

## Advances and Challenges in Soil Sciences: A Review

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### ABSTRACT

*Soil science is a fundamental discipline underpinning global food security, environmental sustainability, and climate change mitigation. This review examines recent advances and persistent challenges in soil sciences, encompassing developments in digital soil mapping, soil microbiome engineering, carbon sequestration strategies, nanotechnology-based remediation, and artificial intelligence applications. Despite significant technological progress, challenges including soil degradation affecting approximately 40% of global land, heavy metal contamination, nutrient depletion, and climate-induced changes to soil processes continue to threaten agricultural productivity and ecosystem services. The review synthesises findings from contemporary research to highlight how emerging technologies such as remote sensing, machine learning, and precision agriculture are transforming soil assessment and management. Furthermore, critical gaps in policy frameworks, knowledge dissemination, and interdisciplinary collaboration are discussed. The paper concludes with recommendations for integrating innovative approaches with sustainable land management practices to address the escalating global soil crisis.*

**Keywords:** Soil Health; Digital Soil Mapping; Soil Microbiome; Carbon Sequestration.

### INTRODUCTION

Soil is one of the most critical natural resources on Earth, serving as the foundation for terrestrial life, agricultural production, and ecosystem functioning. As a complex, dynamic system comprising mineral particles,

organic matter, water, air, and a vast diversity of living organisms, soil provides essential services including nutrient cycling, water filtration, carbon storage, and habitat provision (Lehmann & Kleber, 2015).

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The discipline of soil science has undergone transformative advances in recent decades, driven by technological innovations in remote sensing, molecular biology, data analytics, and nanotechnology. However, the global soil resource base faces unprecedented threats from degradation, contamination, and climate change, demanding urgent scientific attention and policy intervention.

According to the United Nations Convention to Combat Desertification (UNCCD), approximately 40% of the world's land is currently degraded, affecting the livelihoods of nearly 3.2 billion people worldwide (UNCCD, 2024). The Food and Agriculture Organization (FAO) has estimated that 33% of global soils are moderately to highly degraded due to erosion, salinisation, compaction, acidification, and chemical contamination (FAO, 2015). These alarming statistics underscore the need for comprehensive reviews that synthesise current knowledge, identify research gaps, and chart future directions in soil science.

The emergence of digital soil mapping (DSM) techniques leveraging satellite remote sensing and machine learning algorithms has revolutionised our ability to characterise and monitor soil properties across spatial and temporal scales (McBratney et al., 2003). Concurrently, advances in metagenomics and next-generation sequencing have unveiled the extraordinary complexity of the soil microbiome, revealing that a single gram of soil may harbour up to 10 billion microorganisms representing thousands of species (Fierer, 2017). These discoveries have profound implications for sustainable agriculture, bioremediation, and climate change mitigation.

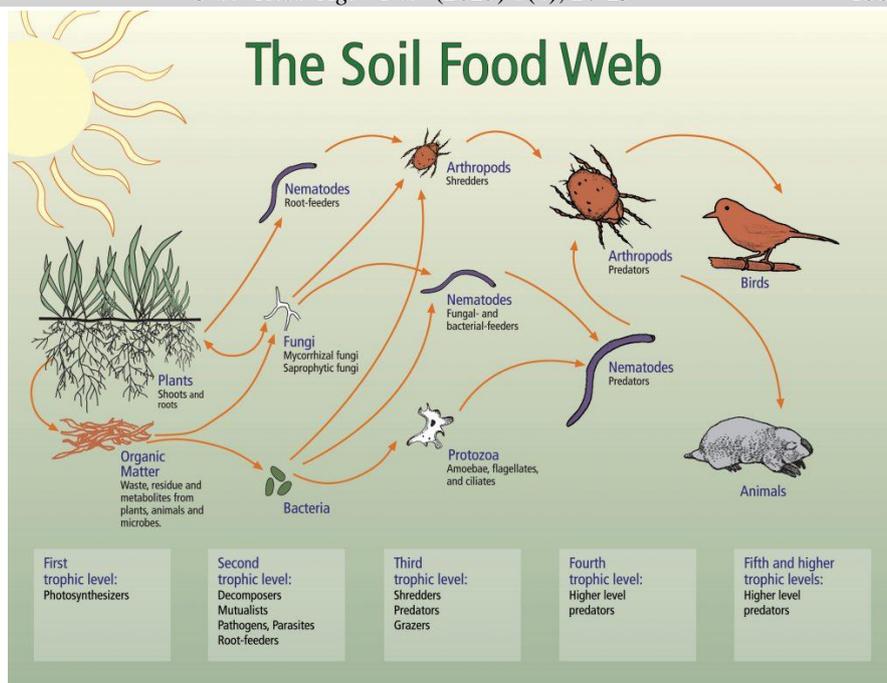
This review paper critically examines the major advances and challenges in soil

