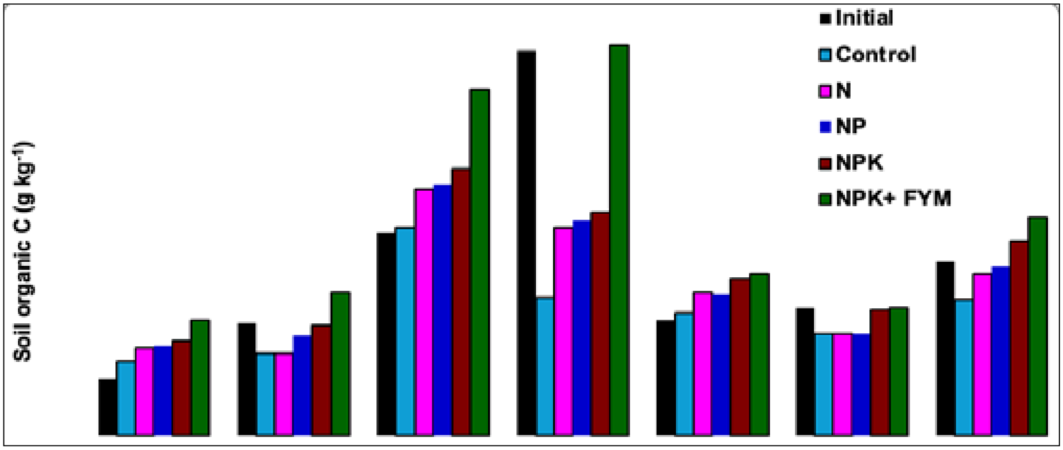

Fig. 4: Long-term effect of nutrient management options on SOC content (AICRP-LTFE, 2019)

input, contained climate change, and promoted agronomic biofortification with pro-health nutrients. They recommended adopting INM (INSAM) for building soil health in all its aspects i.e., sustaining productivity, environmental services, filtration of contaminants and pollutants, and human health. Fertilizers, manures, composts, green manure, crop residues, municipal solid/liquid wastes, and biofertilizers are major ingredients of INM. Production of quality organic inputs and ensuring their timely availability at farmers' doorstep needs to be incentivized through some policy instrument.

4.5. Site Specific Nutrient Management

Site-specific nutrient management (SSNM) aims to increase profit through high yields and high efficiency of fertilizers, using locally-adapted nutrient best management practices tailored to the field- and season-specific needs for a crop. The inductive approach of nutrient prescription (Ramamoorthy *et al*. 1967), culminated in to AICRP-STCR, brought out soil-test and crop response-based fertilizer and INM recommendations for different crops. These prescriptions are found useful for moderate yield targets. Studies on SSNM, however, revealed that high productivity goals (*i.e.*, up to 80% of the variety-specific genetic yield potential) could be attained without impairing soil health, using decision support systems and tools like Nutrient Expert, GreenSeeker, chlorophyll meter, and leaf color charts. There is need to evaluate these newer approaches through well-designed experiments in different soils and crops.

4.6. Conservation Agriculture and Soil Health Restoration

Conservation agriculture (CA), a knowledge-intensive soil management system, is solution to several challenges viz. soil health deterioration, climate aberrations, water scarcity, farm profitability, human health, etc. (Jat *et al*. 2023). The CA has potential to deliver soil health and environmental benefits as well as sustainable yield gains, provided all three core principles are applied simultaneously and consistently along with location- and crop-specific best management practices. It provides a viable solution to crop residue burning, which has emerged as serious cause of environment pollution, SOC depletion and loss of soil nutrients particularly in the Indo-Gangetic Plains. Studies undertaken in rice-wheat and maize-wheat systems in South Asia revealed an improvement in soil physical properties, enhanced microbial activity in top soil, and a surge in the SOC, especially in the labile pool. In the calcareous soils of Eastern IGP, long-term adoption of CA in rice-wheat system indicated a decrease in soil calcareousness. Impact of CA on soil biological parameters and rhizospheric biodiversity is less understood, and there is need to study in detail the microbial community structure, species dynamics and microbe-mediated processes under CA systems. In fact, detailed soil health evaluation under CA in Indian soils is often constrained due to lack of long-term CA experimentation sites under different soil types and agro-climatic conditions.

