Review

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Abstract

Soil health is fundamental for food security, climate regulation, and ecosystem resilience, yet global research and development efforts remain uneven and fragmented. To date, no study has comprehensively integrated development investments, scientific output, and technological innovation into a unified assessment of global soil health dynamics. Addressing this gap, this study provides a multi-scalar analysis of soil health research from 1990 to 2025 by combining international project data and scientific publications activity across six key thematic domains. This time frame captures the transition from conventional soil research to modern molecular and next-generation sequencing (NGS)-based approaches. Using a PRISMA-based methodology, we analyzed 1,402 World Bank projects, 190 microbiome-related projects from CORDIS, and bibliometric data from Scopus, Web of Science, and PubMed. Results show sustained global growth in soil research, with nutrient management and soil degradation remaining dominant, while soil microbiome research and carbon sequestration have expanded rapidly, particularly after 2015. Despite this growth, significant regional disparities persist, with research concentrated in Asia, Europe, and North America. To address the lack of a coherent microbiome-based soil health assessment system, we propose a structured microbial indicator framework based on twelve functional microbial groups, evaluated through culturable abundance, functional gene abundance, and relative abundance. Additionally, we introduce a unified, database-driven microbiome reference framework that interprets soils relative to known types and conditions. This approach enables more standardized, scalable, and context-aware diagnostics, supporting the identification of healthy, degraded, and transitional soil states.

Keywords: soil health; soil degradation; soil microbiome; soil carbon sequestration; nutrient management; tillage; climate change; soil health assessment; microbial indicators; sustainable land management; global soil governance

1. Introduction

Soil is far more than the physical substrate beneath our feet; it is a living and highly dynamic system that underpins ecosystem functioning, food production, and human well-being. It supports a wide range of essential processes, including plant growth, water regulation, nutrient transformations, and the maintenance of an immense and largely hidden biological diversity [1]. In fact, soils are estimated to host nearly 59% of all life on Earth, making them the most biologically diverse habitat on the planet [2]. Even at very small scales, this complexity becomes evident, a single gram of soil may contain thousands of species and millions of microorganisms, interacting through intricate networks that drive nutrient cycling, plant productivity, and carbon dynamics. Consistent with this, the FAO highlights that soils support approximately 95% of global food production and form the foundation of resilient agrifood systems [3].

Despite this central role, soil is increasingly under pressure. Current estimates suggest that around 75% of global soils are already degraded, with projections indicating that up to 90% could be affected by 2050 if current trends persist [4,5]. Much of this degradation is linked to intensified agricultural practices. For instance, the widespread use of fertilizers, often characterized by excessive nitrogen inputs relative to phosphorus and potassium, has disrupted nutrient balances and altered ecosystem functioning. Excess nitrogen contributes to eutrophication and water contamination, while inefficient phosphorus use accelerates the depletion of finite reserves and creates accessibility challenges, particularly in low-income regions. At the same time, insufficient potassium availability can limit plant water-use efficiency, reducing resilience to drought and threatening long-term productivity [6]. Tillage practices further influence soil structure and function, although their effects are not always linear. Variations in tillage intensity can alter aggregate stability, pore structure, gas exchange, and the turnover of organic matter. Both excessive disturbance and soil compaction, often associated with heavy machinery, can degrade soil structure, reduce infiltration capacity, and disrupt hydraulic processes, ultimately impairing soil functionality [7].

These pressures do not act in isolation. Climate change is increasingly interacting with land management practices, amplifying their impacts. Rising temperatures, shifting precipitation patterns, and more frequent extreme events are already destabilizing key soil processes and reducing ecosystem multifunctionality in both croplands and grasslands [8]. Even relatively small temperature increases can have measurable consequences; for example, a 1 °C rise has been associated with a 10–25% increase in pest incidence and potential reductions in major crop yields of up to 7.4% [9].

Looking ahead, the implications are substantial. The global population is projected to reach 9.8 billion by 2050 and exceed 11 billion by the end of the century [10], placing additional pressure on already stressed agricultural systems. Meeting this demand is expected to require roughly a 70% increase in caloric production [11], raising fundamental questions about whether current soil management practices are sustainable in the long term. In this context, soil health emerges not only as an environmental concern but as a central component of global food security and climate resilience.

Soil health, by integrating physical, chemical, and biological dimensions, provides a useful framework for understanding and managing soil systems in a holistic way. However, despite the rapid growth of soil-related research and policy initiatives, the global research landscape remains fragmented. Many studies focus on individual thematic areas or rely exclusively on bibliometric indicators, often overlooking the role of development investments and technological innovation. Moreover, comparative analyses that account for regional differences using normalized indicators, such as population or land area, are still limited, and relatively few studies have examined how research priorities have shifted across major policy periods.

To date, there has been no comprehensive effort to jointly integrate development investment and scientific output into a unified assessment of global soil health dynamics. To address this gap, the present study provides a multi-scalar analysis of global soil research from 1990 to 2025 by integrating international project data and scientific publications across six key thematic domains. Starting the analysis in 1990 allows a consistent long-term assessment of global trends and, as a result, captures the transition from conventional soil research to modern molecular and NGS-based approaches. Specifically, the study aims to: (i) quantify temporal trends in research and investment; (ii) evaluate thematic convergence and regional differentiation; and (iii) identify emerging research frontiers and structural imbalances. In addition, the study advances a microbiome-based framework for soil health assessment, integrating functional microbial groups with complementary indicators, and outlines a unified reference-oriented approach to support more consistent and interpretable microbiome-based evaluation of soil systems.

2. Materials and Methods

This review brings together data from international development projects, peer-reviewed scientific literature, and patent records (handled in supplementary materials) to capture soil health from policy, research, and innovation perspectives. The study was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent and consistent approach to identifying, screening, and selecting relevant projects, publications, and patents [12].

2.1. Projects

Project data were collected from the World Bank Group database [13] using the keywords "soil health", "soil quality", and "soil degradation" to capture initiatives related to soil functionality, restoration, and sustainable land management. Only projects implemented between 1990 and 2025 were included, excluding pipeline and dropped projects, resulting in 1,402 active and completed projects. To account for the emerging field of soil microbiome research, additional data were obtained from the CORDIS database using the keyword "soil microbiome" [14], as no such projects were identified in the World Bank dataset. Soil health refers to studies addressing the overall functioning of soil as a living system, often in connection with soil organic matter. Soil quality reflects physico-chemical properties and traditional indicator-based assessments of soil condition. Soil degradation includes processes that reduce soil functionality, such as erosion, nutrient depletion, and contamination. Soil microbiome refers to research focusing on soil microbial communities, including diversity, composition, and functional potential. Applying the same temporal range and restricting to English-language records, 190 projects were retained and grouped into sub-periods for temporal analysis. The full selection procedure is provided in supplementary file 1, Figure S1.

