frontiers | Frontiers in Soil Science

TYPE Review
PUBLISHED 23 May 2025
DOI 10.3389/fsoil.2025.1549290

Mapping the conceptual and intellectual structure of soil health research (1996–2021): a terms co-occurrence and co-cited reference network analysis

Mohamed Houssemeddine Sellami[1,2], Mauro Mori[1*] and Fabio Terribile[1]

[1]Department of Agriculture, Università degli Studi di Napoli Federico II, Naples, Italy, [2]Interdepartmental Research Centre on the "Earth Critical Zone", University of Naples Federico II, Naples, Italy

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Elizabeth Stockdale,
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Lisa Alexandra Lobry de Bruyn,
University of New England, Australia

*CORRESPONDENCE
Mauro Mori
mori@unina.it

RECEIVED 20 December 2024
ACCEPTED 30 April 2025
PUBLISHED 23 May 2025

CITATION
Sellami MH, Mori M and Terribile F (2025) Mapping the conceptual and intellectual structure of soil health research (1996–2021): a terms co-occurrence and co-cited reference network analysis.
Front. Soil Sci. 5:1549290.
doi: 10.3389/fsoil.2025.1549290

Soil health has emerged as a critical area of research due to its role in sustainable agriculture, environmental conservation, ecosystem services and policy frameworks like the EU Soil Strategy. Since the 1990s, research has expanded rapidly, yet unevenly, marked by fragmented thematic priorities and methodological approaches. This study employs bibliometric analyses—term co-occurrence and co-cited reference networks—to map the conceptual and intellectual structure of soil health research from 1996 to 2021. By analyzing 984 peer-reviewed articles, we identified three major research clusters: (1) Agricultural Research & Soil Management, emphasizing agronomic practices such as fertilization and crop yield optimization; (2) Soil Health & Agricultural Sustainability, focusing on carbon dynamics, conservation tillage, and policy alignment; and (3) Microbial Ecology & Soil Health, highlighting soil biota, enzyme activity, and long-term biological impacts. Seminal works by Karlen et al., which established foundational frameworks linking soil quality to ecosystem services, and Mbuthia et al., demonstrating microbial resilience under conservation practices, emerged as pivotal drivers of field evolution. Emerging trends favor sustainable practices, amendments, and biological indicators. The analysis reveals critical gaps, including limited integration of pedological modeling to quantify ecosystem services and insufficient long-term studies on conservation agriculture. These findings advocate interdisciplinary collaboration among agronomists, microbiologists, policymakers, and climate scientists to align soil health metrics with global targets (e.g., SDGs, EU Soil Monitoring Law), providing a roadmap to integrate soil health into climate-smart land-use policies.

KEYWORDS

soil health, sustainable agriculture, bibliometric analysis, soil management, terms co-occurrence, co-cited network analysis

1 Introduction

Soil health has become a pivotal concept in sustainable agriculture, reflecting the intricate and multifaceted roles that soils play in ecosystem functioning, agricultural productivity, and environmental sustainability (1). In addition, more recently Soil Health has become a focus for policy since few soil policies are in place in different countries (e.g. new EU Soil Strategy, COM/2021/699 final; Soil Monitoring Law COM/2023/416 final).

As a result of this growing interest, it is timely to address some key questions of the research: What are the major areas of focus in soil health research according to peer-reviewed literature? How are these major areas interconnected? Where are the most active research areas? Which are the key papers for each area? Are there critical transitions in the development of the soil health research field? Where are the turning points? And finally, what have been the publication trends in soil health research over the past 25 years? Addressing these questions improve understanding of the trajectory of soil health science and can help guide future research.

The concept of soil health encompasses various dimensions, including physical, chemical, and biological properties, and its assessment is vital for understanding soil functionality, resilience (2, 3) In addition, more recently a range of stakeholders have asked for an increased connection between soil health assessment and the ability of soils to provide ecosystem services (e.g. SDGs: SDG2 on zero hunger; SDG6 on water quality; SDG12 on sustainable production, SDG13 on carbon capture and SDG 15 on soil health and biodiversity preservation.