sciences, organised around five thematic areas: (i) soil health assessment and monitoring, (ii) digital soil mapping and remote sensing, (iii) soil microbiome and biological innovations, (iv) carbon sequestration and climate change, and (v) soil contamination and remediation. The paper aims to provide a comprehensive synthesis of contemporary research while identifying critical gaps and future research priorities.

## 2. Soil Health Assessment and Monitoring

Soil health, defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans, has emerged as a central paradigm in modern soil science (Doran & Zeiss, 2000). The concept integrates physical, chemical, and biological properties to provide a holistic assessment of soil functionality. Several standardised frameworks have been developed to evaluate soil health, including the Cornell Comprehensive Assessment of Soil Health (CASH), the Soil Management Assessment Framework (SMAF), and the Haney Soil Health Test (Lehmann et al., 2020).

Physical indicators of soil health include bulk density, aggregate stability, water-holding capacity, porosity, and infiltration rate. These parameters directly influence root penetration, water availability, and aeration. Chemical indicators encompass soil pH, cation exchange capacity (CEC), organic matter content, and nutrient availability, which collectively determine the soil's capacity to supply essential elements for plant growth (Bünemann et al., 2018). Biological indicators, including microbial biomass carbon, soil respiration, enzyme activities, and earthworm abundance, reflect the vitality of the soil's living component and its role in nutrient cycling and organic matter decomposition.



**Figure1. Physical, chemical, and biological indicators of soil health assessment (Source: ATTRA Sustainable Agriculture, NCAT)**

Recent advances in soil health monitoring include the integration of proximal soil sensing technologies, such as visible-near infrared (vis-NIR) spectroscopy and portable X-ray fluorescence (pXRF) analysers, which enable rapid, non-destructive, and cost-effective assessment of multiple soil properties simultaneously (Viscarra Rossel et al., 2006). The development of in-field soil health sensors using microbial diversity data represents a promising frontier, with projects such as the TRUTH Project (Thriving Roots Underpinning Total Soil Health) in the United Kingdom pioneering farmer-led soil microbiome data collection for developing practical soil health monitoring tools (HGF, 2026).

