

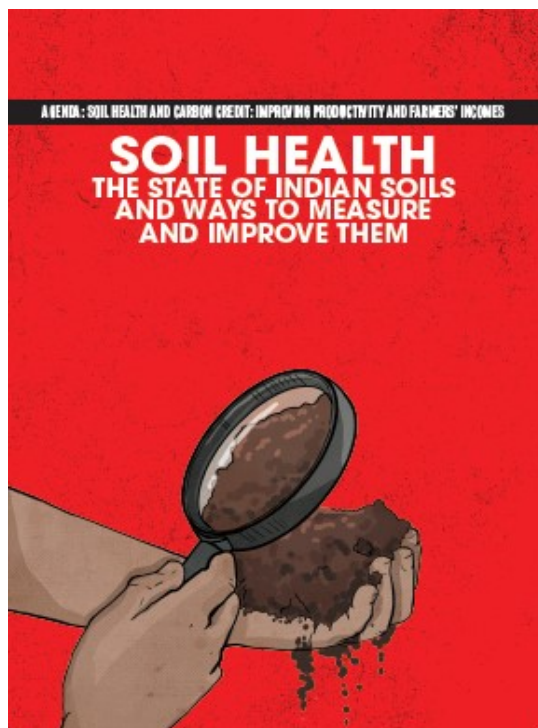


Understanding soil biological health and importance for sustainable food systems

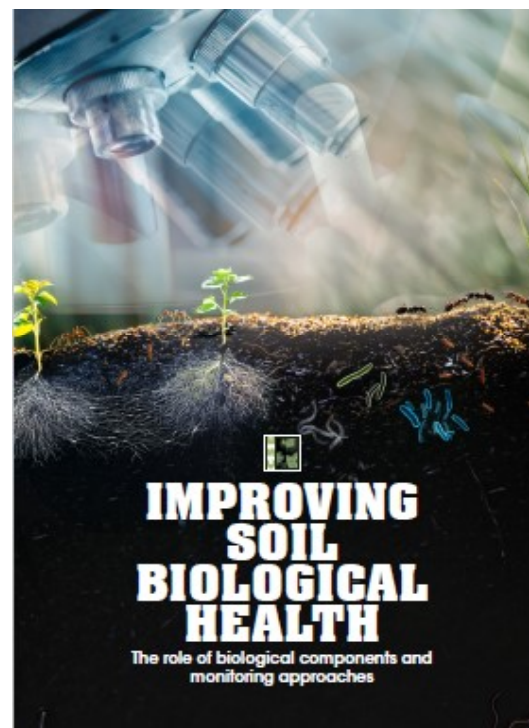
**Residential Training Programme:
Leveraging Agroecology for Livelihood
September 29, 2026**

Rajeshwari Sinha, CSE





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SUSTAINABLE FOOD SYSTEMS





Soil is the natural body on the Earth's surface, consisting of layers composed of weathered mineral materials, organic material, air, and water.

- natural medium for plant growth
- regulates hydrological and nutrient cycles
- maintains biological activities
- sequesters vast amounts of atmospheric carbon.

Soil health refers to the **overall capacity of soil to function** as a vital **living system** and sustain plant, animal, and the entire ecosystem. It is determined by its **physical, chemical, and biological** health.

Soil fertility is the capacity of soil to supply essential nutrients to crops in plant-available forms, in adequate quantities and correct proportions.

Soil productivity refers to the crop yield under a given set of conditions.

A fertile soil may not always be productive, as its ability to grow a crop and produce yield can depend on several external factors (e.g. irrigation, temperature, etc.)



Soil nutrient standards as per Soil Health Card (Mrida Swasthya Card) scheme

- **Twelve parameters**
 - **Macronutrients** (nitrogen, phosphorus, potassium, and sulphur)
 - **Micronutrients** (zinc, iron, copper, manganese, and boron)
 - **Soil organic carbon (SOC)**
 - **pH, Electrical conductivity**
 - Primary focus on chemical attributes
 - Does not test for biological parameters
 - SOC is often considered a proxy indicator for soil biological health; linked to cost-effectiveness, technical and operational feasibility

- pH - Acidic: < 6.5; Normal: 6.5-8.2; Alkaline: > 8.2
- EC (dSm/m) - Normal: < 1; Medium: 1-3; Harmful: > 3
- Organic Carbon (per cent) - Low: < 0.5; Medium: 0.5-0.75; High: > 0.75
- Available Nitrogen (kg/ha) - Low: < 240; Medium: 240-480; High: > 480
- Available Phosphorus (kg/ha) - Low: < 28; Medium: 28-56; High: > 56
- Available Potassium (kg/ha) - Low: < 140; Medium: 140-280; High: > 280
- Sulphur (ppm) - Low: < 10; Medium: 10-20; High: > 20
- Magnesium (ppm) - Low: < 1; Medium: 1-2; High: > 2
- Calcium (ppm) - Low: < 1.5; Medium: 1.5-3.0; High: > 3.0
- Zinc (ppm) - Low: < 0.5; Medium: 0.5-1.0; High: > 1.0
- Ferrous (ppm) - Low: < 5; Medium: 5-10; High: > 10
- Manganese (ppm) - Low: < 5; Medium: 5-10; High: > 10
- Copper (ppm) - Low: < 0.2; Medium: 0.2-0.4; High: > 0.4