As a result, over the past few decades, the scientific community has increasingly focused on developing robust indicators and methodologies to assess soil health, thereby fostering a rich body of literature that spans multiple disciplines and approaches (4). The exponential growth of soil health research has outpaced consensus-building efforts, resulting in fragmented conceptual frameworks and persistent debates over definitions and assessment methodologies. To navigate this complexity, a systematic and quantitative approach is necessary. Bibliometric analysis provides a powerful quantitative method for evaluating academic literature. Bibliometric analysis enables researchers to identify patterns, trends, and influential works within a given field, providing a comprehensive perspective on the evolution and current state of soil health research (5). In this review, we aim to explore the conceptual and intellectual landscape of soil health research over a 25-year period. By employing a comprehensive bibliometric analysis, we seek to map the evolution, trends, and key thematic areas within this field. This review serves as a complementary extension to our previous work (6) which focused on the influence of agronomic practices on soil health indicators. We focused on the same period 1996–2021 to better understand the history of soil health research trend. The analysis of the most recent years (e.g. 2022–2024) would have required a special care because currently the fashionable term "soil health" is often over-used regardless of the paper content.

The primary objective of our previous review was to understand soil health indicators through a bibliometric analysis centered on the evolution of soil health research, with a special emphasis on experimental studies conducted in agricultural soils (6). We analyzed publishing trends, authorship patterns, and the co-occurrence of authors' keywords, highlighting the social structure of research collaboration among authors, institutions, and countries. This method shed light on the contributions of various stakeholders and regions to the field of soil health (6), though it was limited by the inherent bias of authors' subjective keyword choices. This choice often reflects cultural and scientific attitudes by authors. This study attempts to overcome this limitation—hopefully—achieving a more objective view of each analyzed paper by applying the analysis to the entire text of both titles and abstracts of all soil health selected papers.

Further depth is provided through consideration of the conceptual and intellectual structures underpinning the reported work, using "terms co-occurrence" and "co-cited reference network" (later, quotations of these terms will omit ") analysis to achieve this objective. Terms co-occurrence offers a more comprehensive, unbiased, and detailed analysis of the text, making it a powerful tool for gaining a deeper understanding of the conceptual landscape of a research area (7, 8). It helps in identifying emerging trends and understanding the semantic relationships between different concepts, which are crucial for a thorough bibliometric analysis (8, 9). By using terms co-occurrence, we can uncover the intricate connections and thematic evolution within soil health research, thus enhancing our understanding of the field's development and future directions. On contrast, authors' keywords co-occurrence analysis highlights the intended focus areas of individual studies, it may not fully capture the evolving terminology and emergent themes that characterize the wider body of literature (10). While authors' keywords offer targeted perspectives, they can be constrained by the specific language and scope chosen by the researchers. Therefore, terms co-occurrence analysis is preferred as it allows for the identification of significant terms and phrases that recur across a large number of publications, thereby providing a more comprehensive overview of the conceptual landscape. Co-cited reference network analysis complements the conceptual structure by mapping the intellectual structure of the field (11, 12). While the terms co-occurrence analysis shows how different themes and topics are linked by looking at how often certain terms appear together, the co-cited reference technique focuses on the connections between the studies that are cited in the research. This method helps us identify seminal works and influential authors who have shaped the discourse on soil health (13, 14). This method reveals the foundational theories and methodologies that have driven research advancements and highlights the interconnectedness of different research strands (15, 16). This intellectual structure also helps us identify gaps in the research, pointing out areas where further study could be valuable. Additionally, it reveals how the field has evolved over time, highlighting changes in focus and the emergence of new ideas (17, 18).

Through this dual focus on conceptual and intellectual structures, this bibliometric analysis not only delineates the historical trajectory and current state of soil health research but also identifies research gaps and potential future studies, offering a roadmap for advancing soil health research in alignment with global sustainability goals. As soil health continues to gain prominence in scientific and policy agendas, bibliometric analyses can help inform evidence-based decision-making and foster collaborative research efforts.

2 Materials and methods

2.1 Methodology

To better understand how soil health research has evolved over the previous 26 years (1996–2021), this review adopted a bibliometric analysis to provide a holistic view of the impact of agronomic practices on soil health. Details of the methodology used in this review topic area are given by Sellami and Terribile (6). Briefly, literature was retrieved from the Scopus database by searching for articles containing the term "soil health" in the title, abstract, or keywords. The search was limited to peer-reviewed journal articles published in English between 1996 and 2021. To ensure relevance, the selection was restricted to subject categories including Agricultural and Biological Sciences, Environmental Science, Biochemistry, Genetics and Molecular Biology, Earth and Planetary Sciences, Immunology and Microbiology, and Multidisciplinary fields.