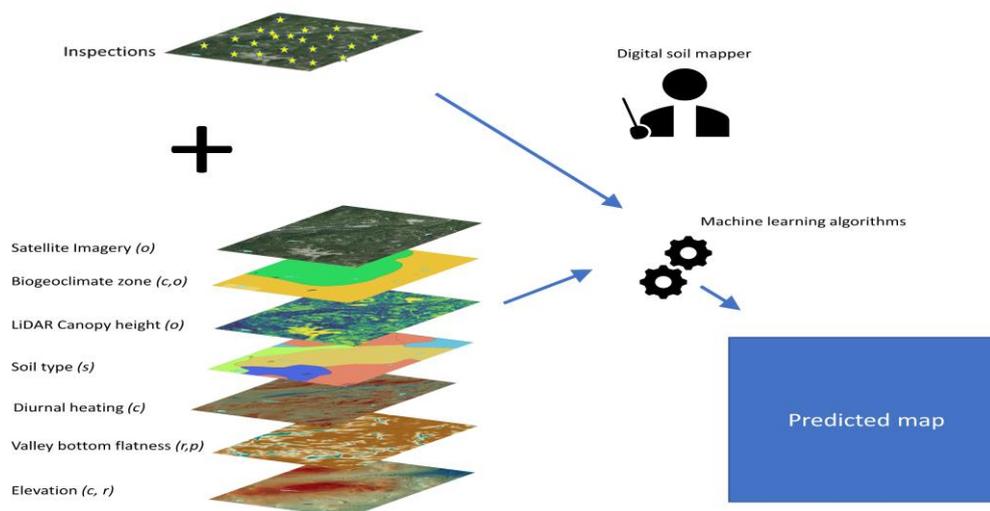
Despite these advances, significant challenges remain in standardising soil health assessment protocols across different agroecological zones, soil types, and land-use systems. The lack of universally accepted threshold values for soil health indicators complicates decision-making for farmers and policymakers (Rinot et al., 2019). Furthermore, the integration of biological indicators into routine soil testing remains limited in many developing countries due to cost constraints and insufficient laboratory infrastructure.

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### 3. Digital Soil Mapping and Remote Sensing

Digital soil mapping (DSM) represents one of the most significant methodological advances in contemporary soil science. DSM integrates field observations and laboratory analyses with environmental covariates derived from remote sensing data to create spatially explicit soil information systems (McBratney et al., 2003). The approach leverages the scorpan model, which relates soil properties to environmental factors including climate, organisms, relief, parent material, age, and spatial position.

The proliferation of high-resolution satellite platforms, particularly Sentinel-2 and Landsat-8, has significantly enhanced DSM capabilities. Sentinel-2, with its superior spatial resolution (10 m), multi-spectral capabilities, and frequent revisit cycle, has emerged as the most extensively utilised satellite platform for soil property prediction (Mgohele et al., 2024). Machine learning algorithms, including Random Forest (RF), Support Vector Machines (SVM), and Artificial Neural Networks (ANN), have demonstrated superior performance in predicting soil texture, organic carbon content, and moisture dynamics compared to traditional geostatistical methods (Wadoux, 2025).



**Figure2. Digital soil mapping framework integrating multi-temporal remotely sensed data with machine learning (Source: Zeraatpisheh et al., 2020, *Science of the Total Environment*)**