Source: Soil Health Card (SHC) Scheme: Manual for District-Level Functionaries, (2017)

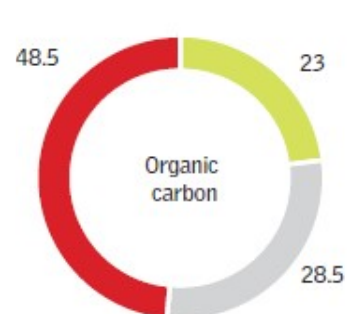




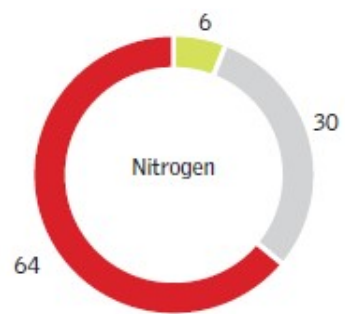
Samples tested across states under SHC scheme, 2023-25

About 1.3 Cr samples for different parameters

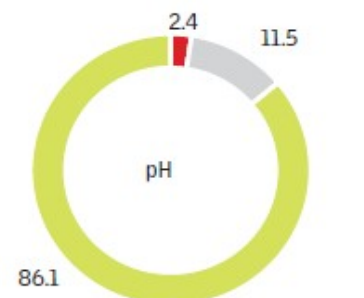
Macronutrients, pH status of soil: National level



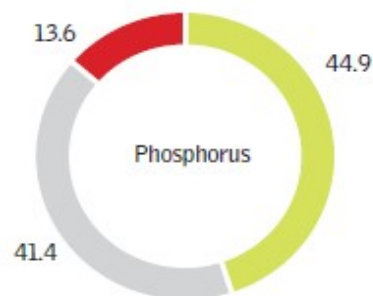
■ % High ■ % Medium ■ % Low



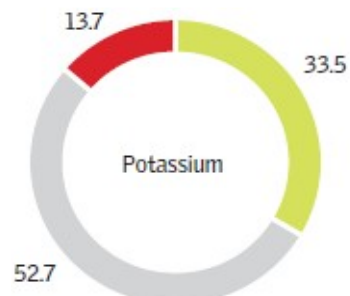
■ % High ■ % Medium ■ % Low



■ % Alkaline ■ % Acidic ■ % Neutral



■ % High ■ % Medium ■ % Low



■ % High ■ % Medium ■ % Low

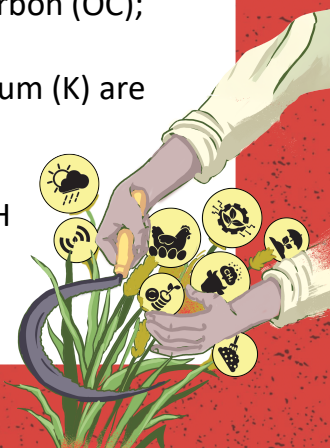
Majority of Indian soils deficient in nitrogen (N) and organic carbon (OC);

