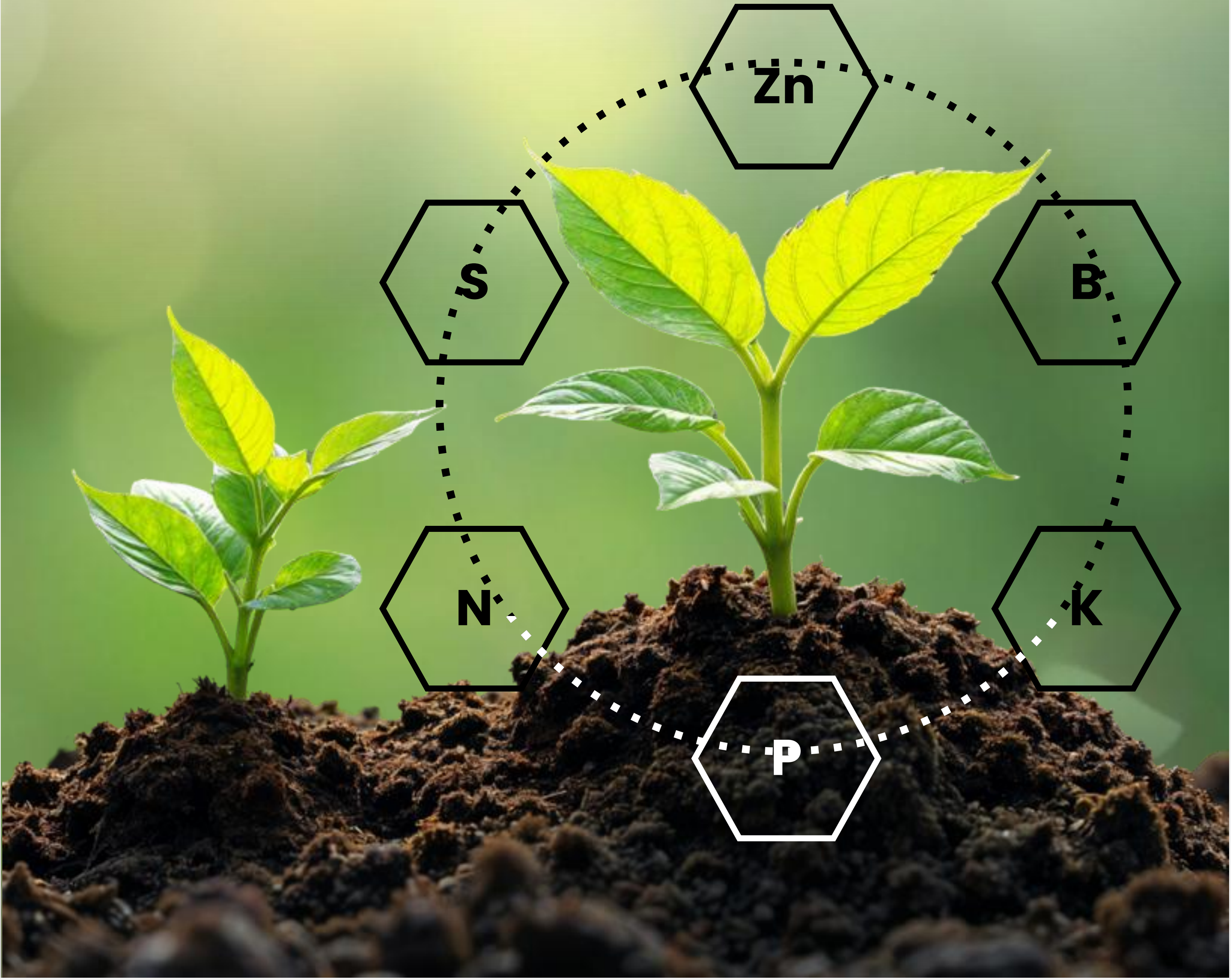
HEALING SOILS IN INDIA:

FOR BETTER CROP HEALTH AND HUMAN NUTRITION

BISWABARA SAHU | RITIKA JUNEJA | SACHCHIDA NAND | ASHOK GULATI



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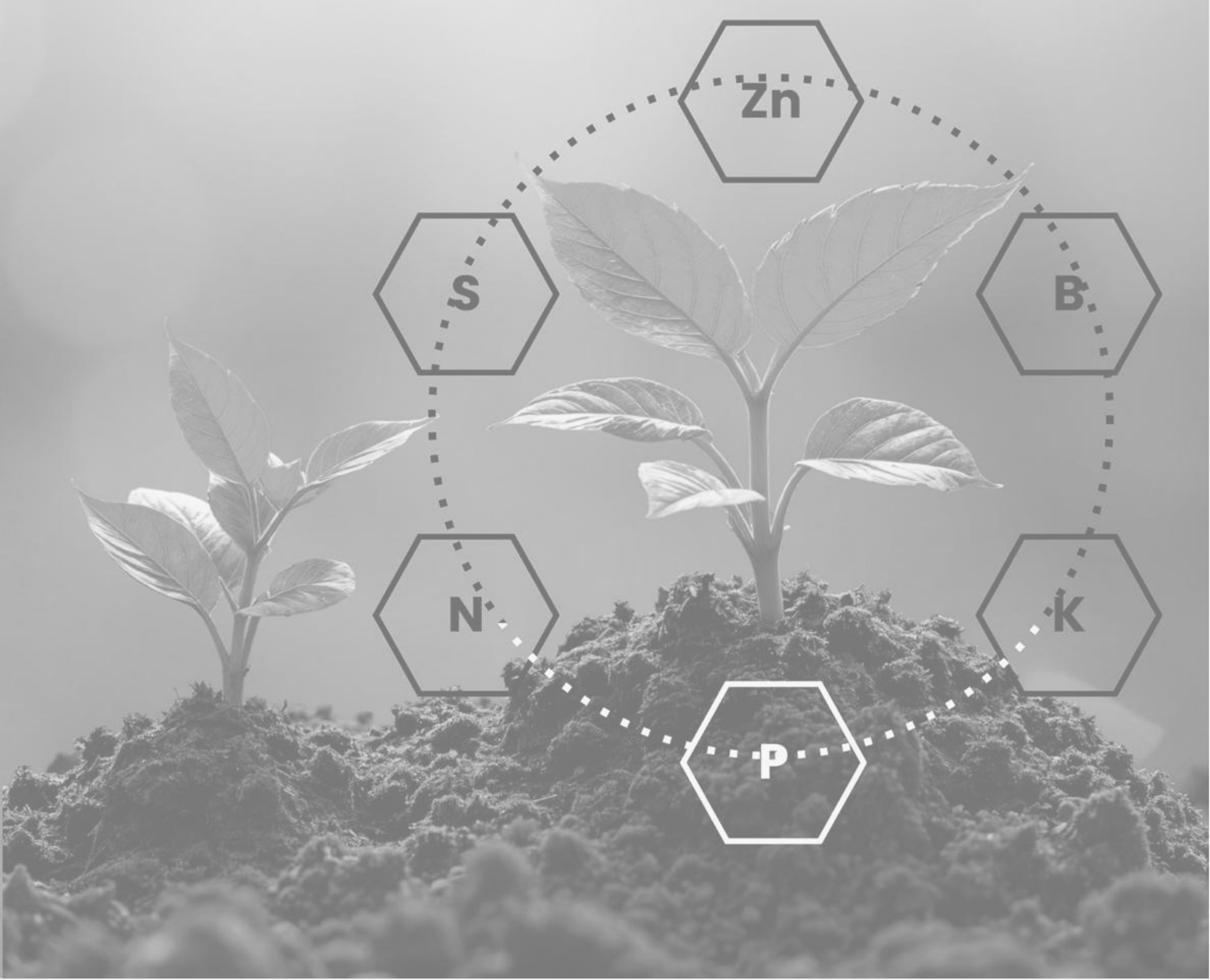

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ABBREVIATIONS

AICRP	All India Co-ordinated Research Project
As	Arsenic
B	Boron
BD	Bulk Density
BIS	Bureau of Indian Standards
C	Carbon
CCD	Chronic Daily Dose
CEC	Cation Exchange Capacity
CEIC	Centre for Economics and Information Centre
CGWB	Central Ground Water Board
CNNS	Comprehensive National Nutrition Survey
Cr	Chromium
Cu	Copper
DBT	Direct Benefit Transfer
FAI	The Fertiliser Association of India
FAO	Food and Agriculture Organization
Fe	Iron
GHG	Green House Gas
GHI	Global Hunger Index
Hg	Mercury

HYV	High Yielding Variety
ICAR	Indian Council of Agricultural Research
IFA	International Fertiliser Association
IISS	Indian Institute of Soil Science
ITPS	Intergovernmental Technical Panel on Soils. Towards a definition of soil health.
kg	Kilogram
kg/ ha	Kilogram per Hectare
LTFE	Long Term Fertiliser Experiment
MDQI	Mineral Density Quality Index
Mg/ ha	Megagram per Hectare
Mt	Million Tonne
Mn	Manganese
MoA&FW	Ministry of Agriculture and Farmers Welfare
MSPE	Micro and Secondary Nutrients and Pollutant Elements in Soils & Plants
NA	Nicotianamine
NABL	National Accreditation Board for Testing and Calibration Laboratories
NBS	Nutrient Based Subsidy
NBSS & LUP	National Bureau of Soil Survey & Land Use Planning
NFHS	National Family Health Survey
$NH4^{+}$	Ammonium ion
$NO3^{-}$	Nitrate ion
NPK	Nitrogen Phosphorus Potassium

NUE	Nutrient Use Efficiency
Pb	Lead
PD	Particle Density
PIB	Press Information Bureau
PLFS	Periodic Labour Force Survey
ppm	Parts per Million
PSB	Phosphorus Solubilizing Bacteria
RD NP	Recommended Dose of Nitrogen and Phosphorus
RDA	Recommended Dietary Allowance
RDF NPK	Recommended Dose of Fertiliser (Nitrogen, Phosphorus, Potassium)
S	Sulphur
SDG	Sustainable Development Goals
SHC	Soil Health Card
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TNAU	Tamil Nadu Agricultural University
UPAg	Unified Portal for Agricultural Statistics
WHO	World Health Organization
Zn	Zinc

GLOSSARY

Term	Definition
Adsorption	Adhesion of ions (e.g., phosphate, potassium) onto the surface of soil particles or organic matter.
Agro-Climatic Zones	Land areas classified based on climate, soil, rainfall and cropping pattern for region specific agricultural planning.
Available nutrients	Nutrient elements in soil that plants can readily absorb and use for growth
Balanced Fertilisation	Application of all essential nutrients in appropriate proportions matching crop requirements and soil supply.
Biofertilisers	Living microorganisms that enhance nutrient availability to crops (e.g., nitrogen fixing bacteria, P solubilizing microorganisms).
Biofortification	Enhancement of the nutrient content of food crops (e.g., Zn, Fe, vitamins) through crop breeding or agronomic practices.
Carbon Sequestration	Long-term storage of carbon in soils or biomass, reducing atmospheric CO_2 concentration.
Chelates	Stable complexes formed between metal ions (Fe, Zn, Cu, Mn) and organic molecules, preventing precipitation and increasing plant uptake.
Chlorosis	Yellowing of leaves due to insufficient chlorophyll, often from nutrient deficiencies (e.g., N, Fe, Mg).
Crop Diversification	Cultivating different types of crops (e.g., cereals, pulses, oilseeds, vegetables) on the same farm.
Deficiency	A condition where plants lack essential nutrients leading to visible symptoms and poor growth.
Denitrification	Microbial reduction of nitrate into gaseous nitrogen (N_2, N_2O), causing nitrogen loss from soil to the atmosphere.
Fertigation	Supplying fertilisers directly through irrigation water for efficient nutrient and water use.

Fixation of Phosphorus	The process by which soluble phosphate reacts with soil minerals (Fe, Al, Ca) forming insoluble compounds unavailable to plants.
Geogenic causes	Naturally occurring processes originating from geological sources.
Green manuring	Growing and ploughing under specific plants (like legumes) to enrich soil with organic matter and nutrients.
Integrated Nutrient Management (INM)	The combined use of chemical fertilisers, organic manures and biofertilisers to maintain soil fertility and crop productivity.
Khaira Disease of Rice	A zinc deficiency disorder in rice characterized by bronzing/brown spots on leaves and stunted growth.
Mineralization	Microbial breakdown of organic matter releasing inorganic nutrients (e.g., N, P, S) available for plant uptake.
Monocropping	It is the agricultural practice of growing the same crop on the same land year after year without rotation.
N: K_2O Ratio	The proportion of nitrogen to potassium nutrient applied, for nutrient balance, crop yield and quality.
N: P_2O_5 Ratio	The proportion of nitrogen to phosphate applied, important for balanced nutrient application.
Necrosis	Death of plant tissue, typically appearing as brown or black lesions along leaf margins or tips.
Nitrification	Microbial conversion of ammonium (NH_4^+) into nitrate (NO_3^-) nitrogen form.
Nutrient Balance/ Budget	The equilibrium between nutrient inputs (fertilisers, manures, deposition) and outputs (crop uptake, erosion, other losses) in a soil-crop system.
Nutrient Mining	Depletion of soil nutrients when crop removal exceeds nutrient application leading to long-term fertility decline.
Soil Erosion	Removal and displacement of the upper layer of soil due to forces like water, wind or human activities, leading to land degradation.
Solubilization of Minerals	Microbial or chemical transformation of insoluble soil minerals into plant available forms (e.g., phosphate solubilization by bacteria).
Volatilization of Ammonia	Loss of nitrogen as ammonia gas (NH_3) from soil and surface applied fertilisers, under high pH and temperature.

FOREWORD

Healthy soils are not just an agricultural asset but the very foundation of crop health and human nutrition. Soils enriched with balanced macronutrients and micronutrients such as zinc (Zn) and iron (Fe) do more than support crop yields, they influence the nutritional quality of staple foods and, by extension, the health of millions of people.

Yet, decades of intensive cropping, dependence on nitrogen-centric fertilisers, and inadequate replenishment of organic matter have systematically eroded soil health across the country. Widespread deficiencies in essential nutrients and declining levels of soil organic carbon hinder plants' ability to take up nutrients efficiently, degrade biological soil functions, and result in crops that are often nutrient-poor. These trends contribute to persistent "hidden hunger," where the food system meets caloric needs but fails to deliver adequate micronutrients essential for healthy growth and development.

This report makes the case that improving soil health must be central to India's food and nutrition security. It highlights the urgent need to move beyond high-volume, generic fertiliser use toward a more nuanced approach — one that emphasises precision agriculture, integrated nutrient management and 4R stewardship (right time, right source, right rate, and right place). A key innovation discussed here is the strategic use of customized fertilisation, formulated to suit specific soil–crop–climate conditions, which can improve nutrient uptake, correct soil imbalances and enhance overall soil fertility and crop nutritional quality.

By aligning policy, products and on-ground practices to restore and sustain soil health, India can build productive, resilient and nutrient-dense cropping systems that better support human health and ecological balance. It is our hope that the insights and recommendations contained in this report will drive effective action, inspire innovation in soil management and testing, and contribute to a future where healthy soils underpin healthy crops and healthy people.

SHEKHAR AIYAR
DIRECTOR & CHIEF EXECUTIVE
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PREFACE

India's soils, the very foundation of its agriculture and food systems, are under severe and escalating strain, with consequences that reach far beyond farm fields. On an average India loses about 5.3 billion tonnes of topsoil each year, affecting nearly 120 million hectares (Mha) of total geographical land, primarily from water (82.6 Mha) and wind (12 Mha) erosion. Due to various soil erosion 16.4 tonnes per hectare (t/ha) of topsoil is lost every year, far exceeding the sustainable soil loss threshold of 5-12 t/ha/yr (NAAS, 2021). This loss annually removes 5.4-8.4 Mt of primary nutrients (NPK) in total, threatening soil health and productivity.

At the same time, widespread soil nutrient imbalances reveal how exhausted our soils have become. Soil Health Card (SHC) assessment of 2024-25 shows that less than 10 percent of Indian soils have high or sufficient nitrogen (N), only 45 percent have sufficient phosphorus (P), 32 percent have sufficient potassium (K) and just 25 percent are sufficient in soil organic carbon (SOC), well short of the 1–1.5 percent range considered desirable for tropical and subtropical soils. SOC is a critical indicator of soil structure, microbial activity, and nutrient cycling.

Our soils also suffer from a deficiency of micronutrients like sulphur (S), iron (Fe), zinc (Zn), boron (B), etc. These deficiencies range from moderate to severe. These nutrient imbalances reflect decades of intensive cropping, heavy reliance on N-dominant fertilisers such as urea, and insufficient return of organic matter to the land. This decline has consequences that extend well beyond just soil fertility. Poor soil health is intrinsically linked to the nutritional quality of food — crops grown on nutrient-deficient soils tend to be lower in essential micronutrients such as Zn and Fe. This phenomenon helps explain persistent public health challenges. The National Family Health Survey (NFHS-5) data shows that 35.5 percent of children under five are stunted, 32.1 percent underweight, and 19.3 percent wasted, underscoring that food security must encompass nutritional outcomes and not just caloric sufficiency. Nutrient shortages in soils translate into nutrient-poor diets, contributing to a silent but widespread form of malnutrition that undermines physical and cognitive development of human.

Restoring soil health is therefore not just an agricultural objective — it is a public health imperative and a prerequisite for sustainable development. Reviving soil health demands a multifaceted approach that integrates improved policy frameworks, better soil nutrition products, and scalable field practices tailored to region-specific conditions. This includes rebalancing fertiliser use, expanding soil testing to include biological and physical indicators, enhancing organic matter inputs, and mainstreaming regenerative agricultural practices.

This report presents an in-depth analysis of the historical and current status of India's soils, with a particular focus on SOC and the complete spectrum of essential nutrients. It examines the drivers of degradation — from erosion to nutrient misuse — and the influence of fertiliser policy on nutrient dynamics. The overarching aim is to inform the design and scaling of data-driven, region-specific soil nutrition solutions that can improve crop health, enhance the nutrient quality of food, and help shift the nation's agriculture toward true nutritional security.

AUTHORS

ABSTRACT

India's remarkable economic and agricultural transformation over the past six decades underscores both its achievements and emerging challenges in food and nutritional security. From producing 82 million tonnes (Mt) of foodgrains in 1960–61 to approximately 357.7 Mt in 2024–25, India has not only met the caloric needs of its rapidly growing population but has also become the largest exporter of rice globally, shipping over 20.2 Mt in FY2025 alone. At the same time, the country administers the PM-Garib Kalyan Yojana (PMGKY), the world's most extensive public food distribution scheme, which supplies 5 kg of free rice or wheat monthly to more than 800 million people. This combination of high production and subsidised access to basic staples has led to historic public food stocks, with the Food Corporation of India holding close to 57 Mt of rice — nearly four times the strategic buffer norm as of mid-2025. These gains have occurred alongside a significant reduction in extreme poverty, which has declined from 27.1 percent in 2011 to 5.3 percent in 2022. Despite these positive trends in food availability and poverty alleviation, chronic undernutrition persists, particularly among children. The National Family Health Survey (NFHS-5, 2019–21) shows that 35.5 percent of children under the age of five are stunted, 32.1 percent are underweight, and 19.3 percent are wasted, revealing that caloric sufficiency alone does not guarantee nutritional well-being. These figures highlight the need to broaden the definition of food security to include nutrient quality, dietary diversity, and the micronutrient content of diets.

A significant but often under-recognised driver of nutritional outcomes is soil health. The mineral composition of soils influences not only crop yields but also the concentration of micronutrients in food crops. Research studies also demonstrate a biological pathway through which soil nutrient deficits can translate into widespread micronutrient deficiencies in humans, driving a hidden form of malnutrition that persists despite abundant food supplies. Assessments under the Soil Health Card (SHC) scheme reveal that large proportions of Indian soils are poor in essential nutrients such as nitrogen (N), soil organic carbon (SOC) and micronutrients like zinc (Zn) and boron (B), limiting both productivity and crop nutrient density. These imbalances stem from longstanding imbalanced use of fertilisers, limited integration of organic matter, and inadequate attention to micronutrient replenishment, resulting in soils that may produce high yields but with compromised nutritional quality. Given the multifaceted links between soil health, crop health and human nutrition, this report advocates for a holistic policy, product and practice shift. Structural changes are needed in fertiliser policy to encourage balanced nutrient use, enhanced soil diagnostics to inform precision nutrient management, expanded research and development of tailored fertiliser

products, the customization of fertiliser grades as per crop and soil requirement and promotion of agronomic practices following 4R principle of nutrient management (right time, right source, right rate and right place) for precision input and efficient nutrient management. The practices together can restore physical, chemical and biological soil health. By nurturing soil ecosystems to be nutrient-rich and biologically active, India can improve agricultural productivity and the micronutrient quality of food crops, thereby contributing to better health outcomes and long-term national development.

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EXECUTIVE SUMMARY

India's journey from a 'ship-to-mouth' economy in the 1960s to the world's largest exporter of rice is a story of agricultural resilience and policy transformation. The Green Revolution, powered by High Yielding Variety seeds (HYVs), fertilisers and irrigation, helped India achieve food self-sufficiency. However, this success has come at a steep environmental cost. Despite spending USD 22-25 billion every year on fertiliser subsidy, productivity gains remain modest and soil health continues to deteriorate. One stark illustration: the subsidy on urea (a source of N) exceeds 80%, whereas subsidies for P and K fertilisers (worked out based on import parity price) are roughly 45% and ~5% respectively (and about 8.8% for S during the 2025 Kharif season. In contrast, micronutrient fertilisers such as Zn, Fe and B receive virtually no direct subsidy except when coated or fortified where the additional subsidy rates are only INR 300 per tonne for B and INR 500 per tonne for Zn. These low subsidy levels distort relative fertiliser pricing, encourage farmers to over apply N while under applying P, K and micronutrients, and thus lead to imbalanced nutrient use.

The consequences are serious. Staple crops like rice and wheat are increasingly Zn deficient, contributing to stunting in children and undermining their lifelong earning potential. Soil organic carbon (SOC) is at a dangerously deficient status with three fourth of tested samples having SOC below 0.75% (SHC 2024-25). The suboptimal SOC levels undermine soils' capacity to supply nutrients and support optimum microbial activity in soil. SOC, due to its nutrient-holding capacity, promotes N retention in soil. Consequently, the suboptimal SOC levels in Indian soils represent a primary cause of low soil N content, even after decades of excessive N application. At the same time, the fertiliser-to-grain response ratio has plummeted from around 1:13 in the 1970s to just 1:2.7 in 2015 (in irrigated areas). Inefficient application of urea fertiliser has resulted in substantial N losses, with only 35-40% of the externally applied N being absorbed by the crops. This means that more than half of the applied fertiliser remains unutilized and gets lost from the soil-water system through volatilization, leaching, runoff, emissions of nitrous oxide (N_2O) and other pathways. These N losses harm groundwater quality (in nitrate form), increase greenhouse gas (GHG) emissions (including N_2O, which has ~273 times the warming potential of CO_2) and degrade soil by causing mineral depletion, acidification and lowering enzymatic activity needed for nutrient cycling. P deficiency in Indian soils also limits crop growth and affect long-term soil fertility: while large amounts of total P may be present, only a small fraction is plant-available due to fixation by Fe, aluminium or calcium compounds, especially in acidic or calcareous soils. This deficiency leads to weak root systems, poor tillering and reduced yield as well as impaired uptake of other elements. Frequently, P removal by crops exceeds replenishment, resulting in nutrient depletion and declining fertility over time. Another pressing concern is that 20-30% of the fertiliser subsidy gets diverted to non-agricultural purposes and never reach the intended beneficiaries (Economic survey, 2015-16). This leads to significant fiscal burdens for a government. India now stands at a critical juncture. To feed a population projected to reach 1.67 billion by 2050, it must shift from blanket fertilisation to science-based, precision soil nutrition management based on 4R principle of input application (right time, right source, right rate and right place). That requires rigorous soil testing and fertiliser customization tailored to crop and regions' needs.

Today this is far more than an agricultural concern, it is a public health imperative. This study examines the existing and changing status of India's soils over time, with particular attention to SOC, often called the fundamental soil health attribute along with primary, secondary and micronutrients. It investigates key drivers of soil degradation and explores the influence of fertiliser policy. The broader objective is to design and scale data driven, region specific soil nutrition products and practices that boost crop productivity and enhance the nutritional quality of food. Only by restoring soil health can India transcend food security and achieve nutritional security, while protecting biodiversity and the long-term well-being of its soils, water, air and its people.

NUTRIENT STATUS OF INDIAN SOILS

HISTORICAL EVIDENCES OF NUTRIENT DEFICIENCY IN INDIAN SOILS

Multiple studies carried out over time across districts and agro-ecological zones of India consistently show that Indian soils have faced serious and widening nutrient deficiency. One of the earliest large-scale assessments by Ramamoorthy and Bajaj (1969), based on about 1.3 million soil samples, revealed widespread shortages of major nutrients. N was deficient (< 280 kg/ha) in 117 of 224 districts, P (< 10 kg/ha) in 106 of 226 districts, and K (< 120 kg/ha) in 36 of 184 districts, indicating substantial macronutrient constraints.

Subsequently, nation-wide analysis by Chaudhari (2019), has reported N deficiency (< 560 kg/ha) in more than 95% samples, similar to Motsara, (2002a) where 89% samples had low to medium N (<560 kg/ha). It is notable that Chaudhari (2019)'s study has classified both low and medium nutrient levels as deficient. This study also reported P deficiency (< 10 kg/ha) and K deficiency (< 280 kg/ha) to the tune of 94% and 48% respectively. These findings clearly indicate that Indian soils are constantly under nutrient deficiency despite over application of fertiliser N. N deficiency, despite its over-application owes to the fact that our soils contain suboptimal (<0.75%) levels of SOC which reduces the inherent nutrient holding capacity of the soils. This implies that the added N which is not taken up by the crops; does not even stay in the soil systems, rather leaches to the ground water below or releases to the atmosphere above.

While low N is aggravated by poor SOC status, deficiency of other nutrients is a result of underapplication of those nutrients during crop cultivation. These concerns are reinforced by ICAR's Long Term Fertiliser Experiments (LTFE). The study shows that avoiding P application drives its deficiency through depletion of native P (known as P mining) to the tune of 2.7 – 34.2 kg/ha/yr. Similarly, intensive cropping and imbalance fertiliser use causes K mining. Even where K fertilisers are applied, crop removal often exceeds inputs, causing K depletion to the tune of 85 -261 kg/ha/yr (Singh et al., 2019a). Another long-term nutrient budget analyses (1970- 2018) by Pathak et al. (2024), shows that Indian agricultural soils experienced an overall P deficit of 0.06 Mt and a large cumulative K depletion of about 5.27 Mt, reflecting continuous K mining by crops. In addition to the primary nutrients, the S deficiency (< 10 ppm) has worsened in the country (70 districts in the early 1990s to 300 districts during 2010) (Tandon, 2010). Together, these studies depict a long-term and increasingly complex nutrient depletion scenario in Indian soils.