2.2. Research Papers

Scientific literature was collected from Scopus [15], Web of Science [16], and PubMed [17]. The search strategy was organized around six thematic domains: (1) "soil health" AND "soil organic matter", (2) "soil degradation", (3) "soil microbiome" OR "soil microbiology", (4) "soil carbon sequestration" AND "climate change", (5) ("nutrient management" OR "fertilizer" OR "fertilization" OR "fertilisation") AND "soil", and (6) ("tillage" OR "till") AND "soil". These domains were selected to reflect the FAO's holistic definition of soil health as the capacity of soil to function as a living system that sustains productivity, environmental quality, and human health [18,19]. At the same time, they capture its key dimensions, including intrinsic properties (such as soil organic matter and microbiome), major threats (soil degradation), ecosystem services (carbon sequestration), and management interventions (nutrient and tillage practices). This structure is consistent with both classical soil science frameworks and more recent bibliometric analyses of soil research clusters, helping to ensure broad coverage while minimizing thematic overlap [20]. The search was limited to publications from 1990 to 2025, written in English, and classified as articles or review papers.

Although all three databases were screened, Scopus consistently provided the most extensive coverage across all thematic domains. For this reason, Scopus records were used as the primary dataset for bibliometric and quantitative analyses, while Web of Science and PubMed were retained to support comparative assessment of annual publication trends. The full literature screening and selection process is presented in supplementary file 1, Figure S2. Furthermore, keywords associated with scientific publications were also extracted and analyzed to capture thematic patterns in the literature. Following standardization and cleaning, keywords were ranked based on their frequency of occurrence, defined as the number of documents in which each keyword appears. For each research theme, the top 15 most frequently occurring keywords were selected to represent dominant research directions. These keywords were further grouped into thematic categories based on their conceptual similarity, enabling cross-theme comparison of major research domains.

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2.3. Data Processing and Statistical Analysis

All data processing, statistical analyses, and visualizations were carried out in R (R Foundation for Statistical Computing, Vienna, Austria) [21]. Data cleaning and restructuring were performed using the packages *dplyr* and *tidyr* [22,23].

Temporal analyses were based on annual aggregation of project and publication counts (1990–2025). Projects were summarized by starting year and thematic domain, with multi-topic projects counted in each relevant category. In selected analyses (Figure 1), soil health, soil quality, and soil degradation were grouped, while soil microbiome was analyzed separately. Regional patterns were assessed using World Bank classifications and expressed as percentage shares. Trends were visualized using line plots, while cross-database comparisons combined Scopus bar plots with Web of Science and PubMed line overlays. Keywords were standardized (e.g., lowercase, removal of inconsistencies), and a subset of relevant terms was selected (see Supplementary File 1). In addition to the bibliometric and statistical analyses, a comparative visualization of microbiome differences between healthy and degraded soils was constructed based on literature-derived relative abundance data. Representative values for dominant microbial taxa were compiled across multiple soil types, including chernozem, forest, alluvial, peat, and saline soils. Paired comparisons between conditions were visualized using dumbbell plots.

Additional analyses related to country-level comparisons and patent activity are provided in Supplementary file 1.

3. Results and Discussions

3.1. Evolution of Soil-Related Projects

The temporal evolution of soil-related projects between 1990 and 2025 reveals distinct phases linked to shifts in global environmental governance (Figure 1). Project activity increased rapidly in the early 1990s, rising from 17 projects in 1990 to over 60 by the mid-decade, coinciding with the policy momentum of the Rio Earth Summit [24] and the establishment of the UN Convention to Combat Desertification [25], which elevated land degradation on the global agenda.

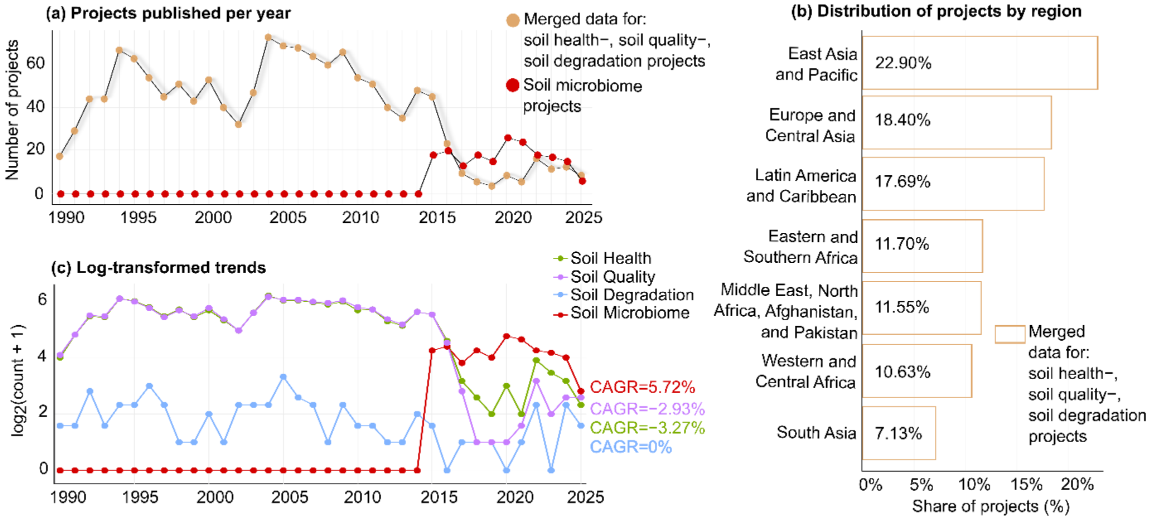

Figure 1. Temporal trends, growth dynamics, and regional distribution of soil-related projects (1990–2025). (a) Annual number of projects worldwide, comparing combined soil health, soil quality, and soil degradation projects with microbiome-related projects. (b) Regional distribution expressed as percentage share of total projects for the combined soil health, soil quality, and soil degradation domains. (c) Log-transformed trends ($\log_2$[count + 1]) and compound annual growth rates (CAGR) of major soil themes, highlighting differences in growth dynamics across topics.