Phosphorus (P) and potassium (K) are levels better

Soils largely have neutral pH

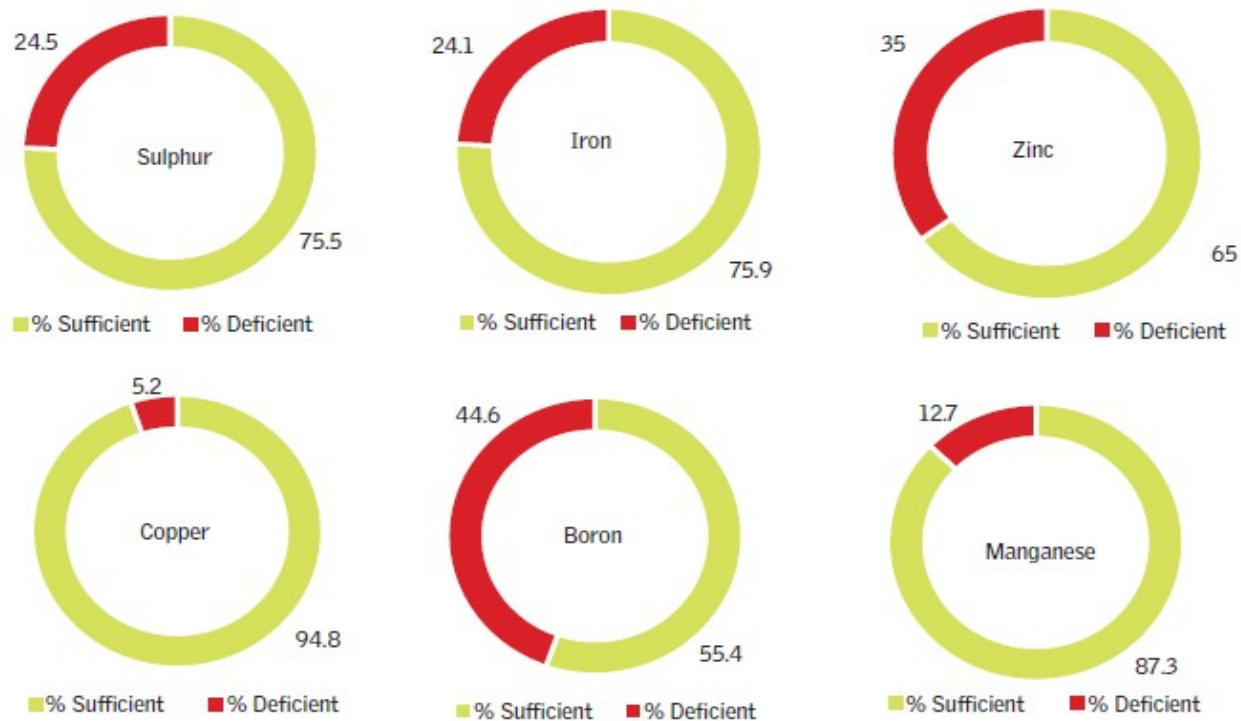
Source: Soil Health Card Nutrient Dashboard, Ministry of Agriculture and Farmers Welfare

SUSTAINABLE FOOD SYSTEMS





Micronutrients, status of soil: National level



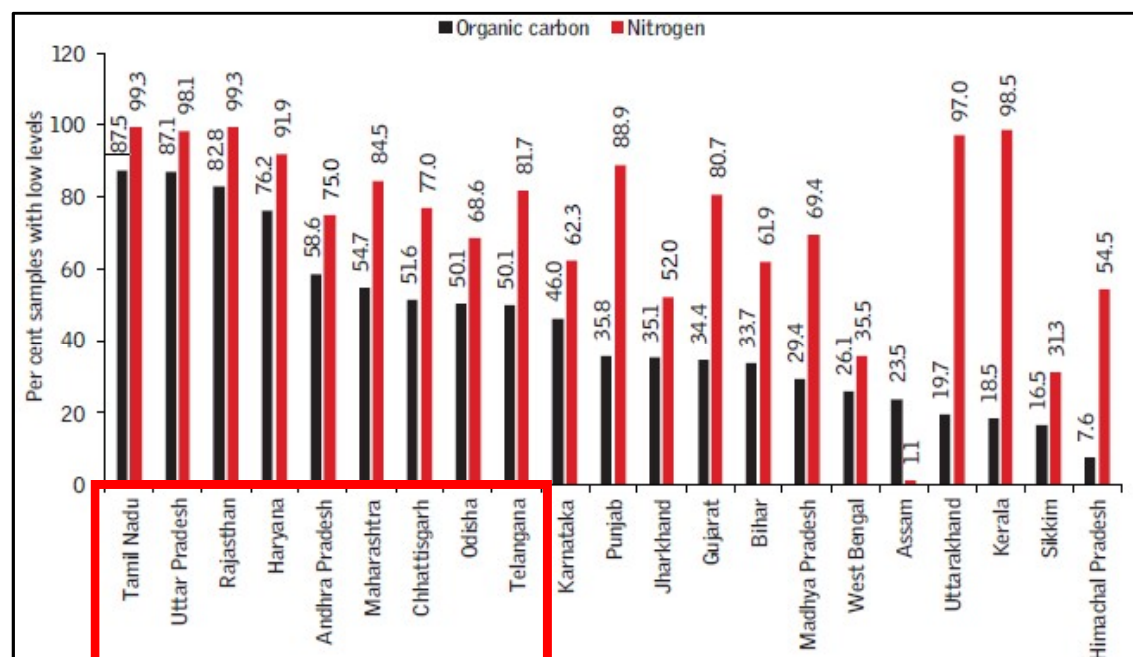
Notable deficiency in zinc and boron levels; others sufficient

Source: Soil Health Card Nutrient Dashboard, Ministry of Agriculture and Farmers Welfare

SUSTAINABLE FOOD SYSTEMS



Organic carbon and nitrogen in agriculturally-relevant states, 2023-25



Source: Soil Health Card Nutrient Dashboard, Ministry of Agriculture and Farmers Welfare

- >50 per cent samples in **nine states** with 'low' organic carbon
- >50 per cent samples in **18 states** with 'low' nitrogen



Correlation: fertilizer consumption and samples with low soil nutrient levels

N fertilizer and soil N

Moderately +ve correlation ($R=0.36$)
between N consumption
and samples with low soil
N
Suggesting N fertilizer
consumption **does not**
result in corresponding
improvement in soil N
levels

