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The silent crisis beneath: A comprehensive review of soil health degradation in intensive agroecosystems with a special focus on India

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Abstract

In intensive agroecosystems and especially in the Global South, soil degradation is rapidly becoming a threat to food security. The literature reviewed in this work is not older than 2020 to 2025, aimed at evaluating the causes, mechanisms, and consequences of degradation, and with a specific focus on the Indo-Gangetic Plains (IGP) of India. We track the origins of the input-intensive model of the Green Revolution to generate second-generation soil issues: stoichiometric nutrient imbalance, decreasing Soil Organic Carbon (SOC) pools, and ubiquitous micronutrient deficiencies. The quantitative data show that about 32 percent of the Indian territory is degraded and the average rates of soil erosion are 16.4 t ha⁻¹ yr⁻¹. We also judge the evidence of remedial interventions such as Conservation Agriculture (CA), microbiome engineering, and AI-assisted digital soil mapping, and examine the Soil Health Card scheme and future research directions in deep-soil carbon sequestration and in the carbon credit markets.

Keywords: Carbon sequestration, indo-gangetic plains, land degradation, nutrient mining, regenerative agriculture, soil health

1. Introduction

1.1 The Silent Crisis: Global Soil Health in the Anthropocene

Soil underpins the global food system, regulates the carbon cycle, and supports most terrestrial biodiversity—yet it is essentially non-renewable on human timescales (Kraamwinkel *et al.*, 2021; Lal, 2025) ^[15, 17]. With world

population projected to reach 9.7 billion by 2050, the pressure on this finite resource is intensifying. The Food and Agriculture Organization's latest Status of the World Soil Resources (2025 update) estimates that 33 percent of global soils are already moderately to severely degraded by erosion, salinization, compaction, acidification, and chemical pollution (Smith *et al.*, 2024) ^[26].

Table 1.1: Evolution of Indian Agriculture: From Green Revolution to Soil Degradation

Era / Period	Dominant Paradigm	Key Management Practices	Soil Health Outcome	Key Statistic (Status)
Pre-Green Revolution (< 1965)	Subsistence Farming	Organic manures (FYM) Mixed cropping (pulses + cereals) Fallowing (land rest)	Stable but Low Fertility: Soil biological activity was high, but nutrient pools were insufficient for high yields.	Fertilizer consumption: < 1 kg ha ⁻¹ Avg. Yield: ~0.8 t ha ⁻¹
Green Revolution Phase I (1965–1990)	Yield Maximization	Introduction of HYVs (Wheat/Rice) Expansion of irrigation Nitrogen-centric fertilization (Urea)	Nutrient Mining Begins: Rapid extraction of native P and K reserves. Soil physical structure remained intact.	N-Response Ratio: 13.4 kg grain per kg N (High Efficiency)
Intensification Phase (1990–2015)	Input Intensification	Rice-Wheat Monoculture Mechanized Tillage (Tractors) Decline in pulse rotations	"Second Generation" Problems: Groundwater depletion, micronutrient deficiencies (Zn, Fe), and Plough Pan formation.	Water Table Decline: ~0.5–1.0 m yr ⁻¹ (Punjab) Micronutrient deficiency: ~45% soils Zn deficient
Current Crisis Phase (2015–Present)	System Fatigue	Over-reliance on agrochemicals Crop Residue Burning Abandonment of organic amendments	Biological Collapse: Loss of SOC (<0.5%), heavy metal toxicity, and multi-nutrient imbalance.	N-Response Ratio: 3.7 kg grain per kg N (Low Efficiency / Soil Fatigue)

"As illustrated in Table 1.1, the transition from the subsistence era to the current intensive phase has resulted in a precipitous decline in fertilizer response ratios, signaling a fundamental loss of soil biological resilience (ICAR-IIFSR, 2024) ^[11]."

The trade-off is stark: global cereal production tripled between 1960 and 2020, but soil organic carbon and micronutrient stocks declined across much of the same land. Recent meta-analyses estimate that 100 billion tonnes of fertile soil are lost each year to unsustainable farming—10 to 40 times faster than natural pedogenesis can rebuild it (FAO, 2024). The problem extends well beyond crop yields. Degraded soils lose their capacity to sequester carbon, feeding back into climate change rather than buffering against it (Efthimiou, 2025) ^[4].

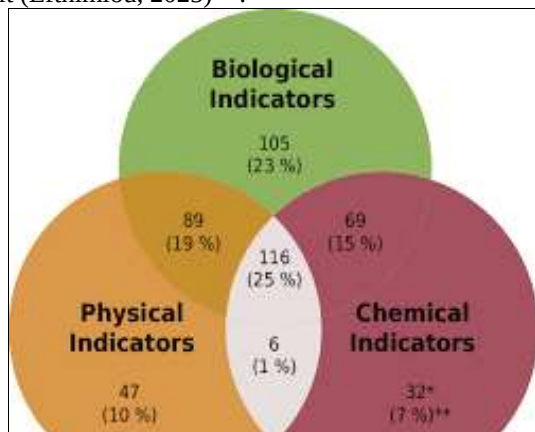


Fig: The Intersection of Soil Health: A conceptual framework illustrating the interdependence of Physical, Chemical, and biological indicators. (Adapted from FAO, 2024).