A second peak occurred between 2003 and 2006, reaching approximately 70 projects in 2004. During this period, soil-related initiatives became more closely aligned with food security, poverty reduction, and climate mitigation. In particular, the recognition of soil organic carbon as a key component of climate regulation strengthened the integration of soil governance into climate policy frameworks [26–28]. After 2010, project numbers gradually declined, particularly between 2016 and 2019. However, this trend reflects a shift toward integrated, cross-sectoral programs following the introduction of the Sustainable Development Goals [29], where soil-related activities are often embedded rather than explicitly labeled. This pattern was further influenced by the COVID-19 pandemic, which redirected funding priorities [30,31]. A modest recovery after 2020 aligns with renewed interest in regenerative agriculture and nature-based solutions [32], suggesting a process of mainstreaming rather than decline.

A comparison with soil microbiome projects highlights a clear shift in scientific focus. While traditional themes such as soil health, soil quality, and soil degradation dominated until the mid-2010s, microbiome-related research has expanded rapidly since 2015. This divergence is also evident in log-transformed trends (Figure 3c), where soil health increasingly reflects biological functioning and ecosystem resilience, while soil quality remains associated with physico-chemical properties. Microbiome research exhibits the strongest growth (CAGR = 5.72%), whereas soil quality (−2.93%) and soil health (−3.27%) show declining trends, and soil degradation remains relatively stable. These patterns indicate a shift from traditional indicator-based approaches toward biologically driven, system-oriented soil research.

At the same time, soil research exhibits a combination of thematic convergence and regional differentiation. Globally, core topics such as soil and water pollution, land management, climate change, and water resources form a shared conceptual framework, consistent with recent bibliometric evidence [33,34]. Despite this convergence, regional priorities differ substantially. East Asia and the Pacific show strong emphasis on pollution and climate-related themes, reflecting pressures from industrialization, urbanization, and intensive land use [35,36]. In contrast, Eastern and Southern Africa focus more on disaster risk management and resilience, driven by droughts, climate variability, and land degradation [37].

Regionally, project distribution remains uneven. East Asia and the Pacific (22.90%), Europe and Central Asia (18.40%), and Latin America and the Caribbean (17.69%) dominate, reflecting stronger institutional capacity and research investment (Erdogan et al., 2021; FAO, 2025, 2024b). African regions also contribute substantially, driven by vulnerability to land degradation and sustained international support [18,38,39]. In contrast, South Asia (7.13%) remains underrepresented, likely due to institutional constraints and the integration of soil-related activities into broader programs.

3.2. Three-Decade Trends in Soil Research

Building on the regional and thematic patterns described earlier, the temporal analysis provides further insight into how global soil research priorities have evolved over time. Figure 2 shows a steady increase in publication output from 1990 to 2025, with gradual growth in the early decades followed by a marked acceleration after 2010 and especially after 2020.

The largest absolute increases are observed in *soil degradation* and *nutrient management*, reflecting their central role in addressing land degradation, agricultural sustainability, and food security. As discussed previously, these trends are closely linked to pressures from intensive agricultural practices, nutrient imbalances, and climate-driven disruptions to soil processes. Recent research further emphasizes integrated nutrient management and soil conservation strategies as key responses to these challenges [40,41].

In relative terms, however, the most rapid expansion is observed in the *soil microbiome* domain. Although initially limited, microbiome-related research has accelerated significantly since the early 2000s, with a sharp increase after 2015, positioning it as one of the most dynamic frontiers in soil science [42–44]. *Soil carbon sequestration and climate change* also show strong growth, reflecting the increasing integration of soil processes into climate mitigation strategies. In contrast, *soil health and organic matter* display more stable and moderate growth, indicating a more mature research area.

These developments align with broader policy and institutional shifts, including the Sustainable Development Goals and the Paris Agreement, which have reinforced the role of soils in climate and sustainability agendas. As noted earlier, the recent expansion of research activity also reflects increased global collaboration and technological advancement, despite temporary disruptions during the COVID-19 period [45,46]. These observed trends confirm a structural transition in soil research toward more integrative, biologically driven, and solution-oriented approaches, with increasing emphasis on resilience, carbon management, and microbiome-based understanding of soil systems.