P fertilizer and soil P

Almost no correlation
(**$R = -0.09$**) between P consumption and samples with low soil P levels

Suggesting that P fertilizer consumption **does not seem to influence** soil P levels

K fertilizer and soil K

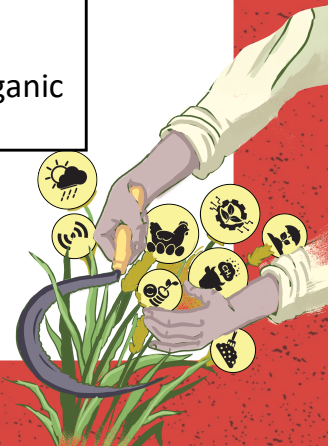
Weak negative correlation ($R=(-)0.21$)
between total K fertilizer
consumption and samples
with low soil K

Suggesting that K fertilizer
consumption **favourably
influences** soil K levels

Total NPK fertilizer and soil organic carbon

Moderately +ve correlation (R=0.47) between avg NPK consumption and samples with low soil organic carbon

Suggesting NPK fertilizer consumption **does not result** in corresponding improvement in soil organic carbon levels





Reasons for declining soil health in India

1

Overuse and imbalanced fertilizer use

- About 20% rise in consumption in last decade
- **Urea-skewed** consumption (subsidy structures); 68% of total fertiliser consumption (2023-24)
- N:P:K ratio national average is 9.8: 3.7: 1, against recommended 4:2:1
- Other nutrients **under-applied**
- Negatively impacts pH, SOC, nutrient uptake, soil biology

2

Intensive and chemical-dependent agronomic practices

- **High-yielding varieties**
- **Monocropping dominance**-depletion of soil nutrients, restricted soil microbial diversity, pest/disease build-up
- **Excessive tillage**-destabilized soil structure, disturbed soil fauna
- **Pesticide use**
- **Excessive irrigation**

3

Soil erosion

- Widespread erosion (**water, wind**) strips fertile topsoil
- Nutrient, SOC rich biologically active layer removed
- **One mm** topsoil lost annually in India (water driven); ~ 5.3 billion tonnes soil lost
- Reduced agricultural productivity, increased floods and droughts, biodiversity loss





Long-term impacts of declining soil health

Green Revolution in India achieved grain sufficiency; but it has come at a cost

- **High** cost of production
- **High** dependence on chemical inputs
- **Fertiliser response ratio collapse:** From 12:1 in 1960s to 5:1 in recent decades
- **Reduced** carbon sequestration potential and accelerated soil **degradation**
- **Diminished resilience:** Heightened vulnerability to climate stressors like floods and droughts
- **Nitrate pollution:** Leaching of excess chemicals into ground-water systems
- **Hidden hunger:** Growth of nutrient-poor crops leading to micronutrient deficiencies





Importance of soil biological health



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Soil biological components and their functions

- **Microbiota** (< 0.1 mm)
(bacteria, actinomycetes, fungi, algae)
- **Microfauna** (< 0.1 mm; **micro-predators**)
(protozoa, nematodes)
- **Mesofauna** (0.1–2.0 mm; **litter-transformers**)
(mites, pseudoscorpions)
- **Macrofauna** (2.0–20 mm; **eco-system engineers**)
(earthworms, termites, ants, beetles)
- **Megafauna** (> 20 mm)
(small mammals, frogs, snakes, lizards)

Soil is home to
>25% of
planet's
biodiversity

Just 8 cm of
soil, has **13 x**
10¹⁵ living
organisms

1g healthy soil has
more organisms
than people on the
Earth



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Soil organisms	Ecological functions
Microbiota (< 0.1 mm)	
Bacteria (e.g., <i>Bacillus</i> sp., <i>Rhizobium</i> sp., <i>Pseudomonas</i> sp.)	Nutrient cycling, fix atmospheric N, produce polysaccharides that improve soil structure and water retention
Actinomycetes	Decompose cellulose and chitin, contribute to humus formation, may fix N in association with some non-leguminous plants
Fungi (e.g., mycorrhizae, saprophytes)	Decompose complex lignin and cellulose, symbiotic bonds with roots to expand nutrient/water uptake, stabilise soil aggregates
Algae and cyanobacteria (e.g., <i>Nostoc</i> , <i>Anabaena</i>)	Primary producers performing photosynthesis, fix N, release oxygen to support aerobic life, form beneficial symbiotic association
Microfauna (< 0.1 mm; the micro-predators)	
Protozoa (e.g., amoebae, ciliates, flagellates)	Regulate bacteria/microbial populations through grazing, influence N mineralisation and availability
Nematodes	N mineralisation, distribution of biomass within plants, some are microbe predators or plant-predators, bio-indicators of soil health
Mesofauna (0.1–2.0 mm; the litter-transformers)	
Mites	Shred plant litter for microbial decomposition, regulate microbe population by predation
Collembola (springtails)	Feed on fungi and litter, accelerate decomposition in surface soils
Pseudoscorpions	Predators feeding on mites and springtails
Macrofauna (2.0–20 mm; the eco-system engineers)	
Earthworms	Mixing soil layers to enable soil formation and maintain soil structure, create vertical channels for aeration/water drainage, produce nutrient-rich castings, bio-indicators of soil health
Termites	Build mounds to modify soil profiles, facilitate distribution and in-situ decomposition of organic litter
Ants	Build nests incorporating huge amounts of organic matter/nutrients in deeper soil layers
Beetles	Bury animal waste in sub-vertical galleries, enrich soil fertility, larvae influence root health
Other insects (e.g., spiders, snails, centipedes)	Act as predators, shredders, or detritivores that break down surface litter
Megafauna (> 20 mm)	
Small mammals (e.g., moles, rodents)	Primarily dig soil for food or shelter enabling soil mixing, aeration
Herpetofauna (e.g., frogs, snakes, lizards)	Role in high-level soil food web