1.2 Historical Evolution: The Green Revolution and its Shadow

Understanding current soil conditions in the Global South requires some historical context. The Green Revolution of the mid-1960s was a direct response to the threat of famine in countries like India. It introduced high yielding varieties (HYVs) of wheat and rice, increased irrigation facilities and popularized the use of synthetic manure (mainly N-P-K) and pesticides.

The Green Revolution did allow food production to expand without converting millions of additional hectares of forest to farmland, but it altered the soil ecosystem in the process. Pre-Revolution agriculture relied on organic manures, crop rotation, and periodic fallowing, which maintained baseline soil biological activity. The rice-wheat monocultures that followed on the Indo-Gangetic Plains replaced that diversity with near-total dependence on synthetic inputs.

By the 2020s, the model was showing clear signs of exhaustion. Long-term fertilizer experiments in India show that the agronomic efficiency of nitrogen fell from 13.4 kg grain per kg N in 1970 to just 3.7 kg grain per kg N by 2020 (ICAR-IIFSR, 2024) ^[11]. Diminishing returns of this magnitude are not a fertilizer problem—they indicate that the soil's physical and biological capacity to convert inputs into yield has been fundamentally compromised. The result is the current era of second-generation soil problems: yield stagnation alongside rising input costs and growing environmental contamination.

1.3 Defining Soil Health: A Tri-Partite Framework

Treating soil as a chemical bank—a store of N, P, and K to be drawn down and topped up—has long been recognized as insufficient. Modern soil science defines soil health as the capacity of a soil to function as a living ecosystem that

sustains plants, animals, and people over time. That capacity depends on three interdependent sets of indicators:

Physical Indicators: These are those that control the structure of the soil. Important parameters are bulk density, which influences root penetration; the aggregate stability which defines resistance to erosion and crusting; and infiltration rate which defines water use efficiency. Surface sealing and the development of subsurface "plough pans" in intensive tillage systems has been caused by the destruction of macro-aggregates.

Chemical Indicators: These have long been the most attended. These are pH, Electrical Conductivity (EC), Cation Exchange Capacity (CEC) and availability of macronutrients/micronutrients. The stoichiometric imbalance or the disruption of natural ratios (i.e., C: N, N:P) of microbial mineralization processes is also a critical modern issue.

Biological Indicators: The most sensitive and least attended to. These are Soil Organic Carbon (SOC) pools (labile vs. recalcitrant), microbial biomass carbon (MBC) and enzymatic activities (e.g., dehydrogenase, phosphatase). The latest studies stress that biological markers tend to be the earliest warning mechanisms displaying the signs of degradation long before the chemical or physical alterations can be detected (He and Du, 2023; Purohit *et al.*, 2024) ^[10, 22].

1.4 Soil Health and the Sustainable Development Goals

Soil health has direct bearing on several of the United Nations Sustainable Development Goals (SDGs).

SDG 2 (Zero Hunger): This is directly connected to the availability of nutrients. Poor soils yield crops of lower healthy content (hidden hunger) and deficiency of micronutrients in the human body (e.g., Zinc and Iron deficiency).

SDG 13 (Climate Action): Soils comprise the second largest active pool of carbon on planet earth after the oceans. The sequestration rate of degraded agricultural soils can be 0.9-1.85Pg C/y, which can compensate a large part of anthropogenic emissions in the world (Lal *et al.*, 2023) ^[18]. On the contrary, further degradation emits accumulated carbon and CO₂ as well as methane (CH₄).

SDG 15 (Life on Land): It is aimed at fighting the desertification process and preventing land degradation. The presence of healthy soils, micro-flora up to macro-fauna, would help sustain the ecosystems through the support of the terrestrial biodiversity.

1.5 The Indian Context: The Crisis in the Indo-Gangetic Plains

India concentrates many of the global soil crisis's pressures into a relatively small area—high population density, intensive cropping, and climate vulnerability together. The Indo-Gangetic Plains (IGP), spanning Punjab, Haryana, and Uttar Pradesh, produces roughly 50% of India's grain buffer and is the primary food-producing region of South Asia. The data from that region are not encouraging.

Data from the Indian Council of Agricultural Research (ICAR) and recent satellite analysis (2024) show the following:

- **Land Degradation:** Approximately 96.4 million hectares

(29.3% of India's total geographical area) is undergoing land degradation.

- **Nutrient Mining:** In Punjab, the average nutrient removal by the Rice-Wheat system is ~650 kg/ha/year, whereas the addition through fertilizers is only ~350–400 kg/ha/year. This negative balance is mining the soil's native reserves of Potassium (K) and micronutrients (Zn, Mn, Fe).
- **Groundwater & Salinity:** Inefficient flood irrigation and poor drainage have led to secondary salinization and sodicity in nearly 6.73 million hectares.
- **Carbon Bankruptcy:** Most soils in the IGP have an SOC content of <0.5%, far below the critical threshold of 1.0% required for maintaining soil structure and microbial function.

This review synthesizes recent scientific literature (2020–2025) to provide a comprehensive analysis of these degradation mechanisms. Unlike earlier reviews focused primarily on chemical fertility, this paper takes a whole-system view of soil health—integrating physical compaction, biological decline, and policy failures. It evaluates emerging remedial technologies from conservation agriculture to AI-driven soil mapping, and identifies the policy and research changes needed to shift Indian agriculture from soil-depleting to soil-building practices.