PRESENT STATUS OF NUTRIENT DEFICIENCIES IN INDIAN SOILS

According to the 2024–25 cycle, roughly half of the ~8.9 million samples had SOC below 0.5% and around three quarter of soil samples report to have SOC below 0.75% as per SHC 2024-25 and ICAR- National Bureau of Soil Survey and Land Use Planning (ICAR – NBSS & LUP) (Bhoomi Geoportal). However, there is often a debate as to how much SOC is considered sufficient. While the World Food Laureate, Dr. Rattan Lal, prescribes that the carbon content in soils should be at least between 1-1.5% in tropical and sub-tropical regions, by that, most Indian soils fall well below this threshold. However, it is also argued that thresholds of 1-1.5% SOC for tropical zones is difficult to reach due to India's hot, humid climate, which speeds up decomposition of SOC and carbon loss via microbial oxidation.

The recent SHC cycle (2024-25) also highlighted other nutrient status in Indian agricultural soils. The report shows that only 7% of the 8.9 million soil samples analyzed have sufficient level of N (N >560 kg/ha) while high P (>25 kg/ha) and K levels (>280 kg/ha) are reported in 45% and 32% soil samples, respectively. Similarly, deficiencies of S, B, Fe, and Zn are observed in about 25%, 45%, 24%, and 35% of samples, at critical threshold limit of <10 ppm, <0.5 ppm, <4.5 ppm and <0.6 ppm respectively.

The available micronutrient and S status of Indian soils have also been analyzed by ICAR's All India Coordinated Research Project on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants (ICAR- AICRP on MSPE), using 0.24 million surface samples (0-15 cm) collected during 2012 – 18. It reveals that nearly half of the soil samples are deficient in S (58.6%), B (44.7%) and Zn (51.2%) at threshold limit of < 22.5 ppm, < 0.7 ppm and < 0.9 ppm respectively (Shukla et al., 2021). The critical limits of S and micronutrients have been re-standardized by this ICAR's national project. The recalibration of critical limits is done through on-farm trials and corresponding the soil nutrient levels with plant responses. However, it is noteworthy that these new critical limits defined by ICAR- MSPE differ significantly from those used by SHC scheme. This difference in critical limits result in different deficiency status reported by ICAR and SHC. Adoption of the revised standards is essential for accurately depicting India's nutrient deficiency scenario.

CAUSES OF SOIL HEALTH DEGRADATION IN INDIA

There are various factors driving the deterioration of soil health in India. Among the geogenic factors, soil erosion contributes to extensive degradation of soil in hilly regions and surface soils of the farmlands, affecting agricultural productivity (NAAS, 2021). Due to such erosions, India loses 16.4 tonnes per hectare (t/ha) of topsoil on average annually, far exceeding the permissible soil loss rate of 5–12 t/ha per year. This loss leads to a total loss of 5.4–8.4 Mt of primary nutrients per annum (NAAS, 2021). Anthropogenic factors like erroneous agricultural policies heavily influence the products and practices adopted by farmers in our country. Distorted fertiliser pricing encourages farmers to overuse highly subsidized urea, while discouraging the balanced use of other essential nutrients (i.e., P, K, secondary nutrient and micronutrients). Similarly, free supply of power for irrigation and guaranteed procurement with generous MSPs in states like Punjab and Haryana also push farmers toward rice and wheat centric cropping systems, reducing crop diversity. Lack of coherent policy supporting high efficiency fertilisers, organic inputs amendments (e.g., farmyard manure, biochar, composts, biofertilisers), amendments (liming material or gypsum) or fertiliser customization dampens innovation in these areas. Since these products are rarely available or affordable, their adoption remains very low. On the farming side, frequent disturbance of soils, addition of little organic matter (Haddaway et al., 2017) and reliance on inefficient irrigation methods (such as flood irrigation) contribute to decline in SOC, produce multiple nutrient deficiencies, causes water logging, GHG emissions (Karki et al., 2023) and other forms of soil health deterioration.

IMPACT OF SOIL HEALTH ON PLANT GROWTH AND NUTRITION

Deteriorating soil health has disrupted the plant response to added nutrients, ultimately lowering the yield potential and nutrient use efficiency (NUE). Despite steady increases in fertiliser consumption, there are instances of reduced crop yield per unit input. Historically, in irrigated regions of India, about 13-14 kg of foodgrains (cereals and pulses) was produced per kg of NPK fertiliser in the early 1970s which has decreased to 2.7 kg per kg of NPK fertiliser by 2015 (Chaudhari, 2019). While considering fertiliser response ratio of irrigated and non-irrigated regions together, the fertiliser response ratio for foodgrains have dropped from 12.1 kg grain/kg NPK in the 1960s to about 5 kg during 2010-2017 (Katyal, 2019). Over the decades, the NUE for N has steadily declined in India, from about 49% in 1961 to 41% in 2022 (FAOSTAT, 2025), reflecting decreased incorporation of externally applied N into plant N. Moreover, overapplication of N fertilisers cause nitrate to leach into groundwater, leading to contamination.

Consumption of nitrate contaminated water (exceeding beyond safe limit of 45 mg/L, BIS standard 2012) raises health risks, including illnesses in humans and conditions like blue baby syndrome in infants (Picetti et al., 2022; Karwowska and Kononiuk, 2020; Ward et al., 2018). Nitrate also lowers crop quality by reducing vitamin C content. On the other hand, under application of P primarily affects crops growth, impacting its health and nutrition, which ultimately impacts human nutrition. As P plays a vital role in plant growth and development, serving as a key component for bother cellular energy transfer and reproduction. When P is deficient, plants suffer from severe reductions in biomass, root and shoot growth, photosynthesis, and overall nutrient uptake, which drastically limits productivity (Wissuwa et al., 2005). These deficiencies not only disrupt plant metabolism but also weaken crop resilience to stresses (Khan et al., 2023). Long-term inadequate P fertilisation depletes soil reserves and accelerates soil fertility decline. A very common example is remarkable deformities in plant leaves (Lagat, 2015). This gives rise to bigger concerns highlighting inefficiencies and possible negative impacts on soil health from imbalanced fertiliser use.

The rate of application of essential nutrients also affects the growth and efficiency of crops and the nutritional quality, plants' defense mechanism and other essential biochemical pathways associated with molecular levels of the cell. Nutrient rate and ratio have effect on keeping the quality and shelf life of fruits and vegetables through enzyme activation, biomolecule production, pigment formation, vitamin and antioxidant development, mineral absorption, etc. The underuse of P, K and other secondary and micro nutrients have evidential signs of reduced crop quality. Therefore, the 4R stewardship of nutrient application (right time, right source, right rate and right place) has great impact on the use efficiency of nutrients as well as yield and quality of produce.

IMPACT OF CROP HEATH ON HUMAN HEALTH AND NUTRITION

P being a structural component of various biomolecules (ATP, DNA, RNA), biochemical pathways (energy metabolism), protein metabolism, etc., has essential role in plant development. P is also an essential nutrient for humans and is found in bones and teeth, cell membranes, nucleic acids. So, when crop growth is limited by soil P, and other nutrient uptakes by crops are hampered (Meng et al., 2021). The resulting food produced may be both lower in yield and nutrient richness and can lead to health impacts like muscle weakness, bone pain, dental weaknesses, etc.

The crop varieties also have an impact on human nutrition. For example, modern HYV of rice and wheat show a 19-33% decline in essential micronutrients like Fe and Zn compared to traditional varieties (Debnath et al., 2023). This reduces these staples' ability to meet dietary needs by almost half. Such nutrient deficiencies cause "Hidden Hunger," where calorie intake is adequate but micronutrient deficiencies persist. Global studies have shown overlapping regions between soil Zn deficiency and human Zn deficiency (Cakmak et al., 2017). Studies by IISS Bhopal and AIIMS Bhopal have also confirmed a strong correlation between soil Zn and grain and animal blood serum Zn levels (Shukla et al., 2016).

WAY FORWARD TOWARDS IMPROVED SOIL HEALTH FOR BETTER CROP HEALTH AND HUMAN NUTRITION

i. **REFORM FERTILISER POLICY:** The first-best reform is to gradually dismantle price controls while protecting farmers through equivalent direct income support. A deregulated fertiliser market would spur innovation, improve efficiency, and restore correct price signals for balanced use of N, P and K. Promoting micronutrients, soluble fertilisers through fertigation, and fertiliser customisation would further enhance productivity. However, main constraint lies in identifying tenant farmers, many of whom remain outside formal land records. This can be addressed through triangulation of agricultural data, combining land records, PM-KISAN databases, fertiliser sales, crop sowing information, satellite imagery and procurement records, etc. Advances in AI and machine learning can make such integration feasible.

   A credible second-best option is to bring urea under the Nutrient Based Subsidy (NBS) regime, as was originally envisaged in 2010. Rationalizing subsidies by reducing support for N while increasing it for P and K, without raising the overall subsidy bill, would correct price signals. Such recalibration would nudge farmers towards more balanced nutrient application, raising NUE and improving soil health.

ii. **PROMOTE INNOVATIVE FERTILISER PRODUCTS**: To improve NUE and reduce environmental impact, we must scale up advanced fertiliser technologies, including customized nutrient blends, water-soluble formulations, slow-release and nano-fertilisers, biofertilisers, all aligned with site- and crop-specific recommendations. Farmers should therefore use P fertilisers (such as Diammonium Phosphate- DAP, Single Super Phosphate- SSP and especially Triple Super Phosphate- TSP), K fertilisers (Muriate of Potash- MOP, Sulphate of Potash- SOP) and micronutrient products (e.g., Zn and Fe sulphates) together with nitrogenous sources for truly balanced nutrition.

   TSP plays a critical role because it typically contains around 46% P_2O_5 and is highly water-soluble. Its rapid availability supports early root development, flowering and fruiting, while helping restore soil fertility where traditional P-sources have lagged. By using TSP for fertiliser customisation (alongside N, K, secondary and micronutrients) it is possible to correct deep-rooted P deficits, boost crop's fertiliser response and enhance crop nutritional quality. Even water-soluble and precision-formulated fertilisers are particularly useful where drip irrigation or fertigation is used, enabling rapid, targeted nutrient delivery during critical growth stages (e.g., flowering, grain-fill). Biochar and other organic carbon inputs enhance soil structure, water retention and nutrient-holding capacity, while biofertilisers (microbial inoculants) fix atmospheric N, solubilize P and mobilize K, thereby improving soil microbiology, reducing reliance on synthetic chemicals, and supporting long-term soil health.

The 4R stewardship framework forms the cornerstone of efficient nutrient management, advocating for the application of fertilisers during the right time, using the right source, at the right rate, and in the right place. This principled approach optimizes nutrient delivery precisely to crop needs and soil conditions, minimizing waste, environmental losses such as leaching or runoff, and unnecessary costs. Nutrient management practices designed based on 4R concept are proven to be efficient as it promotes optimum nutrient uptake by crops and reduces loss at the same time. As TSP is a dominant and highly soluble source of P, promoting TSP alongside its customization and precision delivery based on the 4R stewardship, we can address not just quantity (yield) but quality of produce (Sinclair et al., 2025), and move toward a more sustainable, efficient fertiliser regime.

iii. **STRENGTHEN SOIL HEALTH AND NUTRIENT MANAGEMENT PRACTICES**: A sustainable way forward for enriching soil organic matter in Indian agricultural fields lies in systematically integrating organic inputs and adopting practices that enhance SOC. Farmers can recycle nutrients back into the soil through the addition of crop residues, soil mulching and the application of composted organic inputs such as farmyard manure, vermicompost and biochar. Green manuring, using leguminous crops, and crop diversification can improve soil fertility while enhancing microbial activity and carbon sequestration. Sustainable water management practices like micro irrigation (drip and sprinkler irrigation), fertigation can save water while meeting the water demand of crops at critical plant growth stages. Problem soils with chemical constraints can be better managed through addition of amendments (lime in acid soils, gypsum in alkaline soils) or leaching of excess salts in salt affected soils for improved soil health and better productivity. These integrated practices and improved inputs can rehabilitate degraded soils, preserve long-term fertility, stabilize and boost crop yields and enhance resilience across India's varied agro-climatic zones. But to translate these into reality on the ground, sustained policy reform is indispensable specifically, rethinking large subsidies on fertilisers, electricity/power and water and revisiting open-ended procurement for wheat and rice. Only with such reforms can the incentives align toward sustainable agriculture, ecological balance, soil health, plant health, human health and nutrition.

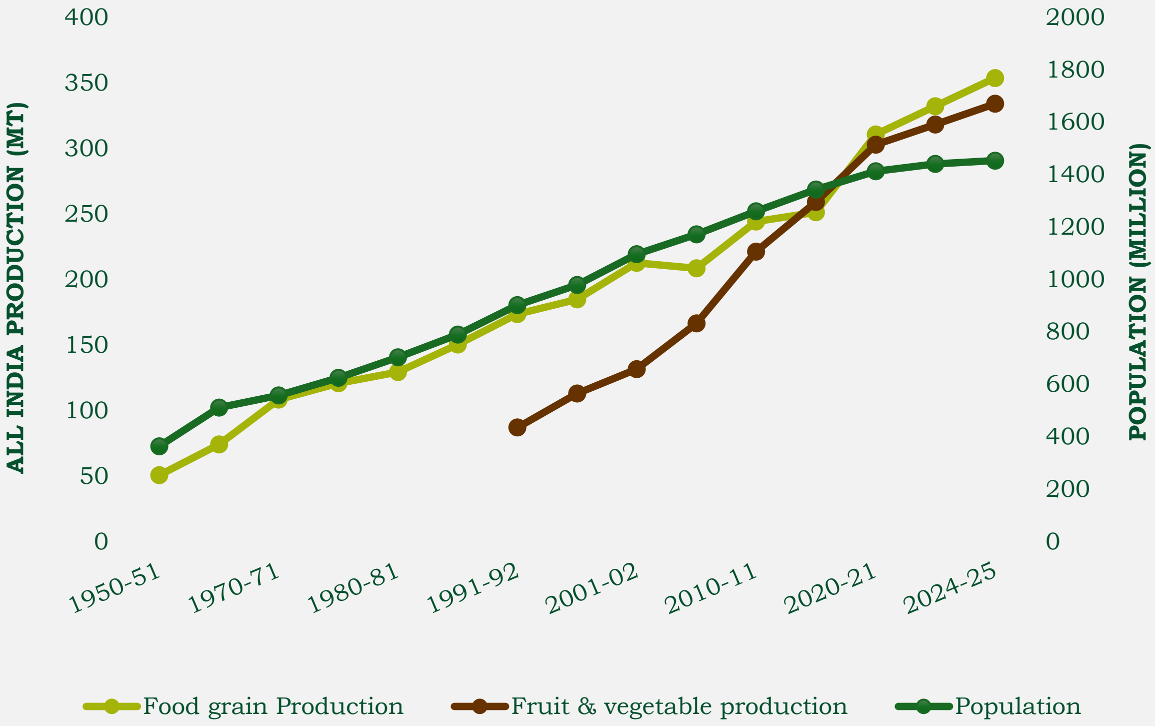
1

INTRODUCTION

Soil is the unconsolidated mass present as the upper most layer of earth surface. It supports life on earth by offering various ecosystem functionalities. Soils are composed of soil solids (mineral and organic matter) and pore spaces that hold water and air. From edaphological point of view, it supplies foothold for the plants to grow and is the primary source of the majority of essential nutrients and moisture to the plant. 95% of animal's food is produced in soil. It is also the second largest sink of carbon after ocean. Globally, the amount of carbon stored in soil is estimated to be 1500 Pg (Scharlemann et al., 2014) which is three times the carbon share of live biomass (560Pg) (Ontl and Schulte, 2012). The numerous numbers of microorganisms present in soil make it a living system. Like any other living system, soil possesses health. Soil health refers to the capacity of soil to function as a living ecosystem that sustains plants, animals, and humans and support ecosystem services (ITPS, FAO). With the increasing population load, global per capita arable land has reduced from 0.36 ha in 1961 to 0.18 ha in 2021. The numbers are worse for India where the per capita arable land has declined from 0.35 ha in 1961 to 0.11 ha in 2021 (World Bank Data, 2025) and is predicted to go down to as low as 0.09 ha in 2050 (ICAR). Tremendous amount of pressure is exerted on a piece of land to produce crops to meet the food and nutritional demand of population, at the same time soil health needs to be preserved. Soil fertility (the inherent capacity of soil to supply essential nutrients to plants in adequate amounts and suitable proportions at the right time) is an integral part of soil health. Along with nutrient cycling, healthy soils regulate water infiltration and retention, gas exchange, soil biodiversity, pest and disease cycle, induces biotic and abiotic stress resistance in plants needed for agricultural productivity. Deterioration of soil health significantly hampers its ecosystem services reducing the fertility and production potential of soil. India faced a serious deficit in food production in the 1950s. With green revolution, highly efficient synthetic fertilisers, crop protection chemicals, HYV and water management through irrigation were introduced to the farmers which improved nutrient supplementation to the crops and protected the crops against biotic stresses like weeds, insects and diseases resulting in higher production than before. HYVs gave more yield compared to the native or indigenous land races. Due to such adoption, the foodgrain production was boosted from 50.8 Mt in 1950 to 108 Mt in 1970-71 to 353.9 Mt in 2024-25 (World Bank, PIB a, b, UPAg portal). Likewise, horticulture production in India experienced a boom. The total horticultural production increased from 96.6 Mt in 1991-92 (Horticultural statistics at a glance, 2021) to 362.1 Mt in 2024-25 (CEIC). The fruit and vegetable production has increased from 87.16 Mt in 1991-92 to 357.7 Mt in 2024-25 (**FIGURE 1.1**). At the same time, the human and livestock population of India increased drastically necessitating the need for higher crop production. During the

1970s, India had more than 60% population under extreme poverty and food security was the first and foremost concern to avoid any starvation deaths. Green revolution was the need of the hour with an intention to produce more food. For example, due to green revolution, the per capita annual foodgrain production experienced a significant increase from 145 kg (1966-67) to 194.27 kg (1970-71) and reached 243.30 kg in 2024-25 (**FIGURE 1.2**). The annual per capita for vegetable and fruit has also increased significantly in the country.

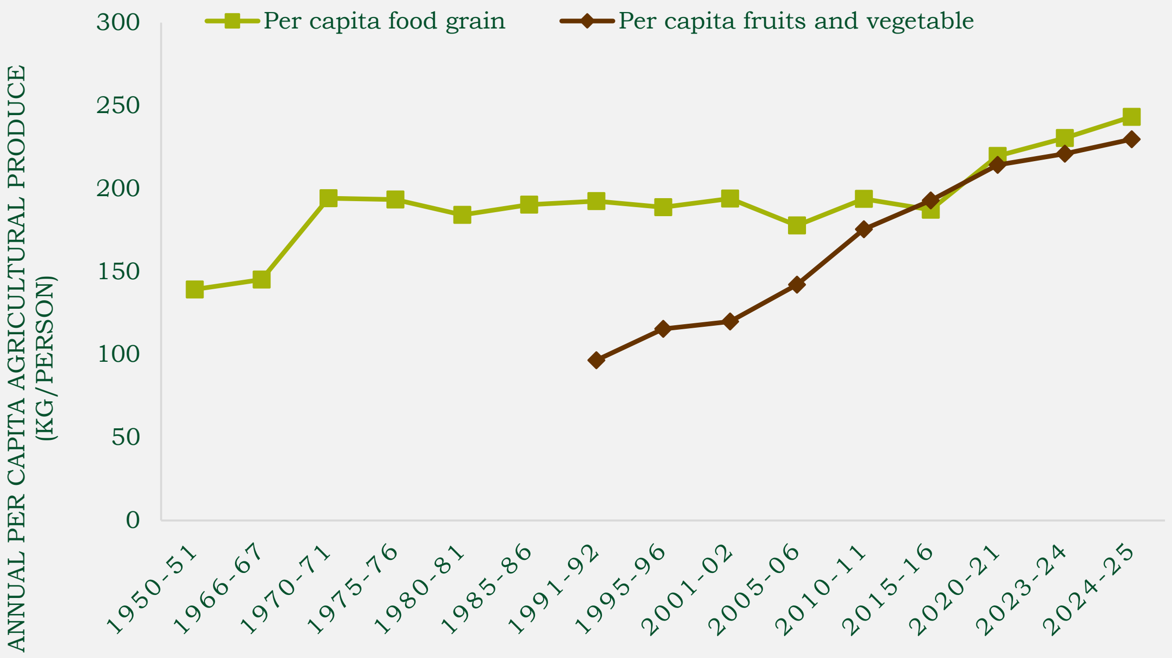
FIGURE 1.1: TIME SERIES PRODUCTION STATISTICS OF FOODGRAINS, FRUITS AND VEGETABLES VIS-À-VIS POPULATION GROWTH IN INDIA



Sources: Foodgrain: PIB, UPAg.portal; Fruits and vegetables: FAI, Horticultural statistics, MoAFW 2nd advance estimate of horticulture production; Population: macrotrends.net

The increased production following the green revolution raised critical sustainability concerns in the coming years when the practice was carried out blindly without understanding the prevailing scenario. The indiscriminate use of agrochemicals with a hope to get higher yield with every unit of additional input is found to jeopardize the agricultural system by constantly declining soil health, water and environmental quality, etc. The Indian agriculture system is going through multiple ailments like poor yield of major crops, dominance of low soil fertility, low SOC and lack of crop rotation, reduced use efficiency of inputs like fertilisers, faulty water management practices and crop protection chemicals are some of the factors causing the decline in soil health and crop yields. Though India has witnessed a remarkable increase in foodgrain and horticultural production in recent years, the country struggles with achieving true nutritional security. According to the Global Hunger Index 2024, India ranks 105 out of 127 countries, with 13.7% of its population undernourished and 35.5% of children under five suffering from stunting. This indicates that higher production alone does not guarantee better nutrition. Since soil forms the very foundation of most of the food we produce and serves as the primary source of nutrients for plants, it becomes essential to understand and adopt better soil management practices. Healthy, well-nourished soils can produce nutrient rich crops, which in turn plays a crucial role in improving human health and addressing the challenge of malnutrition.

FIGURE 1.2: PER CAPITA FOODGRAIN AND HORTICULTURAL PRODUCE IN INDIA (1950-2025)



Source: Author's own calculation based on production and population statistics

The report provides a comprehensive explanation of the fundamentals of healthy soil and evaluates the status of Indian soils in terms of SOC content, as well as primary, secondary, and micronutrient levels based on various soil analysis reports. It highlights the factors contributing to the deteriorated soil health scenario, analyzing them from policy and practice perspectives. The report emphasizes the critical role of soil health in plant growth and nutrition, and how it ultimately impacts human nutrition. Following the introduction, Section 2 explains the key characteristics of healthy soils, while Section 3 presents the soil health status of India, drawing from soil health card data and findings of various All India Coordinated Research Projects (AICRP) conducted by the ICAR. Section 4 explores the causes of soil health deterioration, and Sections 5 and

6 establish scientific linkages between soil health, plant growth and nutrition and human nutritional outcomes. Finally, Section 7 outlines potential interventions and recommendations for restoring soil health and building a resilient soil ecosystem for sustainable agricultural and nutritional security.

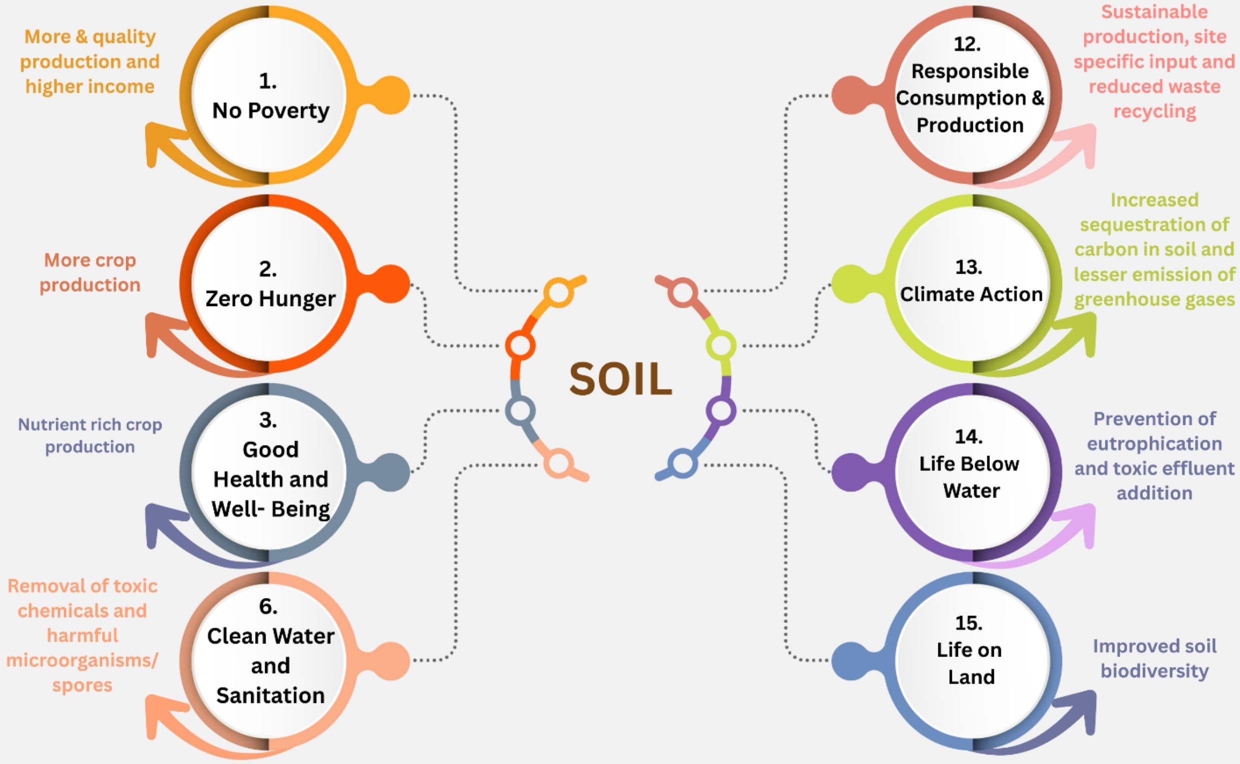
2

INDICATORS OF SOIL HEALTH

Soil health is the continued capacity of the soils to sustain life on earth (plant, animal and human) through various ecosystem services. The wide range of ecosystem services provided by soils are providing foot hold to the vegetation, supply optimum moisture and nutrients to the plants and micro flora for their growth and development, crop production, filtration of toxic chemicals, water infiltration and storage, biodiversity conservation, maintenance of ground water and surface water quality, nutrient cycling, induction of biotic and abiotic resistance in plants, secretion of beneficial bioactive molecules by the microorganisms, recreational activities, forest, wild life and biodiversity preservation, infrastructure development and also act as raw material for handicraft and artifact making, cultural heritage, etc. The complex interactions among soil properties, climate, vegetation and land management practices determine soil health. Due to diversity of direct and indirect beneficial services provided by the soil, this entity is linked with United Nations' Eight sustainable development goals (SDGs) (**FIGURE 2.1**). To meet food security or nutritional security, our focus cannot be one directional, hence, food security and agricultural sustainability must go hand in hand. Sustainable agriculture combines agronomic, socio-economic and environmental sustainability that holistically serves the 3 P Concept of sustainability i.e., People-Planet-Profit.