Therefore, articles mentioning only "soil quality" without "soil health" were excluded to center our analysis on "soil health," a term increasingly prominent in agricultural research and policies like the EU Soil Strategy and Soil Monitoring Law. Unlike "soil quality," which lacks consistent definition—from the FAO's Land Evaluation framework (1970s) to the EJP SOIL glossary—and remains debated, "soil health" offers a unified focus suited to agricultural systems. Including "soil quality" would have created a heterogeneous dataset, hindering clear comparisons. This choice aligns our bibliometric study with current agricultural soil health priorities.

We applied four selection criteria to focus exclusively on agricultural soil health: (i) studies conducted in field conditions, excluding greenhouse, pot, laboratory, and mesocosm experiments; (ii) research on agricultural soils, omitting forest, pasture, and urban soils; (iii) studies centered on croplands, excluding soilless culture, hydroponics, aquaponics, and potted plants; and (iv) papers emphasizing agronomic management, excluding broader topics like land cover, land use, cropping patterns, integrated farming systems, and fish farming. These exclusions ensure a focus on real-world agricultural conditions, where soil health is influenced by climate, management practices, and natural processes. Forest, pasture, and urban soils were omitted due to their distinct nutrient cycling, microbial interactions, and management strategies, which differ significantly from cropland systems. Including them would have introduced inconsistencies, weakening our ability to draw meaningful conclusions specific to agricultural soil health and its role in sustainable farming practices.

Therefore, a total of 984 published peer-reviewed papers met the eligibility criteria and were included in the bibliometric analysis. Figure 1 illustrates the analytical framework employed in this work. For detailed review, all the selected studies underwent metadata extraction using Excel software. This extraction encompassed various pieces of information, including article details (such as authorship, journal name, publication year, DOI or title, and affiliation), soil characteristics (particle size distribution for soil texture, soil type classification), study particulars (intervention duration, investigated treatments, number of treatments, experimental design, level of true replication, plot size, spatial extent ranging from plot to country). Additionally, each document was scrutinized for soil indicators, encompassing chemical, physical, and biological properties, as well as soil function, soil processes, and soil ecosystem services. Furthermore, we determined whether the authors employed diverse soil model systems in their respective studies.

2.2 Data analysis

The terms co-occurrence network analysis technique for mapping the conceptual structure of the soil health literature was executed with the help of VOSviewer (V1.6.19) software application (19). This analysis adopted LinLog/modularity method to normalize the strength of the links between terms (20). In our terms clustering process, we configured the cluster parameters with a resolution of 1, a minimum cluster size of 1, and the exclusion of small cluster merging. For the intellectual structure of the soil health literature, the co-cited reference network was generated with the help of Citespace (V6.2.R4) software application (21). In this analysis, we employed three structural metrics to assess the structural quality of the co-cited reference network. These metrics included the modularity Q index, mean silhouette score (S), and betweenness centrality value. The modularity Q index evaluates the network divisibility into smaller components, with higher values indicating less overlap between network clusters and, when $Q > 0.3$, signifying the importance of the cluster structure (21). The mean silhouette score gauges cluster quality and homogeneity, with values exceeding 0.5 indicating homogeneous cluster structures and values exceeding 0.7 suggesting reliable clusters (21). Betweenness centrality measures a node's capacity to connect with other nodes and identify critical points linking multiple groups, with centrality values exceeding 0.1 signifying greater influence (22, 23).

Furthermore, we conducted an in-depth analysis of temporal metrics, which included the investigation of citation bursts, a key indicator of a research topic's significance, and the calculation of sigma. In bibliometric analysis, a citation burst represents a sudden and statistically significant increase in the number of citations a publication receives within a defined period. This phenomenon, detected using Kleinberg's burst detection algorithm in CiteSpace, identifies publications that have gained rapid and intense scholarly attention, often signaling emerging trends, influential studies, or paradigm shifts. Notably, citation bursts highlight impactful contributions even when the total citation count of a paper remains relatively moderate. By analyzing citation bursts, researchers can track the evolution of scientific discourse, pinpointing key publications that have shaped the trajectory of a field (21). Additionally, we incorporated sigma value, a composite metric that integrates betweenness centrality and citation bursts

(22), providing a more refined measure of a publication's structural and temporal influence within a citation network. To contextualize these findings, we employed a timeline perspective, offering a dynamic visualization of cluster evolution over time. This method allows fora deeper understanding of how research topics have developed, persisted, or declined, offering meaningful perspectives on the long-term impact and significance of various scholarly contributions.