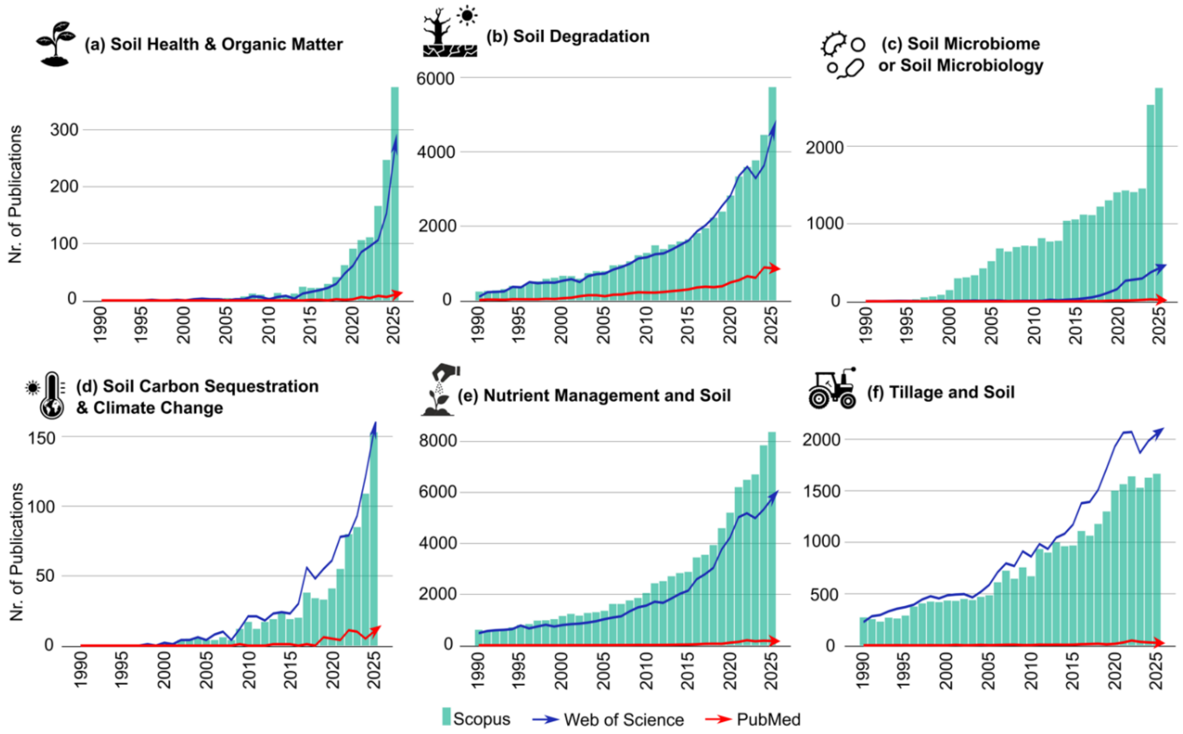

Figure 2. Temporal trends in soil research themes (1990–2025). Annual publications are shown for six topics: (a) Soil Health & Organic Matter; (b) Soil Degradation; (c) Soil Microbiome; (d) Soil Carbon Sequestration & Climate Change; (e) Nutrient Management; and (f) Tillage. Green bars (Scopus) indicate primary counts, while blue (Web of Science) and red (PubMed) lines enable comparison. Axes represent publications per year and time (1990–2025).

3.3. Dominant Research Themes Revealed by Keyword Analysis

To better understand the primary focus of research across different soil-related themes, a keyword-based analysis was conducted. The results presented in Figure 3 reveal not only diversity but a clear dominance of specific research directions across themes. While each theme retains distinct focal points, several keywords consistently emerge as central across domains, particularly soil organic matter, soil organic carbon, and microbial communities, highlighting their foundational role in contemporary soil science. A cross-theme synthesis demonstrates a pronounced convergence toward three core dimensions: carbon dynamics, microbial processes, and agricultural management practices. This convergence reflects a fundamental shift in soil research toward integrated, function-oriented perspectives, where soil organic matter is recognized as a key regulator of ecosystem functioning [47], and microbial communities are increasingly understood as primary drivers of nutrient cycling and soil resilience [48].

However, despite this convergence, the analysis also reveals a critical limitation: the persistent fragmentation of soil health assessment approaches. Different research domains rely on isolated indicators, ranging from gene-level and biochemical measurements to management-based and environmental descriptors, without a unified framework to integrate them. This fragmentation has been widely recognized as a major challenge in soil science [49]. Additionally, the dominance of microbiome-related, carbon-focused, and environmentally driven keywords indicates not only current research priorities but also the direction in which the field is evolving. These patterns clearly demonstrate that soil health is increasingly being approached as a biologically driven and system-level concept. Nevertheless, the absence of a standardized framework capable of integrating microbial, functional, and management-related dimensions remains a key gap. Addressing this gap is essential for advancing soil health assessment beyond descriptive indicators toward a more coherent and operational system. In this context, microbiome-based approaches emerge not merely as a growing research trend, but as a central component in the development of a multidimensional framework linking biological activity, soil function, and sustainability outcomes.

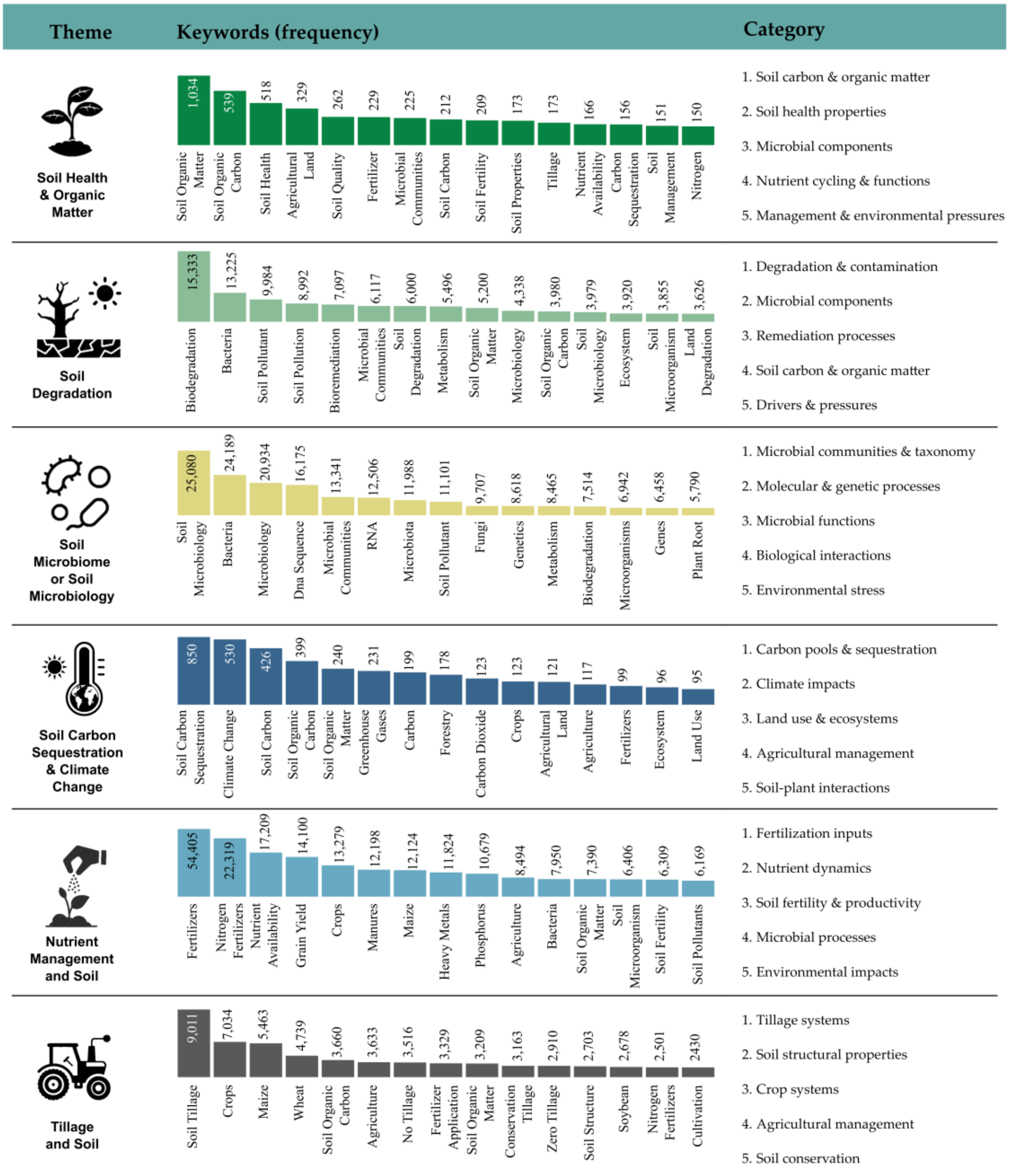

Figure 3. Keyword frequency and thematic categorization across soil research domains. Keywords were extracted from Scopus records, standardized, and ranked according to frequency of occurrence, defined as the number of documents in which each keyword appears. For each of the six predefined research themes (Soil