The key components of environmental sustainability are soil, air and water quality. While air and water quality are measured through their degree of pollution, soil quality is a measure of pollutant levels in soil and the overall capacity of soil to sustain biological productivity and promote plant and animal health. Soils, due to their buffering capacity, react slowly to land management practices. Thus, detecting soil health deterioration is often difficult in absolute terms unless nonreversible damage has taken place (Nortcliff, 2002). Soil health is better assessed by a set of sensitive soil attributes that estimate the status of soil depending on the domain of study. Soil health from a pedological point of view is a measure of its physical, chemical, and biological fitness. While the management practices do not have any effect on the inherent (static) properties of soil like minerology and texture, soil's biological properties are sensitive to management practices and associated changes. The physical properties like bulk density (BD), soil structure, texture, soil porosity, aggregate distribution and stability contribute to the overall structural framework and regulate the flow of components like soil water and air in the system.

FIGURE 2.1: LINKAGE OF SOIL HEALTH WITH UNITED NATION'S SUSTAINABLE DEVELOPMENT GOALS



Source: Adopted from Hou et al., 2020

Chemical properties are due to the chemical transformations of the nutrients and organic matter regulating soil nutrient dynamics and soil reaction (pH, electrical conductivity, adsorption, desorption, chelation, fixation, oxidation, reduction, cation and anion exchange capacity, buffering capacity, etc). The biological attributes are associated with the biological population, diversity and activities, and dynamics of biomolecules secreted by them. For example, microbial biomass carbon (MBC), soil respiration, organic matter mineralization, enzyme activity, plant growth promoting substance secretion, organic matter decomposition, humification, etc.). The list of major soil parameters and their role in soil health maintenance are listed in **TABLE *2.1***.

The optimum concentration and condition of these attributes lead to a healthy ecosystem functionality of soil to support better plant growth and nutrient accumulation. Healthy soil is a representation of stable soil structure and provides a safe habitat for microbes to proliferate and act. A healthy soil streamlines flow of water within soil pores and reduces chances of excessive drainage loss or seepage loss. Due to the carrying capacity of soil, native plant nutrients and added nutrients stay in the system for a longer period of time and gradually get transformed to plant available forms and are released into the soil solution. As a result of which the nutrient leaching loss is also avoided. A healthy soil creates a conducive environment for microbial growth and activity that regulates biological cycles and drives healthy plant growth with more and better-quality produce.

TABLE 2.1: ROLE OF DIFFERENT PHYSICAL, CHEMICAL AND BIOLOGICAL PROPERTIES IN SOIL HEALTH MAINTENANCE

Attributes	Soil Parameters	Role in Healthy Soil
PHYSICAL PROPERTIES	Bulk density (BD) and particle density (PD)	Regulates amount of pore space and pore distribution, enables the smooth operation of agricultural implements.
	Aggregate stability and aggregate distribution	Stability of soil against physical forces (rain drop, wind erosion, etc.), amount of stable macro and micro aggregates, turnover of micro and macro aggregates, protective micro habitat for soil flora and fauna.
	Water infiltration and percolation	Provides entry of water into soil system, transportation of water within system, measures the chances of seepage and deep percolation loss.
	Soil water holding capacity	Ability to hold soil moisture for a longer period, release of soil moisture from pore spaces for plant uptake.
	Porosity	Regulates the amount of soil water and its availability to plant roots, soil aeration.
CHEMICAL PROPERTIES	Soil pH	Regulates the chemical cycle of nutrients, regulates nutrient dynamics and forms in soil, it also affects the microbial diversity in soil and affects soil's buffering capacity.
	Soil electrical conductivity	Regulates the concentration of salt in soil solution, also affects the inflow and outflow of water from soil to roots, affects microbial population.
	Buffering capacity	Restricts changes in soil system due to application of agrochemicals, higher the buffering capacity better is the soil, maintains soil pH and nutrient availability.
	Cation exchange capacity (CEC)	Regulates the concentration of cations in soil solution and ultimately affecting its availability to plant roots.
	Nutrient dynamics and availability	Regulates the forms and concentration of essential nutrients in soil and its availability to plants, controls the chemical transformations of nutrients in soil and its availability to plants.

BIOLOGICAL PROPERIES	Soil organic carbon (SOC)	Works as substrate for the microbes to proliferate, improves water holding capacity
		of soil, regulates soil temperature, balanced and gradual supply of nutrients over a long period of time, heavy metal deactivation, stable structure formation, humification and nutrient holding, reduces evapotranspiration from soil, improves soil porosity and reduces bulk density of soil.
	Microbial biomass carbon (MBC)	It is the indication of microbial population in soil.
	Microbial diversity and population	Enumerates soil biodiversity, species richness and microbial population density is captured.
	Microbial respiration or mineralization	Represents activity of microbial population present in soil, rate of organic matter turnover.
	Soil enzyme activity	Represents abundance and concentration of extracellular and intracellular enzymes, activity of these biochemicals in various biological cycles and chemical transformation of nutrients in soil.

Soil health is measured by calculating soil health indices (SHI). The SHI is estimated according to the nutrient availability or presence of soil constraints which estimates the suitability of a piece of land for various activities like crop production, grazing, forestry, livestock rearing and other recreational activities. SHI is also calculated with a combination of plant growth supporting factors. Some of the common soil heath indicators identified by different researchers are total stock and availability of essential plant nutrients which affect growth and yield of crops, soil organic matter (SOM) content, soil bulk density, water holding capacity, microbial biomass carbon, soil respiration, organic matter mineralization, etc. There exists a complex phenomenon between soil parameters, climate, topography, vegetation and management practices that governs the soil health.

There are other indicators of soil health like soil erosion, desertification, soil compaction, hard pan formation, etc. These attributes of soil are affected by both geogenic factors (due to geography of land) and anthropogenic factors (manmade activities). Geogenic factors are natural phenomena and impossible to control. However, restrictions and manipulation of anthropogenic factors is feasible. During soil health indexing, the anthropogenic factors affecting soil functions are analyzed critically under the prevailing climatic conditions.

3

SOIL HEALTH STATUS OF INDIA

3.1 INDIA'S SOIL HEALTH STATUS VIS-À-VIS GLOBAL PICTURE

India is an agriculture dominant country where about 46% of the working population are involved in agriculture and allied activities directly (PLFS), 2023-24. India's agricultural landscape is vast and diverse with 56.5% irrigated area and a cropping intensity of 156%. While India is the world's largest producer of pulses and jute and the second-largest producer of rice, wheat, sugarcane, and vegetables, it faces significant challenges in soil health and fertility management. Around 95% of human food comes from soils, thus serves as the foundation of plant and human nutrition. The SHC Scheme, initiated by the Government of India in 2015, has provided valuable insights into the current status of Indian soils, highlighting widespread nutrient and SOC deficiencies. SOC is the carbon component of soil organic matter (SOM). It is used to describe the organic constituents in soil in various stages of decomposition such as tissues from dead plants and animals, materials less than 2 mm in size, and soil organisms (FAO, 2017). So, SOC is the carbon constituent of organic matter present in soil. SOC due to its multidimensional role in maintaining soil physical, chemical and biological activities, gets maximum attention in soil health. It helps in maintaining stable soil structure, provides substrate to the microbes for their growth, increases water holding capacity, thereby improving the nutrient retention capacity of the soils. The sensitive climatic condition and varying topography makes the SOC very sensitive to agricultural management practices. It is prone to loss under excessive pedoturbation (tillage) and sub-tropical climatic condition of India. The food sector contributes to around 26% of the global GHG emission out of which solely crop production practices cause 27% emission share of food sector. A huge loss of antecedent soil C pool (50 to 75% of native soil carbon or loss of around 30 to 60 Mg C/ha in terms of magnitude) has occurred due to land conversion, cultivation and erosion associated with it in most agricultural ecosystems (Lal, 2007). The magnitude of this loss is high in South, central Asia and Sub-Saharan African regions where the climate is the major driving factor of soil native carbon loss supplemented with faulty management practices. Dr Rattan Lal, pioneer of soil carbon dynamics suggested that the optimal level of SOC should be 1.5-2% in root zone (0-30 cm depth) of temperate regions (Lal, 2023; Lal et al., 2015) and 1-1.5% in the root zone of tropics (Lal, 2023, 2013). Several studies have shown that Indian soils are low in SOC levels in the top plow layer (0- 20 cm depth) (Bhattacharyya et al., 2008; Srinivasarao et al., 2009; Banger et al., 2015; Sreenivas et al., 2016). As per FAO GLOSIS data, the soil carbon stock of India (0-30cm depth) is 20-25 Mg C/ha. Another study by Minasny et al. (2017) showed that India is among the low SOC countries with a carbon stock of 30-35 ton /ha land in 0-30 cm depth. Similarly, as per SOC variability status mapping of 2015 by the NBSS & LUP of India, the carbon stock of most of the Indian surface soil ranged from 15-30 ton/ha (Bhoomi Geoportal, 2025). The north and northwestern part of the country had carbon stock of <20 ton/ha during 2015. In a subtropical country like India, the soil carbon is prone to losses through oxidation and has limited potential for sequestering carbon. However, measures to sequester organic matter/carbon in soil for a longer period of time through sustainable agricultural management practices is recommended by scientists (Bhattacharyya et al., 2008; Mandal et al., 2007). The sustainable crop management practices like organic manuring along with synthetic nutrient input, less soil disturbance, cover cropping, crop rotation, legumes in crop rotation, organic mulching, green manuring, and biochar application have a positive impact on long term sequestration of organic matter in soil improving soil fertility, soil health and crop yield.

Though the level 1-1.5% SOC in tropical soils is suggested by soil carbon researchers, but achieving such a level in the Indian scenario is difficult due to various climatic and soil constraints. The sequestration of C is not the same in tropics as that in temperate climate. In India's hot and humid climate, organic matter in the soil decomposes quickly. This means any added organic carbon is used up fast by microbes and becomes tough to accumulate in soil beyond certain limits or at a slow rate. Analysis of carbon sequestration potential under five long term experiments suggested that due to the sub-tropical climate, lesser percentage (on average 18%) of added carbon is converted to SOC and rest are oxidised (Mandal et al., 2007). The prevailing hot and humid climate of India aggravated the loss of C due to microbial decomposition or oxidation, so maintaining SOC is given more emphasis by researchers. The SOC in tropical and sub-tropical climates being unstable due to the above reasons needs constant application of organic manures along with chemical fertilisers as a long-term practice. At the same time, the added organic matter needs to be managed through sustainable management practices that will induce stabilization of carbon in soil rather than intensifying the loss due to rapid decomposition and mineralization.

Globally, the status of Indian soil in terms of nutrient availability and soil constraints is poor where more than half of the land possesses partial constraints or major constraints showing their unsuitability for agriculture activity (FAO soils portal). N in soil is prone to loss through various phenomena viz; leaching loss, volatilization, denitrification, etc. However, organic matter owing to its greater surface area, higher charge density, more functional groups and water holding capacity, plays an important role in reducing nutrient leaching, particularly through holding the N in soil (Lehman et al., 2003).

It is essential to measure the nutrient supplying capacity of the soil which is a measure of soil fertility and soil health. Soil nutrient analysis categorizes the soil under low, medium, and high categories. This level is different for each nutrient depending on their equilibrium, rate of release, requirement by the crop and crop response. The critical value of each nutrient categorized as low, medium, and high is given in **ANNEX TABLE 1**.

3.2 PORTRAYAL OF SOIL HEALTH STATUS OF INDIA

The SHC scheme was launched in 2015, and two successful rounds of soil testing have been completed while further cycles are going on. In the first cycle, 25.4 million, in the second cycle 27.4 million soil samples and in the recently completed cycle of 2024-25, 8.9 million soil samples were analyzed (**TABLE 3.1**). The insights of soil fertility status of the entire nation according to the SHC cycle I, II and the recently completed cycle are presented below. These reports give a clear picture of the significant regional variations and widespread nutrient deficiencies crucial for soil health and agricultural productivity.

TABLE 3.1: SUMMARY OF SOIL HEALTH CARD (SHC) CYCLES AND SAMPLE TESTING

Soil health card cycle	Year	Samples Tested (million)
Soil health Card Cycle I	2015-2017	25.4
Soil health Card Cycle II	2017-2019	27.4
Soil health Card	2024-2025	8.9

Sources: Soil Health Card Website (Scheme Progress)

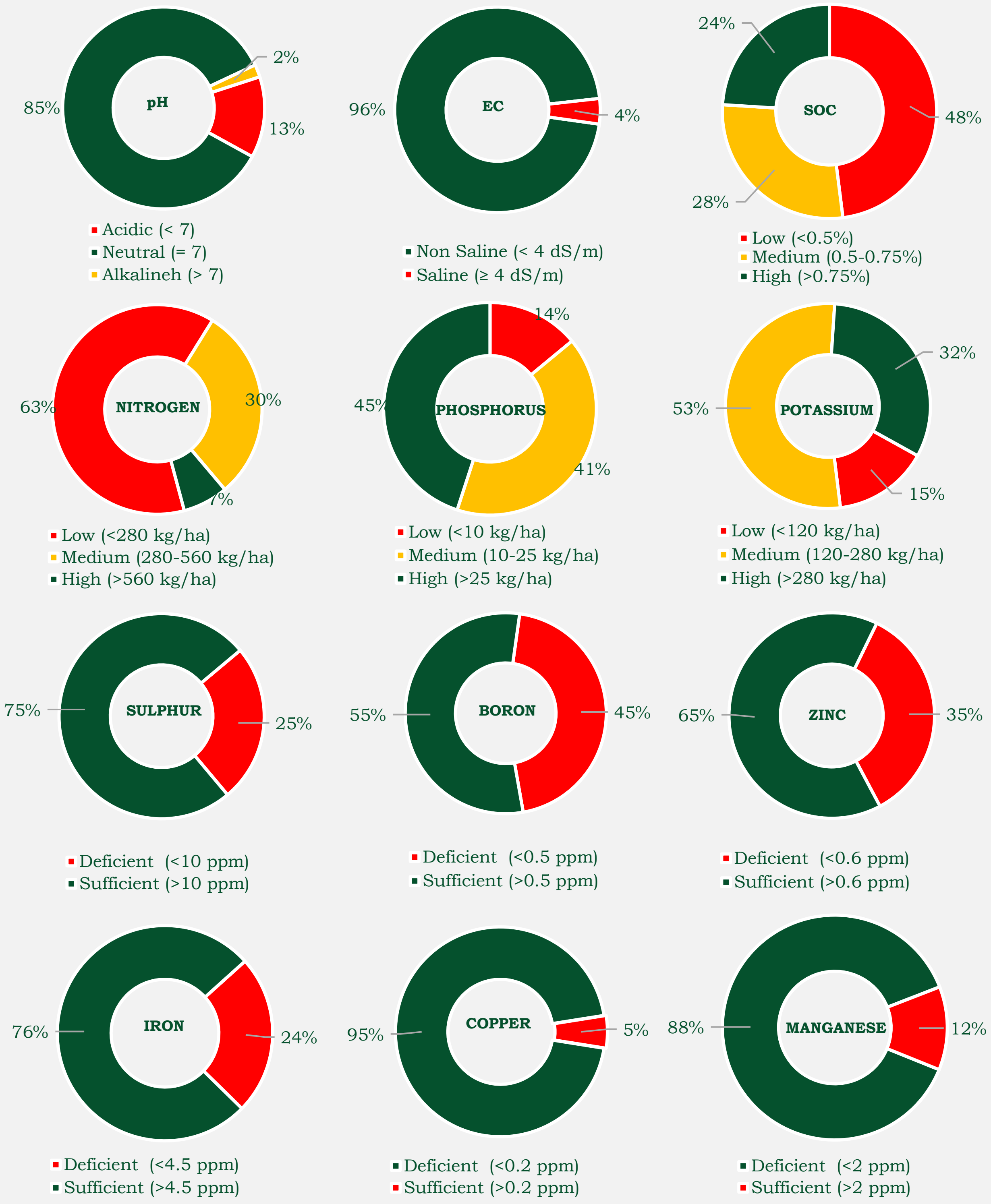
ω *SOIL ORGANIC CARBON (SOC)*

The SOC, the main driving factor of soil health and soil's protection, is found to be low in a major proportion of the soil samples analyzed. The soils with SOC level below 0.5% are considered to be low in SOC in India, between 0.5-0.75% is medium and above 0.75% is high SOC. The cycle I report of SHC scheme (201517) showed 36% samples (out of 25.3 million samples analyzed) to be low in SOC (<0.5%) (Singh et al., 2025) which then increased to 48% (of 8.9 million samples analyzed) during SHC 2024-25 (SHC Portal). In the same duration (2024-25), along with remarkably low SOC status, another 28% samples were medium in SOC content and only 24% samples tested were found to contain high or sufficient SOC (i.e., >0.75%) (**FIGURE 3.1**). Similarly, a pervasive low SOC of India indicates severe deficiency in organic matter content of soils during cycle I, II and 2024-25. During all these three time periods, dominant portion of samples had low SOC (36%, 33% and 48% in the mentioned durations respectively).

States showing widespread SOC deficiencies were Rajasthan, Tamil Nadu, Uttar Pradesh, Haryana, etc. during the cycle II and 2024-25 period (**FIGURE 3.2**). The SOC deficiency in these states were to the tune of >80% where highest SOC deficiency was observed in Tamil Nadu soils (87.75%) followed by Uttar Pradesh state (86.76%). Andhra Pradesh, Chhattisgarh, Telangana and Maharashtra which are agriculture dominant states containing low SOC in their soils. In states like Madhya Pradesh, Gujarat, Jharkhand, around one third of the samples were low in SOC. As per the spatial variability map of India generated by the ICAR - NBSS & LUP, 72.7% of Indian soils have SOC below 0.75% and only 13.3% soils have SOC in the range of >1% (Bhoomi Geoportal, 2025).

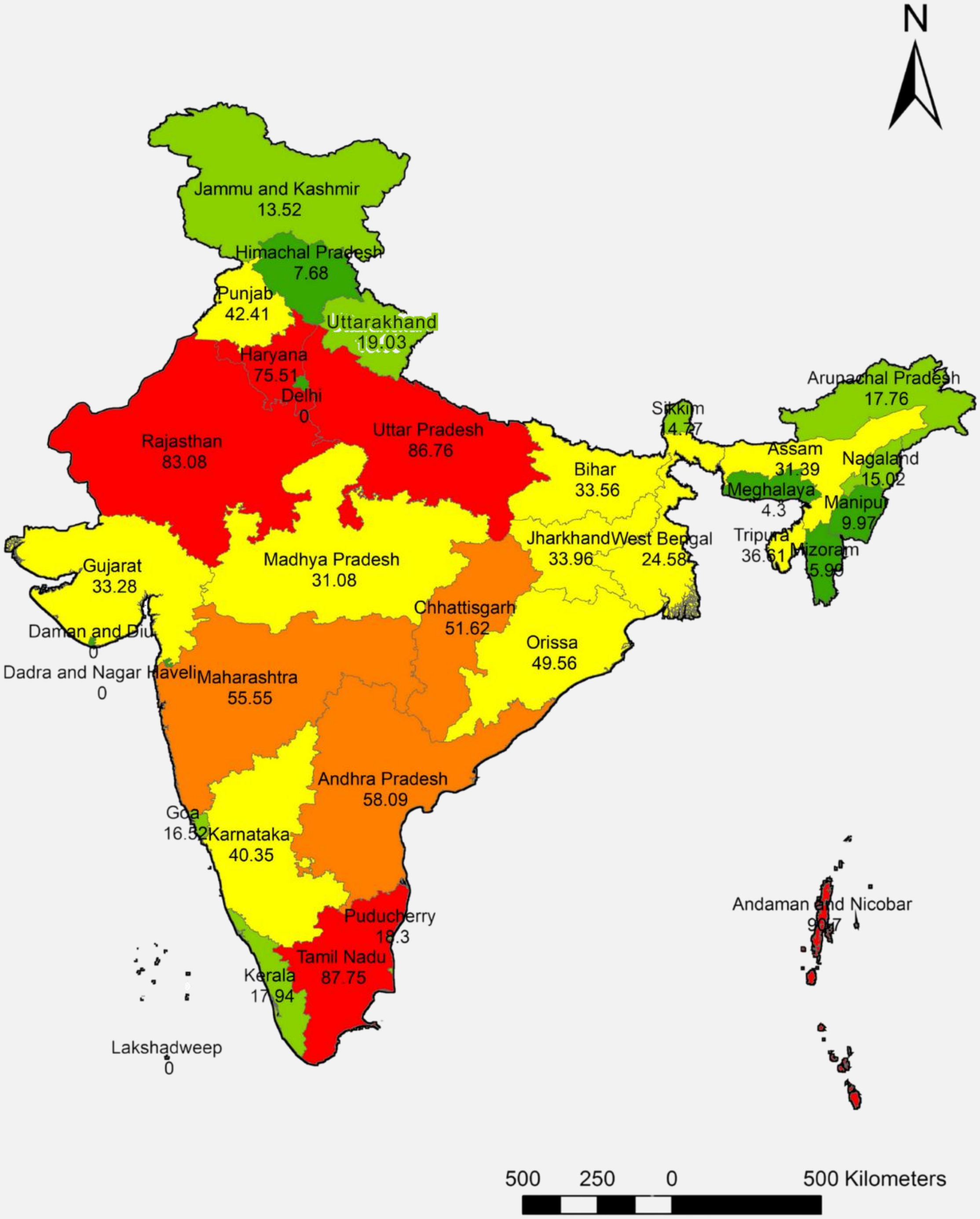
The SOC status of soils across various Indian states have been studied by various researchers in different time spans (**TABLE 3.3**). The studies undertaken were mostly regional, yet large-scale representative samples were analyzed according to the purpose of the respective study. The study undertaken by ICRISAT in the dryland regions of certain states of India are presented hereafter (**TABLE 3.3**). Among the samples analyzed, dry land soils of Andhra Pradesh showed 76% of soil samples having SOC deficiency, Rajasthan 38%, and Madhya Pradesh 22% (samples collected during 2002-06), highlighting considerable regional variability even within semi-arid regions of India. Karnataka's dryland soils exhibited a notably high deficiency, with 70% samples found low in SOC. Comprehensive fertility reports covering Rajasthan, Uttar Pradesh, Punjab, Haryana, Madhya Pradesh, Chhattisgarh and Gujarat from 1995 to 2011 carried out by Chambal fertilisers reported 56.5% soils categorized as low in SOC, while an additional 27.3% were in the medium range, underscoring a widespread issue of suboptimal level of organic carbon across north-western states of India. Additionally, the Soil Fertility Atlas for Karnataka (soil sampled during 2011-12) reported 52% of samples having low SOC (<0.5%). Another study carried out by ICRISAT in dryland regions of Tamil Nadu during 2004-06, reported 57% low SOC status out of the 119 samples analyzed.

FIGURE 3.1: SOIL HEALTH STATUS OF INDIAN SOILS AS PER SOIL HEALTH CARD SCHEME (2024-25)



Source: Soil Health Card Website (Scheme Progress) 2024-25

FIGURE 3.2: PERCENTAGE DISTRIBUTION OF LOW SOIL ORGANIC CARBON IN SOME AGRICULTURALLY DOMINANT STATES OF INDIA IN 2024-25



Source: Author's own compilation from Soil Health Card report

Collectively, these findings emphasize SOC deficiency to be common with inter-state variability in different climatic conditions and land patterns (watershed) across India. Intensive cultivation with limited, insufficient or no organic input has excruciating effect on the native SOC declining it further (Lal, 2013). A regional study done by Antil et al. (2011) showed that continuous cultivation of crops without organic input has led to decline in SOC level from 0.45% in 1967 to 0.21% during 1992 under pearl millet-wheat cropping system of Entisol soil of India.

TABLE 3.2: SOIL ORGANIC CARBON STATUS OF INDIAN STATES AS REPORTED BY MAJOR RESEARCH STUDIES

Study	Area	Year of Sampling	No. of Samples	Depth (cm)	% Deficiency	Reference
Soil fertility analysis by ICRISAT	Dry land regions of Andhra Pradesh, Rajasthan, Madhya Pradesh	AP- 2002-04 RJ- 2003-06 MP- 2002-04	AP- 1926 RJ- 179 MP - 55	0-15	AP- 76% RJ- 38% MP- 22%	Wani, Chander and Sahrawat (2012)
Soil fertility analysis by ICRISAT	Dry land regions of Karnataka	2005-06	1260	0-15	70%	Wani et al., 2012
Soil Fertility Status of North-Western States of India	Rajasthan, UP, Punjab, Haryana, MP, Chhattisgarh, Gujarat	1995-2011	696,584	0-15	56.5% low, 27.3% medium	Chambal Fertilisers Soil Fertility Report, 2012
Soil Fertility Atlas, Karnataka	Karnataka, South India	2011-12	92642	0-15	52% low	Wani et al., 2011
Soil fertility analysis by ICRISAT	Dry land regions of Gujarat, Tamil Nadu	GJ- 2004 TN- 2004-06	GJ- 82 TN- 119	0-15	GJ- 12% TN- 57%	Sahrawat et al., 2007

N.B: Samples with low SOC (< 0.5% SOC) are considered deficient where medium level is not mentioned.

However, the studies carried out earlier at different point of time were site specific or climate specific. Therefore, these results are limited in their comparability with the current SOC status documented in the SHC report.

ω *STATUS OF AVAILABLE N IN INDIAN SOILS*

The essential nutrients are required by the plants in sufficient amount for their optimum growth and crop development. The N, P and K are the major primary nutrients, whereas S, Ca and Mg are the secondary macro nutrients. The Fe, Mn, Cu, Zn, B, and Mo are the micro nutrients. The concentration of these nutrients in soil in plant available form is crucial to determine the fertility of soil in plant growth point of view. As per a study by Chaudhari et al. (2019), 95%, 94% and 48% soils are deficient in available N (<560 kg/ha), P (< 25 kg/ha) and K (< 280 kg/ha) respectively. It is noteworthy that in Chaudhari's report the soil samples falling in low and medium category of nutrient levels (for N, P, K) are combinedly considered to be deficient. The study also reported that the Zn, Fe, copper and manganese deficiencies in Indian soils are to the tune of 41% (0.6 ppm), 14% (4.5 ppm), 8% 0.2 ppm) and 6% (2 ppm) respectively. Similarly, Indian Society of Soil Science reported that 89%, 80% and 50% Indian soils are deficient in N, P and K with the same threshold limit as used by Chaudhari, 2019. The S, Zn, B, deficiencies are to the tune of 41%, 49%, 33% respectively at threshold limit of <10 ppm for S, < 0.6 ppm for Zn and <0.5 ppm for B (ISSS technical bulletin, 2016).