2. Causes of Soil Health Degradation

Soil degradation in intensive agroecosystems is not caused by any single event but by the accumulation of physical, chemical, and biological pressures over decades of high-input agriculture. This section examines the six primary drivers of decline, with particular attention to the Indo-Gangetic Plains (IGP).

2.1 Nutrient Depletion and Stoichiometric Imbalance

The primary driver of yield stagnation in Indian agriculture is nutrient mining: crop nutrient removal consistently outpaces replenishment.

Mechanisms of Nutrient Mining

Modern high-yielding varieties (HYVs) are nutrient-intensive. In the Rice-Wheat System (RWS) prevalent in North India, a typical annual harvest (yielding ~7 t ha⁻¹ rice and ~5 t ha⁻¹ wheat) removes approximately 300 kg Nitrogen (N), 30 kg Phosphorus (P), and 300 kg Potassium (K) per hectare from the soil profile (ICAR-IIFSR, 2024)^[11]. While N and P are partially replenished through synthetic fertilizers (Urea and DAP), Potassium is largely neglected. Consequently, Indian soils are undergoing a "silent K crisis," with net negative balances estimated at 10 million tonnes of K annually (Kaduwal *et al.*, 2023)^[13].

NPK Imbalance:

The ideal N:P:K application ratio for cereal crops is 4:2:1. However, distorted subsidy policies favouring Urea have skewed this ratio dramatically. Recent soil testing data (2024–2025) from Punjab and Haryana reveals actual application ratios averaging 11.8:4.6:1, and in some districts reaching as high as 30:8:1 (FAO, 2025)^[5]. This stoichiometric imbalance disrupts microbial mineralization, as soil microbes require balanced Carbon (C) and Nitrogen

(N) ratios to decompose organic matter efficiently.

Micronutrient Deficiencies ("Hidden Hunger")

The exclusive focus on macronutrients has stripped soils of essential trace elements. The All India Coordinated Research Project (AICRP) on Micro- and Secondary Nutrients (2025 report) highlights critical deficiencies:

- **Zinc (Zn):** 38% of Indian soils are deficient, directly impacting crop immunity and grain quality.
- **Boron (B):** 37% deficiency, affecting reproductive growth in pulses and oilseeds.
- **Iron (Fe) & Sulphur (S):** Rising deficiencies (12–29%) due to the shift away from sulphur-containing fertilizers like Single Super Phosphate (SSP).

2.2 Soil Erosion and Organic Matter Loss

Soil erosion is the physical displacement of the topsoil—the most biologically active layer rich in organic carbon and nutrients.

Quantitative Losses

India suffers from one of the highest erosion rates globally. The average soil loss is estimated at 16.4 t ha⁻¹ yr⁻¹, significantly exceeding the permissible tolerance limit (T-value) of 4–10 t ha⁻¹ (Nawazuzzoha *et al.*, 2024).

- **Water Erosion:** In the Shivalik foothills and undulating plains, sheet and rill erosion are dominant. Intensive rainfall events, exacerbated by climate change, detach soil particles exposed by tillage.
- **Wind Erosion:** In the arid regions of Rajasthan and southern Haryana, wind erosion removes lighter soil fractions (clay and organic matter), leaving behind coarser sand particles.

Impact on SOC Pools

Erosion damages SOC through two separate mechanisms.

1. **Preferential Removal:** Erosion selectively removes light-fraction organic matter, which is less dense than mineral soil.
2. **Mineralization:** Tillage-induced erosion breaks open soil aggregates, exposing protected carbon to microbial oxidation.

This has resulted in SOC levels in the IGP plummeting to 0.3–0.4%, far below the 1% threshold required for sustaining soil aggregates.

2.3 Agrochemical Overuse and Toxicity

Heavy reliance on synthetic chemicals has altered the soil's biochemical environment, leaving it loaded with persistent toxic residues.

Pesticide Persistence

India is the second-largest consumer of pesticides in Asia. In 2023–24, herbicide consumption (particularly Glyphosate and Pendimethalin) surged to replace manual weeding. Residues of these chemicals bind to soil colloids and persist for months. Studies indicate that Glyphosate residues inhibit the activity of dehydrogenase and urease enzymes, which are critical proxies for overall microbial metabolic activity (Shekhawat *et al.*, 2022)^[23]. Furthermore, these chemicals disrupt the signalling pathways of beneficial Nitrogen-fixing bacteria (*Rhizobium* spp.).

Heavy Metal Contamination

In peri-urban agricultural belts (e.g., around Delhi, Ludhiana, Varanasi), the use of untreated industrial wastewater for irrigation has introduced heavy metals such as Cadmium (Cd), Lead (Pb), and Arsenic (As) (Sharma *et al.*, 2007; Kumar *et al.*, 2019) ^[25, 2].