Health & Organic Matter, Soil Degradation, Soil Microbiome, Soil Carbon Sequestration & Climate Change, Nutrient Management, and Tillage), the top 15 most frequent keywords are shown. Keywords were further grouped into broader conceptual categories based on semantic similarity. Categories represent higher-level thematic groupings of the keywords and are used to enable cross-theme comparison of dominant research domains.

3.4. Geographical Distribution and Growth Trends in Soil Research

The continental distribution of research output reveals pronounced structural asymmetries in global soil science (see Supplementary file 1, figure 5). Asia and Europe dominate across most thematic domains, with North America also maintaining a substantial presence, while Africa, South America, and Oceania remain comparatively underrepresented despite facing significant soil degradation pressures. Asia leads in key areas such as Soil Health and Organic Matter, Soil Degradation, Soil Microbiome, and Nutrient Management, reflecting intensive agricultural systems, rapid industrialization, and expanding research capacity. Europe and North America follow, supported by strong regulatory frameworks and sustained investment in soil monitoring and sustainable land management.

In contrast, lower contributions from Africa, South America, and Oceania are likely linked to limitations in research infrastructure, long-term datasets, and funding availability [50,51]. This imbalance is particularly evident in Soil Degradation research, where Africa remains underrepresented despite high vulnerability to land degradation, consistent with previous assessments highlighting structural constraints in data availability and research capacity [19,25].

A similar pattern is observed in Soil Microbiome research, where Asia shows the strongest dominance, supported by advances in sequencing infrastructure and increased investment in genomic technologies, while other regions remain constrained by limited laboratory and bioinformatics capacity [52,53]. In Soil Carbon Sequestration and Climate Change, Europe leads, reflecting the strong integration of soil carbon into climate policy frameworks, including carbon farming and land-use regulations [54,55]. Likewise, Europe and North America dominate Tillage and Soil research, supported by long-term experimental systems and mechanized agricultural practices, whereas other regions remain less represented due to structural and technological limitations [51,56].

Log-transformed trends (Figure 4) further highlight differences in growth dynamics across themes and indicate a broader shift in research focus. Soil Microbiome exhibits the highest growth rate (CAGR = 23.46%), followed by Soil Carbon Sequestration and Climate Change (20.34%) and Soil Health and Organic Matter (17.89%). In contrast, Tillage and Nutrient Management show more moderate growth, while Soil Degradation remains relatively stable. These patterns suggest a transition from traditional, practice-based approaches toward biologically driven and climate-oriented soil research, consistent with the increasing emphasis on system-level processes and ecosystem resilience.

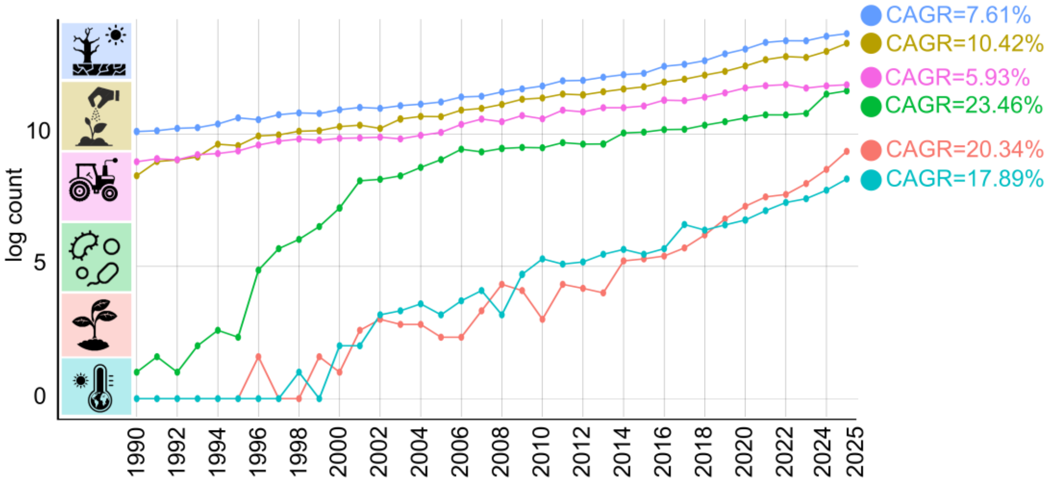

Figure 4. Log-transformed publication trends (log$_2$[count + 1]) for all themes from 1990 to 2025. Lines represent annual outputs and CAGR values summarize long-term growth dynamics.

3.5. Methodological Approaches in Soil Microbiome Research

Building on the trends identified in the previous sections, the increasing prominence of microbiome-related research highlights the need to examine how soil microbial communities are studied and assessed. Soil microbiome research faces several methodological challenges, including the control of soil chemical and physical variability, the selection of appropriate reference conditions, and limited comparability across studies [57]. These challenges are further exacerbated by the lack of standardized methodologies, which hinders cross-study comparison, data integration, and the development of consistent soil health indicators [58]. In addition, linking specific microbial taxa to ecological functions remains difficult, as closely related organisms may exhibit contrasting roles depending on environmental conditions or horizontal gene transfer. Furthermore, widely used DNA-based sequencing approaches primarily reflect genetic potential rather than actual biological activity, thereby overlooking the substantial proportion of dormant microorganisms present in soils [59]. As a result, interpretations based solely on taxonomic or genomic data may not fully capture functional dynamics within soil systems.