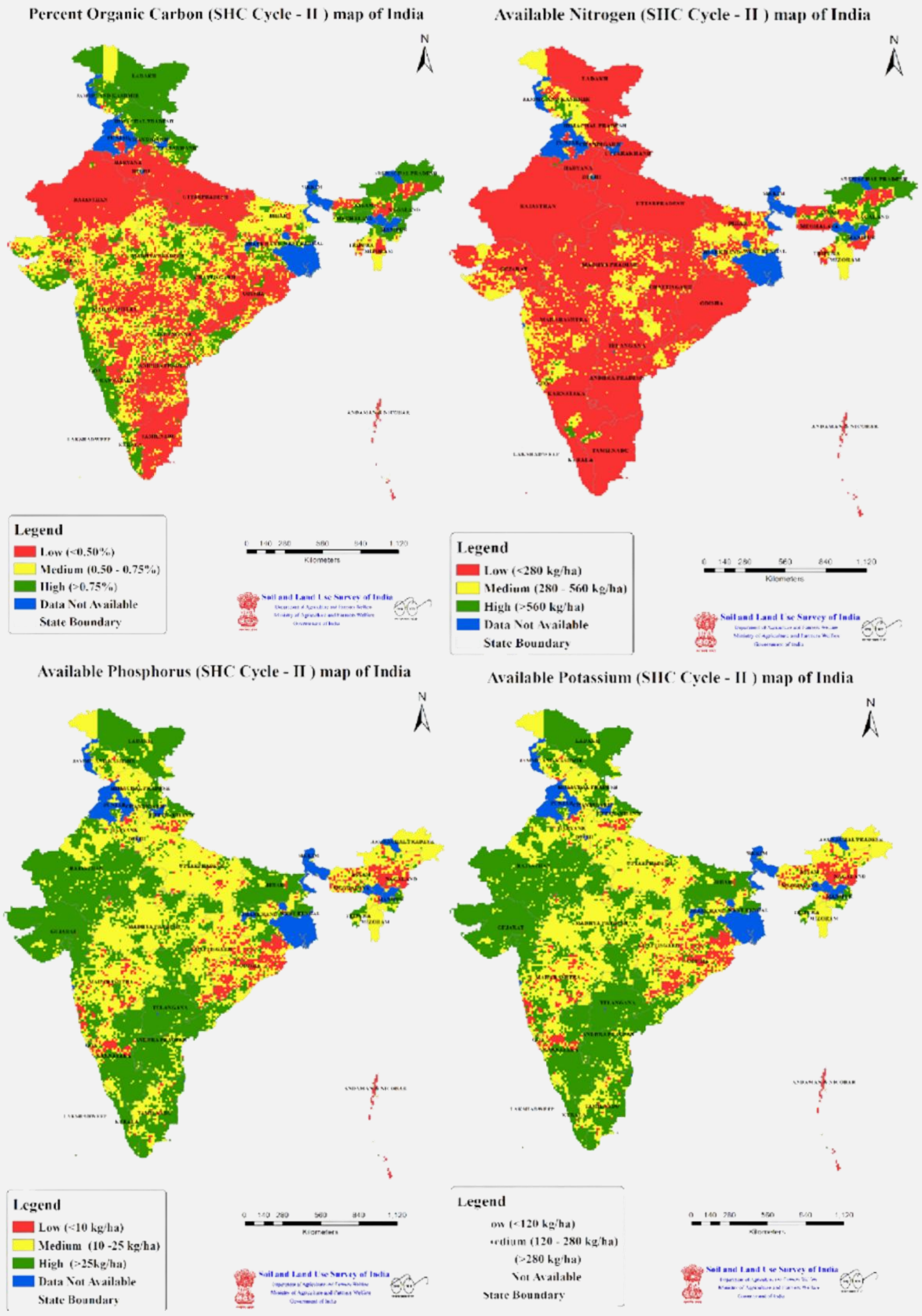
Through SHC, the fertility status of soils is studied widely in India. Like SOC, soil N deficiency is a severe issue across most Indian states and the sufficiency is limited as per the SHC report of 2024-25, cycle I and II report (**FIGURE 3.3, ANNEX TABLE 2** respectively). The report revealed that in almost all the states and union territories' a very small portion of soils have sufficient N levels. SHC cycle I, II clearly showed that only 1.5% 2.7% soil samples were having sufficient or high amount of N (> 560 kg/ha) in soil respectively. It is concerning that even during the 2024-25 soil analysis cycle, almost entire nations' soil samples were found to be poor in available N (**TABLE 3.3**). On a national scale only 7% soils are sufficient or high in available N (>560 kg/ha). The states showing critically poor soil N levels are Tamil Nadu, Uttar Pradesh, Punjab, Chhattisgarh, Maharashtra, Haryana, Rajasthan, etc. as <10% of these states' soils registered sufficient or high N levels (**TABLE 3.3**; **ANNEX TABLE 2**). The susceptibility of added N to disappear from soil through various processes like volatilization, leaching loss, denitrification makes the soil deficient in N. The losses are aggravated in the absence of SOC since it imparts a major role in holding the nutrient in soil for a relatively longer period of time and convert it into recalcitrant form through the humification process (Ryals et al., 2014).

TABLE 3.3: PERCENTAGE DISTRIBUTION OF PRIMARY ESSENTIAL NUTRIENT FALLING IN HIGH/ SUFFICIENT CATEGORY IN SOME AGRICULTURALLY DOMINANT STATES OF INDIA IN 2024-25

States	**Available Nitrogen**	**Available Phosphorus**	**Available Potassium**
Critical limits	**>560 kg/ha**	**> 25 kg/ha**	**> 280 kg/ha**
Andhra Pradesh	13.86	22.21	14.4
Assam	41.8	59.69	8.72
Bihar	0.92	75.61	20.62
Chhattisgarh	0.17	8.8	45.3
Gujarat	0.22	63.01	59.63
Haryana	0.01	56.07	30.83
Jharkhand	0.54	25	8.13
Karnataka	5.05	57.46	40.2
Kerala	0.04	73.73	29.19
Madhya Pradesh	0.59	25.56	39.31
Maharashtra	0.96	24.05	66.11
Odisha	2.31	29.96	21.37
Punjab	0.04	29.28	15.74
Rajasthan	0.29	69.12	51.61
Sikkim	3.48	72.57	30.42
Tamil Nadu	0.04	35.82	45.62
Telangana	2.34	88.77	48.66
Uttar Pradesh	0.13	15.29	10.66
West Bengal	1.74	72.77	33.03

Source: Soil Health Card Portal

FIGURE 3.3: SOIL ORGANIC CARBON, NITROGEN (N), PHOSPHORUS (P) AND POTASSIUM (K) FERTILITY STATUS OF SOILS OF INDIA (2017-19)


Percent Organic Carbon (SHC Cycle - II) map of India

Available Nitrogen (SHC Cycle - II) map of India

Available Phosphorus (SHC Cycle - II) map of India

Available Potassium (SHC Cycle - II) map of India

Source: Soil and Land Use Survey of India

ω *STATUS OF AVAILABLE PHOSPHORUS IN INDIAN SOILS*

P is another essential macronutrient, vital for root development, flowering, and fruiting. Its chemistry in soil is pH and climate specific. It is prone to binding by cations like calcium, aluminium and Fe and becomes limited in acidic, alkaline soil pHs and calcareous soils. As per SHC 2024-25 report, only nearly half of the nation's soils i.e., 45% of the samples have sufficient levels of available P in soil (>25 kg/ha) (**FIGURE 3.1**). Similarly, the SHC cycle I and II recorded P sufficiency only in 23.1% and 17.7% of soil samples out of 25.4 million and 27.4 million soil samples tested during those cycles respectively (Soil health card portal). However, it is important to note that the sampling locations being hugely different in both the time period, the deficiency status cannot be directly compared (Envistat- 2024, MoSPI). For the recent cycle (2024-25), among the agriculturally important states, the chronic insufficient levels are observed in Chhattisgarh followed by Uttar Pradesh where only 8.8% and 15.3% soil samples had sufficient P levels (> 25 kg/ha). While acidic soil pH might be a cause for P shortfall in Chhattisgarh, Odisha; alkaline pH prevailing in Uttar Pradesh, Maharashtra, Madhya Pradesh, Karnataka, Punjab, Bihar also impact the availability of P to the plants. The imbalance fertilisation might also be the factor for P deficiency in such soils (e.g., N: P_2O_5 of Jharkhand 3.1:1, Bihar 3.1:1, Uttar Pradesh 3.1:1, Haryana 3.7:1, Punjab 4.2:1 according to Fertiliser Statistics Report, 2023-24). P deficiency is also widespread, particularly acute in the central, northern and north-eastern regions.

• PHOSPHORUS MINING

LTFE experiment conducted by ICAR at various sites showed that growing crops without addition of phosphatic fertilisers creates a negative balance of P in soil ranging from 2.7-34.2 kg/ha/yr depending on the soil type (**TABLE 3.4**). It suggests that no or under application of P extracts the native soil P without any opportunity to replenish it at the source.

TABLE 3.4: EFFECT OF IMBALANCED FERTILISATION ON APPARENT PHOSPHORUS BALANCE IN SOIL IN LTFE

Site Details		P Added (kg/ha)		P Removed (kg/ha)		P Balance (kg/ha/yr)	
Sites ↓	**Treatments →**	**RDN + no PK**	**RDF NPK**	**RDN + no PK**	**RDF NPK**	**RDN + no PK**	**RDF NPK**
Ranchi, Jharkhand (40 years)		0	52	2.7	16.4	-2.7	35.6
Akola, Maharashtra (20 years)		0	76	11.9	38.6	-11.9	37.4
Barrackpore, West Bengal (40 years)		0	65	34.2	50.7	-34.2	14.3

Site Details		**P Added (kg/ha)**		**P Removed (kg/ha)**		**P Balance (kg/ha/yr)**	
Sites ↓	**Treatments →**	**RDN + no PK**	**RDF NPK**	**RDN + no PK**	**RDF NPK**	**RDN + no PK**	**RDF NPK**
Jagtial, Telangana (15 years)		0	52	33.9	47.2	-33.9	4.8
Ludhiana, Punjab (40 years)		0	52	24.8	37.3	-24.8	14.7
Jabalpur, Madhya Pradesh (34 years)		0	70	15.63	28.95	-15.63	41.05
Coimbatore, Tamil Nadu (43 years)		0	52	17.3	21.9	-17.3	30.1

RDN- recommended dose of nitrogen, RDF- recommended dose of fertiliser. In the parenthesis by the side of LTFE site, the duration of long-term experiment is mentioned.

Source: Singh et al., 2019a

- **PHOSPHORUS DYNAMICS**

The availability of P to plant is dependent on soil factors like the soil type, type of clay, climatic condition, soil pH, soil organic matter, microbial population, etc. They have significant role in P mobility to the plant as it affects the dynamics of available P (solubility and forms) in soil. P is immobile in soil while mobile in plants. This means movement of P in the soil system is slow while once absorbed by plants, it moves to the tips or the upper parts of plant quite quickly. The immobile nature of P is the reason that staying in soil for a longer duration aggravates its fixation on the clay surface by Fe, Al and Ca, which makes it unavailable to the plant (Ma et al., 2021). The neutral pH is the optimum soil reaction that has a positive effect on the availability of P to the plants; however, acidic and alkaline pH with good amount of reactive Fe, Al and Ca successfully form complexes with phosphate ions making them insoluble (Tisdale et al., 1985). Similarly, abundance of positively charged clay acts as a factor of P fixation converting the soluble P into insoluble form (Tisdale et al., 1985). The bound P (insoluble) can gradually become available (soluble form) upon microbial decomposition and release to the soil solution. P being immobile in soil moves slowly within the soil system. The plant requires P for optimum root and shoot development and flowering. Of the various molecular forms of P, plant roots can absorb only the primary ($H_2PO_4^-$) and secondary (HPO_4^{2-}) ortho forms of P. Therefore, to benefit the crops, the applied phosphatic molecule must be efficiently converted into one of these two forms. The primary ortho-phosphate form ($H_2PO_4^-$) dominates in mildly acidic soil which can be absorbed about 10 times as efficiently as the secondary ortho form (HPO_4^{2-}) (Lagat et al., 2015).

Application of microbial inoculants like P solubilizing microorganisms/ bacteria (PSM/B) has the potential to gradually convert the bound or insoluble P into soluble form and make it available to the plant (Pang et al., 2024). These microbial consortia can convert insoluble forms into a soluble (available form) from both organic and inorganic sources through various mechanisms. For example, species like *Bacillus* and *Pseudomonas*, release organic acids and enzymes that dissolve the insoluble forms of P present in native soil minerals, organic manures and P fertilisers. This process increases the concentration of plant available P, improving the efficiency of applied nutrients. Through better nutrient mobilization, plant growth promoting substance secretion and root interaction, PSM inoculants boost P utilization efficiency and promote root proliferation, vigorous plant growth, higher biomass production and improved yield quality, making the combined use of P inputs and PSM, a sustainable approach for efficient P management in agriculture.

The SOC plays an important role in the P dynamics and its availability to the plants. Organic matter is found to coat the binding sites of the clay through formation of chelates, reducing the P binding capacity of the soil (Jindo et al., 2023). In Indian soils, the SOC being low in major parts of the country is another reason for the frequent insolubility of applied or available P in soil. Due to the adsorption and fixation effects of soil on P, the applied P fertiliser rapidly becomes fixed, resulting in a P fertiliser utilization efficiency of only 10–25% (Dong et al., 2023). So, to meet the requirement of the plant for its optimum growth and yield, application of phosphatic fertiliser to the crops is needed despite the available P content being medium to high in many regions. The low P regions require external application to meet the crop demand and soil build up for better soil health and sustainability.

ω *STATUS OF AVAILABLE POTASSIUM IN INDIAN SOILS*

K deficiency remains significant in specific pockets of India. As reported by SHC cycle 2024-25, around 32% soil samples had sufficient/ high levels of available K content in soil (>280 kg/ha) (**FIGURE 3.1**). Similarly, during SHC cycle I and II, the sufficient available K was captured in 56.9% and 30.2% soil samples respectively. As mentioned above, the samples being hugely different cannot be compared directly between two time periods (Envistat 2024, MoSPI). Out of the 19 agriculturally important states mentioned in **TABLE 3.3,** only 3 states reported satisfiable levels of available K as per SHC report 2024-25. A severe suboptimal K level (<280kg/ha) was observed in Assam, Bihar, Jharkhand, Uttar Pradesh, Punjab, Andhra Pradesh, Haryana, Kerala, Odisha, West Bengal and Madhya Pradesh where below 40% soil samples of each state recorded K levels in sufficient range i.e., >280 kg/ha (It is noteworthy that the states also showed widespread poor soil K levels during 2017-19 (SHC cycle II) as well. The imbalance of nutrient input serves as a significant factor for such state of soil K fertility level. According to Fertiliser Statistics Report (2023-24), the N: K_2O ratio of Assam is 6.9:1, Bihar 13.5:1, Jharkhand 52.2:1, Uttar Pradesh 28.1:1, Punjab 43.7:1, Haryana 44.3:1, Odisha 8.7:1, Telangana 14.7:1 and Madhya Pradesh 22.5:1 during 2023-24. Intensive cropping practice, dominated with cereal-cereal crop rotation and under application of

K fertiliser might be a potential factor for negative balance of available K in Indian soils (Vijayakumar et al., 2024; Ramamurthy et al., 2017).

- **POTASSIUM MINING**

Cereal crops which are high K demanding crops, in the absence of ample amount of K input led to mining of native soil K from soil making it deficient over a period of time (Tan et al., 2012; Romheld and Kirkby, 2010). The continuous depletion of nutrient with each crop harvesting is known as nutrient mining. A study by Walia et al. (2024) shows that the removal of K from rice-wheat cropping fields far exceeds the amount of external addition of K due to intensive cropping characterized by imbalanced fertilisation practices, inadequate K & organic matter addition and widespread cultivation of HYVs that worsen the soil fertility even more. Worldwide, there has been scanty application of K fertilisers replacing (balancing) only 35% of the K which is taken up by the crop (Singh et al., 2021). The LTFE conducted by ICAR showed a negative balance of K to the tune of 85-261 kg/ha/yr depending on soil type in no K added plots. The results showed a negative K balance of 56-188 kg/ha/yr even in K added fields (**TABLE 3.5**). The findings show that even in K fertilized fields, the crop removal is much more than the supplied K, depleting the native soil K year after year. Such findings suggest recalibration of fertiliser doses for crops according to soil type and climatic zones in India.

TABLE 3.5: EFFECT OF IMBALANCED FERTILISATION ON APPARENT POTASSIUM BALANCE IN SOIL IN LTFE

Site Details		K Added (kg/ha)		K Removed (kg/ha)		K Balance (kg/ha/yr)	
Sites ↓	Treatments →	RD NP + no K	RDF NPK	RD NP + no K	RDF NPK	RD NP + no K	RDF NPK
Ranchi, Jharkhand (40 years)		0	2640	3400	6320	-85	-92
Barrackpore, West Bengal (40 years)		0	6000	7680	8440	-192	-111
Ludhiana, Punjab (40 years)		0	2000	4540	5380	-113	-84.5
Jabalpur, Madhya Pradesh (34 years)		0	2220	8668	9760	-261	-188
Coimbatore, Tamil Nadu (43 years)		0	1760	5360	7280	-134	-138
Bangalore, Karnataka (45 years)		0	3100	3250	6500	-130	-136

RD NP-recommended dose of N and P, RDF-recommended dose of fertiliser. In the parenthesis by the side of LTFE site, the duration of long-term experiment is mentioned.

Source: Singh et al., 2019a

- **POTASSIUM DYNAMICS**

In India’s cereal dominant cropping systems, nutrient mining of K is occurring at an alarming rate due to the consistently insufficient and imbalanced application of this essential nutrient. Cereals like rice, wheat and maize have high K demands, but farmers consider N fertiliser application and neglect other essential nutrients. K is ignored by most of the growers despite its critical role in plant growth, plant physiology, water regulation, and stress tolerance. This inadequate replenishment leads to continuous depletion of soil K reserves. The K mining is intensified by the region's specific clay mineralogy and climatic conditions. Soils rich in 2:1 clay mineral, such as illite and vermiculite, have a high capacity to fix potassium, rendering it non-exchangeable and less available to plants (Najafi-Ghiri and Abtahi, 2013). However, climatic factors such as frequent wetting and drying cycles common in paddy cultivated regions and rainfed agriculture can influence K dynamics by enhancing the transformation of soil solution K into non-exchangeable forms (due to expansion and contraction of clay) (Shakeri and Abtahi, 2020), thereby affecting its concentration in the soil solution. Yet, without sufficient external inputs, these natural processes cannot compensate for high crop uptake, leading to continuous K depletion and declining soil fertility.

ω *STATUS OF AVAILABLE SECONDARY AND MICRONUTRIENTS IN INDIAN SOILS*

The distribution and availability of micronutrients is a complex function of parent material, geogenic processes and anthropogenic processes (Shukla et al., 2021). The status of secondary and micronutrient deficiency percentage in 2024-25 cycle and cycle II (2017-19) are given in **FIGURE 3.1** and **ANNEX TABLE 3** respectively. During SHC cycle I and II, S deficiency (<10 ppm) was 58.2% and 30.3%, B deficiency (< 0.5 ppm) was 7.3% and 40.2%, Zn deficiency (< 0.6 ppm) was 45% and 38.2% and Fe deficiency (< 4.5 ppm) was 36.1% and 34.8%, respectively.

As per the recently completed SHC cycle (2024-25), one fourth of the soils have S deficiency in India (< 10 ppm). The percentage deficiency was similar during SHC cycle II for available S. There is a highly varied picture of S deficiency in soil with extreme scarcity in some states. The major agriculturally dominant states, Bihar, Odisha, Maharashtra, West Bengal, Uttar Pradesh, Karnataka showed S deficiency in SHC cycle II and 2024-25. The deficiency percentage is 45% for soil B in India as per SHC report 2024-25. B deficiency is high in Bihar, Assam, Odisha, Karnataka, Punjab in both the cycles. States like Jharkhand and West Bengal also showed significant B deficiency.

Overall, Zn deficiency in Indian soil accounts for 35% of soil samples, while that of Fe is 25% as per SHC report 2024-25. Zn deficiency is relatively high in Karnataka, Maharashtra, Madhya Pradesh, Rajasthan, Odisha, Telangana, Chhattisgarh and Uttar Pradesh. Fe deficiency across states has been fluctuating with a remarkably high deficiency in Maharashtra, Rajasthan, Karnataka, and Telangana according to the SHC report. Fe deficiency is also significant in Haryana, Gujarat and Uttar Pradesh. Cu and Mn deficiencies are generally less widespread than other micronutrients.

To understand the micro and secondary nutrient status of the soils of the country, a comprehensive analysis was done by the ICAR - IISS, Bhopal under the All India Coordinated Research Project (AICRP) on Micro and Secondary Nutrients and Pollutant Elements in Soils and Plants (MSPE). Under this project, 0.24 million number of surface soil samples (0–15 cm depth) from 615 districts across 28 states of India were analyzed during 2012-18 for their secondary and micronutrient content. The survey revealed wide spread deficiency of S, Zn, B and Multi-nutrient deficiency. The soils were categorized into acute deficient, deficient, latent deficient, marginally sufficient, adequate and high as per the categorization given in **TABLE 3.6**. The deficiency percentage was estimated by combining acute deficient, deficient and latent deficient values together (Shukla et al., 2021).

TABLE 3.6: CRITICAL LIMITS OF AVAILABLE S AND MICRONUTRIENTS FOR AGRICULTURAL SOILS OF INDIA

Nutrients	**Deficient**			**Marginal**	**Sufficient**	
	Acute deficient	Deficient	Latent deficient	Marginal sufficient	Adequate	High
Available S (ppm)	≤7.5	>7.50–≤ 15	>15.0–≤ 22.5	>22.5–≤ 30	>30.0–≤ 40	> 40
Available Zn (ppm)	≤0.3	>0.30–≤ 0.6	>0.60–≤ 0.9	>0.90–≤ 1.2	>1.20–≤ 1.8	> 1.8
Available B (ppm)	≤0.2	>0.20–≤ 0.5	>0.50–≤ 0.7	>0.70–≤ 0.9	>0.90–≤ 1.1	> 1.1
Available Fe (ppm)	≤2.5	>2.50–≤ 4.5	>4.50–≤ 6.5	>6.50–≤ 8.5	>8.50–≤ 10.5	> 10.5
Available Cu (ppm)	≤0.2	>0.20–≤ 0.4	>0.40–≤ 0.6	>0.60–≤ 0.8	>0.80–≤ 1	> 1
Available Mn (ppm)	≤1	>1.00–≤ 3	>3.00–≤ 5	>5.00–≤ 7	>7.00–≤ 9	> 9

Source: Shukla et al., 2021

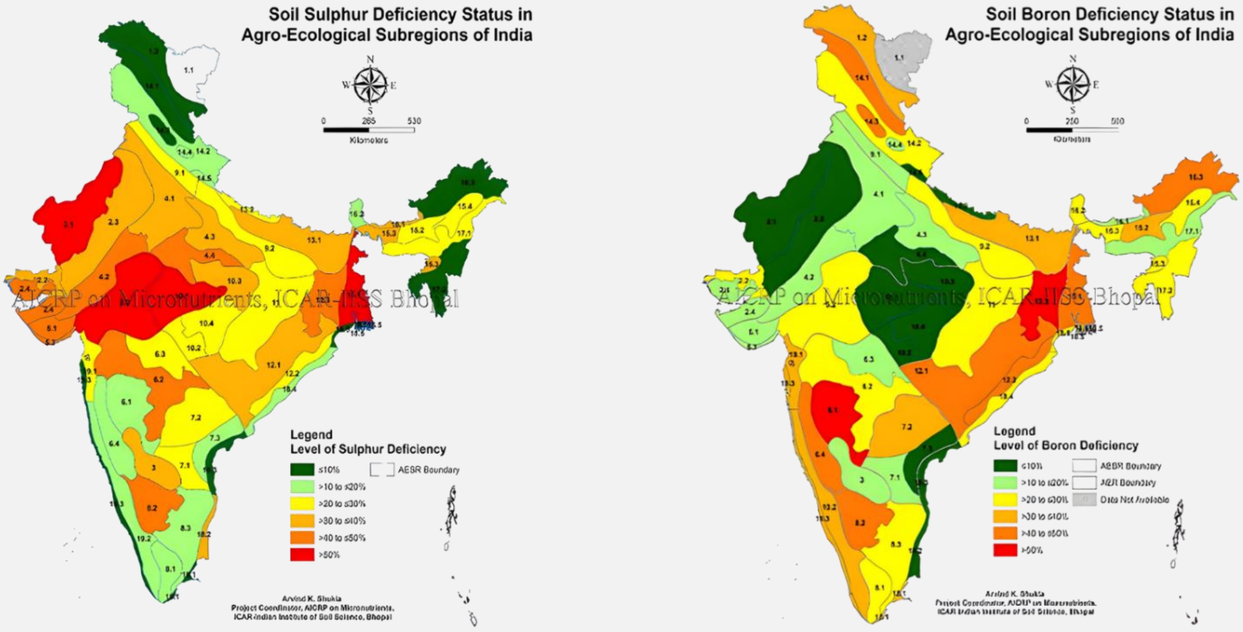
According to the study, 58.6% samples were deficient in available S (< 22.5 ppm) (11.4%, 29.4%, 17.8% in acute deficient, deficient, latent deficient respectively). Similarly, 44.7% samples are deficient in B (< 0.7 ppm); 51.2% in Zn (< 0.9 ppm); and 19.2% in Fe (< 6.5 ppm) (acute, deficient and latent deficiency combined) (Shukla et al., 2021). The deficiencies of S, Zn and B were more prevalent than those of Fe, Cu and Mn. The status of secondary and micronutrients were also analyzed on individual state level under the same project. From the analysis, it is observed that Bihar (70.1%), Assam (65.8%), Maharashtra (65.9%), Rajasthan (78.2%), Odisha (67.2%), West Bengal (78.5%), Uttar

Pradesh (61.6%), Gujarat (79.2%) and Telangana (59.8%) soils are deficient in soil S at the threshold limit of < 22.5 ppm (**FIGURE 3.4**). B deficiency is significant in Assam (76.2%), Bihar (63.4%), Jharkhand (74.9%), Odisha (72.2%), West Bengal (64.7%), Karnataka (57.4%), Maharashtra (72%) and Punjab (32.5%) at threshold limit of < 0.7 ppm (**FIGURE 3.4**). There has been a widespread Zn deficiency in the country. However, the Zn deficiency is prominent in Madhya Pradesh (82.9%), Uttar Pradesh (60.6%), Rajasthan (79.9%), Karnataka (50.5%), Chhattisgarh (55.6%), Bihar (53%), Telangana (54.8%), Odisha (54.6%), Maharashtra (58.6%) and Tamil Nadu (45%) at threshold limit 0.9 ppm (**FIGURE 3.5**). Rajasthan (65.6%), Uttar Pradesh (31.3%), Maharashtra (36.4%), Karnataka (26.4%) and Gujarat (43.7%) soils are deficient in Fe at threshold limit <6.5 ppm (**FIGURE 3.5**). Many states' soils also showed multiple nutrient deficiencies, with two-nutrient, three nutrient and up to five nutrient deficiencies. The most frequent combination was S+ Zn deficiency, found on average in 9.3% of sites, ranging from 0.1% to nearly 30% depending on the state. This combined deficiency (S levels < 10 ppm and Zn levels < 0.9 ppm) was predominant in Bihar, Gujarat, Karnataka, Madhya Pradesh, Odisha, Rajasthan, Uttar Pradesh and Maharashtra. Zn and S are known to improve the quality of grains especially in pulses and oilseeds. These multi-nutritional deficiencies indicate a widespread and regionally significant challenge to soil fertility in India. According to recent spatial variability maps (adopted from AICRP on MSPE report of IISS Bhopal), 67.4%, 47.1%, 42.1% and 15.3% soils of India are deficient in plant available S (< 10 ppm), B (< 0.7 ppm), Zn (< 0.9 ppm) and Fe (< 6.5 ppm) respectively (Bhoomi Geoportal, 2025).