Note: The classification of soil organisms is based on their body width.



Functions of a biologically healthy soil

1

Nutrient availability and fertiliser use efficiency

- Microbes **drive major nutrient cycles** (e.g. C, P, N, K)- microbial decomposition and mineralization
- Organic matter converted to **plant-available nutrient forms**
- **Enhance nutrient uptake:** bacteria-root symbiotic relationships, fungal hyphae networks
- **Improved fertiliser use efficiency (FUE)**

2

Improved soil structure and water retention

- Extracellular polymeric substances, glomalin from bacteria/ fungi bind soil; **better soil aggregation**
- **Better water holding capacity** due to humus formation; **deep water infiltration** due to fungal hyphae
- Tunnel network of earthworms, termites **improves soil aeration, porosity, water penetration**
- Improved soil physical health; stabilized soil architecture

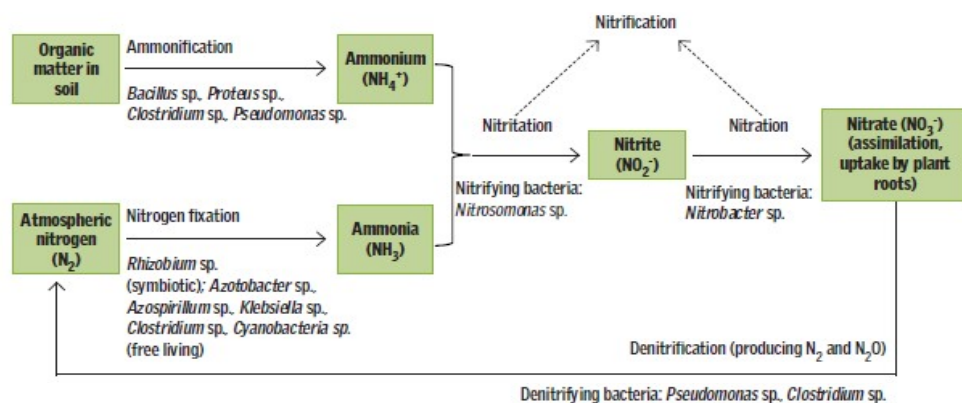
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Potential to reduce GHG emissions

- Improved **carbon sequestration** potential ('carbon-sink')
- Plant residues converted to stable humus, necromass (by microbes; storing carbon)
- **Reduce N₂O emissions** through multiple pathways
- Indian soils can sequester estimated **6-7 Tg of carbon** annually under improved biological management

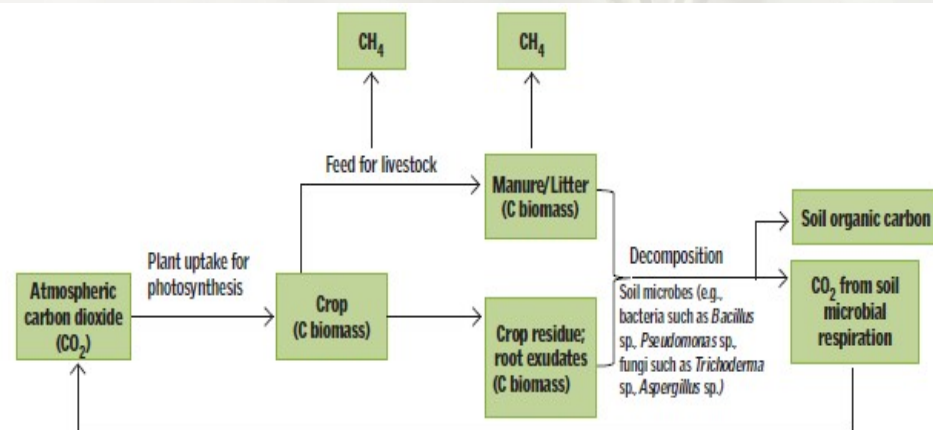


Role of microbes in soil nutrient cycles: nitrogen, carbon



- *Rhizobium* sp. (N fixation)
- *Bacillus* sp. (ammonification)
- *Nitrosomonas* sp. and *Nitrobacter* sp. (nitrification)
- *Pseudomonas* sp. (denitrification)