- Bioavailability: Unlike organic pollutants, heavy metals do not degrade. They accumulate in the topsoil (0–15 cm) (Kumar *et al.*, 2019; Zeeshan Manzoor *et al.*, 2024) ^[2, 30].
- Toxicity: Recent analysis shows Cd concentrations in wastewater-irrigated soils exceeding safe limits by 3–5 times. These metals displace essential cations (Ca²⁺, Mg²⁺) on soil exchange sites, destroying soil structure and poisoning the food chain (Zeeshan Manzoor *et al.*, 2024) ^[30].

2.4 Tillage and Mechanisation: The Physical degradation

The shift from bullock-drawn ploughs to heavy tractors and combine harvesters has induced severe physical degradation.

Soil Compaction and the "Plough Pan":

Repeated puddling (wet tillage) for rice cultivation is designed to destroy soil aggregates and reduce percolation. While beneficial for rice, it creates a high-density subsurface layer known as a plough pan at 15–20 cm depth.

- Bulk Density: The bulk density in the plough pan often exceeds 1.65 g cm⁻³, effectively functioning as a concrete barrier.
- Root Restriction: This layer restricts the root growth of subsequent crops like wheat, confining them to the top 15 cm and making them susceptible to lodging and water stress (Yadav *et al.*, 2025) ^[29].

Energy-Carbon Trade-offs

Intensive tillage accelerates the oxidation of SOC. Conventional Tillage (CT) exposes soil carbon to atmospheric oxygen, releasing it as CO₂. It is estimated that shifting from Conventional Tillage to No-Till (NT) can sequester 0.4–0.8 t C ha⁻¹ yr⁻¹ (Lal *et al.*, 2023) ^[18], yet adoption remains low due to machinery constraints.

2.5 Monoculture Systems and Biological Vacuum

The Rice-Wheat cropping sequence has been practiced continuously on ~10.5 million hectares in the IGP for over four decades.

Feedback Loops

Monoculture violates the ecological principle of diversity.

- **Pathogen Buildup:** Continuous cropping of cereals selects for specific soil-borne pathogens, such as the Cereal Cyst Nematode (*Heterodera avenae*) and *Fusarium* wilt, which thrive in the absence of break crops.
- **Allelopathy:** Crop residues from certain varieties release allelochemicals (e.g., phenolics from decomposing rice straw) that can inhibit the germination of the succeeding wheat crop if not managed properly.
- **Functional Redundancy:** Monoculture reduces the diversity of the soil microbiome. A diverse microbiome has "functional redundancy," meaning if one species is lost, another takes over its role. In simplified RWS soils, this resilience is lost, making the system fragile to climate shocks.

2.6 Salinity and Water Mismanagement

Salinity is the accumulation of soluble salts, while sodicity is the dominance of exchangeable sodium. Both are expanding in the semi-arid IGP due to hydrological mismanagement.

Secondary Salinization

In canal-irrigated areas, seepage from unlined channels raises the water table. When the water table reaches within 2 meters of the surface, capillary action pulls salt-laden water up. The water evaporates, leaving white salt crusts on the surface.

- Sodicty: Use of bicarbonate-rich groundwater causes soil dispersion. Sodic soils become hard when dry and sticky when wet, leading to poor infiltration (hydraulic conductivity < 0.2 cm hr⁻¹) and aeration stress.
- Climate Interaction: Rising temperatures increase evapotranspiration rates, accelerating capillary rise and salt accumulation, rendering vast tracts of land barren (Lal, 2025) ^[17].

Table 2.1: Critical Limits vs. Current Status of Nutrients in Indian Soils (Source: AICRP, 2025)

Nutrient	Critical Limit (mg/kg)	% Samples Deficient (2025)	Dominant Limitation
Nitrogen (N)	280 (kg/ha)	92%	Low SOC; Volatilization losses
Phosphorus (P)	10	56%	Fixation in acidic/alkaline soils
Potassium (K)	108	18% (Rising)	Mining in intensive RWS
Zinc (Zn)	0.6	38%	High pH; Antagonism with P
Sulphur (S)	10	29%	Lack of SSP use; Leaching
Iron (Fe)	4.5	12%	Oxidation in aerobic soils

3. Consequences of Soil Degradation

Soil degradation is not just an environmental metric. It shows up as stagnant crop yields, rising costs for farmers, declining nutritional quality in food, and accelerating environmental damage. These consequences are interconnected and self-reinforcing.

3.1 Yield Stagnation and the "Yield Gap"

The most direct consequence of soil degradation is stagnating crop yields. Despite newer varieties and higher fertilizer use, productivity across the Indo-Gangetic Plains (IGP) has plateaued.

The Law of Diminishing Returns

Historical data from long-term fertilizer experiments (LTFE) reveals a disturbing trend: the Partial Factor Productivity (PFP) of fertilizers has plummeted. In the 1970s, applying 1 kg of NPK nutrients yielded ~13.4 kg of grain. By 2020, this efficiency dropped to just 3.7 kg grain/kg NPK (ICAR-IIFSR, 2024) ^[11]. This phenomenon, known as "soil fatigue," indicates that the soil's physical and biological capacity to support crop growth has been compromised.

- **Yield Gap:** There exists a significant “yield gap”—the difference between potential yield (demonstrated in research plots) and actual farmer yields. In wheat, this gap is estimated at 1.2–1.8 t ha⁻¹ in Punjab and Haryana. This gap is no longer due to a lack of inputs, but due to the soil’s inability to respond to them (ICAR-IIFSR, 2024; Mishra *et al.*, 2024) ^[11, 19].