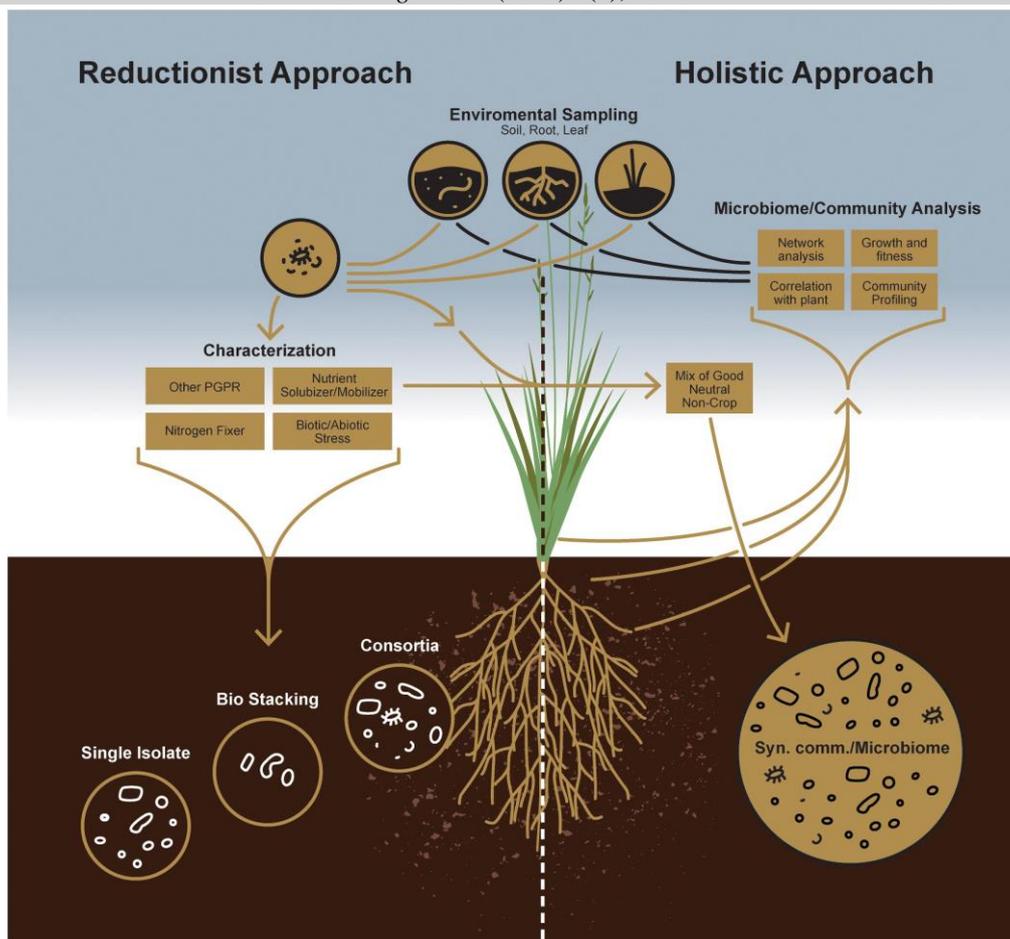
Ji (2025) proposed an advanced DSM framework integrating remote sensing and machine learning to enhance soil organic carbon (SOC) predictions at national and continental scales, demonstrating that hybrid modelling approaches outperform individual models. The study emphasised the importance of selecting appropriate temporal satellite data, particularly images from bare soil periods, for improving cropland SOC monitoring. Furthermore, multi-source satellite image fusion, reported in 35% of recent studies, has been shown to improve prediction accuracy by leveraging complementary spectral information (Mgohele et al., 2024).

The application of artificial intelligence (AI) in soil science has expanded rapidly, with applications spanning decision support systems, image classification, soil property prediction, and expert systems (Wadoux, 2025). Deep learning architectures, including convolutional neural networks (CNNs) and recurrent neural networks (RNNs), are increasingly being deployed for automated soil classification from satellite imagery and spectroscopic data. However, challenges related to data fusion, model interpretability, and the transferability of trained models across different environmental settings continue to limit widespread adoption.

#### 4. Soil Microbiome and Biological Innovations

The soil microbiome, comprising bacteria, fungi, archaea, protists, and viruses, represents one of the most biodiverse ecosystems on Earth. Advances in metagenomics, metatranscriptomics, and metabolomics have revealed that soil microbial communities play fundamental roles in nutrient cycling, organic matter decomposition, plant pathogen suppression, and greenhouse gas regulation (Fierer, 2017). A teaspoon of healthy soil may contain more microorganisms than there are people on Earth, yet the majority of these organisms remain uncharacterised.

Soil microbiome engineering has emerged as a frontier research area with applications in sustainable agriculture and environmental remediation. Strategies including artificial microbial consortia (AMC), synthetic communities (SynComs), and host-mediated microbiome selection are being developed to enhance crop resilience, disease resistance, and nutrient acquisition (Quiza et al., 2015). The UK Crop Microbiome Cryobank project, involving Rothamsted Research, CABI, and the James Hutton Institute, has created a comprehensive soil microbiome resource for academic research and commercial development, alongside the public database AgMicrobiomeBase (HGF, 2026).