In recent years, regenerative agriculture (RA) has emerged as another sustainable and nature-positive soil management approach that involves CA plus other best management practices including integrated farming systems and harnessing the native biological processes. Principles of RA include minimum tillage, maintaining soil cover, improving C sequestration, encouraging water percolation, relying more on biological nutrient cycles, crop diversification, and integration of livestock. These sustainable soil management practices aim to maintain or enhance the soil's ability to provide essential ecosystem services for long-term productivity and environmental benefits, including improved fertility, water storage, and biodiversity. Such practices should essentially be farmer-centric, as they look after the land not only for the present but also for the future. At present, RA is practiced on ~180 Mha globally, and its economic benefits are most evident in smallholder farms. Benchmark sites on RA and CA need to be established under different agro-ecologies to study the long-term impacts of these systems vis-à-vis conventional farming on the processes of C sequestration, nutrient cycling, root architecture, and climate change adaptation.

4.7. Soil Health Management in Arid Ecologies

Soils of the arid region have several limitations: very low SOC (often <0.2%), coarse soil texture, poor water holding capacity, low cation exchange capacity, high rate of infiltration (30-40 mm/h), and high soil temperature regimes. Therefore, soil health improvement in arid regions is a challenging task. Maintaining favorable soil moisture regime by designing the irrigation systems, particularly micro-irrigation, enhancing decomposition rate of crop residues (even weeds and non-palatable plants), addition of FYM or compost, and use of slow release fertilizers or coated fertilizers could be helpful. Since wind erosion is a severe land degradation process in arid region, sand dune stabilization technology proved quite effective. Surface sealing by application of adhesive materials from naturally occurring substances (e.g. plant residues, waste materials, natural gums etc.), utilizing native soil microbes for development of plant growth regulators, isolation of glomalin-producing microbes from native and their further utilization for improving soil aggregation, and adoption of locally-recommended good agricultural practices (e.g., cover cropping) are some proven ways for soil health restoration.

4.8. Strengthening Transfer of Technology

At present, the pace of technology assessment and transfer, especially soil and other natural resource management technologies is extremely slow, often depriving the farmers from their due benefits on one hand and allowing unabated soil health deterioration on the other. All innovations and management technologies must be validated on farmers' fields in a farmer-participatory mode. The strength of farmer-to-farmer extension and social media need to be understood and utilized effectively. Scientists have to develop a mindset that inspires working closely with the farming community for translating the results of science into measurable transformation on area basis. Strong scientist-stakeholder partnership is essential for setting research priorities as well as development, validation and scaling of the sustainable soil management technologies.

5. GOVERNMENT INITIATIVES FOR SOIL HEALTH RESTORATION

Government of India implemented several schemes during different Five-Year Plans to support restoration of soil health. These schemes were mostly launched and handled by erstwhile Department of Agriculture and Cooperation (DAC), now renamed as Department of Agriculture and Farmers Welfare (DA&FW). In 1991-1992, a scheme named 'Balanced and Integrated Use of Fertilizers' was launched with the broad objective to promote balanced application of fertilizers in different crops. Later, this scheme was integrated with the 'Macro Management Scheme' during the X Five Year Plan, which involved *inter alia* the State Departments of Agriculture for distributing Soil Health Cards (SHCs) to farmers. Initiated during 1980s, the 'National Project on Development and Use of Biofertilizers' was another important scheme that strengthened the infrastructure for the production and promotion of biofertilizers and increased farmers' awareness about this economical and sustainable ingredient of the INM. National Biofertilizer Development Centre (NBDC), Ghaziabad along with six Regional Centres in different states was established under this scheme. When the Department introduced a specialized scheme 'National Project on Management of Soil Health and Fertility' during the XI Five Year Plan, different soil health management initiatives received a great momentum. Expansion of STL network, promotion of INM, liming acidic soils, applying gypsum to sodic soils, promoting micronutrient application, and inclusion of pulses were the main components of this scheme. In addition, National Food Security Mission (NFSM) and *Rashtriya Krishi Vikas Yojana* (RKVY), two other national flagship programs, also addressed soil health-related issues.

During XII Five Year Plan, a centrally sponsored scheme named 'National Mission on Sustainable Agriculture (NMSA)' was launched, wherein all the ongoing schemes related to sustainable agriculture with a special emphasis on soil & water conservation, water use efficiency, soil health management and rainfed area development were subsumed. In 2015, *Paramparagat Krishi Vikas Yojana* (PKVY) was launched as an extended component of SHM under the NMSA, aiming at promotion of organic farming, thereby improving soil health. 'National Mission on Natural Farming (NMNF)' launched in 2024 with an outlay of Rs. 2481 crore, is a recent initiative mandated with promotion of natural farming for improving soil health, restoring ecosystems and reducing input cost to achieve greater climate resilience. Natural Farming is a chemical-free farming approach involving livestock (preferably local breed of cow), integrated natural farming methods and diversified cropping systems rooted in the Indian traditional knowledge. Subsequently, NBDC is renamed as National Centre for Organic and Natural Farming (NCONF) with a revised and expanded mandate. In addition, a few fertilizer policies *viz*., Customized Fertilizer Policy (2008) and Nutrient-based Subsidy (2010) were aimed at promoting site-specific and balanced use of fertilizers, thereby improving soil health.