3.2 Economic costs for farmers

Soil degradation carries a significant economic cost that farmers bear largely on their own.

- **Rising input costs:** to hold yields steady, farmers apply ever-larger amounts of fertilizers and agrochemicals, driving up the cost of cultivation. Recent economic analysis suggests that 15–20% of the cost of cultivation in the IGP is now spent on managing soil constraints (e.g., reclamation of salinity, extra micronutrients) (Cariappa & Krishna, 2024) ^[3].
- **National Economic Loss:** At a macroeconomic level, land degradation costs India an estimated 2.5% of its GDP annually. This includes direct losses from reduced crop output and indirect costs such as silting of reservoirs and loss of biodiversity (FAO, 2025) ^[5].

3.3 Nutritional decline and human health ("hidden hunger")

Soil quality and human nutrition are directly connected. Intensive cropping on depleted soils produces what researchers call the "dilution effect": grain yields remain high, but the concentration of micronutrients per kilogram of grain falls.

Micronutrient Malnutrition

- **Zinc and Iron:** As soil Zinc (Zn) and Iron (Fe) pools are mined, their translocation into the grain decreases. Analysis of wheat grains from the IGP shows a 17–28% decline in Zn and Fe content over the last 50 years. This directly correlates with the high prevalence of Zn deficiency (stunting) and Fe deficiency (anaemia) in the Indian population, particularly among women and children (Lal, 2025; Zeeshan Manzoor *et al.*, 2024) ^[17, 30].
- **Heavy Metal Toxicity:** In peri-urban areas irrigated with wastewater, the bioaccumulation of Cadmium (Cd) and Lead (Pb) in vegetables poses a severe cancer risk. Crops grown on these soils often exceed the Codex Alimentarius safety limits for heavy metals (Zeeshan Manzoor *et al.*, 2024) ^[30].

3.4 Environmental consequences and greenhouse gas emissions

Degraded soils cease to function as environmental buffers and instead become sources of pollution.

- **Greenhouse Gas (GHG) Emissions:** Healthy soils sequester carbon. Degraded, tilled soils release it.
 - a. **Nitrous Oxide (N₂O):** The indiscriminate use of Urea on degraded soils leads to low Nitrogen Use Efficiency (NUE ~30-40%). The remaining nitrogen is lost via volatilization and denitrification, releasing N₂O, a greenhouse gas 298 times more potent than CO₂.
 - b. **Methane (CH₄):** In puddled rice soils, anaerobic conditions drive methanogenesis. The destruction of soil structure exacerbates this by creating prolonged waterlogged conditions.
- **Eutrophication:** Soil erosion carries phosphorus-laden sediment into water bodies. This nutrient loading triggers algal blooms, leading to eutrophication and the death of aquatic ecosystems (Nawazuzzoha *et al.*, 2024).

Summary Table: The Cascade of Degradation

Table 3.1: The Cause-Impact-Outcome Matrix of Soil Degradation

Primary Cause	Direct Soil Impact (Mechanism)	Systemic Outcome (Consequence)
Nutrient Mining	Depletion of K, Zn, B, S pools; Stoichiometric imbalance (N:P ratio disruption).	Agronomic: Yield stagnation; "Hidden Hunger" (low grain nutrient density).
Intensive Tillage	Physical pulverization of aggregates; Oxidation of Soil Organic Carbon (SOC).	Environmental: Release of CO ₂ ; Loss of soil structure (crusting/compaction).
Agrochemical Overuse	Toxicity to non-target organisms; Residue persistence.	Biological: Decline in beneficial microbes (PGPR); Pesticide residues in food chain.
Residue Burning	Thermal destruction of organic matter and microbial biomass.	Health/Climate: Air pollution (PM2.5); Loss of potential C and N inputs.
Water Mismanagement	Secondary salinization; Rise in water table.	Economic: Land abandonment; High cost of reclamation (gypsum/drainage).

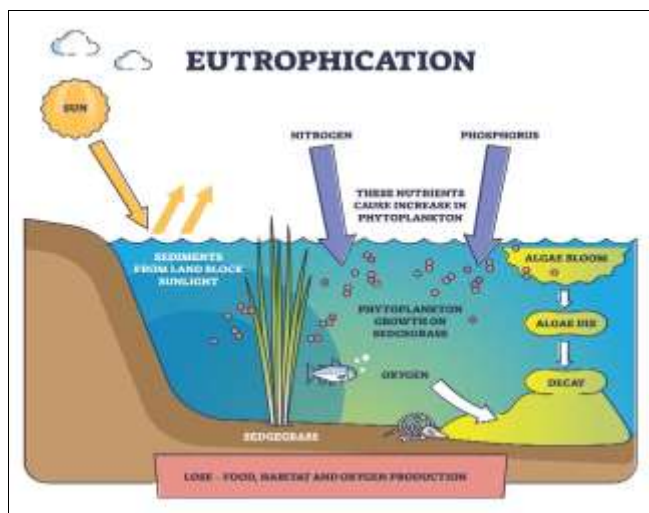


Fig: The pathway from soil degradation to human malnutrition (Adapted from Lal *et al.*, 2023) ^[18].