3 Results and discussion

3.1 Terms co-occurrence network analysis

Figure 2 presents a network analysis of terms co-occurrence, focusing on 156 highly relevant terms that occurred a minimum of 10 times in the titles and abstracts of 984 articles. This network comprises 156 nodes, 7787 links, and a total link strength of 30124. Each node within this network represents a term, with its size proportional to its frequency of appearance. The connections between terms are based on their co-occurrence patterns in the 984 publications. Terms that frequently appear together are positioned closer on the map, illustrating their stronger associations.

Notably, the analysis reveals the presence of three distinct clusters of terms that—obviously—share common thematic content but also reveals three separate research topics on soil health. Each cluster is composed by a set of sub-clusters; for the sake of readability, we named these clusters and sub-cluster with headings which capture the main theme of each (sub-) cluster.

Within the co-occurrence network data, the red term cluster is related to the Agricultural Research and Soil Management (Figure 2A). This cluster centers on agronomic practices, soil fertility, and nutrient management, emphasizing fertilization strategies—both organic and inorganic—alongside crop growth, soil testing, and environmental impacts. This cluster underscores the critical role of management practices in enhancing soil health and agricultural productivity, reflecting a practical focus on optimizing soil conditions to support sustainable farming systems."

We can partition this cluster into six subgroups (Table 1).

- **Subgroup 1—Fertilizer and Nutrient Management**: This subgroup focuses on the critical aspects of enhancing soil fertility and crop nutrition, addressing both organic and inorganic fertilization methods, including inorganic fertilizer, organic manure, and integrated nutrient management. Researchers in this field explore strategies to

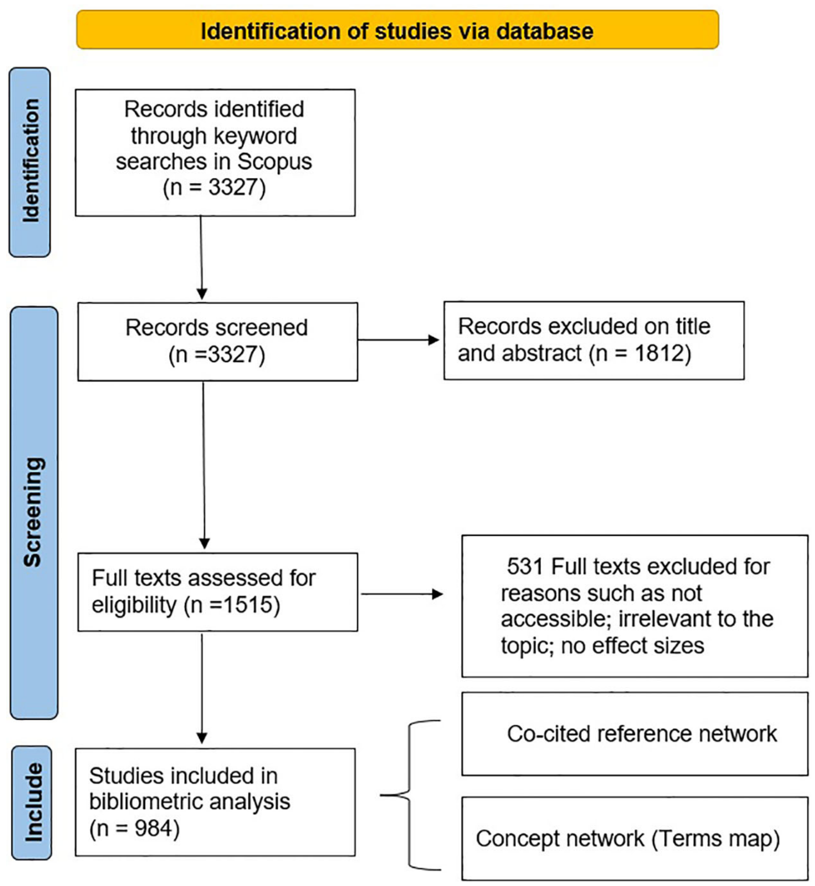

FIGURE 1
Research analysis framework for bibliometric analysis on soil health.