However, it is notable that the deficiency status of S, B, Zn, and Fe reported by the SHC scheme and ICAR's AICRP on MSPE differs significantly. This discrepancy arises from the different critical deficiency limits adopted by the two agencies. The SHC evaluates soil S and micronutrient deficiency using earlier pot experiment-based critical limits, whereas ICAR-AICRP on MSPE has redefined these limits through multi-location field trials that assessed crop responses to varying soil S and micronutrient levels, thereby establishing a different deficiency range for crops **(TABLE 3.6 *vs* ANNEX TABLE 1)**. The SHC vis a vis ICAR-AICRP MSPE critical limits for S are < 10 ppm and < 22.5 ppm; for B are < 0.5 ppm and < 0.7 ppm; for Zn are < 0.6 ppm and < 0.9 ppm and for Fe are < 4.5 ppm and < 6.5 ppm respectively. AICRP on MSPE approach allows a more precise classification of S and other micronutrient status into acute deficiency, latent deficiency, and deficiency categories. Although the deficiency ratings reported by the two agencies differ, both provide strong evidence of widespread secondary and micronutrient deficiencies in Indian soils.

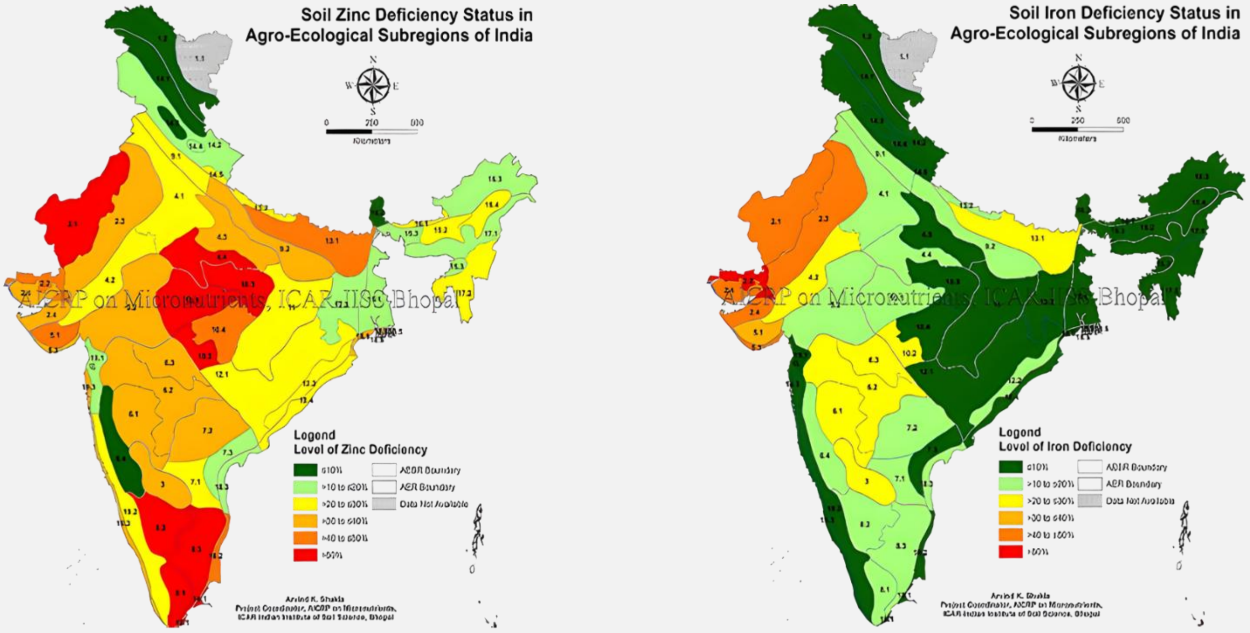
Similarly, in a study of 0.39 million surface soil samples from the farmland of 68 coastal districts of India, the deficiency of S, Zn and B was quite significant. Out of the samples studied, 54%, 49%, 46%, 17% were deficient in S, Zn, B, Fe, respectively as per ICAR's new defined critical limit. This shows that S, Zn and B shortages are the most widespread secondary and micronutrient problems throughout India and are remarkably deficient in the coastal soils (IISS Annual Report 2021).

FIGURE 3.4: AVAILABLE SULPHUR (S) AND BORON (B) STATUS IN INDIAN SOILS



Source: AICRP on MSPE, Shukla et al., 2021

FIGURE 3.5: AVAILABLE ZINC (Zn) AND IRON (Fe) STATUS OF INDIAN SOILS



Source: AICRP on MSPE, IISS, ICAR

ω *CRITICAL LIMIT OF PLANT ESSENTIAL NUTRIENTS IN SOILS AND DEFICIENCY STATUS*

The critical limit approach for soil nutrients refers to identifying the minimum soil nutrient concentration at which a crop will achieve maximum yield without experiencing deficiency symptoms. The statistical method of critical limit estimation was given by Cate and Nelson in 1971. Below the critical limit, crops don't yield its full potential and is considered deficient for nutrients in soil. Over the years, critical limit approach has been adopted by various researchers to find out the fertility status of soil for a particular crop and a nutrient. The critical limit approach is used to set the sufficient limit of any nutrient in soil. For example, a study in the vertosols of Madhya Pradesh, Telangana and Jharkhand for rice has found out the critical limit of K to be 335 kg/ha which is significantly higher than the general critical limit set for K in Indian soils i.e., 280 kg/ha (Singh et al., 2019). The critical limit of plant essential nutrients in different soil types in different states of India as estimated by various researchers through critical limit approach is given in **TABLE 3.7**. From the analysis it is clear that around 30 to more than 50% soil have essential nutrients below critical limit for crops like rice, wheat, groundnut, green gram, potato, etc.

TABLE 3.7: CRITICAL LIMITS OF PLANT ESSENTIAL NUTRIENTS IN SOILS FOR DIFFERENT MAJOR CROPS IN DIFFERENT STATES OF INDIA AND THE DEFICIENCY STATUS[1]

Sl. No	States (Soil type)	Soil Type	Crop	Nutrient (unit)	Critical Limit in Soil	Present Status (Deficiency)	References
1.	Odisha	Red and Laterite	Rice, groundnut, potato	S (mg/kg)	10	5-16 (50% samples below CL)	Sarangi et al., 2018
2.	Odisha	Red and Laterite	Rice, groundnut, potato	B (mg/kg)	Rice= 0.56, Gnut=0.52 Potato= 0.56	5-16 (50% samples below CL)	Sarangi et al., 2016b
3.	Odisha	Red and Laterite	Rice, groundnut, potato	Zn (mg/kg)	Rice= 0.8 Gnut=0.7 Potato= 0.7		Sarangi et al., 2016a
4.	West Bengal	Alluvial	Rice	Zn (mg/kg)	0.75	0.60-0.97 (35% samples below CL)	Mahata et al., 2012
5.	West Bengal	Inceptisol	Rice	P, K, S, B and Zn (Mehlich 3) (mg/kg)	P=14.7 K= 51.2 S=22.9 B= 0.65 Zn= 1.27	P= 3.22-32.5 K= 38.9-327 S= 28.3-82.8 B= 0.33-0.99 Zn= 0.50-1.87 (55, 10, 60, 45, 75% samples below CL for P, K, S, B, Zn respectively)	Seth et al., 2018

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[1] The studies referenced here assess nutrient critical limits for commonly grown crops in India; other elements are not included because data was unavailable at the time of data compilation

Sl. No	States (Soil type)	Soil Type	Crop	Nutrient (unit)	Critical Limit in Soil	Present Status (Deficiency)	References
6.	West Bengal	Alfisol	Rice	P, K, S, B and Zn (Mehlich 3) (mg/kg)	P=8.2 K= 117.3 S=21.9 B= 0.40 Zn= 2.15	P= 4.3-25.4 K= 52.3-260 S= 9.0-34.0 B= 0.16-0.67 Zn= 1.11-3.65 (55, 50, 45, 60, 45% samples are below CL for P, K, S, B, Zn respectively)	Seth et al., 2018
7.	Uttar Pradesh	Alluvial	Rice	Zn (mg/kg)	0.53	0.30-1.30 (35% samples below CL)	Singh and Umashankar, 2018
8.	Madhya Pradesh (Bhopal), Telangana (Jagtial) and Chhattisgarh (Raipur)	Vertisol	Rice and Wheat	K (kg/ha)	335		Singh et al., 2019b
9.	Madhya Pradesh	Vertisol	Wheat	Zn (mg/kg)	0.59	0.2-2 (46% samples below CL)	Tagore et al., 2017
10.	West Bengal	Alluvial and red-lateritic	Wheat	B (mg/kg)	0.53	0.35-1.1 (33% samples below CL)	Saha et al., 2018
11.	Haryana		Wheat	Phosphorus (kg P/ha)	17.38, 22.65 and 35.94 (normal, Ni and Cr polluted soil respectively)		Swami and Singh, 2008
12.	Maharashtra (Rahuri)		Sorghum	Potassium (kg/ha)	557		Meena et al., 2015
13.	Manipur	Acidic soil	Green gram	Phosphorus (kg/ha)	20	9.84-23.50 (55% samples below CL)	Kashyap et al., 2021
14.	Manipur	Acidic soil	Rice	Nitrogen (kg/ha)	257	185-331.06 (48% samples below CL)	Devi et al., 2020

CL= Critical Limit

3.3 TIME SERIES ESTIMATE OF ESSENTIAL NUTRIENTS IN INDIAN SOILS

During the 1920s, the importance of soil fertility evaluation gained recognition in India, as researchers sought to understand the factors influencing agricultural productivity. Several studies were undertaken in this period, but these efforts were largely confined to small, localized areas rather than being conducted on a national scale. Consequently, comprehensive reports or systematic data on soil fertility covering the entire country remains scarce, leaving significant gaps in our understanding of soil health during that era.

After the popularity of soil fertility in India, the Royal Commission on Agriculture (1926) assessed the fertility status of different parts of India and presented a report in 1929. The report stated that nitrogen, P and organic matter were low in some soil types (like red, black and alluvial) but K and lime levels were adequate. While P was not abundant, its deficiency was less pronounced than in other Indian soils (Abrol and Nambiar, 1997). Post-Green Revolution, the emphasis on rapidly increasing productivity through intensive soil farming practices such as HYV, continuous cereal cropping, extensive tillage, heavy use of fertilisers, pesticides and irrigation have led to unbalanced management that accelerated the degradation of soil health and environmental quality (ISSS, 2016).

The nutrient status of Indian soils is analyzed by various scientists at various time periods where the deficiency captured are expressed at district level by Ramamoorthy and Bajaj (1969) and by Ghosh and Hasan (1980). The study carried out by Ramamoorthy and Bajaj with 1.3 million samples collected in early 1960s up to 1967 showed that out of 224 districts, 117 districts out of 224 districts studied reported low available N levels (<280 kg/ha), out of 226 districts, 106 districts were low in P (< 10 kg/ha) and out of 184 districts, 36 districts were low in K (< 120 kg/ha). Similarly, the study reported by Ghosh and Hasan in 1980s observed 9.2 million samples collected from 365 districts of India. Out of the districts, 95.1% districts were deficient in available N (< 560 kg/ha). The soil nutrient status given by Motsara in 2002 took 3.62 million samples into consideration collected during 1997-99 from all over India. The analysis report presented that 63% samples were low in available N (< 280 kg/ha), 42% samples low in available P (< 10 kg/ha) and 13 % samples were deficient in available K (< 120 kg/ha). Though an all-India level analysis was carried out in the above three studies, the status cannot be compared over time for various reasons like change in cropping pattern, management practices, change in climatic pattern, occurrence of natural calamities, etc., as suggested by various soil scientists as well (Motsara, 2002b; Tandon,1986). This imposes the limitation of comparing the historical data with the present SHC data as the above-mentioned factors affect the dynamics of nutrients in soil (EnviStats India-2024, MoSPI; Tandon, 1986). However, the consistency of deficiency reported and poor nutrient levels is clear from these reporting.

The time series analysis of available K carried out by Ramamurthy et al. (2017) where the available K status of 4.5 million soil samples from various states of India during the early 1970s (Ghosh and Hasan, 1976) are compared with 11 million soil samples collected during 1997-99 (presented by Hasan and Tiwari, 2002). The general trend of available K was analyzed where available K content below 108 kg/ha was low, 108-280 kg/ha was medium and K content above 280 kg/ha was categorized as high. The study showed that the available K status in Indian soils had declined, shifting from medium and high levels in early 1970s to medium and low levels by 1999. A similar pattern of decreasing available K has been observed in several benchmark soils by Bansal et al. (2002) where 1000 benchmark soils from 0-15 cm depth were studied in 10 years interval during 1997 across different states. A study conducted by ICRISAT between 2002 and 2006 analyzed 3,622 soil samples from farmers' fields in watershed areas across Andhra Pradesh, Karnataka, Tamil Nadu, Rajasthan, Madhya Pradesh and Gujarat to assess soil fertility in India's dryland regions. The results showed widespread deficiency of available and low to moderate levels of available P, while K levels were generally adequate (Sahrawat et al., 2007). Another set of soil analysis was carried out by ICRISAT to evaluate the nutrient content of farmers field soils of semi-arid tropics of Andhra Pradesh, Karnataka, Rajasthan, Madhya Pradesh, Tamil Nadu and Kerala (Wani et al., 2015). Under such program, a total of 0.95 million samples from 0-15 cm depth were collected during 2001-2012. Variable rates of deficiencies were reported in different states analyzed. A high proportion of samples from Andhra Pradesh were deficient in S (< 10 ppm) (79%), B (< 0.5 ppm) (85%) and Zn (< 0.6 ppm) (69%), while deficiencies in K (< 120 kg/ha) (12%) and P (<10 kg/ha) (38%) were relatively lower. Gujarat soils showed particularly high B (100%) and Zn (85%) deficiencies and moderate deficiencies for P (60%) as per the above critical limit. Karnataka's large sample revealed significant deficiencies in organic carbon at threshold limit of <0.5% (52%), P (< 10 kg/ha) (41%), B (<0.5 ppm) (62%) and Zn (<0.6 ppm) (55%). Kerala was notable for severe S (< 10 ppm) (96%) and B (< 0.5 ppm) (100%) deficiencies. Madhya Pradesh and Rajasthan showed high P (< 10 kg/ha) (74% and 45%, respectively), S (< 10 ppm) and B (0.5 ppm) deficiencies. Tamil Nadu exhibited deficiency rates for organic carbon (57%), P (51%) and B (89%) at the same critical limits mentioned above.

To present soil S deficiency, the result of 0.13 million samples analyzed in different soil testing laboratories over 20 years (from 1991 to 2010) was compiled by Dr HLS Tandon at the threshold value of <10 ppm. After the analysis, 42.3% were found deficient in available S (Tandon, 2010). S deficiency was observed in about 70 districts in the 1990s which then increased to nearly 300 districts during 2010s. The deficiency was severe particularly in rainfed and dryland areas. The continuous soil depletion of S due to negative balance and inadequate addition was the reason stated by Tandon (2010).

It is noteworthy that between 1980 and 2008, under the AICRP on MSPE, a total of 0.25 million soil samples were analyzed to assess the status of micronutrients and S across the country. These studies revealed widespread deficiencies of secondary and micronutrients, with Zn deficiency (at threshold limit <0.6 ppm) recorded in 48.6% of samples (Shukla et al., 2014). The AICRP on MSPE report of 2008 also showed a very severe soil Zn deficiency at the above-mentioned threshold limit in Uttar Pradesh, Madhya Pradesh, Bihar and Gujarat (out of 9 states studied) (Singh et al., 2008). In a subsequent phase of the project (2012–2018), approximately 0.24 million soil samples were collected and analyzed for their micronutrient content. The general trend indicated a decline in Zn deficiency from 48.6% to 36.5%, based on the prevailing critical limit of 0.6 ppm for available Zn (Shukla et al., 2014) which after re-evaluation of the critical limit to 0.9 ppm, showed Zn deficiency in 50% of soil samples (Shukla et al., 2021), a considerably higher proportion than indicated earlier. This critical limit had been originally established through controlled pot experiments (Takkar et al., 1989) and was later reconsidered in view of results generated from on-farm trials conducted under farmers' field conditions. These field-based studies have led to the formulation of revised standardized critical limits, wherein a soil sample with available Zn below 0.9 ppm is now categorized as deficient (Shukla et al., 2014).

Despite these scientific revisions, the SHC scheme employs the older 0.6 ppm threshold that underestimates the actual extent of S and micronutrient deficiency. For example, SHC reports S, B, Zn and Fe deficiency in 25%, 45%, 35% and 24% soil samples against around 50% deficiency in case of S, B, Zn and around 25% deficiency in Fe as per ICAR-MSPE soil deficiency reporting respectively. Applying the revised critical limits to SHC reporting would definitely reveal a more pronounced deficiency of Zn and other essential nutrients especially Fe, S and B in the country.

As a reason for poor soil nutrient status, various long-term fertiliser experiments conducted by ICAR-AICRP on LTFE across diverse cropping systems and soil types consistently demonstrate that imbalanced fertilisation, such as the sole application of N without P and K, leads to a decline in the available P and K levels of soil at most experimental sites **(TABLE 3.8)**. For example, in the sorghum-wheat system at Akola and rice-wheat system at Pant Nagar, available P and K content decreased significantly under imbalanced nutrient application compared to initial soil values. While available N generally showed an increase compared to the initial status (such as at Akola, Jabalpur, Ludhiana), the N levels remained deficient according to crop requirements. This indicates that imbalance fertilisation i.e., continuous sole N fertilisation without balanced replenishment of P and K depletes the soil reserves of these essential nutrients. Neglecting phosphatic and K nutrition weakens soil fertility and health and undermines the plant's natural defense system, reducing its resistance to both biotic and abiotic stresses. P and K are pivotal for root vigour, energy transfer, enzyme activation and stress tolerance, and their deficiency leads to weakened plants, susceptible to diseases and environmental extremes, inferior grain quality and significantly reduced yields. Thus, there is a critical need for balanced and integrated nutrient management practices to maintain long-term soil health.

Nutrient budget that represents the balance sheet between nutrient inputs (fertilisers, manures, deposition, etc.) and outputs (crop uptake, erosion, other losses) in a soil-crop system, is estimated by researchers to capture the nutrient build up (surplus) or mining (deficit) in the system. A detailed study conducted by Pathak et al. (2024) estimated the N, P and K nutrient budgets of Indian soils for five decades from 1970 to 2018 using equation based empirical models. The nutrient budget was calculated as the difference between nutrient inputs such as inorganic fertilisers, manure, biological fixation, atmospheric deposition, crop residue and seeds; and outputs, including crop uptake and losses from soil through various pathways like leaching, volatilization, erosion and fixation.

TABLE 3.8: IMPACT OF LONG-TERM IMBALANCED FERTILISATION ON SOIL PRIMARY NUTRIENT CONTENT OBSERVED THROUGH FIELD EXPERIMENTS

Study site	**Soil Type**	**Years of experiment**	**Cropping system**	**Available Nitrogen**		**Available Phosphorus**		**Available Potassium**	
				Initial	100% RDN	Initial	100% RDN	Initial	100% RDN
Akola	Vertisol	20	Sorghum-Wheat	120	232	8.4	8.1	358	204
Coimbatore	Vertisol	43	Finger Millet Maize	178	178	11	10.12	810	493
Jabalpur	Vertisol	34	Soybean-Wheat	193	204	7.6	10.3	370	243
Ludhiana	Mollisol	40	Maize-Wheat	87	112	9	17.6	88	89
Pant Nagar	Mollisol	40	Rice-Wheat	392	226	18	9.93	125	89
Parbhani			-	216	199	16	10.26	766	664
Pattambi	Alfisol	19	Kharif rice-Rabi rice	-	-	15.57	8.79	173	49
Raipur		20	Rice-Wheat	236	213	16	8.38	474	386

RDN= recommended dose of N

Source: Singh et al., 2019a

The results for 2010 reveal a net positive balance for N (+1.16 Mt), whereas P and K showed persistent negative balances (-0.06 Mt and -5.27 Tonnes respectively), indicating significant depletion of these essential primary nutrients from Indian soils (Pathak et al., 2024). This negative balance for P and K is likely explained by the persistent imbalance in fertiliser application, with more attention to N application. As observed from ICAR's LTFE, omission or suboptimal application of P and K fertilisers lead to consumption of native P, K from soil to fulfil the plant requirement, leading to its depletion from soil system. The constant imbalance led to deterioration of soil health and reduced nutrient supplying capacity. It is crucial to note that several sources have pointed out about a significant amount of nitrogenous fertiliser being diverted to non-agricultural sectors and across border in India[1], thereby rendering the calculated N balance an overestimate (Economic Survey, 2015-16; Cost of Cultivation Survey, 2012-13). While Pathak et al. (2024) provides equation-driven analysis which is a comprehensive overview of primary macronutrient balances in Indian croplands, its outcomes are not directly comparable to real-time SHC data, as the latter reflects actual field variability and diagnostic analyzes, unlike empirical simulation outputs.

3.4 KEY FINDINGS FROM SOIL HEALTH ANALYSIS

India has endured persistent nutrient deficiencies in its agricultural soils over several decades, a phenomenon substantiated by comprehensive empirical evidence. SOC concentrations are predominantly suboptimal, with assessments from the ICAR- NBSS & LUP's report and SHC programs indicating that 73–76% of soils register below the pivotal 0.75% threshold requisite for soil fertility and biological functionality and around half of the soil samples fall register low SOC levels (i.e., < 0.5% SOC). N deficiency prevails ubiquitously, over decades. The statement is supported by the fact that <5% of districts in historical evaluations and < 10% samples in recent analyses by Chaudhari (2019) and across all SHC cycles (cycle I, II, 2024-25) show sufficient level of soil N (> 560 kg/ha). The persistent low levels of available N in Indian soils stem from the suboptimal SOC concentrations prevalent across most agricultural landscapes, as SOC inherently bolsters the soil's nutrient retention capacity—particularly for N—by mitigating losses through mechanisms such as volatilization, leaching, and denitrification. Along with N, the poor levels of P and K are of much concern. Of particular concern is the rampant mining of P and K attributable to insufficient nutrient replenishment, manifested in cumulative negative balances of -0.06 tonnes for P and -5.27 tonnes for K during 1970–2018. The overexploitation of soil P and K caused due to insufficient nutrient input is also evidenced from the reports of ICAR'S LTFE which advocates an annual P and K mining of 2.7- 34.2 kg/ha/yr and 85- 261 kg/ha/yr (Singh et al., 2019a). Deficiencies in secondary nutrients such as S (< 10 ppm) which expanded from 70 districts in the 1990s to nearly 300 by the 2010s (Tandon, 2010) further delineate this crisis. Analysis of approximately 0.25 million soil samples from the AICRP-MSPE, collected between 2012 and 2018, revealed widespread deficiencies: 58.6% of soils lacked S (using a revised threshold of 22.5 ppm), 44.7% were B deficient (0.7 ppm), and 51.2% showed low Zn levels (0.9 ppm). By contrast, SHC I (2015–17), based on 25.4 million samples and older limits (<10 ppm for S, <0.5 ppm for B, <0.6 ppm for Zn), reported S deficiency in 58.2% of samples, B in 7.3%, and Zn in 45% discrepancies likely due to differing sampling sites or critical thresholds that warrant further scrutiny. In Cycle II (2017–19), B deficiency persisted at 40.2% across 24.5 million samples (threshold: 0.5 ppm) justifying a robust nutrient short fall across the nation at present scenario. It is notable that updating SHC's critical limit as per new revised ICAR's threshold standard would even enlarge the sample size having deficient amount of secondary and micronutrients justifying the criticality of the prevailing situation.

4

CAUSES OF SOIL HEALTH DEGRADATION IN INDIA

From the moment a seed is sown, the unseen world beneath our feet dictates the fate of our crops—and, ultimately, our food. This hidden realm, brimming with nutrients, water, and an astonishing diversity of life, determines what we eat and how well our ecosystem's function. Yet across the globe—and most notably in India—this vital resource is fading, becoming a silent crisis that demands our attention. Soil degradation is a major but largely neglected global problem that threatens agricultural productivity, food security, and ecosystem health. Around one-third of soils worldwide are degraded (Soil Atlas, 2024). Every year, billions of tonnes of fertile topsoil are lost globally. The extent and severity of soil degradation are influenced by both natural processes which we call the geogenic factors and human activities i.e., anthropogenic factors, with human-induced factors being particularly significant.

4.1 GEOGENIC FACTORS

A seminal 2015 paper in the Indian Journal of Fertilisers by ICAR scientists A.K. Patra, N.K. Lenka and A.K. Biswas, identified several key drivers that accelerate soil health decline. Among the natural processes driving soil degradation, widespread soil erosion stands out as the most severe and alarming factor, stripping away the fertile topsoil that sustains agricultural productivity. The loss of this nutrient-rich layer directly reduces land productivity, hampers crop yields and accelerates environmental challenges such as water pollution and climate change. India accounts for nearly 104.2 million hectares (Mha) of arable land area which is degraded (NAAS, 2021). Out of 120.4 Mha degraded land (out of total geographic area), soil erosion accounts for the bulk of degradation, a massive 94.6 Mha, broken down into 82.6 Mha from water-induced erosion and 12.0 Mha from wind erosion. This means that the majority of degradation in the country is due to soil being literally washed or blown away. Recent estimates underscore the gravity of the issue. As per N. K. Lenka, Principal Scientist and Head of the Soil Physics Division at ICAR-IISS, of the country's total geographical area of 360 Mha, 115 to 120 Mha is already degraded. On average, India loses about one millimetre of topsoil annually due to erosion, translating into an alarming 16.4 tonnes per hectare per year. This means that over 5.3 billion tonnes of soil are lost every single year, carrying away around 5.4-8.4 Mt of plant available nutrients essential for crop growth (NAAS, 2021). To put this into perspective, the national mean annual potential soil loss is 21 t/ha per year, far exceeding the sustainable threshold of 5–12 t/ha per year. In other words, Indian soils are eroding nearly twice as fast as they can regenerate, creating a widening gap that threatens the foundation of agriculture. Nearly 29% of the total eroded soil is permanently lost to the sea, while 61% is simply transferred from one place to another and the remaining 10% is deposited in reservoirs (Bhattacharyya et al. 2015).

This accelerated erosion has cascading effects on food security, water resources and climate stability. Sediments from eroded soil choke rivers and reservoirs, reducing water quality and storage capacity, while nutrient depletion forces greater dependence on chemical fertilisers disrupting soil ecosystems. If left unchecked, soil that is currently marginal could become completely unfit for cultivation, posing a serious risk to agricultural sustainability and rural livelihoods.

Soil erosion occurs when dirt is left exposed to strong winds, hard rains and flowing water. In some cases, human activities, especially farming and land clearing, leave soil vulnerable to erosion. For example, when farmers till (plow) the soil before or after growing a season of crops, they leave it exposed to the elements for weeks or months. The overgrazing of farm animals like cattle and sheep can leave large areas of land devoid of ground-covering plants that would otherwise hold the soil in place. Another practice that has devastating consequences for soil health is deforestation, particularly clearcutting, a widespread practice of the industrial logging industry. When trees are cleared away, the land is left exposed to wind and rain without the security of roots to prevent the soil from being swept away. Climate is a major driver of erosion. Changes in rainfall and water levels can shift soil, extreme fluctuations in temperature can make topsoil more vulnerable to erosion and prolonged droughts can prevent plants from growing, leaving soil further exposed (Keith Mulvihill, 2021).