4. Remedial Measures: Science, Practice, and Policy

Restoring degraded agroecosystems requires moving away from the logic of simply adding more inputs. There is no single fix—effective remediation combines physical conservation, nutrient management, biological restoration, and digital diagnostics. This section evaluates these interventions based on long-term trial data from 2020–2025.

4.1 Conservation Agriculture (CA): The Physical Foundation

Conservation Agriculture (CA) is defined by three linked principles: minimum soil disturbance (no-tillage), permanent organic soil cover (residue retention), and crop diversification. Evidence from long-term trials (7+ years) in North India comparing CA with Conventional Tillage (CT) have demonstrated that CA systems sequester significantly more carbon. Recent studies across the IGP show that while short-term (3-year) carbon changes are negligible, 5-year CA adoption significantly improves particulate organic carbon (POC) fractions and crop yields (Mishra *et al.*, 2024; Kakraliya *et al.*, 2024) ^[19, 14]. Diversifying RWS with crops like mungbean also enriches soil fertility through biological nitrogen fixation and increases the system's overall protein output (Gora *et al.*, 2022; Gathala *et al.*, 2022) ^[8, 6].

Scientific Mechanism

- **Aggregate Stability:** No-till (NT) systems preserve the structural integrity of soil macro-aggregates (>0.25 mm). The absence of mechanical pulverization allows fungal hyphae and glomalin (a soil protein) to bind soil particles, protecting Soil Organic Carbon (SOC) from microbial oxidation.
- **Thermal Regulation:** Surface residue acts as an insulating mulch, moderating soil temperature fluctuations. In the heat-stressed Indo-Gangetic Plains (IGP), residue retention lowers maximum soil temperature by 2–4°C during the critical grain-filling stage of wheat, reducing terminal heat stress (Kaduwal *et al.*, 2023) ^[13].

Evidence from Trials: Long-term experiments (7+ years) in North India comparing CA with Conventional Tillage

(CT) have demonstrated:

- **Carbon Sequestration:** CA systems sequester significantly more carbon. Studies estimate a sequestration rate of 0.33 t C ha⁻¹ yr⁻¹ in the top 15 cm under CA, compared to a net loss in CT systems.
- **Water Use Efficiency (WUE):** The "Happy Seeder" technology, which sows' wheat directly into standing rice stubble, improves hydraulic conductivity and reduces evaporation, saving 15–20% (approx. 150 mm) of irrigation water.

Limitations

The main practical barrier is the transition period. Farmers typically see a yield drag of 5–8% in the first 2–3 years, as soil microbes immobilize nitrogen while decomposing the high-C:N rice straw. Yields generally recover once soil biological activity stabilises.

4.2 Integrated Nutrient Management (INM): Restoring Stoichiometry

INM moves beyond the N-P-K paradigm to manage the "soil nutrient bank" holistically, integrating inorganic fertilizers with organic amendments.

Scientific Mechanism

- **Cation Exchange Capacity (CEC):** Organic amendments (FYM, compost) increase the soil's CEC, essentially expanding the "pantry size" of the soil to hold nutrients like K⁺, Ca²⁺, and Mg²⁺, preventing leaching.
- **Nutrient Synchrony:** Unlike synthetic fertilizers which release nutrients in a pulse (often exceeding plant uptake rates), organic sources mineralize slowly, matching the crop's uptake curve.

Emerging Mineral Interventions: Recent research (2024) highlights the efficacy of Polyhalite, a natural multi-nutrient mineral (K₂Ca₂Mg (SO₄)₄ · 2H₂O). Unlike Muriate of Potash (MOP) which supplies only K and Cl, Polyhalite addresses the widespread S, Ca, and Mg deficiencies in the IGP. Trials in rice-wheat systems show that substituting MOP with Polyhalite improved root volume by 2.64% and K uptake by 30%, rectifying the stoichiometric imbalance (Sheoran *et al.*, 2024) ^[24].

4.3 Soil Biological Management: Engineering the Microbiome

The most research-active area in soil remediation is the microbiome. Restoring soil function means restoring its living component. Plant Growth Promoting Rhizobacteria (PGPR) and bio-inoculants containing strains like *Azotobacter*, *Pseudomonas*, and *Bacillus* are being used to "unlock" unavailable nutrients. Furthermore, long-term fertilization coupled with rhizobium inoculation has been proven to remodel soil bacterial community compositions, promoting niche reconstruction that naturally suppresses pathogen buildup (Wei *et al.*, 2023; Purohit *et al.*, 2024) ^[28, 22].

Plant Growth Promoting Rhizobacteria (PGPR): Bio-inoculants containing strains like *Azotobacter*, *Pseudomonas*, and *Bacillus* are being used to "unlock"

unavailable nutrients.

- **Mechanism:** These bacteria produce organic acids (gluconic, citric) that solubilize fixed phosphorus (making it available to plants) and synthesize siderophores that chelate iron.
- **Evidence:** Application of liquid bio-fertilizers in wheat has shown to save 20–25 kg N ha⁻¹ without yield penalty.

Arbuscular Mycorrhiza Fungi (AMF): AMF form a symbiotic relationship with plant roots, extending the depletion zone of the rhizosphere.

