



# IMPROVING SOIL BIOLOGICAL HEALTH

The role of biological components and monitoring approaches



Rajeshwari Sinha  
Sustainable Food Systems Programme  
CSE  
May 25, 2026

[WWW.CSEINDIA.ORG](http://WWW.CSEINDIA.ORG)



## CSE's latest report

Report based on research conducted with experts from different stakeholder groups:

- **Scientific community**
- **Civil society**
- **State agriculture departments**
- **Soil testing agri-tech start-ups/laboratory**

Reflects cumulative understanding developed based on insights and inputs shared by experts from diverse stakeholder groups



Download [here](#)



## 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





## Current status of nutrients in Indian soil

### Soil Health Card Scheme (2023-2025)

- Severe **nitrogen** deficiency: 64% samples tested low [ $<240$  kg/ha])
- **Phosphorus**: 13.7% tested low [ $<28$  kg/ha])
- **Potassium**: 13.7% tested low [ $<140$  kg/ha])
- **Boron**: 55.4% tested low
- **Zinc**: 35% tested low [ $<0.5$  ppm]
- **Organic carbon**: 48.5% tested low [ $<0.5\%$ ]
- **Weak correlation** between N fertiliser consumption and soil N availability
- **Weak correlation** between NPK fertiliser consumption and SOC

### ICAR's long-term field studies

- 2019–2024: **33% of area had SOC  $<0.5\%$**  [ $>0.25$  million samples; 620 districts; 29 states]
- 2012-2018: **~60% soils sulphur deficient**; significant **deficiencies in B, Fe, Cu, Mn** [0.24 million surface soil samples]

### Other scientific studies

- **SOC deficiency in 12-76%** soil samples tested
- Widespread; interstate variability





## 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 (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



CSE

# Importance of soil biological health



[WWW.CSEINDIA.ORG](http://WWW.CSEINDIA.ORG)



# 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 10<sup>15</sup>** living organisms

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

[WWW.CSEINDIA.ORG](http://WWW.CSEINDIA.ORG)

Soil organisms	Ecological functions
<b>Microbiota (&lt; 0.1 mm)</b>	
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., Nostoc, Anabaena)	Primary producers performing photosynthesis, fix N, release oxygen to support aerobic life, form beneficial symbiotic association
<b>Microfauna (&lt; 0.1 mm; the micro-predators)</b>	
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
<b>Mesofauna (0.1–2.0 mm; the litter-transformers)</b>	
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
<b>Macrofauna (2.0–20 mm; the eco-system engineers)</b>	
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
<b>Megafauna (&gt; 20 mm)</b>	
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

3

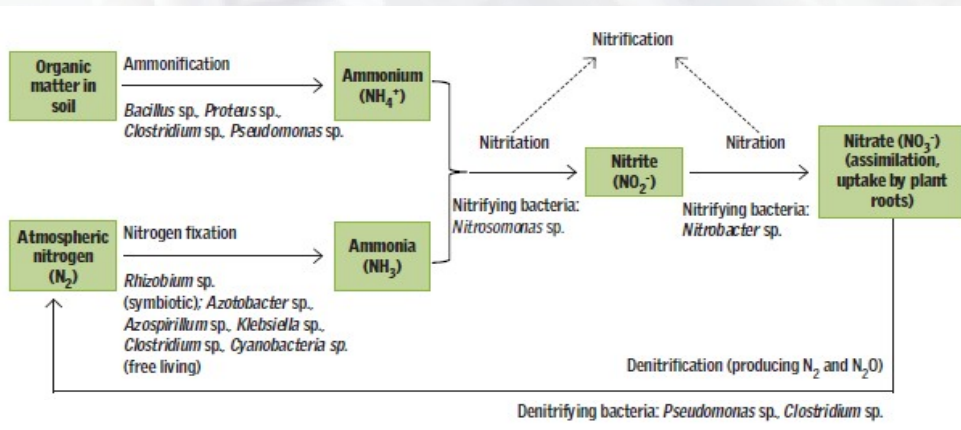
### Potential to reduce GHG emissions

- Improved **carbon sequestration** potential ('carbon-sink')
- Plant residues converted to stable humus, necromass (by microbes; storing carbon)
- **Reduce N<sub>2</sub>O emissions** through multiple pathways
- Indian soils can sequester estimated **6-7 Tg of carbon** annually under improved biological management