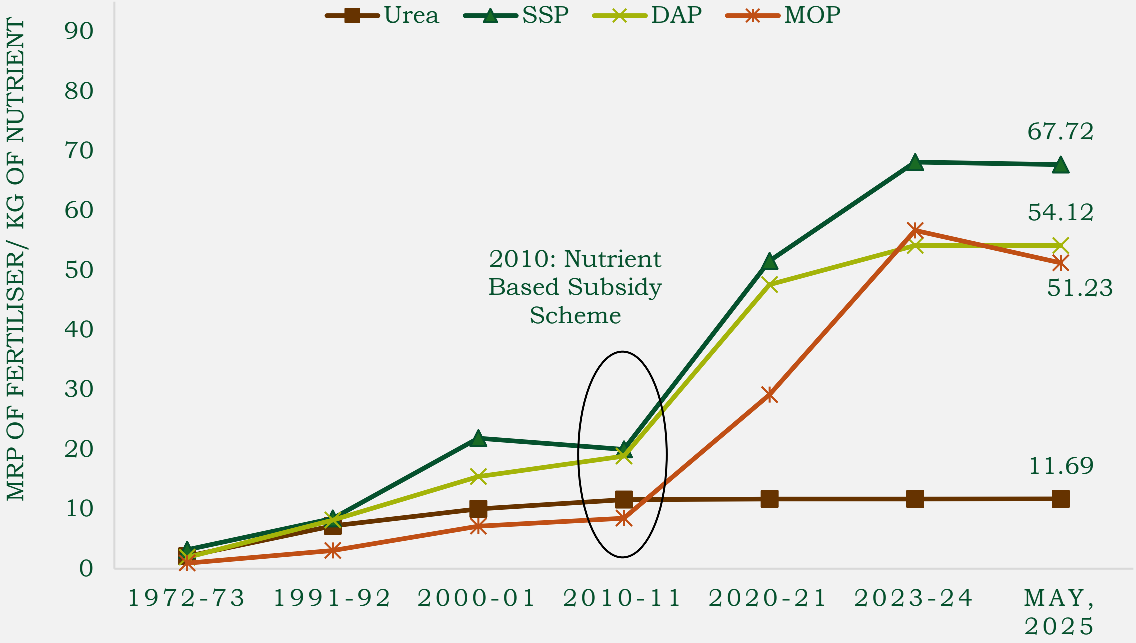
As highlighted above, natural forces like wind erosion, water erosion, desertification and climate change make soil vulnerable to degradation. However, human interventions intensify this process, with one of the most critical factors being the imbalanced use of fertilisers, driven largely by distorted fertiliser pricing in India.

4.2 DISTORTED FERTILISER POLICY AND NUTRIENT IMBALANCE

India’s fertiliser sector operates under heavy subsidization, with subsidies reaching INR 1.88 trillion, accounting for nearly 4.5% of the Union Budget in 2024-25 (Revised Estimate). The roots of this subsidy system can be traced back to the Retention Price Scheme (RPS) introduced by the Government of India in 1977 in response to the global oil crisis (Ministry of Chemicals and Fertilisers, 2020). Under this scheme, the government compensated manufacturers for the gap between the cost of production and the statutorily fixed sale price.

In 1992, the prices of P and K fertilisers were decontrolled. To encourage balanced nutrient application, the government introduced price concessions for products like diammonium phosphate (DAP), mono-ammonium phosphate, and NP/NPK complex fertilisers (Sharma, 2014). In 2003, the New Pricing Scheme (NPS) replaced the RPS for urea, linking the subsidy to the type of feedstock used in its production. Further reforms came in 2010 with the Nutrient Based Subsidy (NBS) Scheme, which provided subsidies based on the nutrient content (N, P, K, S) of fertilisers. However, urea pricing remained untouched due to its political sensitivity and concerns over feasibility. As a result, despite multiple policy shifts since 1977, urea continues to be the most heavily subsidized fertiliser in India. Notably, subsidy on urea has never been withdrawn (Sharma and Thaker, 2010). Currently, around 80–85% of urea's production cost in domestic plants is subsidized, compared to ~45% for phosphatic fertilisers (calculated based on import parity price) and a mere 5% for K fertilisers (Kharif, 2025). This distorted pricing structure has created a significant price disparity between urea and other N, P and K fertilisers, fuelling the excessive use of urea for decades. As shown in **FIGURE 4.1**, urea prices have remained almost flat, while prices of P and K fertilisers have escalated because their subsidy adjustments did not keep pace with the rising production costs. The Maximum Retail Price (MRP) of DAP, which was once about double that of urea, is now over five times higher due to the flawed implementation of the NBS policy (2010). Similarly, the price ratio of Muriate of Potash (MOP) to urea shifted from 1:1 to nearly 5:1 after NBS was introduced.

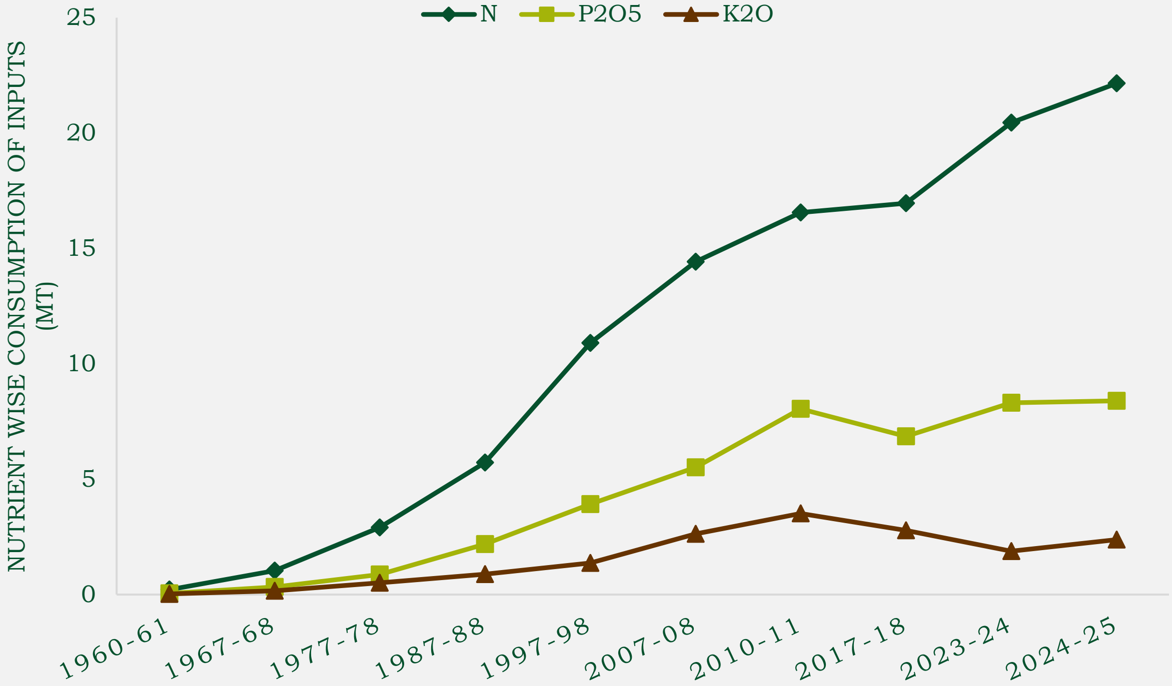
FIGURE 4.1: MAXIMUM RETAIL PRICE OF FERTILISER PRODUCTS PER UNIT OF NUTRIENTS



Source: FAI, Fertiliser Statistics Report, 2023-24

As a result, over the decades, there has been a significant transformation in nutrient consumption patterns in India, with a strong skew toward N use. Farmers often apply nitrogen-based fertilisers, especially urea, in large amounts, assuming more N leads to more yield. As can be seen from **FIGURE 4.2**, N consumption showed a steep and consistent rise. On the contrary, P (P_2O_5) and K (K_2O) consumption increased at a much slower pace and remains significantly lower than N, thus exacerbating the problem of nutrient imbalance resulting in undesirable environmental consequences.

FIGURE 4.2: NUTRIENT WISE FERTILISER CONSUMPTION IN INDIA



Source: FAI, Fertiliser Statistics Report, 2023-24

The fertiliser pricing policies implemented at different points in time have significantly influenced the N:P:K consumption pattern in Indian agriculture (**TABLE 4.1**). Price distortions arising from these policies have led to an imbalanced use of nutrients, as farmers' choices are highly sensitive to relative fertiliser prices. The N:P:K ratio widened notably following the partial decontrol of fertilisers during 1992, when urea remained heavily subsidized compared to phosphatic and K ones, making urea relatively cheaper. A similar trend was observed after the introduction of NBS policy in 2010, when the N:P:K ratio increased from 4.3:2:1 (2009-10) to 8.2:3.2:1 (2012-13). These shifts collectively resulted in a skewed N:P:K ratio, reflecting the direct impact of policy induced price signals on nutrient consumption patterns.

TABLE 4.1: ALL INDIA CONSUMPTION RATIO OF N AND P_2O_5 IN RELATION TO K_2O (N:P:K RATIO)

Year	**N: P_2O_5: K_2O**
1960-61	7.3:1.8:1
1967-68	5.5:2:1
1977-78	5.8:1.7:1
1991-92	5.9:2.4:1
1992-93	9.5:3.2:1
1997-98	7.9:2.9:1
2007-08	5.5:2.1:1
2009-10	4.3:2:1
2012-13	8.2:3.2:1
2023-24	11.8:4.6:1
2024-25	10.9:4.4:1

Source: Fertiliser Statistics Report, 2024-25, FAI

The nutrient imbalances are especially evident at the state level, with some regions, notably Punjab, Haryana and Rajasthan, exhibiting alarming disparities. Punjab is a classic example where the N, P and K balance has gone for a toss. Compared to recommended doses, as per the package of practices given by Punjab Agriculture University (PAU), Punjab is using 61% more N than is needed, 89% less K, and 8% less P. Similarly, Telangana is overusing N by 54% but 82% less K, and 13% less P. The situation in other states is also similar (**TABLE 4.2**). As a result, farmers see a lot of greenery on their farms, due to the high use of N, but not enough grain due to relatively lower doses of P and K. The highly imbalanced use of N, P and K, and the neglect of micronutrients, leads to suboptimal results on agricultural productivity and affects farmers' profitability that leads to significant environmental damage, a situation largely driven by the current fertiliser subsidy policy. Considering, the NUE of current nitrogenous fertiliser in Indian agriculture is around 35-40%. The rest of the fertilisers' quantity, especially N, is going into the atmosphere as nitrous oxide, which is 273 times the global warming potential of carbon dioxide. It also leads to soil acidification and loss of microbial activity. The leached nitrate can contaminate the groundwater and volatilized N (as GHG) acts as a factor of global warming.

TABLE 4.2: DEVIATION IN PER HECTARE NPK CONSUMPTION FROM RECOMMENDED DOSE IN STATES OF INDIA (2022-23)

States	**Recommended dosage of fertilisers (kg/ha)**			**Actual dosage of fertilisers (kg/ha)**			**% Deviation**		
	N	P	K	N	P	K	N	P	K
Punjab	118	51	33	190.4	47.1	3.7	61%	-8%	-89%
Haryana	124	46	34	159.2	43.8	3.7	28%	-5%	-89%
Uttar Pradesh	125	57	40	144.3	45.1	4.4	15%	-21%	-89%
Rajasthan	69	42	15	50.6	18.9	0.5	-27%	-55%	-97%
Bihar	112	53	39	163.5	50.4	11.3	46%	-5%	-71%
Assam	57	32	54	45.8	12.7	7.4	-20%	-60%	-86%
West Bengal	100	54	59	83.4	46.9	27.9	-17%	-13%	-53%
Andhra Pradesh	104	53	51	144.7	74.1	20	39%	40%	-61%
Telangana	91	47	45	140.5	53.2	8.2	54%	13%	-82%
Madhya Pradesh	67	54	27	60.8	30.5	2.5	-9%	-44%	-91%
Maharashtra	69	52	40	64.1	37.3	11.9	-7%	-28%	-70%

Deviation from RDF

🟩 50% and more	🟧 -20 to -50%
🟩 20-50%	🟥 -50% and lower
🟨 -20 to 20%	

Source: Fertiliser Statistics 2022-23 and CRISIL Forthcoming Report

Despite excessive N application compared to P and K, creating a skewed N:P:K ratio, the actual availability of N in the soil remains low due to multiple loss pathways and declining SOC content. Over application and inefficiencies result in poor N utilization across India's agricultural system. Ironically, massive subsidies on urea are doing more harm by polluting the atmosphere than boosting crop yields. Adding to the problem, 20-25% of urea is reportedly diverted to non-agricultural uses or smuggled into neighbouring countries. This unsustainable practice must end.

The heavy reliance on synthetic nutrients, combined with indiscriminate and excessive use of pesticides, fungicides and herbicides, often without considering crop or area specificity, harms beneficial soil microbes, disrupts natural pest predators and fosters pesticide resistance. The cultivation of nutrient-intensive crops accelerates the depletion of essential soil nutrients, leading to nutrient mining. This occurs when the amount of nutrients removed during crop harvest exceeds the quantity replenished in the soil. Nutrient mining is a key factor behind the severe NPK imbalance observed in India. Timely replenishment of harvested nutrients is critical for maintaining soil fertility and ensuring sustainable productivity.

4.3 FAULTY SOIL AND CROP MANAGEMENT PRACTICES

INTENSIVE TILLAGE AND PUDDLING IN RICE CULTIVATION

Improper land use exacerbates the nutrient loss and physical constraints like soil sealing, compaction, hard pan formation, etc. Excessive pedoturbation through tillage induces loss of SOC and threatens microbial biodiversity. Continuous ploughing loosens soil structure, making them prone to erosion. Intensive tillage causes substantial soil disturbance, accelerating the decomposition and loss of native SOC (Chowaniak et al., 2020; Haddaway et al., 2017). SOC plays a pivotal role in enhancing soil fertility, nutrient availability, and overall nutrient content, so its depletion severely undermines soil health and productivity. Additionally, puddling and prolonged water stagnation in rice cultivation promote anaerobic conditions that drive high methane emissions while facilitating N losses via nitrate leaching and denitrification (Buresh et al., 1993). Along with the nutrient losses, repeated puddling of soil destroys the soil structure by breaking aggregates, promotes hardpan formation and reduces permeability in subsequent crops there by restricting root growth and microbial activity (Jat et al., 2019; Pandey et al., 2012).

LACK OF CROP ROTATION AND DIVERSIFICATION

Monocropping and inappropriate crop rotation practices (e.g. cereal-cereal rotation), HYVs without any soil nurturing practices (like organic matter addition and/or residue retention), exhaust specific nutrients, aggravating nutrient mining. Lack of crop diversification and reduced biodiversity is driven by highly subsidized inputs chiefly free power and fertiliser (especially urea) coupled with open-ended procurement of rice and wheat. As a result, rice production has swollen beyond ecological limits, contributing to groundwater depletion (at more than 1.5 feet every year since the last two decades or more), contamination, soil degradation, and increased GHG emissions. What began as a policy for food security has turned into an ecological disaster (Singh et. al., 2024). This is exacerbated by the Public Distribution System, which distributes free rice and wheat to more than 800 million people, while the government claims to have lifted ~248 million people out of multidimensional poverty from 2013-14 to 2022-23 (Niti Aayog, 2024).

This model demands the procurement of some 60 Mt of grains annually to sustain the system, hence it creates a self-reinforcing cycle.

LOSS OF SOC AND MINIMAL USE OF ORGANIC INPUTS

Decline in SOC due to persistent soil disturbance, through high intensity tillage (Bai et al., 2008; Lal, 2006), coupled with residue removal (Yang et al., 2019), crop residue burning (Lal, 2006) is another driving factor of declined soils' capability. SOC loss reduces nutrient-holding capacity, water retention, and microbial activity, weakening soil resilience.

FAULTY WATER MANAGEMENT AND LACK OF SOIL CONSERVATION AND RECLAMATION MEASURES

Water application through flood irrigation causes waterlogging and nutrient leaching, especially in poor textured soils (Surendran et al., 2021; Puy et al., 2017) and causes salinity build up as compared to drip irrigation especially when poor quality irrigation water is used (Kahlon et al., 2008). It reduces water use efficiency and increases irrigation costs (Sharmasarkar et al., 2001). Practices like soil mulching, cover cropping, contour farming are rarely adopted by Indian farmers, leading to soil erosion, poor moisture retention and deep percolation losses. Extreme soil pH generated due to geogenic and anthropogeny causes need soil reclamation measures for optimum nutrient use by crops. However, lack of awareness and unavailability of inputs are often commented on by farmers. Improper pH limits nutrient availability and restricts the plant growth physiologically (e.g., shorter plant roots due to aluminium toxicity under extremely acidic soil).

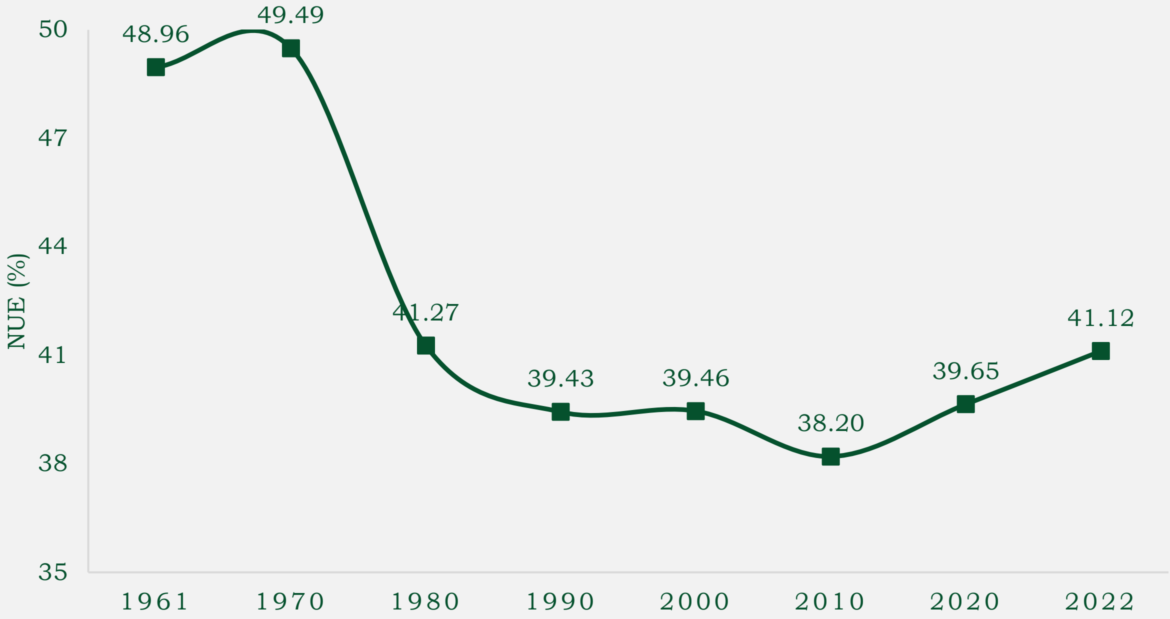
5

IMPACT OF SOIL HEALTH ON CROP HEALTH AND NUTRITION

5.1 FERTILISER RESPONSE RATIO AND NUTRIENT USE EFFICIENCY (NUE)

The NUE is a measure of efficiency of plants to absorb and convert applied nutrients into crop yields or its translocation into the plant parts. A higher NUE implies more nutrient incorporation into plant biomass and less nutrient loss to the environment. However, in India and globally, NUE of N has steadily declined over the past several decades (**FIGURE 5.1**). The NUE showed a gradual declining trend from around 49% in 1961 to 38% in 2010 and increased slightly to 41% in 2022. However, the NUE declined as compared to initiation of green revolution era whereas there are clear evidences of increased N application into crop fields in India (FAOSTAT, 2025). Thus, the over application is damaging the soil and reducing the benefit: cost ratio of farmers.

FIGURE 5.1: NUTRIENT USE EFFICIENCY (NUE) IN INDIA OVER THE DECADES



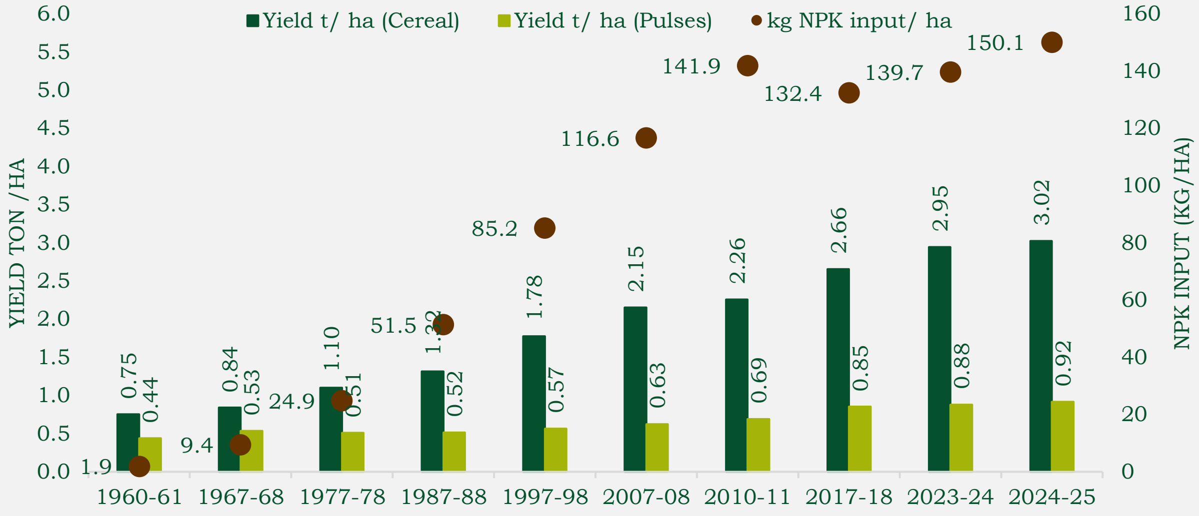
Source: FAOSTAT, 2025

Apart from nutrient use efficiency which is the ratio of nutrient uptake by the crop to the nutrient applied, there are other ways of measuring the nutrient use efficiency. Some of the other techniques are agronomic nutrient use efficiency and physiological nutrient use efficiency. The agronomic nutrient use efficiency (ANUE) measures the increase in yield per unit nutrient input (Yield increase/ nutrient input) whereas the physiological nutrient use efficiency (PNUE) captures the increase in yield per unit increase in nutrient uptake (yield increase/ increase in nutrient uptake) (Kumar et al., 2021; 2015). Studies have also reported that the ANUE of N in rice varied from 18- 28 kg grain yield increase per kg of N input (Mohanty et al., 2023; Kumar et al., 2015; Gupta and Sandhu, 2009). Similarly, a study by Kumar et al (2015) has reported the PNUE of rice in the range of 21-28 kg grain per kg N uptake. Another study by Kumar et al (2021) estimated the ANUE of N in maize around 4 kg grain yield increase/ kg N supplied. However, the ANUE and PNUE are very much variable according to crop type, variety, soil type and climatic conditions.

5.2 FERTILISER CONSUMPTION AND FERTILISER RESPONSE RATIO

Green revolution has encouraged the farmers to apply more of nutrient rich synthetic fertilisers in the field which had gradually increased the crop yield (cereal and pulses) from the unit land; however, the yield increase did not synchronize with the rate of nutrient consumption in a piece of land which is indicated in **FIGURE 5.2**. The fertiliser input has taken a leap from 1960s to 2025 but could not reflect in crop production to the same tune suggesting that the efficiency of added fertilisers is not met as it used to be during the green revolution.

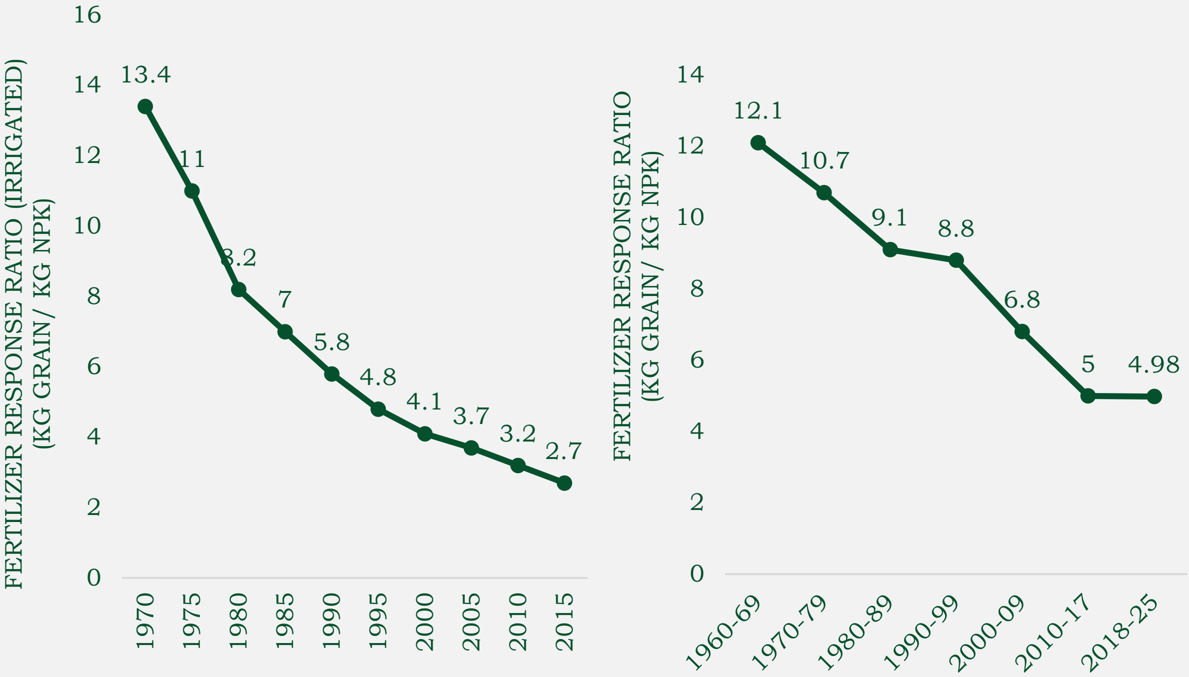
FIGURE 5.2: TREND OF PER HECTARE NPK INPUT VS CEREAL AND PULSE YIELD



Source: FAI, Fertiliser Statistics Report, 2023-24, Annual report 2024-25 (MoAFW), UPAg portal

The aftermath of injudicious application of synthetic fertiliser post green revolution can be explained through overall fertiliser response in terms of crop yield to each unit of added nutrient. The fertiliser response ratio is a measure of kilograms of grain produced per kilogram of NPK fertiliser applied. Studies show that there has been a significant decline in fertiliser response ratio over several decades (Chaudhari, 2019; Chaudhari et al., 2015; Biswas and Sharma, 2008). In the irrigated areas of India, a kilogram of NPK fertiliser input could give 13.4 kg of grain yield in 1970 that steadily decreased to around 7 kg/kg NPK in 1985 (**FIGURE 5.3**). The decline continued into the new century, with the ratio dropping to approximately 4.1 in 2000, 3.2 in 2010, and reaching about 2.7 kg grain/kg of NPK input by 2015 in irrigated regions of India.