- **Mechanism:** Fungal hyphae can explore soil pores too small for root hairs, accessing phosphorus and water from the micropores.
- **Impact:** In zinc-deficient soils of Punjab, AMF inoculation increased grain Zn concentration by 12–15%, offering a biological solution to the "hidden hunger" problem.

The biological interventions in Section 4.3 represent a meaningful departure from chemical dependency, but they come with a practical constraint: their effectiveness varies considerably by soil type and location. A PGPR consortium that works well on phosphorus-fixing Alfisols in Karnataka may produce marginal results on the sodic, calcium-saturated Inceptisols of western Uttar Pradesh. Applying blanket AMF inoculation without first assessing indigenous mycorrhizal populations can cause competitive exclusion rather than crop benefit. Both cases point to the same problem: current agricultural advisory systems cannot prescribe site-specific biological treatments without granular, field-level soil data. Precision digital diagnostics, addressed in the next section, are the practical bridge between biological innovation and field application (Purohit *et al.*, 2024; Mishra *et al.*, 2024) [22, 19].

4.4 Digital Soil Health Monitoring: Precision Diagnosis

The traditional "grid sampling" method is labour-intensive and slow. The integration of Remote Sensing (RS) and Machine Learning (ML) is revolutionizing soil diagnosis.

Mechanism:

- **Spectral Indices:** Satellite platforms (Sentinel-2, Landsat 8) capture reflectance data. Bare soil indices (BSI) and vegetation indices (NDVI) are correlated with soil properties.
- **AI Models:** Machine Learning algorithms (Random Forest, Neural Networks) integrate satellite data with environmental covariates (relief, climate) to predict soil properties.

Recent Advances (2024–2025): Studies have successfully mapped Soil Organic Carbon (SOC) stocks at a regional scale with high accuracy ($R^2 > 0.84$) using hyperspectral imaging (Gouda *et al.*, 2024) [9]. This allows for Variable Rate Technology (VRT), where fertilizer spreaders adjust rates automatically based on the digital soil map, preventing overuse in fertile zones and under-use in degraded zones.

4.5 Climate-Smart Soil Practices

Adapting soil management to the reality of climate change.

Biochar Application: Biochar is a carbon-rich solid

produced by pyrolysis (thermal decomposition of biomass in low oxygen).

- **Mechanism:** Biochar is highly recalcitrant (stable for 100s of years) and has a massive surface area. It acts as a "soil reef," providing habitat for microbes and increasing water holding capacity (WHC).
- **Impact:** In sandy loam soils, biochar application has been shown to increase WHC by 18%, critical for drought resilience (Purohit *et al.*, 2024) [22].

Laser Land Levelling: A physical intervention that eliminates micro-relief (undulations).

- **Impact:** Precise levelling improves water distribution uniformity, increasing Water Use Efficiency (WUE) by 25–30% and reducing nutrient leaching.

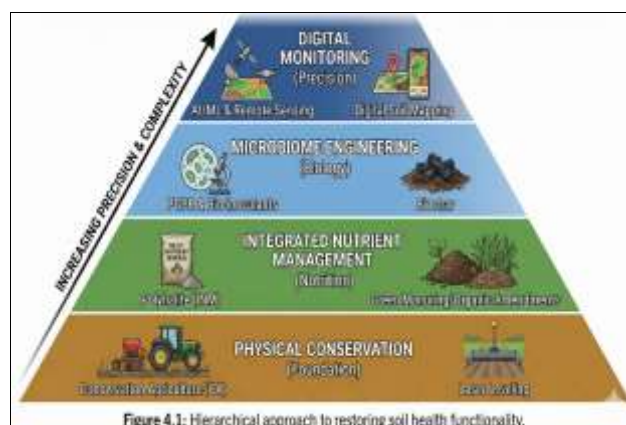


Figure 4.1: Hierarchical approach to restoring soil health functionality.

5. Policy Frameworks and Indian Initiatives

Shifting Indian agriculture toward soil-restorative practices is as much a governance problem as a scientific one. Several national schemes have been launched to address soil degradation, but the gap between policy design and field-level uptake remains wide.

5.1 The Soil Health Card (SHC) Scheme: A Critical Review

Launched in 2015, the SHC scheme is the world's largest soil testing program, aiming to provide every farmer with a nutrient status report and fertilizer recommendations every three years. A 2024 impact study by the National Institute of Agricultural Economics and Policy Research (NIAP) revealed mixed results. In regions where adopted, farmers optimized chemical fertilizers, reducing urea use by up to 9%, which subsequently improved paddy and wheat yields by 5–6% (Kumar *et al.*, 2023; Jayalakshmi *et al.*, 2021) [16, 12]. However, in the intensive IGP belt, adoption rates remain low (<30%). The primary bottlenecks include "blanket recommendations," delays of up to six to eight months in receiving test results, and poor accessibility to testing laboratories (Patel *et al.*, 2022; Ghaswa *et al.*, 2019) [21, 7].

- **Scale and Reach:** As of 2025, over 230 million cards have been distributed. The scheme has successfully created a baseline awareness about soil testing, shifting the discourse from "yield maximization" to "nutrient management."
- **Impact Assessment:** A 2024 impact study by the National Institute of Agricultural Economics and Policy

Research (NIAP) revealed mixed results.