To address these limitations, a range of analytical approaches have been developed, targeting different dimensions of the soil microbiome, including microbial biomass, community composition, functional potential, and metabolic activity. These methods vary in analytical resolution, technical complexity, and data requirements. Importantly, no single approach is sufficient to capture the full complexity of microbial functioning, reinforcing the need for methodological harmonization and the complementary use of multiple techniques depending on the specific objectives of the study. Table 1 summarizes the principal methodological categories used in soil microbiome research, highlighting their analytical targets, key strengths, and inherent limitations, and providing a basis for integrating microbial indicators into soil health assessment frameworks.

Table 1. Summary of methods used to analyze soil microbial communities and their functional attributes.

Method category	Method	Research question	Key strengths	Key limitations	References
Classical & biomass-based methods	Culture-based methods (CFU counts)	How many viable, culturable microorganisms are present?	Simple; enables strain isolation	<1 of microbes are culturable	[60,61]
	Microbial biomass C/N (fumigation–extraction)	How much living microbial biomass is present in soil?	Integrative estimate of living microbial biomass	No taxonomic or functional resolution	[62,63]
	Phospholipid fatty acid (PLFA) analysis	How large is the living microbial community and what are its major groups?	Quantitative; functional group resolution	Low taxonomic specificity	[64,65]

Molecular & sequencing methods	Metabarcoding / targeted amplicon sequencing (16S rRNA, ITS)	Who is there?	High throughput; widely comparable; cost-effective	Provides relative, not absolute abundance; limited functional insight	[66,67]
	Shotgun metagenomics	What can they do (genetic potential)?	Unbiased, stable DNA; broad functional coverage	High cost; complex data analysis, does not indicate activity	[68,69]
	Metatranscriptomics	What genes are being expressed?	Reflects real-time microbial activity	RNA instability; high technical complexity	[69,70]
	Metaproteomics	What proteins are produced?	Direct evidence of functional expression	Protein extraction, interference from humic substances, identification of low-abundance proteins	[71,72]
	Metabolomics	What are the biochemical outputs?	Captures final functional outcomes	Difficult compound identification	[73,74]
Emerging & field-deployable methods	Biosensors (aptamer-, enzyme-, or microbe-based)	What specific process or compound is active now?	Real-time, in situ monitoring	Still under development	[75,76]
	Portable qPCR / lab-on-chip systems	How much of a specific gene or pathogen is present?	Rapid field diagnostics	Limited multiplexing	[77,78]
	Soil health test kits (integrated indicators)	Is the soil generally functioning well?	Farmer-friendly	Low microbial specificity	[79,80]

3.6. Microbial Indicators Based on Key Microbially Mediated Soil Functions (MMSFs)

To address the fragmentation identified across soil research domains, this study proposes a structured microbiome-based framework for soil health assessment based on twelve key microbially mediated soil functions (12 MMSFs) (Table 2). As a central component of this framework, we systematically defined a core set of twelve key microbially mediated soil functions (12 MMSFs) representing the most critical biological processes underpinning soil health. These MMSFs were selected based on their recurrent prominence in literature, their ecological relevance to major soil functions, and their applicability as interpretable microbiome-linked indicators. They were selected to capture essential ecosystem functions related to nutrient cycling, plant-microbe interactions, and environmental resilience, and include nitrogen fixation; phosphorus solubilization; hydrocarbon degradation; potassium solubilization; phytohormone production; organic matter decomposition; siderophore production; mycorrhizal symbiosis (nutrient uptake enhancement); plant growth promotion; bioremediation; antibiotic resistance; and methane oxidation. Together, these functional groups form a comprehensive and functionally integrated representation of soil microbiome activity. To further support the operationalization of this framework, representative microbial taxa associated with each of the twelve functional groups were compiled and are presented in Supplementary file 2. This provides a clear taxonomic reference linking functional potential to microbial community composition.

Table 2. Comparison of key microbially mediated soil functions (MMSFs) in healthy and degraded soils based on culture-dependent counts (CFU g^{-1} soil), culture-independent quantification of functional genes (qPCR gene copies), and relative abundance.

Function*	Indicator	**Degraded soil**	**Healthy soil**
Nitrogen fixation	CFU [81,82]	1.1×10^{2}	3.88×10^{6}
	nifH gene [83,84]	2.88×10^{5} copy/ g of dry soil	$1.0–4.6\times10^{7}$ copies/ g of soil
	Relative abundance [85]	No data available	21.5%
	Representative species (Supplementary Table S2)	[86–116]	
	CFU [117,118]	10^{-2}	4×10^{8}

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Phosphorus solubilization	phoD gene [119]	1.33×10^5 copies/ g of dry soil	5.80×10^7 copy/ g of dry soil
	gcd gene [119,120]	1.46×10^4 copy/ g of dry soil	2.19×10^8 copies/ g of soil
	Relative abundance [121]	0.18%	13.13%
	Representative species (Supplementary Table S2)	[109,122–135,135–171]	
Potassium solubilization	CFU [172,173]	4×10^2	75×10^4
	pqqC gene [174]	3.25×10^4 copies/ g of dry soil	1.44×10^9 copies/ g of dry soil
	Relative abundance [175]	5.46%	12.25%
	Representative species (Supplementary Table S2)	[155,176–187,187–194]	
Phytohormone production	CFU [195,196]	1×10^5	1.5×10^5
	acdS gene [197]	$1.0 \times 10^{1.91}$ copies/ g of soil	1.0×10^{12} copies/ g of soil
	Relative abundance [198,199]	7%	80%
	Representative species (Supplementary Table S2)	[94,200–202]	
Organic matter decomposition	CFU [203]	6.6×10^3	1.5×10^4
	chiA gene [204,205]	1.70×10^5 copies/ g of dry soil	3.5×10^8 copies/ g of dry soil
	cbhI gene [206,207]	0.17×10^4 copies/ g of soil	7.2×10^4 copies/ g of soil
	GH48 gene [206,207]	1.04×10^3 copies/ g of soil	5.96×10^5 copies/ g of soil
	Relative abundance	No data available	No data available
	Representative species (Supplementary Table S2)	[208–214,214–217,217,217–236]	
Siderophore production	CFU [237]	2.6×10^2	2×10^6
	PKS type I [238]	5.77×10^2 copies/ g of dry weight of soil	9.39×10^6 copies/ g of dry weight of soil
	Relative abundance [240]	47%	85%
	Representative species (Supplementary Table S2)	[241–247]	
Mycorrhizal symbiosis (Nutrient uptake enhancement)	CFU [248]	3.0×10^6	1.18×10^8
	AMF-specific 18S rRNA gene [249]	1.2×10^6 copies/ g of soil	2.1×10^8 copies/ g of soil
	Relative abundance [250]	0.06%	98.16%
	Representative species (Supplementary Table S2)	[119,251,251–254,254,255,255–257,257–287]	
Plant growth promotion	CFU [288]	10^5 copies/ g of soil	5.9×10^7 copies/ g of soil
	phoD gene [119]	1.33×10^5 copies/ g of dry soil	5.80×10^7 copies/ g of dry soil
	gcd gene [119,120]	1.46×10^4 copies/ g of dry soil	2.19×10^8 copies/ g of dry soil
	acdS gene [197,289]	8.1×10^1 copies/ g of soil	1×10^{12} copies/ g of soil
	Relative abundance	No data available	No data available
	Representative species (Supplementary Table S2)	[94,108,109,139,229,290–305]	
Bioremediation	CFU [306,307]	10^3	7.32×10^6
	nahAc gene [308]	5×10^3 copies/ g of soil	10^7 copies/ g of soil
	arsC gene [309]	0.88×10^4 copies/ng total DNA	1.56×10^5 copies/ng total DNA
	arsM gene [310]	0.4×10^7 copies/ g of dry soil	2.3×10^7 copies/ g of dry soil
	Relative abundance [311]	8.63%	0.01%
	Representative species (Supplementary Table S2)	[208,312–315]	
Hydrocarbon degradation	CFU [316]	$373 \pm 56 \times 10^3$	$8 \pm 2 \times 10^3$
	alkB gene [317,318]	5.0×10^8 cells/g-soil	0.9×10^4 copies per nanogram of soil