FIGURE 5.3: FERTILISER RESPONSE RATIO (KG GRAIN/KG NPK) OVER DECADES IN INDIA



Source: Biswas and Sharma (2008); Chaudhari et al. (2015), Chaudhari (2019) and Katyal (2019)

Similarly, a downward trend in fertiliser response ratio (decadal average) is evident in agricultural system from the observed values, which have progressively decreased from a high of 12.1 kg grain/kg NPK during 1960-69 to 6.8 kg grain/kg NPK during 2000-09 and 5 kg grain/kg NPK during 2010-17 (**FIGURE 5.3**). This falling ratio fundamentally represents that the amounts of grains produced per unit of fertiliser input has declined gradually over the years. In essence, less grain is being yielded for each kilogram of fertiliser applied compared to previous periods. This diminishing return on fertiliser use strongly suggests that the productivity of soil (the capacity of soil to support plant growth and crop production) is declining with every passing year, indicating a potential degradation in soil health and its capacity to support crop growth efficiently.

5.3 IMPACT OF IMBALANCE FERTILISATION ON CROP HEALTH AND NUTRITION

N plays a vital role in plant growth and chlorophyll formation, supporting photosynthesis and protein synthesis. It also induces biosynthesis of Fe transport peptide and Nicotianamine (NA), enhancing Fe and Zn translocation (Kutman et al., 2010; Shi et al., 2010; Shi et al., 2012). Nicotianamine (NA) facilitates phloem loading and translocation of Fe and Zn to grains (Krüger et al., 2002), where N form and concentration significantly influence plant biochemistry.

Apart from reduced use efficiency in grain production, the excessive application of nitrogenous compounds often leads to its over accumulation in plant parts. The nitrogenous give rise to nitrate (NO_3^-) molecules which is prone to leaching and may be added in the ground water and denitrified under reduced conditions like soil submergence. These occurrences lead to nitrate contamination, eutrophication of aquatic ecosystems, nitrous oxide emissions (which are among the strongest greenhouse gases). The excess accumulation of nitrate in water and its uptake by plants potentially affect it keeping quality and nutritional quality. E.g., delayed ripening and excessive softening in plums (Cuquel, et al., 2011), reduced acidity and poor colour development in tomatoes, bitterness and textural imbalances in cucumbers (Wang et al., 2008). High concentration of NO_3^- in plant parts decrease the concentration of ascorbic acid (Vitamin C) in fruits (Rajashree and Pillai, 2012). Vitamin C is known to inhibit formation of carcinogenic nitroso compounds (Mirvish, 1986). It also led to lower sugar and acidity, delayed maturity and increased storage disorders. A similar finding was also documented by Gülüt and Şentürk (2024) where high rates of N increase the concentration of nitrate (NO_3^-) in plant parts, decrease the concentration of vitamin C in fruits and vegetables. In economic terms, these declines in quality directly jeopardize shelf life and market acceptance negatively affecting its nutritional quality (Zhang et al., 2016). It is observed that among the two ionic forms, ammonium (NH_4^+) form improves micronutrient accumulation in grains as compared to NO_3^- form, (Barunawati et al., 2013). Thus, mechanisms to inhibit rate of nitrification of N fertiliser will improve NUE of plants. For example, slow-release ammonium sulphate and organic N source kept leaf nitrate content within safety limits (Gülüt and Şentürk, 2024).

P is also a critical macronutrient that plays an important role in many metabolic processes in plants, including respiration, glycolysis, photosynthesis, energy generation and transfer, nucleic acid biosynthesis, enzyme activation/inactivation, carbohydrate metabolism, N fixation, protein synthesis, membrane synthesis, etc. (Plaxton and Tran, 2011). Being a key component of adenosine triphosphate (ATP) that drives energy transfer necessary for metabolic functions. It forms a structural part of DNA and RNA, supporting cell growth and reproduction, thereby influencing the development of grains, fruits, and overall plant productivity. Its deficiency also affects the photosynthesis and stress resistance of plant (Khan et al., 2023; Wissuwa et al., 2005). In tobacco and cotton plants, the leaves develop an abnormal dark green colour due to carbohydrate accumulation in the leaves. Maize leaves develop purplish red margins, brown spots are observed in potato tubers due to P deficiency (Lagat, 2015). It also regulates carbon metabolism and contributes significantly to the biochemical processes determining fruit and vegetable quality. The application of P fertiliser enhances fruit sweetness and sensory attributes by modulating sugar metabolism, particularly through its influence on sucrose dynamics (Wu etal., 2021) and delay fruit ripening (Abobatta and Alla, 2023). During the early stages of fruit development, P supply promotes the hydrolysis of sucrose into fructose and glucose but at mid and late stages, P enhances sucrose resynthesis through biochemical pathways. This coordinated regulation increases soluble sugar accumulation and improves the total soluble solids to titratable acidity ratio, contributing to higher fruit sweetness in citrus fruits and tomato (Li et al., 2021; Wu et al., 2021). Collectively, these effects indicate that P enhances sugar accumulation and supports optimal vitamin C formation, improving the overall nutritional and sensory quality of fruits and vegetables.

Similarly, P deficiency and suboptimal P fertilisation consistently exert a negative influence on plant growth, development and physiological characteristics across diverse cropping systems. When the supply of P falls below optimal levels, plants experience a marked reduction in biomass accumulation, diminished root volume, decreased shoot length and lowered rates of photosynthesis, leading to significant yield losses. This insufficient nutrient availability suppresses P uptake and adversely affects the absorption and utilization of other critical nutrients such as N, K, Ca, and Mg, compounding the problem by lowering the overall nutrient content and nutritional quality of plant tissues. Such imbalances commonly lead to poor produce quality and decreased resilience of crops to environmental stresses like drought, heat, salinity and disease attack.

In the long term, persistent omission or suboptimal application of P fertiliser results in the depletion of soil-available P reserves, a steady decline in soil fertility status, and, in many regions, causes cumulative yield reductions in sequential cropping cycles. These impacts on plant architecture, physiology, and chemistry have been systematically documented in studies and meta-analyzes (**TABLE 5.1**), firmly establishing P as essential for maximizing the yield and quality of produce in major agricultural systems worldwide.

TABLE 5.1: EFFECT OF PHOSPHORUS DEFICIENCY AND NO PHOSPHORUS APPLICATION ON PLANT GROWTH AND NUTRITION

No.	Crop (Type of study)	Location	Effects on plants	Reference
1	Wheat, Rice, Maize, Potato, Cotton, Soybean (Review)	Across globe	Delayed flowering, lower nutrient uptake; poor root and leaf development, lower yield and seed production, low biomass, increased susceptibility to abiotic stress (drought, salinity)	Khan et al., 2023
2	Tef (Field experiment)	Amhara Region, Ethiopia	On optimum P addition, grain yield increased by 7.5-8.5%ut P; reduced plant height and grain yield in no P added plots	Melak et al., 2024
3	Rice (Field experiment)	Liaoning Province , China	Plant P deficiency led to significantly decreased P uptake by plant parts, poor root morphology reduced grain yield and quality	Liu et al., 2024
4	Pummelo	Fuzhou, China	Reduced growth of plant parts, reduced absorption of N, K, Mg, Ca, photosynthetic efficiency, increased reductive oxygen species production, stunted growth,	Meng et al., 2021
5	Wheat, maize, soyabean, mustard (meta-analysis from 39 studies)	Germany, United States, Canada, China, Africa	Omission reduced root proliferation, shoot P content, and final yield compared with P-applied plots	Freiling et al., 2022
6	Various crops (Rice, maize, wheat, soybean, potato, onion, sugar beet) long-term (1960-2019)	Across globe	Consistent evidence that omitting P reduces soil test P, depletes reserves over time, and undermines future potential yield and nutrient density	Hopkins and Hansen, 2019
7	Maize grain Long term (1961-2010)	Tribune, Kansas	P alone increased grain yield by 20% and N, P combined increased yield by 225% as compared to no fertiliser. P recovery in plant was 63% 44% with 20 and 40 kg/ha P application.	Schlegel and Havlin, 2017

K plays a dominant role in various enzyme activation in cell. K deficiency negatively affects plant growth, development, yield, and grain quality by impairing several critical physiological and biochemical processes. Insufficient K disrupts key functions such as stomatal opening and closing, and multiple biochemical pathways essential for photosynthesis and nutrient translocation (Gattward et al., 2012). This leads to poor root and shoot development, reduced plant height, and lower leaf area, decreasing crop yield and quality by affecting grain protein content and physical attributes. Moreover, K deficiency compromises plant immunity by impairing hormonal signaling and stress response pathways, making plants more vulnerable to biotic and abiotic stresses (Holzmueller et al., 2007; Cakmak, 2005). Studies reveal that under K deficiency, plants supress the expression of genes involved in hormone activation, pathogen interaction and metabolism (Lu et al., 2023). These disruptions result in reduced productivity and inferior grain quality in crops such as cotton, maize, and mung bean, confirming the essential role of K for optimal plant performance and resilience (Thornburg et al., 2020).

6

IMPACT OF CROP HEALTH ON HUMAN HEALTH AND NUTRITION

Soil health and crop health and nutrition are intrinsically linked to human health and nutrition, serving as the foundation for dietary quality and overall, wellbeing. Plants constitute 90% of the major food source for humans, making the nutritional content of crops crucial.

6.1 NUTRIENT STATUS OF FOODGRAIN AND ITS IMPACT ON HUMAN NUTRITION

There has been substantial reduction in essential micronutrients like Iron (Fe) and Zinc (Zn) in modern high-yielding rice and wheat cultivars compared to traditional indigenous varieties from the 1960s. For instance, a critical investigation by Debnath et al (2023) shows that, Zn and Fe content in rice has declined by approximately 33% (from 19.9 mg/kg to 13.4 mg/kg) and 30% (from 33.6 mg/kg to 23.5 mg/kg) respectively between the 1960s and 2000s. Similarly, wheat saw a 27% decline in Zn and a 19% decline in Fe. This depletion means that the ability of cereals to meet the Recommended Dietary Allowance (RDA) for these crucial minerals is significantly diminishing. For example, the percentage of RDA met for Zn through rice dropped from 33.7% in the 1960s to 15.7% in the 2000s, and for Fe, it declined from 11.2% to 5.6%. Wheat displayed a similar trend where its consumption satisfied 56.9% of an individual’s daily need for Zn and 26.5% of the requirement for Fe during 1960s dropped to 25.5% and 13.7% for Zn and Fe respectively (Debnath et al., 2023). Fe and Zn content of some common rice and wheat varieties are given in **TABLE 6.1**. This reduction is reflected in the declining Mineral Density Quality Index (MDQI) (which is the ratio of essential minerals to toxic mineral concentration in grains). This index offers a numerical assessment of the overall mineral density of crop varieties over time. A higher MDQI score indicates that the crop is beneficial for meeting dietary mineral needs, whereas a lower score indicates depletion and nutritional risk. The MDQI measures the levels of essential minerals and the rise of harmful or less beneficial elements that accumulate when nutrient cycling is not balanced. In the case of rice and wheat, MDQI scores have consistently declined over the decades. For rice varieties specifically, there has been an estimated 77% decrease in MDQI, indicating a significant deterioration in their ability to provide mineral sufficiency. However, polished rice which is a major diet of Indian population, can meet 30% of human estimated average mineral requirement (RDA) if they contain 24–28 mg/kg Zn and 13 mg/kg Fe (Bouis et al. 2011).

TABLE 6.1: IRON AND ZINC CONTENT OF SOME COMMON LAND RACES OF INDIA DURING PRE AND POST GREEN REVOLUTION ERA

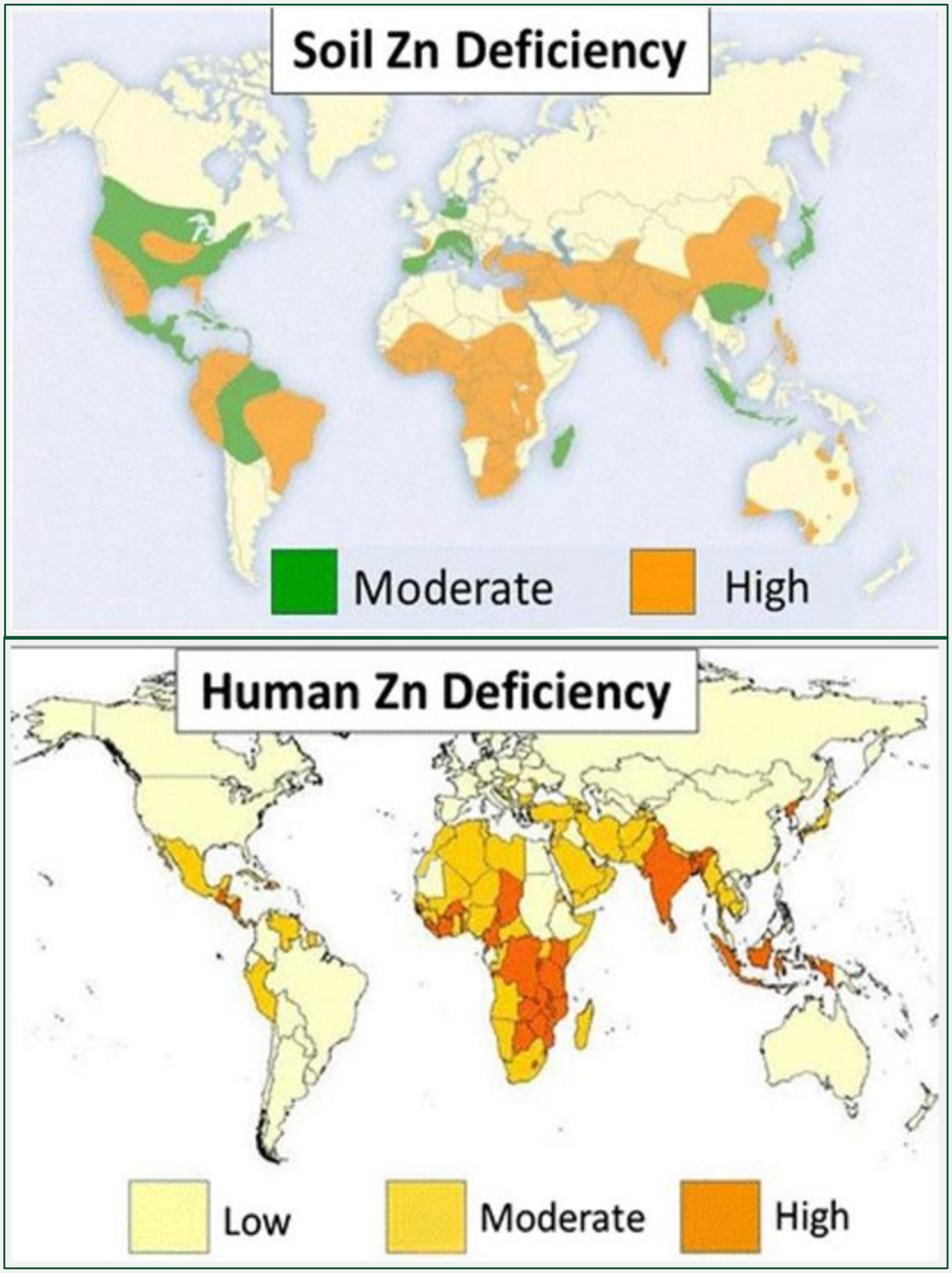
Time line	**RICE**			**WHEAT**		
	Variety	**Iron (Fe)**	**Zinc (Zn)**	**Variety**	**Iron (Fe)**	**Zinc (Zn)**
1960s (Indigenous)	Dular	13.7	33.5	C 306	48.7	43.6
	Mahsuri	11.1-13.3	42.3	Bansi, K65	36.1	38.3
	Kalanamak	14.7-21.3 25.1-30 (brown)	19.8-34.4 (brown)	Malvi	36	27
	Chittimutyalu	16.4-19.8 25.1-30 (brown)	30.1-35 (brown)	-	-	-
2010s (Modern HYV)	Swarna	12.48	10.47	Karan Vandhana	28-32	30-32
	PRH 10	13.03	7.69	PBW 343	25	25
	PB 1121	10.8	10.65	HD 3086	30	30

Sources: Saurabh et al., 2025; Rao et al., 2020; Babu, 2013; Anuradha et al., 2012

6.2 LINKING SOIL NUTRITION WITH HUMAN NUTRITION

The decline in grain Zn density potentially contributes to a situation known as "Hidden Hunger," where individuals consume enough calories but lack essential micronutrients. The International Fertiliser Association (IFA) highlights a direct correlation between micronutrient deficiencies in soils and humans. Globally, about 50% of cereal soils are deficient in Zn, and 30% are deficient in Fe, leading to widespread human malnutrition (Fuge and Johnson 2015). The Food and Agriculture Organization (FAO) reports that around 2 billion individuals suffer from malnutrition (FAO 2013), with Zn and Fe deficiencies being leading factors of illness in the low-income countries (WHO, 2002). Among micronutrients, Indian soils are deficient in Zn (36%) and Fe and which translates into significant health issues like stunting, wasting, weaker immunity, weaker nervous system, anaemia, etc. For example, 16% of pre-school children, 31% of adolescents suffer from Zn deficiency (CNNS report, 2016-18) and 54% Indian population show Fe deficiency with around 57% of women and children being anaemic (NFHS-5 report). A global distribution of Zn deficiency in soil and human body as studied by Cakmak et al. (2017) illustrates a clear geographical overlap between soil Zn deficient regions and intense human Zn deficient region (**FIGURE 6.1**). The correlation suggests that poor soil Zn availability contributes significantly to inadequate dietary Zn intake, and is reflected in human blood serum Zn content. Research further substantiates the correlation between soil and human nutrition showing that increased sufficient soil Zn tests are associated with approximately 11 fewer stunted children per 1000. Similarly, soil Fe availability directly impacts haemoglobin levels (Morton et al., 2023).

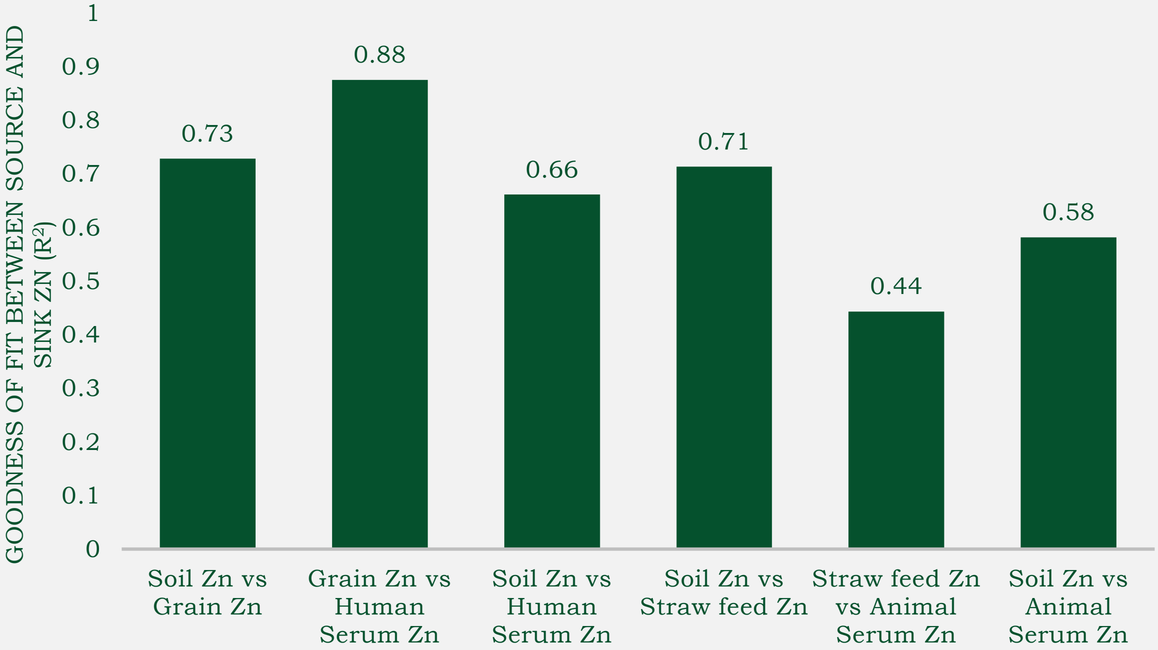
FIGURE 6.1: GLOBAL DISTRIBUTION OF HUMAN ZINC DEFICIENCY AND SOIL ZINC DEFICIENCY



Source: Cakmak et al., 2017

The soil-plant-animal-human continuum for nutrients underscores the systemic impact of soil health. A joint study conducted by AICRP on micronutrients and AIIMS Bhopal reported significant positive correlation between soil Zn levels and grain Zn, human serum Zn, and animal blood serum Zn levels (Shukla et al., 2016) (**FIGURE 6.2**). Balanced nutrition for animals, facilitated by nutrient-rich soil and feed significantly improves the quality of animal produce. This includes enhancements in milk yield, milk fat percentage, and feed conversion efficiency in livestock. These improvements in animal health and productivity contribute indirectly to human nutrition by providing more nutritious animal-derived foods.

FIGURE 6.2: CORRELATION BETWEEN SOIL ZINC LEVEL WITH GRAIN AND ANIMAL SERUM ZINC LEVELS



Source: Shukla et al., 2016

Healthy soil is fundamental to human health. Declining soil fertility and imbalanced nutrient management practices lead to nutrient-deficient crops, contributing to widespread micronutrient deficiencies and "hidden hunger" in humans. Additionally, practices like excessive N application introduce harmful contaminants into the food chain and water sources, leading to various health complications.

6.3 IMPACT OF NITRATE IN FOOD ON HUMAN HEALTH

Essential nutrients have a dominant role in plant structural formation, energy transfer, and many other vital biochemical activities, however availability of all the essential nutrients in proportionate amount is a must for optimum growth and development of plants. Despite the essential role played by N in chlorophyll, nucleotide, protein formation, etc., the over-application of chemical N fertilisers threatens human health through the food and water chain.

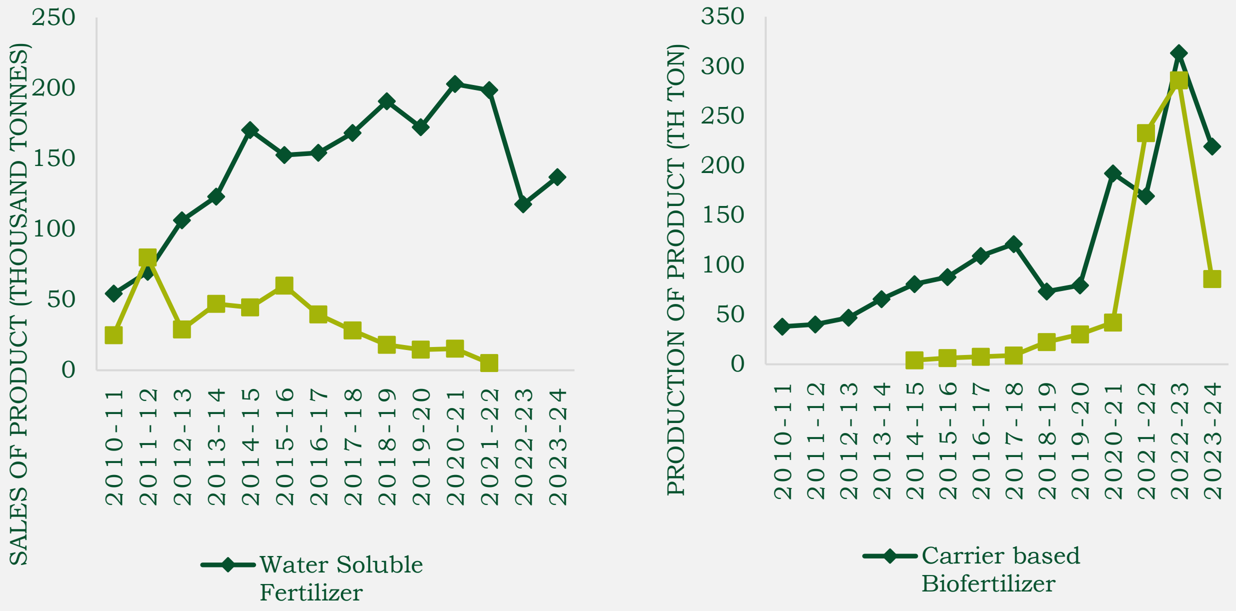
The excessive N fertiliser use can lead to a higher accumulation of nitrate (NO_3^-) which induce health risks directly. For example, accumulation of NO_3^- N in spinach leaves beyond the permissible limit even after 5 days of storage (Gülüt and Şentürk, 2024). Consuming food and water with nitrate levels beyond safe limits (45 mg/L, BIS standard, 2012) is associated with severe health conditions including thyroid issues, carcinogenic effects, neural tube defects during foetus development, diabetes and blue baby syndrome, etc. (Picetti et al., 2022; Karwowska and Kononiuk, 2020; Ward et al., 2018; Ahmed et al., 2017; Ward et al., 2010). As per a review in the World Journal of Diabetes, excess nitrate/nitrate in ground water (40-80 mg/L) is found to increase the risk of type 1 diabetes (Bahadoran et al., 2016). Nitrate contamination in groundwater is a growing concern, with the number of contaminated districts in India rising from 359 in 2017 to 440 in 2023, nearly half of Indian districts (out of 788 total districts in India) have NO_3^- contamination (Annual Groundwater Quality Report 2024, CGWB, GoI).

7

WAY FORWARD TOWARDS IMPROVED SOIL HEALTH FOR BETTER CROP HEALTH AND HUMAN NUTRITION

Since the Green Revolution, India saw huge gains in crop production thanks to chemical fertilisers, HYV seeds and improved irrigation. To maximize yield, fertiliser policies encouraged widespread fertiliser use. But decades of favouring heavily subsidized urea over other essential fertilisers like DAP, TSP, SSP primarily for P and MOP and K sulphate for K have tipped the balance. Farmers apply urea indiscriminately, often ignoring soil type, crop needs and balanced nutrition. This leads to weakening soil health, declining fertiliser response ratio and large swathes of Indian soil showing glaring deficiencies in macro and micronutrients. Also, there is minimal incentive (both market wise and policy wise) for the development, production or adoption of specialized fertilisers (e.g., high efficiency fertiliser products tailored to mitigate micronutrient or secondary nutrient deficiencies and biofertilisers for supplying nutrients and adding organic matter in soil). These are either expensive or not sufficiently subsidized so many farmers avoid them. This entrenches an imbalanced fertiliser use pattern. (**FIGURE 7.1**).

FIGURE 7.1: SALES OF WATER SOLUBLE AND CUSTOMIZED FERTILISERS AND PRODUCTION OF BIOFERTILISERS IN INDIA



Source: Specialty Fertiliser and Micronutrient Statistics, 2023-24, FAI, Biofertiliser Statistics, 2021-22, FAI

In short, the fertiliser pricing regime doesn't just distort markets, it distorts soils, yields and long-term agricultural sustainability. There is an urgent need to realign subsidy policy so that it supports balanced soil nutrition. What makes this realignment powerful is that when subsidy reform is paired with the right products (customized fertilisers, biofertilisers, high efficiency inputs) and sound farming practices, the benefits don't just add up, they multiply. Let us unpack the three "Ps" for soil health i.e., Policy, Products and Practices in details below.