**Figure 3. Soil microbiome diversity and its role in ecosystem functioning and one health (Source: Banerjee & van der Heijden, 2023, Nature Reviews Microbiology)**

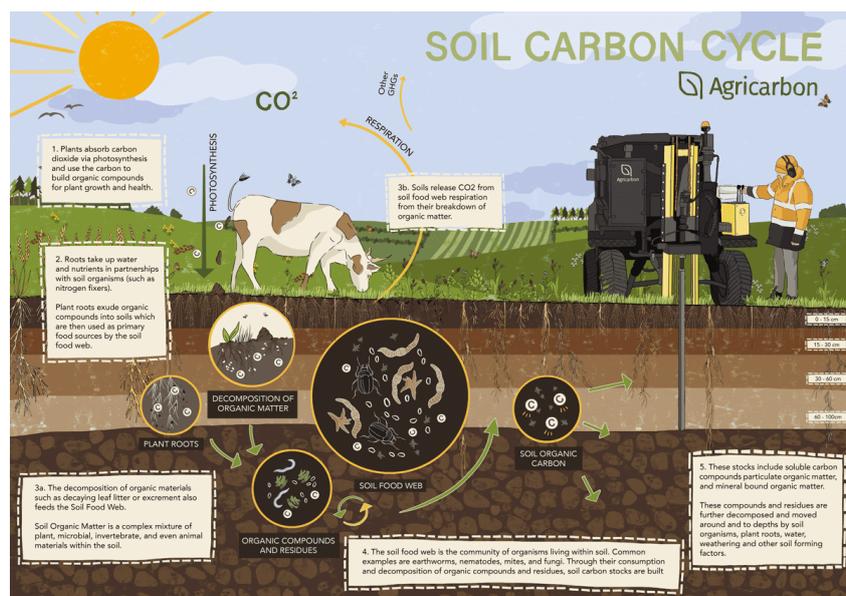
Research by Blazewicz and colleagues at Lawrence Livermore National Laboratory has advanced quantitative stable isotope probing (qSIP) techniques that enable identification and quantification of active soil microbes and their carbon consumption rates (LLNL, 2025). These technologies, combined with nanoscale secondary ion mass spectrometry (NanoSIMS), are revealing how soil microbiomes process and store carbon, with implications for climate change modelling and soil carbon management.

Soil biodiversity has been shown to be positively associated with ecosystem multifunctionality and stability across natural, urban, and agricultural ecosystems (Delgado-Baquerizo et al., 2020). Wagg et al. (2021) demonstrated that microbial diversity loss destabilised four key ecosystem functions—plant biomass production, plant diversity, leaf litter decomposition, and soil carbon uptake—

particularly when over 50% of microbial diversity was lost. These findings underscore the critical importance of conserving soil biodiversity for maintaining ecosystem services and agricultural sustainability.

### 5. Carbon Sequestration and Climate Change

Soils constitute the largest terrestrial carbon pool, storing approximately 2,500 gigatonnes of carbon globally—more than three times the amount held in the atmosphere and four times that in living vegetation (Lal, 2004). However, intensive agricultural practices, deforestation, and land-use change have resulted in significant soil carbon losses, contributing to global greenhouse gas emissions. The potential for soil carbon sequestration to mitigate climate change has attracted considerable research attention, with estimates suggesting that soils could sequester up to 5 gigatonnes of CO<sub>2</sub> annually until 2050 (BCG, 2024).



**Figure4. The soil carbon cycle illustrating carbon inputs, storage mechanisms, and outputs (Source: Agricarbon, 2023)**

Key strategies for enhancing soil carbon sequestration include conservation tillage, cover cropping, agroforestry, organic amendments, and biochar application. Biochar, a carbon-rich material produced through pyrolysis of biomass, has demonstrated significant potential for improving soil water retention, structure, and nutrient availability while sequestering carbon for centuries to millennia (Lehmann et al., 2011). Field trials in India have shown that biochar applications can help rebuild degraded soil structures while capturing carbon, with programmes supported by agricultural universities reporting improved yields and reduced irrigation needs (Dynamic Carbon Credits, 2026).