	Nah gene [319,320]	1.1×10^8 copies/ g of dry mass soil	Not detectable
	Relative abundance [321]	10%	1%
	Representative species (Supplementary Table S2)	[322–351]	
Antibiotic resistance	CFU [352]	$> 2.0 \times 10^4$	6
	sull gene [353]	4.37×10^7	2.12×10^3
	erm(B) [353]	9.57×10^8	Not detectable
	intI1 gene [353]	4.12×10^7	3.17×10^3
	Relative abundance [354]	74%	3%
	Representative species (Supplementary Table S2)	[185,315,355–367]	
Methane oxidizers	CFU [368]	1×10^2	1×10^9
	pmoA gene [369,370]	10^3	1.1×10^8
	Relative abundance [286,371]	0%	57%
	Representative species (Supplementary Table S2)	[372–377,377–379,379–388,388,389]	

*Absolute microbial abundance values vary widely depending on soil type, climate, crop, management system, and analytical method. Therefore, the values presented in Table 3 should not be interpreted as universal thresholds. Instead, they illustrate consistent relative trends across studies, demonstrating that healthy soils are characterized by enhanced activity and representation of key microbially mediated soil functions (MMSFs), whereas degraded soils exhibit reduced or imbalanced functional profiles. Representative microbial taxa associated with each MMSF are provided in Supplementary Table S2. **Toward a unified microbiome reference framework for soil health interpretation.**

For each functional group, three complementary indicators were defined: culturable abundance (CFU-based), functional gene abundance, and relative abundance within the microbial community. These indicators reflect three distinct but complementary dimensions of soil biological status: the cultivable fraction, functional potential, and community structure. The framework is based on the combined evaluation of these dimensions across the selected functional groups. Importantly, it is intended as a comparative and context-dependent system rather than a fixed-threshold model. In practice, soil health assessment involves interpreting indicator patterns relative to reference conditions, such as well-functioning (healthy) versus degraded soils of comparable type and land-use context. Under this approach, soil health is inferred not simply from uniformly higher or lower values, but from the extent to which microbiome profiles support balanced ecosystem functioning, including nutrient cycling, plant-associated processes, and resilience to disturbance. Conversely, deviations from these reference patterns may indicate ecological imbalance or functional impairment. Higher microbial abundance, greater functional gene representation, and balanced community composition in healthy soils generally indicate active nutrient cycling and stable ecosystem functioning, whereas reduced values or imbalanced patterns in degraded soils reflect functional impairment. Importantly, the framework is not based on a single indicator or function, but on the integration of multiple microbial processes.

This integrative approach enables a more comprehensive and operational assessment of soil health by linking measurable microbial indicators to ecosystem functions. The framework is flexible and can be adapted to different soil conditions and research contexts, allowing researchers to apply one or more indicator types across relevant functional groups. In this way, it provides a structured basis for incorporating microbiome data into soil health evaluation and supports the transition toward biologically informed, system-level assessment of soil systems.

Conceptually, this approach would represent an important step toward operational soil microbiome diagnostics. Rather than asking only which taxa or functions are present, it would enable the more informative question of what a given microbiome profile means in relation to known ecological baselines and trajectories. In this sense, a unified microbiome reference framework could provide the missing interpretative layer needed to translate soil microbiome research from descriptive profiling into a comparative, scalable, and decision-supportive tool for soil health evaluation.

Although the microbial indicator framework outlined above provides a structured and functionally informed basis for soil health assessment, a major interpretative challenge remains unresolved: microbiome profiles are still difficult to evaluate meaningfully when treated as isolated measurements. Even when taxonomic composition, functional potential, and abundance-based indicators are available, there is no broadly accepted system that allows soils to be classified consistently into biologically interpretable condition categories, nor is there a robust framework for comparing microbiome states across soil types, environments, or time points. Consequently, soil microbiome data often remain descriptive rather than diagnostically actionable.

To overcome this limitation, we propose a unified, database-driven microbiome reference framework in which soil samples are interpreted relationally rather than independently. In such a system, the microbiome of an individual soil would be positioned within a multidimensional comparative space defined by previously characterized reference soils representing known pedological types and condition states. This would shift soil microbiome interpretation from a static, sample-by-sample approach toward a contextual model in which biological meaning emerges through similarity, divergence, and directional movement relative to defined reference states.