7.1 REALIGNING FERTILISER AND AGRICULTURAL POLICIES

REALIGNING INDIA'S FERTILISER SUBSIDY POLICY

Reorienting fertiliser policy is essential to address the imbalance caused by the current urea-centric system that results in excessive N application while P, K, secondary, and micronutrients are ignored. In India, NUE has dropped to about 35-40% as of recent years, meaning much of the applied N is lost via leaching, volatilization or as nitrous oxide emissions. Nitrous oxide is particularly harmful, with a global warming potential roughly 273 times that of CO_2 over 100 years. The grain to fertiliser response ratio that was about 12:1 in the 1970s has reportedly fallen to 5:1 in more recent decades, indicating diminishing returns on fertiliser inputs. To correct this, policy must shift from blanket fertiliser subsidies toward DBT to farmers' bank accounts matching current subsidy levels but adjusted seasonally (before *kharif* and *rabi*) and according to crop type and irrigation. This will allow farmers to choose balanced fertilisers (enabling them to apply P and K primary nutrients in high demand crops), micronutrients, biofertilisers, and soil-specific formulations, reducing dependency on urea and improving a holistic nutrient use. Deregulating fertiliser prices is also needed as it will reduce the over attractiveness of urea (due to its relatively low price) and curb diversion of subsidized urea to non-agricultural uses or across borders, freeing up government savings. Those savings could then support sustainable practices like fertigation through drip irrigation, organic manuring and rewarding system for lowered carbon footprint in agricultural system. The goal should shift from ensuring food security to achieving nutritional security, climate resilience, and protection of soil, water, air, and biodiversity.

However, a key challenge in operationalizing DBT in this case would be accurately identifying tenant farmers, many of whom are not captured in formal land records. This gap could be bridged by triangulating multiple agricultural data sources—such as official land records, PM-KISAN beneficiary lists, fertiliser sales data, crop sowing information, satellite imagery, and government procurement records—to build a more complete picture of actual land use and tenancy. Advances in artificial intelligence and machine learning could make such data integration feasible and reliable.

A practical "second-best" reform option is to bring urea under the Nutrient Based Subsidy (NBS) regime, as originally intended when NBS was introduced in 2010 for phosphatic and K fertilisers. Under the current structure, urea remains outside NBS and is sold under price control, contributing to its disproportionate use compared with other nutrients. Rationalising the subsidy by lowering support for N (urea) while increasing it for P and K, without increasing the overall subsidy burden would help restore correct price signals. Such a shift could encourage more balanced nutrient application, improving nutrient use efficiency and soil health.

POLICY LEVERS FOR HIGH-EFFICIENCY INPUTS & VARIETY DEVELOPMENT

Policy interventions should promote fortified complex fertilisers, high efficiency fertilisers, slow release and targeted release fertilisers and customized fertiliser mixtures tailored to specific agro-climatic zones to enhance NUE. In efficient nutrient input management, 4R principle justifies alignment of nutrient supply with crop demand and soil conditions. The 4R stewardship, a science-based framework stands for applying the right fertiliser source, at right rate, time, and place/method. Practically this technique enhances nutrient use efficiency through practices like soil testing to determine precise rates, split applications according to crop's peak uptake phases, and targeted placement position essentially via precision tools and technology, minimizing losses from leaching or volatilization. Through 4R principle, decision for customization grades of fertiliser specific to crop needs can be made. Encouraging region specific customized fertilisation ensuring balanced supply of P, K, secondary and micronutrients, while reducing the overuse of a single nutrient especially nitrogen, thereby improving soil health, crop productivity and sustainably. Policy reforms and innovation through research & development and multilocational on-farm trials can incentivize industry to develop region specific products. This will boost farmer adoption by ensuring access to efficient, crop and soil specific solutions.

Policies for streamlining quality standard and licensing procedures for composts, enriched compost, biofertilisers and nano formulations are the need of the hour. Establishing quality testing with easy report access can build transparency building farmers' confidence. This will also prevent entry of duplicate and unauthentic products into the market. Simplification of regulatory norms for product innovation policies can encourage wider production and availability of organic manure and high efficiency fertilisers.

Research for development of various nutrient rich biofortified varieties and stress resistant varieties (disease, pest, salinity resistant varieties, drought tolerant varieties) is required.

POLICIES TO ENCOURAGE CROP DIVERSITY AND SMARTER INPUT USE

The policy of open-ended procurement at minimum support prices (MSP) for certain crops like wheat and rice in Punjab and Haryana has profound effect on farmers' crop choices. Since rice and wheat are essentially "sure bets" under this system, many farmers stick with the familiar rice-wheat rotation, even when soils, water resources or climate would favour more diverse cropping. Part of this problem stems from the Public Distribution System that gives free wheat/rice to more than 800 million people. It has become a chicken and egg problem. Since India has locked itself in free grain distribution, it has to procure roughly 60 Mt of grains each year to feed that system. Thus, policy interventions are needed to regulate this in a manner that avoids mono cropping. Alternate policies should provide opportunity to grow a variety of crops in both irrigated and dry land agriculture areas. Rather than rice-wheat based cropping system, pulses, oilseeds and coarse grains should also be made financially attractive to the farmers. Subsidies for water, power and fertilisers reinforce this bias toward water intensive cereals leading to ecological disaster in these states. So, it is critical that these inputs are priced rationally to conserve resources and avoid side effects of over irrigation. These measures will lead to crop diversification which is in the interest of soil health and nutritional content of food crops.

CAPACITY BUILDING

For long term soil stewardship, converting intensive research to practice and capacity building through policy reform is essential. Establishment of strong soil test based nutrient prescriptions as the default for sale of agricultural inputs is necessary. Proper implementation of soil testing by strengthening the existing soil testing laboratories and creating National Accreditation Board for Testing and Calibration Laboratories (NABL) accredited laboratories in each block in private sector or in public-private partnership mode is essential for accurate recommendations. Similarly, fertiliser testing facilities are inadequate in the country. Expanding these facilities needs to be made in existing state laboratories for latest equipment and qualified manpower. Better farmers' awareness through extensive extension services by state governments, state agriculture universities, Krishi Vigyan Kendra (KVKs) and input suppliers should be more emphasized. The existing programs initiated by the government should be accessed on a regular basis for capturing their efficacy, adoption rates and other technological transformations targeted to be achieved. Creating awareness for sustainable land management practices will improve the soil health and response of crops to added inputs. It can ultimately lead to reduced input requirement and improve the profitability of farmers.

Existing agricultural policies strongly influence farmers' decisions on nutrient inputs, crop selection and land and water management. Hence, revising these policies can improve the flow and availability of critical inputs and shift farmers' mindsets toward adopting more sustainable and efficient management practices.

These policy reforms are key to restoring soil health, preserving groundwater, improving food nutrition, stabilizing yields and making agriculture more climate resilient.

7.2 PRODUCTS FOR IMPROVING SOIL HEALTH

In the past fifty years, due to heavy use of traditional synthetic chemicals and limited use of quality and quantity of organic inputs, poor SOC levels are recorded in agricultural lands. There is a growing need for innovative, highly efficient fertiliser products and quality organic manures that can improve nutrient uptake by plants while simultaneously strengthening soil health and fertility. The phosphatic fertilisers like Single Super Phosphate (SSP), Triple Super Phosphate (TSP), Di Ammonium Phosphate (DAP); K fertilisers like Muriate of Potash (MOP), Sulphate of Potash (SOP); Zn sulphates, Fe sulphates and many other primary, secondary and micronutrient fertilisers should be adopted by farmers according to crop, soil and climate specificity for balanced nutrition to growing plant. Many synthetic fertilisers are the source of more than one essential nutrient e.g., SSP which is majorly used for P also supplies S and calcium to plants. Similarly, triple super phosphate (TSP) is a high analysis P fertiliser (46% P_2O_5) and contains up to 15% Ca. Modern agriculture requires solutions that meet the nutrient demand of crops and reduce nutrient losses, protect the environment, and improve soil structure over time. For example, a meta-analysis of 477 pairwise comparisons of China done by Gong et al. (2024) reported that optimal P fertiliser sources with optimal application rates could improve the maize yield by 22% in high cropping density experiments. The study also reported that use of super phosphates (like TSP, SSP and Ca/Mg phosphates) resulted in higher maize yield with lesser environmental footprints in China.

Some of the most promising products include water-soluble fertilisers, customized fertilisers, nano fertilisers and slow-release fertilisers like urea super granules, coated urea and urea with nitrification/urease inhibitors. Water-soluble fertilisers are almost entirely soluble with minimal insoluble content to avoid clogging in drip irrigation systems. For example, TSP with 46% P_2O_5 highly soluble (>90%), excels for high-P needs in grains and vegetables. Integrating TSP via 4R principles i.e., selecting TSP as the right source for rapid P uptake, applying the right rate based on soil tests and crop demand, at the right time during planting or tillering, and in the right place via banding or deep placement tailored to soil/crop specifics and growth stages can enhance NUE significantly, can also minimize losses in the form of fixation in P-deficient Indian soils or environmental runoffs leading to boosts in yield and better-quality produce. Foliar application of water-soluble fertilisers can curb the nutrient deficiency during critical plant growth stages. These fertilisers give as high as 90% NUE and save water.

Some specialty fertilisers like nano formulations, slow releasing and coated formulations also are important in providing nutrients to the plants as well as up keeping soil health. Nano fertilisers by virtue of their high surface area increase uptake of nutrients to the plants, thus increase use efficiency and reduce leaching losses. Nano formulations like nano urea, nano DAP or nano Zn after careful characterization and field trials can be adopted for specific crops.

BOX 7.1: TRIPLE SUPER PHOSPHATE (TSP) AS AN EFFICIENT SOURCE OF P FOR PLANTS

- TSP contains 46% P_2O_5 making it a richer source of phosphorus for plants than SSP which contains 16% P_2O_5.
- High water-soluble phosphate content of TSP (90% P soluble in water) makes it more efficient for rapid nutrient availability to plants.
- Along with P_2O_5, it contains up to 15% Ca acting as a source of Ca to plants, making it suitable for Ca deficient soils (acidic soils).
- Ca in soil improves soil aggregation through coagulation of soil particles, thereby can prove the physical property of soil.
- Lesser salt index of TSP as compared to DAP makes it a suitable P source in saline and other salt affected soils as it minimizes the risk of salt injury in sensitive crops.
- The low salt index also makes it a suitable choice for arid, semi-arid regions and high P demanding crops without affecting the root zone salt concentration.
- The slightly acidic composition of this fertiliser makes it suitable for neutral and alkaline soils.

Combined application of TSP with microbial mobilizers (like PSM/PSB) or organic manures, improves the phosphorus utilization efficiency. The biological agents enhance the release and uptake of phosphorus in the soil. This makes TSP an excellent source of phosphorus for high nutrient demanding crops, leading to better growth, yield and improved quality of agricultural produce.

Slow-release fertilisers like urea super granules provide N gradually, reducing volatilization and synchronizing nutrient release with crop demand. Coated urea (S coated, polymer coated) delays the dissolution of urea, enhancing N use efficiency and reducing environmental contamination. Nitrification and urease inhibitors (such as NBPT, DCD) slow microbial conversion of urea to nitrate, reducing nitrate leaching and nitrous oxide emissions, thus improving N availability over a longer duration.

In addition to chemical solutions, several organic and biological fertiliser products play a crucial role in improving soil fertility and long-term productivity. Biofertilisers (consortia of microorganisms) such as Rhizobium, Azotobacter, Azospirillum, phosphate and K solubilizing bacteria, organic matter decomposers fix atmospheric N or mobilize bound P and K making them available to plants, hasten organic matter decomposition, induce secretion of plant growth promoting substance, improve soil structure and stimulate beneficial microbial activity. Enriched composts and manures combine organic matter with additional nutrients like micronutrients or P, stimulating microbial activity, and improving soil organic carbon. Organic manure decomposers accelerate the breakdown of farmyard manure, crop residues and green manures, producing nutrient rich humus that improves soil structure and cation exchange capacity. Biochar, produced by pyrolysis of crop residues, enhances soil porosity, moisture holding capacity and nutrient retention, while acting as a long-term carbon sink. Together, these organic solutions complement chemical fertilisers, providing a sustainable, integrated approach to nutrient management and soil health improvement.

BOX 7.2: FERTILISER CUSTOMIZATION FOR IMPROVING SOIL HEALTH

- Fertiliser customization is done based on specific soil, crop, and regional requirements, ensuring balanced nutrient supply tailored to the precise needs of the soil and plants.
- Adoption of fertiliser customization promotes sustainable farming practices following principles like the 4R nutrient stewardship (right time, right source, right rate, and right place). It enhances nutrient cycling, improves soil structure and biological activity for long-term soil resilience.
- This targeted nutrient application based on 4R concept improves the NUE by crops as well as it prevents overuse and nutrient loss, which helps maintain soil fertility and health.
- TSP which is a high analysis, water soluble P fertiliser contains 46% P_2O_5 and can be customised to include other essential nutrients like S, B and Zn to develop crop suitable fertiliser grades of TSP.
- These fertilisers include macro, secondary, and micronutrients uniformly distributed in a ready to use form, correcting nutrient deficiencies and supporting diverse soil microbial functions essential for soil health.

Some of the common customised fertiliser formulations are prepared for rice, sugarcane, maize, and various horticultural crops, for regions like Uttar Pradesh, Telangana, Maharashtra, etc.

7.3 SUSTAINABLE PRACTICES FOR BETTER SOIL HEALTH

REBALANCING NUTRIENT USE THROUGH INTEGRATED NUTRIENT MANAGEMENT

India's soil fertility challenges are driven by imbalanced macronutrient use, SOC decline, and emerging micro and secondary nutrient deficiencies. Balanced fertilisation and integrated nutrient application according to soil type, crop type and variety should be given importance through site specific nutrient management approach. The practices adopted by farmers need to be restructured towards a balanced and integrated nutrient input approach. Application of primary nutrients as per the recommendation along with second nutrient like S and micronutrients are essential for optimum yield and restoring the soil health. Zn, B, S, and Fe should be embedded in recommendations based on deficiency maps. Co-application of macro and micro nutrients can promote optimum plant growth and support nutrient build up in the soil. Integration of organics with mineral fertilisers (FYM, composts, vermicompost, crop residues, enriched compost, city compost, biogas slurry) at scientifically recommended rates need to be adopted for crop production. Balanced fertilisation and integrated nutrient management practices will improve the available nutrient content in the soil and NUE in soil as evidenced from various LTFE conducted by ICAR across the country (Singh et al., 2019a). Application of soil amendments in soils having chemical constraints like acidic soil, alkaline soil and saline soils are needed to be followed for better soil health and nutrient dynamics. For this purpose, liming in acid soils and gypsum application in alkaline soils is recommended according to the severity of soil.

MEASURES FOR IMPROVING SOIL ORGANIC CARBON (SOC)

Soil Organic Matter (SOM) is crucial as it enhances soil fertility, structure, water retention and supports beneficial microbial activity. Sequestering and maintaining it in soil is vital for improving crop productivity, mitigating climate change through reduced carbon footprint and ensuring long term agricultural sustainability. A sustainable way forward for enriching soil organic matter in Indian agricultural fields lies in systematically integrating organic inputs and adopting practices that enhance soil organic carbon. Farmers can recycle nutrients back into the soil through soil mulching, incorporation of crop residues and the application of composted organic inputs such as biochar, farmyard manure, compost and vermicompost. Green manuring, using leguminous crops, can further improve soil fertility while enhancing microbial activity, biological N fixation and carbon addition. The SOC improves water retention, soil structure, microbial activity and nutrient availability, thereby reducing dependency on chemical fertilisers. Formation of stable soil structures through stable aggregates can potentially reduce the intensity of water erosion from cropped lands.

CROP DIVERSIFICATION AND WATER MANAGEMENT PRACTICES

Government should promote integration of variety of crops such as pulses and oilseeds into cropping systems. Akchaya et al. (2025) show that integrating legumes via intercropping or rotation can fix up to ~125 kg N/ha/season, raise SOM, improve structure and porosity, enhance microbial activity and reduce bulk density; all of this contributes to boosts of ~30-35% in main crop equivalent yields and greater biodiversity. It can improve water use efficiency by 20-25%, NUE by 25-30% and lower yield losses from pests and diseases by 20-25% compared to mono cropping systems. Complementing this, conservation practices like minimal tillage, residue retention and cover cropping strengthen soil structure and resilience. Alongside, efficient water management is also important in nutrient efficiency point as it can reduce the chances of nutrient leaching from the soil. Precision water management through drip or sprinkler irrigation, fertigation and optimized irrigation scheduling according to site specificity improves NUE, reduces losses and conserves water. Even though there are subsidies for micro irrigation equipment, the adoption of drip and sprinkler systems is relatively slow. This is compounded by the fact that water and electricity are often subsidized or provided for free in many states, making the transition to water and fertiliser efficient practices less appealing to farmers. Redirecting support toward incentives for water saving technologies and deregulating input prices can shift farmer behavior toward greater sustainability.

In salt affected or rainfed areas, gypsum application, quality water use, mulching, organic amendments (e.g., biochar, compost, FYM) and saline tolerant varieties restore soil health and maintain long term crop productivity. In drylands, there should be emphasis on K application for drought resilience (where responsive), seed priming with biofertilisers, drought resilient varieties and pulses in rotations to improve N supply and NUE.

Thus, by adopting such practices in a holistic and region-specific manner, Indian agriculture can be rebuilt as a resilient system. But all these initiatives require policy reforms in agriculture and fertiliser sectors. Huge subsidies provided for various inputs by centre and state governments will have to be repurposed to promote soil health and sustainable agriculture. The combined effect of rationalized policy, efficient products and sustainable practices will help restore soil health, enhance agricultural productivity and boost sustainability across India’s diverse agro-climatic zones.

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ANNEXURES

ANNEX TABLE 1: CRITICAL LIMIT OF PLANT ESSENTIAL MACRO AND MICRONUTRIENTS IN SOIL AS PER SHC

Nutrient	Low	Medium	High	References
Soil organic carbon (SOC)	<0.5%	0.5-0.75%	>0.75%	TNAU agrictech portal, Dev (1997), MoAFW, GoI,
Available Nitrogen	280 kg/ha	280-560 kg/ha	>560 kg/ha	Arora (2002); MoAFW, GoI
Available Phosphorus	<10 kg/ha	10-25 kg/ha	>25kg/ha	Arora (2002); Dev (1997) MoAFW, GoI
Available Potassium	<120 kg/ha	120-280 kg/ha	>280kg/ha	
Nutrient	**Deficient**	**Sufficient**		
Available Sulphur	< 10 ppm	> 10 ppm		*MoAFW, GoI
Available Iron	< 4.5 ppm	>4.5 ppm		
Available Zinc	< 0.6ppm	>0.6 ppm		
Available Manganese	< 2 ppm	>2 ppm		
Available Copper	< 0.2 ppm	> 0.2ppm		
Available Boron (B)	< 0.5 ppm	>0.5 ppm		

**From "Teachers manual for soil health assessment program" released by Ministry of Agriculture and Farmer's Welfare*

ANNEX TABLE 2: STATE WISE PERCENTAGE DISTRIBUTION OF SOILS WITH HIGH/ SUFFICIENT LEVELS OF MACRONUTRIENTS (SOIL HEALTH CARD CYCLE II, 2017-19)

Sl. No	**States/ UTs**	**% Distribution of soil samples having nutrient deficiency**		
		Available Nitrogen	**Available Phosphorus**	**Available Potassium**
	Critical Limit	**> 560 kg/ha**	**> 25 kg/ha**	**> 280 kg/ha**
1	Andaman and Nicobar	0.2	0.2	0.1
2	Andhra Pradesh	1.7	59.7	53.3
3	Arunachal Pradesh	98.3	0.6	3.8
4	Assam	33.3	2.5	3.6
5	Bihar	0.2	10.8	6.7
6	Chhattisgarh	1.4	15.5	33.4
7	Delhi	0.2	0.9	48.3
8	Goa	18	13.5	29.6
9	Gujarat	1.8	25	42.6
10	Haryana	0.1	5.6	32
11	Himachal Pradesh	7.4	24.3	31.6
12	Jammu and Kashmir	18.2	7.4	7.8
13	Jharkhand	1.8	10.8	10.8
14	Karnataka	14.1	25.6	38.8
15	Kerala	0.1	18.7	24.8
16	Ladakh	7.4	6.4	41.8
17	Madhya Pradesh	0.7	4.3	29.9
18	Maharashtra	4.4	28.6	63.5
19	Manipur	0.1	17.8	10.9
20	Meghalaya	11.6	2.4	9.7
21	Mizoram	0.1	0.6	2.4
22	Nagaland	72.1	2.1	15.5
23	Odisha	0.2	5.9	17.4
24	Puducherry	0.1	3.6	40.6
25	Punjab	3.6	8.4	28
26	Rajasthan	0	6.2	20.5
27	Sikkim	0.1	38.4	28.4
28	Tamil Nadu	0.1	28.3	36.1
29	Telangana	1.6	36.3	38.4
30	Dadra & Nagar Haveli; Daman & Diu	0	11.1	72.8
31	Tripura	4.2	12.6	3.9
32	Uttar Pradesh	0.2	3.9	3.2
33	Uttarakhand	1.4	31.5	17.7
34	West Bengal	1.6	66.3	10.8

Source: Author's analysis from Soil Health Card Cycle II Report

ANNEX TABLE 3: STATE WISE PERCENTAGE DISTRIBUTION OF SOILS WITH DEFICIENCY OF SECONDARY AND MICRONUTRIENTS (SOIL HEALTH CARD CYCLE II, 2017-19)

Sl. No	**States/ UTs**	**% Distribution of soil samples with nutrient deficiency**					
		Sulphur	**Iron**	**Zinc**	**Copper**	**Manganese**	**Boron**
1	Andaman and Nicobar	99.6	0.3	14.9	16.5	0.6	4.5
2	Andhra Pradesh	10.6	28.4	35.6	4.7	9.8	17.2
3	Arunachal Pradesh	37.8	1.0	42.2	13.5	21.7	81.8
4	Assam	2.6	0.8	8.2	0.9	5.3	95.7
5	Bihar	92.1	46.4	51.1	45.0	47.0	98.6
6	Chhattisgarh	35.4	10.4	43.4	3.7	3.4	29.6
7	Delhi	22.5	6.7	0.9	0.8	12.1	14.4
8	Goa	73.5	0.3	16.3	1.9	1.3	55.1
9	Gujarat	21.9	25.1	31.7	6.2	4.9	50.0
10	Haryana	7.9	41.8	29.9	3.5	42.9	40.1
11	Himachal Pradesh	14.6	10.0	9.7	2.8	19.8	4.9
12	Jammu and Kashmir	39.4	31.7	34.8	20.5	44.3	24.8
13	Jharkhand	28.2	8.8	28.1	6.4	13.0	24.6
14	Karnataka	37.1	53.9	62.0	7.5	16.6	54.8
15	Kerala	35.2	2.7	7.7	3.5	5.4	47.5
16	Ladakh	58.3	23.9	29.1	5.9	32.7	54.9
17	Madhya Pradesh	24.2	20.7	42.6	5.8	9.1	27.9
18	Maharashtra	53.6	66.1	53.2	2.8	13.9	46.4
19	Manipur	52.9	3.2	36.4	23.2	2.9	47.4
20	Meghalaya	53.7	9.9	36.0	12.8	36.0	20.2
21	Mizoram	55.6	0.0	18.8	0.0	0.0	0.0
22	Nagaland	2.2	0.2	32.9	6.6	7.0	3.7
23	Odisha	56.7	57.0	48.4	61.8	71.5	69.2
24	Puducherry	0.0	10.6	7.9	0.8	1.9	99.6
25	Punjab	14.2	10.9	13.5	0.5	45.6	64.7
26	Rajasthan	16.1	52.1	50.9	4.9	8.4	57.1
27	Sikkim	8.6	8.0	32.3	11.6	7.3	48.1
28	Tamil Nadu	37.1	33.7	30.2	3.8	24.5	54.5
29	Telangana	19	44.0	40.3	9.4	22.2	23.3
30	Dadra & Nagar Haveli; Daman & Diu	0.6	4.0	7.7	1.0	1.3	2.2
31	Tripura	5.4	1.4	20.2	1.5	1.9	18.3
32	Uttar Pradesh	36.9	25.5	29.7	4.2	15.7	34.9
33	Uttarakhand	24.7	16.1	18.9	10.7	17.8	51.8
34	West Bengal	67.0	1.4	4.9	1.0	11.2	17.9

Source: Author's analysis from Soil Health Card Cycle II Report

ANNEX TABLE 4: STATE WISE PERCENTAGE DISTRIBUTION OF SOILS WITH DEFICIENCY OF AVAILABLE SECONDARY AND MICRONUTRIENTS (AICRP ON MICRO AND SECONDARY NUTRIENTS AND POLLUTANT ELEMENTS IN SOILS AND PLANTS)

State	Sulphur	Iron	Zinc	Copper	Manganese	Boron
Andhra Pradesh	48.5	27.8	50.8	15.6	13.1	27.5
Arunachal Pradesh	13.2	11.6	11.2	17.1	14.8	89.2
Assam	65.8	0.2	61.2	16	3.8	76.2
Bihar	70.1	10.9	53	3.8	23.6	63.4
Chhattisgarh	55.1	10.8	55.6	11.8	10.7	34.9
Goa	60.7	35.5	70.4	66.4	20.9	42
Gujarat	79.2	43.7	60.6	9.6	9.9	70
Haryana	47.6	33.7	31.5	30.7	21.5	9.1
Himachal Pradesh	7.7	8.3	15.3	14.7	13.6	77.3
Jammu Kashmir	37.7	6.8	41.9	8.1	38.9	60
Jharkhand	80.7	0.1	39.9	6.8	1.3	74.9
Karnataka	63.1	26.4	50.5	14.8	18.1	57.4
Kerala	61.9	4.5	14.4	10	21.6	67.8
Madhya Pradesh	71.8	20.4	82.9	9.6	16.4	13.7
Maharashtra	65.9	36.4	58.6	3.4	7.7	72
Manipur	59.2	7	38.1	15.7	16.8	72.8
Meghalaya	59.8	9.8	12.6	11.6	16.7	77.3
Mizoram	49.5	8.1	8.6	13	7.1	73.7
Nagaland	34.5	10.6	14.3	21.7	20.7	85.2
Odisha	67.2	8.5	54.6	16.3	9.3	72.2
Punjab	50.2	21.9	35.3	30.5	55.3	32.5
Rajasthan	78.2	65.6	79.9	65.7	53.6	17.3
Tamil Nadu	29.8	25.5	45	11.3	27	36.9
Telangana	59.8	25.2	54.8	14.2	17.6	59.4
Tripura	37.1	3.4	5.1	2.8	2.3	48.3
Uttar Pradesh	61.6	31.3	60.6	28.4	26.1	39.8
Uttarakhand	52.4	4.6	18.8	17.8	10.6	34.4
West Bengal	78.5	0	30.8	6.3	4.4	64.7
India	58.6	19.2	51.2	11.4	17.4	44.7

Source: Shukla et al., 2021

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