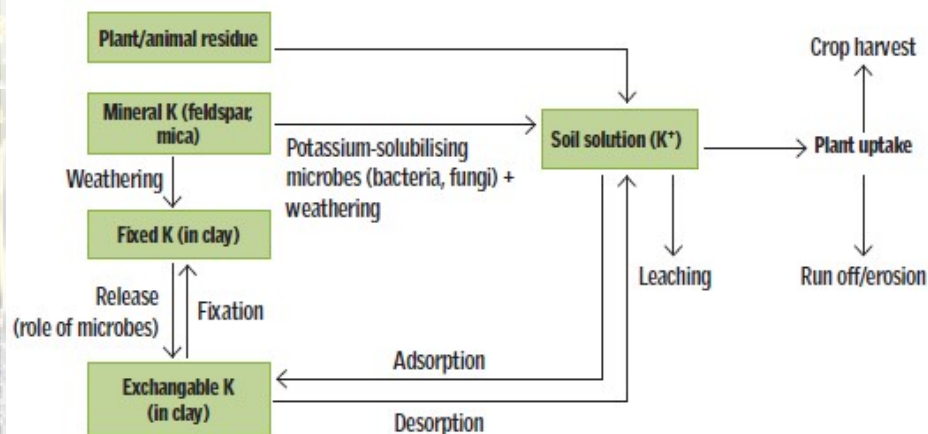
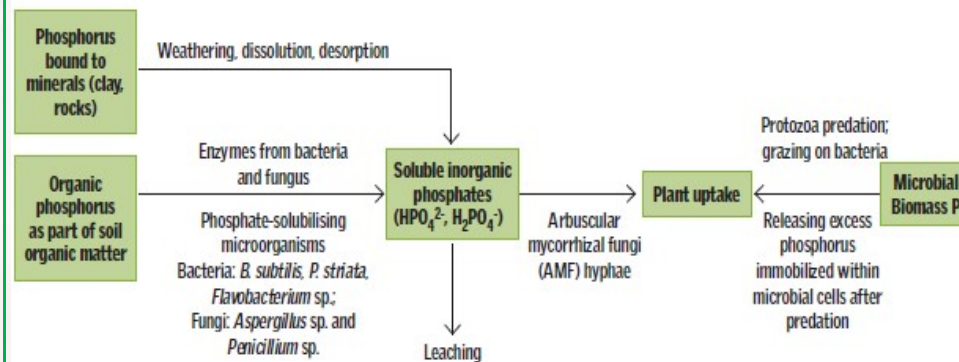
- Bacteria: *Bacillus* sp., *Pseudomonas* sp.
- Fungi: *Trichoderma* sp., *Aspergillus* sp.





Role of microbes in soil nutrient cycles: phosphorus, potassium

- *B. subtilis*, *Penicillium* sp. (phosphate-solubilising bacteria)
- Arbuscular mycorrhizal fungi (plant uptake)



- Potassium-solubilising microbes (bacteria, fungi)



Monitoring biological health of soil



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Challenges to be addressed to monitor biological health of soil

1

Logistical fragility

- Samples require strict cold chains
- Testing to be conducted within 24-72 h
- Presently seems unfeasible at scale

2

Infrastructure and expertise concerns

- Most laboratories lack essential equipment (e.g., laminar air flow, fridge) and qualified soil biologists

3

Operational constraints

- Biological assays time-consuming
- High cost of specialized chemicals, reagents makes routine large-scale testing difficult to afford

4

Lack of benchmarks

- No established national standards or thresholds to help interpret biological results or guide farm interventions





Why SOC is a proxy, but not a true indicator of biological health

SOC may not completely capture soil's biological activity

- **SOC only quantifies carbon in the soil**
 - Whereas biological parameters reflect how carbon is being transformed, cycled, and incorporated into biomass
- **SOC does not capture diversity of soil communities, its expansion or shrinkage**
- **SOC slow to change; biological parameters dynamic**
 - Whereas biological parameters vary with moisture, temperature, farm management, fertiliser application, and similar other factors in much shorter timeframes
- **SOC levels do not differentiate between inert and active C fractions; inflated picture of soil biological health**