The rationale for this concept is illustrated in Figure 5, which summarizes paired comparisons of healthy and degraded soils across several soil types using a dumbbell plot format. The figure depicts the direction and magnitude of changes in the relative abundance of dominant microbial phyla within chernozem [390,391], forest [392], alluvial [393], peat [394,395], and saline soils [396,397]. These comparisons show that degradation is associated with recurring microbiome shifts, while also making clear that the structure and extent of these shifts are strongly soil-type dependent. This duality is critical: it suggests that soil health interpretation requires a reference architecture capable of capturing both broadly recurrent signatures of degradation and the ecological specificity of individual soil systems. Within such a framework, an unknown soil sample would not be judged against universal fixed thresholds alone, but against an appropriate reference background composed of biologically and environmentally comparable soils. Its condition could then be inferred from its relative position within the reference landscape, allowing classification not only into healthy or degraded states, but also into intermediate or transitional conditions. Importantly, the same framework could support longitudinal interpretation, as repeated sampling would make it possible to track directional movement of a soil microbiome toward deterioration, recovery, or stabilization over time.

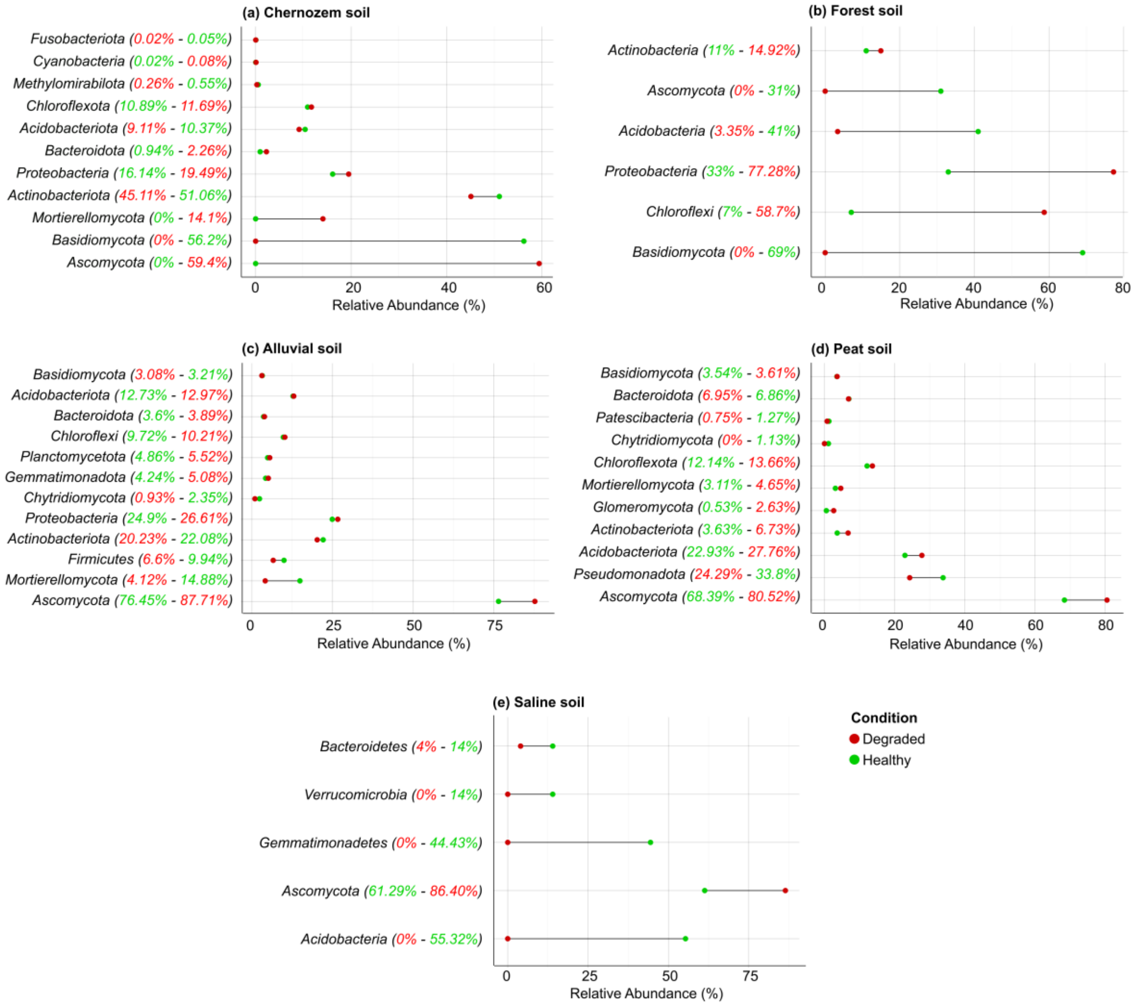

Figure 5. Microbiome-based differentiation between healthy and degraded soils across major soil types using a dumbbell plot representation. Relative abundance (%) of dominant microbial taxa is shown for paired degraded (red) and healthy (green) conditions across five soil types: (a) chernozem, (b) forest, (c) alluvial, (d) peat, and (e) saline soils. Horizontal connecting lines (dumbbells) illustrate the magnitude and direction of change between conditions for each taxon. The figure highlights both consistent and soil-type-specific shifts in microbial community composition associated with degradation, emphasizing that soil health status is reflected in relative changes in microbial abundance rather than absolute values alone. Corresponding references are provided in Supplementary Table S1.

4. Conclusions

This study analyzed global soil research dynamics over the past three decades by integrating project data, scientific publications, and patent activity. The results show a clear expansion of soil-related research, with increasing emphasis on microbiome-driven and climate-oriented themes, while traditional areas such as soil degradation and nutrient management remain central. At the same time, persistent regional and structural imbalances highlight unequal research capacity and innovation across regions. A key finding is the strong convergence of soil research around carbon dynamics, microbial processes, and agricultural management, alongside a clear fragmentation in soil health assessment approaches. To address this gap, the study proposes a structured microbiome-based framework grounded in 12 MMSFs, evaluated through three complementary indicators: culturable abundance, functional gene abundance, and relative abundance. These indicators capture distinct but interrelated dimensions of soil biological systems, including microbial activity, functional potential, and community structure. By linking microbial indicators to key microbially mediated soil functions and overall ecosystem functioning, this framework provides a more comprehensive and operational basis for soil health assessment. In addition, the study highlights the need for a unified, reference-based approach in which soil microbiome data are interpreted relative to well-characterized systems, enabling more standardized, comparable, and context-aware evaluation of soil health. While adaptable across different soil conditions and research contexts, further validation under field conditions is needed.

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