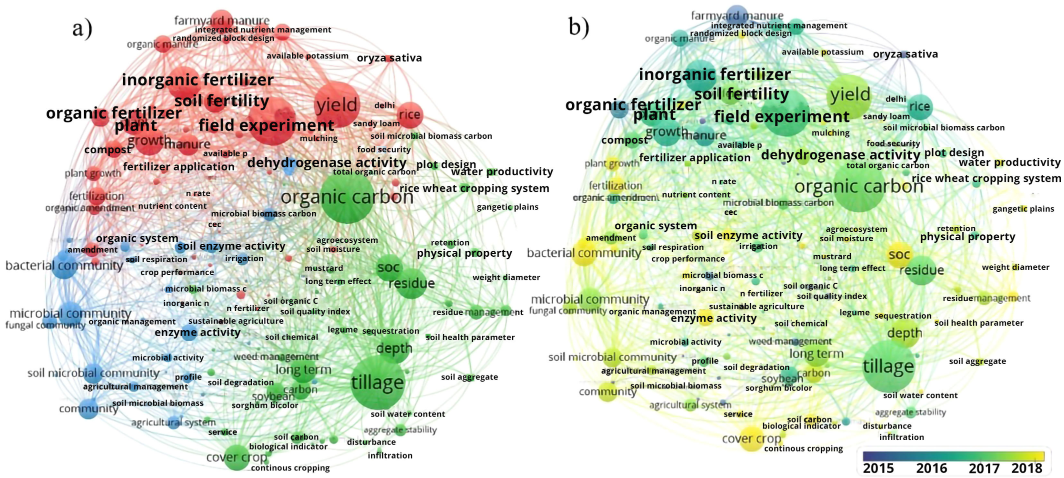

FIGURE 2

(a) Concept network visualization of 156 most relevant terms which appeared at least 10 times in 984 articles. Color: represents a cluster of terms (please see the text for more details); Nodes: represent terms (node size based on number of occurrences); **(b)** Evolution of the terms within the research topic from 2015 to 2018. Source: VOSviewer.

optimize nutrient availability, emphasizing sustainable soil fertility management.

- **Subgroup 2—Crop Growth and Performance:** This subgroup delves into the dynamics of plant growth, crop yield, and various factors influencing agricultural productivity, including crop varieties and biomass production. Researchers in this area investigate factors influencing crop performance, such as plant growth and straw management, aiming to enhance yield and quality.
- **Subgroup 3—Soil Quality and Testing:** This subgroup emphasizes the importance of soil health assessment and its measurement techniques. It encompasses terms related to key soil properties like soil fertility, electrical conductivity, and porosity. Researchers study methods such as soil testing to evaluate soil quality, supporting informed management decisions.
- **Subgroup 4—Environmental Impact and Experimentation:** This subgroup explores the broader environmental implications of agricultural practices. It includes terms related to field experiments, greenhouse gas emissions, and randomized block designs. Researchers here aim to understand how farming practices affect the environment, focusing on experimental approaches to mitigate impacts.
- **Subgroup 5—Agriculture and Sustainability:** This subgroup addresses overarching issues of ecological balance and sustainable agriculture. It encompasses terms related to sustainable agricultural practices and food security. Researchers investigate the intersection of agriculture and sustainability, seeking practices that ensure long-term productivity and environmental health.
- **Subgroup 6—Specific Location and Study**: This subgroup highlights the significance of location-specific research. It includes terms related to geographical contexts, such as Delhi, reflecting unique regional challenges and opportunities posed by different geographical contexts. Researchers focus on tailoring soil management practices to specific locales for optimized outcomes.

The green term cluster is related to Soil Health and Agricultural Sustainability (Figure 2A). This cluster centers on conservation agriculture, carbon sequestration, and agroecosystem resilience. It highlights key topics such as soil organic carbon, tillage effects, cover cropping, and sustainable practices, reflecting a research focus on enhancing soil health while supporting long-term productivity. This cluster underscores a significant shift toward sustainable soil management strategies, aligning with broader goals of climate resilience and environmental stewardship in agricultural systems.