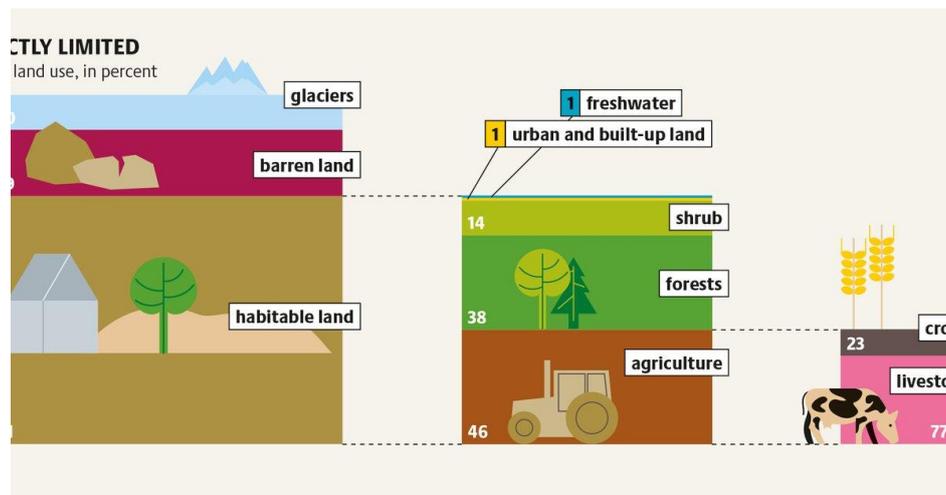
Emerging next-generation approaches to soil carbon removal include enhanced rock weathering (EW), microbial carbon pump technologies, and deep soil carbon injection. A study published in *Nature* demonstrated that EW using crushed basalt applied to agricultural land could contribute 0.16 to 0.30 GtCO<sub>2</sub> per year of carbon dioxide removal in the United States alone by 2050, representing 16–30% of the required carbon removal from technological solutions (Beerling et al., 2025). Organic farming systems have also shown superior carbon sequestration potential compared to conventional systems, with

organic plots demonstrating lower bulk density, higher water-use efficiency, and reduced CO<sub>2</sub> emissions (Beyond Pesticides, 2026).

However, challenges in accurately measuring, reporting, and verifying (MRV) soil carbon changes at scale remain significant barriers to incorporating soil carbon sequestration into carbon markets and climate policy frameworks. The impermanence of biologically stored carbon, heterogeneity of soil carbon dynamics across landscapes, and high costs of comprehensive soil sampling necessitate continued methodological innovation.

## 6. Soil Degradation and Remediation

Soil degradation encompasses a range of processes including erosion, salinisation, acidification, compaction, nutrient depletion, and contamination with heavy metals, pesticides, and emerging pollutants. The UNCCD reported at COP16 in Riyadh that approximately 40% of the world's land is degraded, with droughts increasing by 29% since 2000 due to climate change and unsustainable land management practices (UNCCD, 2024). UNESCO (2024) has projected that degradation levels could rise to 90% by 2050 if current trends continue, directly impacting 3.2 billion people.



**Figure 5. Global soil degradation: causes, extent, and impacts on ecosystems and livelihoods (Source: Soil Atlas, Heinrich Böll Foundation, 2024)**

Nanotechnology has emerged as a promising approach for soil remediation. Nanomaterials including nano zero-valent iron (nZVI), carbon nanomaterials, and metal oxide nanoparticles have demonstrated effectiveness in adsorbing, immobilising, and degrading soil contaminants through mechanisms such as reduction reactions and surface complexation (Patra et al., 2024). Nanobioremediation, combining nanomaterials with biological agents, enhances pollutant degradation efficiency in agricultural soils. Field trials have shown that composite nanomaterials such as carboxymethyl cellulose-nZVI@biochar can significantly reduce the leachability and bioavailability of hexavalent chromium in contaminated soils (PMC, 2025).