The Draft Land Utilization Policy (2013) remains unapproved by the Government. Subsequently, on the request of DA&FW, NAAS developed a Soil and Land Use Policy in 2018 and submitted to the said Department. These policy documents need to be approved and adopted after suitable modification/upgradation, keeping in view future food and nutritional security and agricultural sustainability.

Soil Health Card Scheme

The STLs in different states provided Soil Health Cards (SHCs) to farmers since the X Five Year Plan, and over 70 million SHCs have been distributed till 2014. However, these cards lacked uniformity in terms of soil sampling protocols, soil parameters tested and fertilizer prescription. Information on secondary and micronutrient status was generally absent. During 2015, a comprehensive Soil Health Cards (SHC) Scheme has been launched, which envisaged GPS-enabled soil sampling at a grid of 2.5 ha in irrigated areas and 10 ha in rainfed areas, soil analysis for 12 parameters including S and micronutrients, INM recommendations for major cropping systems of the area, and issue of SHCs to all farmers within a time-frame of two years. The scheme also included strengthening of STLs, trainings and refresher courses for the STL staff, field demonstrations, and awareness programmes for the farmers. So far, 229 million SHCs have already been issued. Thereafter, the Scheme was revised and another 2.3 million SHCs were issued under Model Village Scheme. Now SHC scheme is subsumed with RKVY, with a few initiatives like QR code-enabled sampling, MoUs with schools, and online delivery of recommendations. Although the SHC is a great initiative promoting balanced fertilization and restoration of soil health, yet adoption of SHCs by the farmers was not up to the expectations. Dwivedi and Meena (2015) suggested revision of sampling protocols, inclusion of some physical parameters, and awareness programs, so as to improve the robustness and adoption of SHCs.

6. RECOMMENDATIONS

1. As soil organic carbon (SOC) is a primary determinant of soil health, a National Centre for Soil Carbon Research is necessary to direct systematic soil carbon research across the country and support policy formulation on soil health restoration.
2. Improved understanding of soil biological properties and the behaviour of soil microbes is essential for leveraging the potential of the soil microbiome in soil health management by way of nature positive agriculture. Establishing the threshold levels of important soil biological properties would help inclusion of the same as sensitive indicators of soil health.
3. Given that K fertilizers are imported, policy initiatives are essential for the extraction of K from glauconite deposits. Additionally, it is important to emphasize the utilization of alternative K sources such as waste mica, K-enriched compost, and crop residues.
4. There is need to assess the extent of soil and water pollution caused by metals, metalloids, microplastics, organic pollutants and pathogens, in addition to developing risk assessment protocols and management strategies.
5. A National Soil Spectral Library needs to be established and linked to the ongoing 1:10 K soil data mapping/acquisition, strengthened facilitating uninterrupted data flow across the institutions/stakeholders. A comprehensive Unified Soil Information System is essential to understand spatio-temporal variation in soil health and device effective soil management and agricultural land use planning strategies.
6. Soil health management must promote ecological sustainability involving best management practices aimed at improving input (especially nutrient and water) use efficiency, the integration of natural complements and supplements alongside synthetic inputs, and alternative farming methods, such as conservation agriculture and regenerative agriculture.
7. Since availability of good quality manure in adequate quantity is a major constraint in large-scale adoption of INM, an appropriate policy intervention is essential to incentivise the production of compost by the community of farmers in their village (or cluster of villages), using on-farm and off-farm residues and wastes.
8. A sound Soil Health and Land Use Policy has to be framed on priority, with a focus on safeguarding soil and land resources against indiscriminate exploitation, eco-regional land use planning, and support India's commitment of achieving land degradation neutrality by 2030.
9. To address the challenges of restoring soil health, it is essential to invest in developing scientific capacity for advanced research and education in sub-disciplines, including pedology, soil physics, soil biology and soil biochemistry.

A sufficient number of students and young researchers/faculty must be trained in global universities and institutions having requisite expertise in above areas.

10. The agricultural subsidies, particularly fertilizer subsidies, need to be repurposed and transformed into incentives for adoption of scientifically-proven soil and nutrient management practices. Necessary modalities for payment for ecosystem services (PES) have to be finalized for wider adoption. Protocols for getting benefits of carbon credit and green credit schemes in farm sector should be perfected so as to benefit the eligible farmers.

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