Scientific community sees value in testing of soil biological parameters

Lead organisation (year)	Location	Key observations	Biological parameters tested
University of Agricultural Sciences, Karnataka (2025) ³²	Kodagu district, Karnataka	Organic coffee soils had higher microbial biomass, respiration, and diversity than conventional plots	Microbial biomass C, soil respiration, microbial diversity
IIT Kharagpur (2025) ³³	West Bengal	Conservation tillage with residue retention improved soil biochemical health	Enzymes (dehydrogenase, phosphatase, urease), soil respiration, microbial biomass C
ICAR-Indian Institute of Soil Science (2025) ³⁴	Bhopal, Madhya Pradesh	Agricultural practices shifted soil microbiome composition; organic amendments improved diversity; soil microbes resilient to short-term disturbances	Microbial community composition (16S rRNA), diversity indices
ICAR (2025) ³⁵	Upper Gangetic Plains, India	Integrated organic systems improved biological soil health	Microbial biomass, enzyme activity, organic C
Multi-institutional study (2024) ³⁶	Middle Gangetic Plains (Bihar)	Seasonal variation strongly affected microbial biomass, respiration, and carbon use efficiency	Microbial biomass C and N, soil respiration, metabolic quotient (qCO ₂)

Lead organisation (year)	Location	Key observations	Biological parameters tested
ICAR-Directorate of Rapeseed-Mustard Research (DRMR; 2024) ³⁷	Research farm in DRMR, Rajasthan	Long-term residue recycling, different tillage practices influenced biological indicators, diversified cropping systems, and enhanced microbial activity	Soil microbial biomass, soil enzyme activities, soil chemical changes
Kumaun University & collaborators (2023) ³⁸	Central Himalaya, Uttarakhand	Microbial biomass components exhibited strong seasonal and altitudinal variation	Soil microbial biomass carbon
ICAR-Indian Agricultural Research Institute (IARI; 2021) ³⁹	IARI, New Delhi	Conservation agriculture improved microbial indices, enzyme activities, glomalin, and aggregate stability over conventional tillage	Microbial biomass carbon, soil enzyme activity (dehydrogenase, alkaline phosphatase), glomalin
International Rice Research Institute (2021) ⁴⁰	Multiple sites	Organic and conservation farming enhanced microbial biomass and activity	Microbial biomass C & N, dehydrogenase activity

National projects on soil microbiome and biodiversity: Indian Soil Microbiome Project, Network Project of Application of Microorganisms in Agriculture and Allied Sectors, All India Network Project on Soil Biodiversity and Biofertilisers





Emerging focus on biological parameters in point-of-need testing (1/2)

SRI-GEL

- A probe-based device to measure **soil respiration**.
- By **Tamil Nadu Agricultural University** and **Indian Institute of Soil Science**
- Re-usable gel pad that traps and measures CO₂ released by **actively respiring** soil microbes in 6-8 hours; reflected by colour change in gel pad
- Cost of test: <Rs 50 per soil sample
- Aims for an affordable test for farmers; patent submitted (early Jan 2026)

Soil X Probe

- AI, ML, spectrometry-based probe; real-time; for unskilled users
- By **Reve Nano-Science LLP**
- Monitors five biological parameters— **relative bacterial index, fungal activity index, humus content index, termite influence index, and aflatoxin risk index**
- Results in ~ 1 min; rechargeable, can run 10-11 hrs
- Price Rs 5 lakh; cost per sample quite minimal



Emerging focus on biological parameters in point-of-need testing (2/2)



Soil-Doctor Kit

Portable, semi-automatic, spectroscopy based soil testing system

By EkoSight

- Tests two biological parameters— **microbial biomass, fungal:bacterial ratio** (out of 18)
- Decentralised, village-level '**soil doctor clinic**' model, with stationed '**soil doctors**' (80+ clinics in nine states in Jan 2026)
- Cost per test at these clinics: Rs 500–750 per test).
- Price ~Rs 75,000 (+Rs 10,000 for setup, GST etc).

Soilometer



- Rapid, on-spot soil testing based on colour-based biochemical assay
- By **Biome Technologies Pvt. Ltd.**
- Measures **total viable microbial count (bacteria and fungi)**
- Cost: Rs 300 per test (Kit price Rs 1,500 for five tests; qualitative results in 3 hours)
- >3,000 farmers **trained** in the last 3 years; provided with testing kits, biofertilisers, biopesticides
- '**Soil warriors**' to scale up testing on ground





Possible tests for biological health in SHC scheme (1/2)

1

Sensory tests:

- Soil colour
- Soil odour
- Soil texture

(quick qualitative know-how about soil health; no cost involved)

2

Tests with minimal laboratory needs

Soil test (What it measures)	Method	Cost [#] (per test; broad sense)	Advantages	Concerns
Earthworm population/ castings* [^] (Cast count, density of earthworms)	Dig 1x1x1 m ³ pit; count worms/castings (hand sorting or mustard extraction)	Low	Easy and quick to monitor; not resource intensive	Counting methods can be destructive; high variability due to time, moisture level
Hydrogen peroxide (H ₂ O ₂) test* (Organic matter in soil)	Add few drops of 30 per cent H ₂ O ₂ to soil sample; stronger reaction (bubbles) means higher organic matter content	Low	No equipment needed; easy and not resource intensive; can be repeated over time	Not all soils react with H ₂ O ₂ irrespective of organic matter content
Microbial density/ Microbial population/ Fungi:Bacteria Ratio* (sense of fungal and bacterial population)	Microscopic count; higher fungi population implies good soil health	Low	Technically easy to monitor; need some resources	One-time investment for microscope needed; user should know sample preparation and microscope use