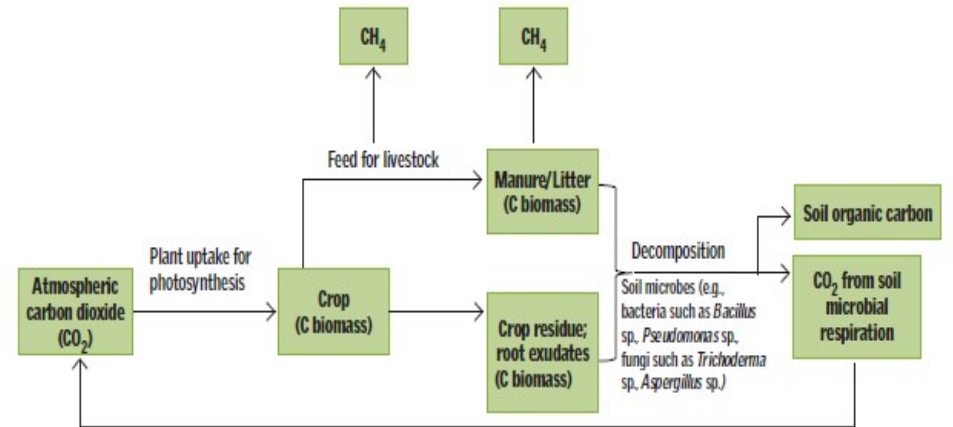


# Role of microbes in soil nutrient cycles: nitrogen, carbon



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

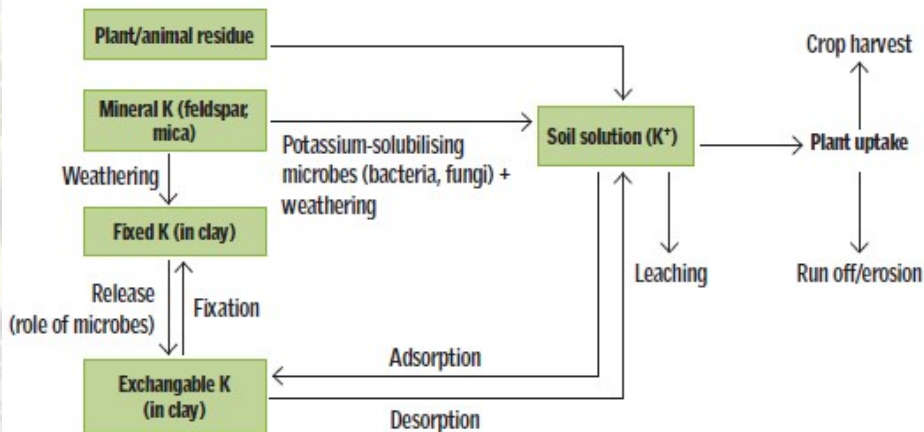
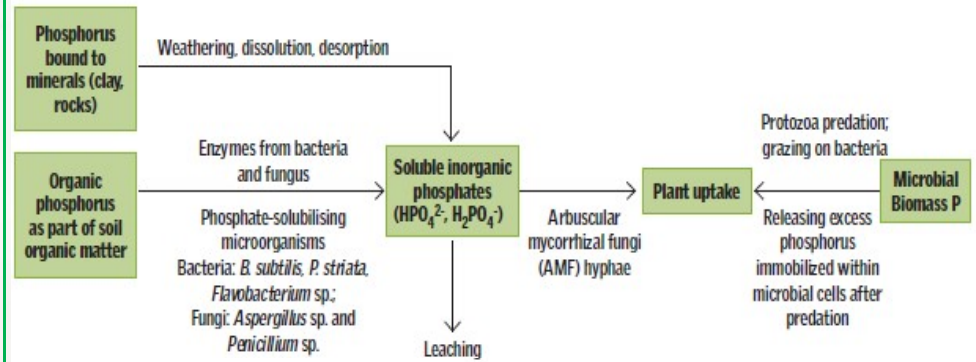
- Bacteria: *Bacillus* sp., *Pseudomonas* sp.
- Fungi: *Trichoderma* sp., *Aspergillus* sp.





## 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



[WWW.CSEINDIA.ORG](http://WWW.CSEINDIA.ORG)



## Monitoring of soil under Soil Health Card scheme

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





# 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) <sup>32</sup>	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) <sup>33</sup>	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) <sup>34</sup>	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) <sup>35</sup>	Upper Gangetic Plains, India	Integrated organic systems improved biological soil health	Microbial biomass, enzyme activity, organic C
Multi-institutional study (2024) <sup>36</sup>	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 <sub>2</sub> )

Lead organisation (year)	Location	Key observations	Biological parameters tested
ICAR-Directorate of Rapeseed-Mustard Research (DRMR;2024) <sup>37</sup>	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) <sup>38</sup>	Central Himalaya, Uttarakhand	Microbial biomass components exhibited strong seasonal and altitudinal variation	Soil microbial biomass carbon
ICAR-Indian Agricultural Research Institute (IARI; 2021) <sup>39</sup>	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) <sup>40</sup>	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 CO<sub>2</sub> 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 <sup>#</sup> (per test; broad sense)	Advantages	Concerns
Earthworm population/ castings* <sup>^</sup> (Cast count, density of earthworms)	Dig 1x1x1 m <sup>3</sup> 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 <sub>2</sub> O <sub>2</sub> ) test* (Organic matter in soil)	Add few drops of 30 per cent H <sub>2</sub> O <sub>2</sub> 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 <sub>2</sub> O <sub>2</sub> 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

<sup>^</sup> Earthworm count is more accurate but cast count can also be an indicator; \*Can be done in field or with minimal laboratory needs; <sup>#</sup>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 <sup>#</sup> (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)

<sup>#</sup>Cost assessment is based on primary inputs





# Conclusion and Way ahead



[WWW.CSEINDIA.ORG](http://WWW.CSEINDIA.ORG)



## Conclusion

- **Need to enhance soil's biological health** to improve declining status of India's soil health
- **Added benefits of improving biological aspects** – increased food productivity, nutritive crops, better farmer incomes, water conservation, prevention of desertification, reduced environmental pollution, building resilience in agriculture sector
- Soil monitoring is still **largely focused on chemical-centric approaches**; absence of national-level monitoring of soil biological parameters (exception of SOC)
- **Recognition to invest in soil biological health has evolved** (scientific community, agri-tech start-ups, civil society coming forward)
- **Including biological parameters in national-level monitoring is the need of the hour**





## 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

For more information, contact:

Rajeshwari Sinha  
Senior Programme Manager  
[s\\_rajeshwari@cseindia.org](mailto:s_rajeshwari@cseindia.org)

Amit Khurana  
Director  
[k\\_amit@cseindia.org](mailto:k_amit@cseindia.org)

Sustainable Food Systems Programme  
Centre for Science and Environment



[WWW.CSEINDIA.ORG](http://WWW.CSEINDIA.ORG)