Nanoscale delivery systems, including nanocarriers and nanosensors, have facilitated precision agriculture approaches to pollutant management, enabling targeted delivery of remediation agents and real-time monitoring of soil conditions (Patra et al., 2024). Nano-fertilisers offer controlled-release nutrient delivery, addressing the problem that conventional fertilisers can experience losses of 50–70% via leaching, volatilisation, or runoff. Field trials demonstrated that polyvinyl alcohol/starch-zinc nano-fertiliser increased wheat yield by up to 87.5% while improving soil organic matter content (PMC, 2025).

Phytoremediation, enhanced through microbiome engineering, represents another environmentally friendly approach. Plant-associated microbiomes can be manipulated to improve the efficiency of contaminant uptake, accumulation, and detoxification in plant tissues, offering a cost-effective and sustainable remediation strategy for contaminated agricultural soils (Quiza et al., 2015).

### 7. Challenges and Future Directions

Despite remarkable advances, soil science faces several persistent challenges that require concerted research effort and policy intervention. First, the scalability of laboratory-proven technologies to field conditions remains a significant hurdle. Many promising innovations in soil microbiome engineering, nanotechnology, and digital soil mapping have demonstrated efficacy under controlled conditions but face challenges in diverse real-world environments characterised by heterogeneous soil types, climatic variability, and socioeconomic constraints.

Second, the digital divide between developed and developing nations continues to limit the adoption of precision agriculture and advanced soil monitoring technologies. Smallholder farmers in the Global South, who manage a significant proportion of the world's agricultural land, often lack access to satellite data, soil testing facilities, and decision-

support tools. Bridging this gap requires investments in affordable sensor technologies, mobile-based soil advisory services, and capacity building programmes.

Third, the integration of soil science with allied disciplines—including ecology, hydrology, climate science, and social sciences—remains insufficient. A transdisciplinary approach is essential for addressing complex soil-related challenges such as the food-water-energy nexus, land degradation neutrality, and sustainable intensification of agriculture (Keesstra et al., 2016). The One Health framework, which integrates human, animal, and environmental health, offers a promising paradigm for advancing soil science within a broader sustainability context.

Fourth, policy frameworks for soil protection remain fragmented and inadequate in many regions. While the European Union has made progress through the Common Agricultural Policy (CAP) and proposed Soil Monitoring Law, many countries lack comprehensive soil legislation. India's Soil Health Card scheme represents a significant initiative, but its effectiveness depends on continuous updating, ground-truthing, and integration with precision agriculture technologies. Global initiatives such as the UN Decade of Ecosystem Restoration (2021–2030) and the Global Soil Partnership provide important frameworks for coordinated action.

### CONCLUSION

Soil science stands at a critical juncture where unprecedented technological capabilities intersect with escalating global challenges. Advances in digital soil mapping, microbiome engineering, carbon sequestration technologies, nanotechnology-based remediation, and artificial intelligence have significantly expanded our understanding of soil systems and our capacity to manage them sustainably. The integration of remote sensing with machine learning has enabled high-resolution soil characterisation at scales previously unattainable, while metagenomics

has revealed the extraordinary complexity and functional importance of soil biodiversity.

However, the global soil crisis—with approximately 40% of land degraded, soil carbon losses accelerating, and contamination from agricultural chemicals and industrial activities expanding—demands a paradigm shift from reactive remediation to proactive prevention and restoration. Future research should prioritise the development of scalable, affordable soil health monitoring tools accessible to smallholder farmers; the translation of microbiome research into practical biofertiliser and biocontrol products; the refinement of soil carbon measurement, reporting, and verification methodologies; and the establishment of comprehensive soil protection policies at national and international levels.

Achieving sustainable soil management requires a transdisciplinary approach that bridges fundamental soil science with agronomy, ecology, engineering, economics, and social sciences. Only through such integrated efforts can we ensure that soils continue to fulfil their essential roles in sustaining food security, regulating climate, maintaining biodiversity, and supporting human well-being for current and future generations.

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#### Author Contribution:

All authors have participated in critically revising of the entire manuscript and approval of the final manuscript.

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