[^] Earthworm count is more accurate but cast count can also be an indicator; *Can be done in field or with minimal laboratory needs; [#]Cost assessment is based on primary inputs



Possible tests for biological health in SHC scheme (2/2)

3

Tests needing some lab infrastructure

4

High-end tests, such as determination of microbial community composition using 16S rRNA sequencing also possible

Soil test (What it measures)	Method	Cost [#] (per test; broad sense)	Advantages	Concerns
Microbial Biomass Carbon (C in living microbes)	Chloroform fumigation-extraction method followed by extraction of carbon using usually with K_2SO_4	Moderate (~Rs 500 per sample)	Good predictor of nutrient mineralization potential; responsive to organic inputs	Fumigation chemicals could be hazardous; need some establishment (e.g. vacuum pump, water bath) and skilled labour
Permanganate Oxidisable Carbon (Labile/active carbon pool)	Chemical oxidation with $KMnO_4$ and colorimetric assay	Moderate (upto Rs 500 per sample)	Quick, affordable; chemicals and equipment present in standard lab	Standardisation required; sensitive to soil texture and mineralogy
Soil respiration (CO_2 evolved by microbial activity)	Closed jar/alkali trap method or use of infra-red gas analysers	Moderate (upto Rs 500 per sample)	Quantitative and reproducible	Time consuming; needs incubation; moisture control critical
Microbial enzyme activity (Dehydrogenase; Soil oxidative enzyme activity)	Colourless Triphenyl Tetrazolium Chloride (TTC) reduced to red Triphenyl Formazan (TPF); TPF measured in spectrophotometer	Moderate (~Rs 500 per sample)	Gives direct sense of metabolic activity of microbial community	Enzyme assays sensitive to storage; interpretation requires expertise; requires soil incubation; need some establishment (e.g. BOD incubator)

[#]Cost assessment is based on primary inputs



PM Programme for Restoration, Awareness Generation, Nourishment and Amelioration of Mother Earth (PM-PRANAM)

- Approved in 2023 to check growing subsidy on fertilizers and promote sustainable agricultural practices
- Scheme pushes for **balanced fertilizer use**
 - Incentives to states/UTs [receive grant equivalent to 50% of their saved fertilizer subsidy]
- In 2023-24, **14 states** collectively reduced their chemical fertilizer consumption by **1.51 million tonne (MT)** across urea, DAP, NPK, MOP, relative to their 3-year avg
 - Karnataka contributed ~30% of the total reduction
 - Maharashtra, West Bengal and Andhra Pradesh contributed 58%
- In 2025-26, **5 States/UTs** collectively reduced their chemical fertilizer consumption by **0.18 lakh metric tonne** across urea, DAP, NPK, MOP, relative to their 3-year avg
 - Dadra and Nagar Haveli, Delhi, Goa, Manipur and Mizoram
 - Incentives under the scheme not yet disbursed





Way ahead



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Way ahead: 1. Improve organic carbon (SOC) content in soil

a. Promote organic and bio-inputs (on-farm and off-farm)

- Increase use of farmyard manure, compost, green manuring, and microbial consortia
- Support farmers with the necessary materials, infrastructure and knowledge to produce organic/natural inputs
- Systemic long-term support to local bio-input research centres

b. Promotion of agronomic practices

- Encourage non-chemical farming, crop diversity, water-use efficiency, and regenerative/agroecological/conservation agriculture practices





Way ahead: 2. Reform chemical fertiliser and pesticide use

a. Reduce chemical fertiliser use

- Improve fertiliser subsidy structure. Include urea in the Nutrient Based Subsidy scheme. Reducing the gap between the price of urea and other fertilisers such as DAP
- Direct financial support to farmers enabling them to opt for non-chemical fertilisers
- Scale up integrated nutrient management
- Encouraging states to utilise PM-PRANAM scheme to reduce chemical fertiliser consumption

b. Phase-off pesticides

- Promote integrated pest management and the use of bio-pesticides





Way ahead: 3. Mainstream monitoring of soil biological health

a. Include biological parameters in the SHC scheme

- Phased approach [select districts, labs, tests]
- Develop thresholds or benchmarks in parallel
- Tests for **microbial biomass carbon** and **microbial enzyme activity (dehydrogenase)** to begin with

b. Strengthen soil testing laboratory infrastructure and scale up capacity

- Understand which parameters to test and their lab requirements
- Invest in capacity-building (e.g., station soil biologists in labs)

c. Promote inclusion of affordable on-farm or point-of-need (PON) testing of soil biological parameters

- Incentives for uptake among farmers
- Ensure quality and result validation
- Encourage village-level entrepreneurship for localized testing

d. Create awareness among farmers and local ecosystem





Thank you

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