- a. **Success:** In regions like Southern India, farmers adopting SHC recommendations reduced Nitrogen use by 8–10% and increased yield by 5–6%, proving the economic viability of balanced fertilization.
- b. **Failure:** In the intensive IGP belt, adoption rates remain low (<30%). The primary bottlenecks are the "blanket recommendations" which often fail to account for site-specific variability, and the lack of reliable supply chains for recommended micronutrients (Zinc, Boron) at local cooperatives (FAO, 2025) ^[5].
- c. **Data Quality:** Critics argue that the grid sampling method (one sample per 2.5 ha in irrigated areas) is too coarse to capture the spatial variability of soil properties, leading to "averaging errors" in fertilizer advisories.

5.2 National Mission on Natural Farming (NMNF)

Recognizing the ecological costs of chemical farming, the Indian government has pivoted towards "Bharatiya Prakritik Krishi Paddhati" (Natural Farming).

- **Policy Target:** The mission aims to convert 7.5 lakh hectares to natural farming by 2026.
- **Scientific Validation:** Preliminary data from ICAR trials (2023–2025) ^[1] suggests that while Natural Farming (NF) leads to an initial yield penalty of 15–20% in cereals, it significantly enhances soil biological quality. Microbial Biomass Carbon (MBC) and earthworm density were found to be 2–3 times higher in NF plots compared to conventional ones. The policy challenge lies in supporting farmers through the 3–5 year transition period where yields dip before stabilizing.

5.3 Carbon Credit Markets: The New Frontier

The "Carbon Credit Trading Scheme" (2023) creates a legal framework for voluntary carbon markets in India.

- **Potential:** Indian soils have the technical potential to sequester 20–25 Tg C yr⁻¹ through improved management. This represents a significant monetization opportunity for farmers.
- **Barriers:** Currently, the market is inaccessible to smallholders due to high Monitoring, Reporting, and Verification (MRV) costs. A survey of 841 farmers in 2024 revealed that 99% had no access to carbon markets, citing complexity and lack of aggregators as primary hurdles (Cariappa & Krishna, 2024) ^[3].

6. Future Research Gaps and Way Forward

While our understanding of soil degradation is robust, significant knowledge gaps persist, particularly regarding deep-soil processes and the scalability of solutions.

6.1 Beyond the Topsoil: Deep Carbon Sequestration

90% of soil sampling is restricted to the top 0–15 cm. However, recent evidence suggests that subsoil (30–100 cm) plays a critical role in long-term carbon storage.

- **Research Gap:** We lack data on the stability of Deep Soil Organic Carbon (DSOC) in the IGP. Deep-rooted crops and agroforestry systems can deposit carbon into these lower horizons where it is protected from microbial oxidation. Future research must quantify these deep pools to accurately calculate national carbon

inventories.

6.2 AI-Driven Hyper-Local Advisory

The current resolution of soil maps is insufficient for precision agriculture.

- **Way Forward:** Developing "Digital Twins" of agricultural fields using hyper-spectral drone imagery and Internet of Things (IoT) sensors. Research should focus on low-cost, handheld spectral sensors that allow farmers to test soil N-P-K in real-time, bypassing the 2-week delay of laboratory testing.

6.3 The "Soil-Gut" Microbiome Axis

There is emerging evidence linking soil biodiversity to the human gut microbiome.

- **Hypothesis:** Crops grown in biologically diverse soils may recruit a specific epiphytic microbiome that, when consumed, enriches the human gut flora. This "Soil-to-Gut" pathway remains largely unexplored and represents a revolutionary frontier connecting agriculture directly to public health.

6.4 Standardization of "Regenerative" Metrics

The term "Regenerative Agriculture" is currently ill-defined and unregulated.

- **Need:** Establishing a unified "Soil Health Index" (SHI) specific to Indian agro-climatic zones. This index should integrate physical, chemical, and biological indicators into a single score (0–100), serving as the standard metric for carbon payments and "eco-labelling" of food products.

7. Conclusion

India's soil crisis has been building for decades but its full scale is only now becoming clear. The evidence in this review converges on one conclusion: the input-intensive model of the 20th century has reached its biological limits. Yield stagnation, widespread micronutrient deficiency ("hidden hunger"), and the continued loss of soil organic carbon are no longer warning signs—they are the current reality, and they indicate that the soil's capacity to absorb further stress is nearly spent.

Addressing this will require an approach as deliberate as the Green Revolution, but aimed at the soil rather than the seed. The shift from "feeding the plant" through chemical fertilization to "feeding the soil" through integrated management is not rhetorical—it has measurable agronomic, economic, and environmental implications.

- In practice, this means using AI and remote sensing for field-level soil diagnosis, deploying bio-inoculants and diversified rotations to restore biological function, and redirecting fertilizer subsidies away from urea toward broader soil health support—compensating farmers for the ecosystem services their land provides, not just the tonnes it produces.

The consequences of inaction are concrete. If current degradation trends continue, the FAO estimates that crop yields in the IGP could fall by 15–20% by 2050 due to compounding climate-soil feedbacks. Restoring soil health is, at this point, both an agronomic necessity and a long-term food security obligation to future generations.

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