We can partition this cluster into four distinct subgroups (Table 1).

- **Subgroup 1—Soil Health and Carbon Content**: This subgroup focuses on the assessment and management of soil health, it encompasses terms related to soil organic carbon, total organic carbon, and biological indicators. Researchers in this field explore sustainable practices to maintain soil health and enhance carbon sequestration.
- **Subgroup 2—Sustainable Agricultural Practices:** This subgroup delves into farming practices that promote sustainability and productivity. It includes terms related to tillage, cover crops, and conservation agriculture. Researchers investigate techniques such as residue management and crop rotation, aiming to balance productivity with environmental preservation.
- **Subgroup 3—Soil Properties and Composition**: This subgroup emphasizes the physical and chemical attributes of soils. It encompasses terms related to texture, depth, and soil water content. Researchers study these properties to understand their influence on soil health, supporting effective management strategies.

TABLE 1 Terms frequency within group cluster in soil health research from 1996 to 2021.

Red Cluster: Agricultural Research and Soil Management		Green Cluster: Soil Health and Agricultural Sustainability		Blue Cluster: Microbial Ecology and Soil Health	
Subgroup	Frequency	Subgroup	Frequency	Subgroup	Frequency
Sub 1—Fertilizer and Nutrient Management		Sub 1—Soil Health and Carbon Content		Sub 1—Microbial Activity and Communities	
inorganic fertilizer	203	soil organic carbon	695	soil enzyme activity	165
fertilization	180	aggregate stability	145	actinomycete	48
amendment	159	soil carbon	145	arbuscular mycorrhizal fungi	16
manure	123	soil microbial biomass c	55	bacterial community	124
farmyard manure	121	total organic carbon	38	fungal community	69
organic fertilizer	86	soil quality index	36	nematode community	20
organic manure	81	mineralization	34	soil microbial biomass	17
compost	80	biological indicator	31	soil microbial biomass carbon	94
integrated nutrient management	68	mineralizable nitrogen	25	soil microbial community	212
green manure	30	soil health parameter	23	microbial activity	40
Sub Total	**1131**	**Sub Total**	**1227**	dehydrogenase activity	76
				urease activity	53
				Sub Total	**934**
Sub 2—Crop Growth and Performance		Sub 2—Sustainable Agricultural Practices		Sub 2—Agricultural Practices and Management	
grain yield	265	tillage	264	agricultural management	49
growth	209	residue management	212	agricultural sustainability	14
rice	170	long term	182	agricultural system	62
plant	117	soybean	126	organic management	68
straw	46	cover crop	123	conventional practice	24
variety	39	conservation agriculture	50	conventional system	16
crop growth	35	legume	42	irrigation	56
mulching	29	rice wheat cropping system	40	pesticide	14
biomass production	20	weed management	39	**Sub Total**	**303**
crop performance	17	continuous cropping	28		
Sub Total	**947**	mustard	18		
		sorghum bicolor	15		
		intercropping	12		
		Sub Total	**1151**		
Sub 3—Soil Quality and Testing		Sub 3—Soil Properties and Composition		Sub 3—Soil Health and Nutrient Content	
soil fertility	102	depth	146	soil nutrient	26
available phosphorus	79	physical property	44	organic matter content	20
available nitrogen	78	soil water content	25	soil respiration	31
electrical conductivity	39	texture	21	soil degradation	24
soil bulk density	37	soil chemical	19	soil health improvement	11

(Continued)

TABLE 1 Continued

Red Cluster: Agricultural Research and Soil Management		Green Cluster: Soil Health and Agricultural Sustainability		Blue Cluster: Microbial Ecology and Soil Health	
Subgroup	Frequency	Subgroup	Frequency	Subgroup	Frequency
Sub 3—Soil Quality and Testing		Sub 3—Soil Properties and Composition		Sub 3—Soil Health and Nutrient Content	
porosity	35	soil characteristic	16	organic input	11
soil moisture	34	**Sub Total**	**271**	**Sub Total**	**123**
available potassium	28				
sandy loam	25				
CEC (cation exchange capacity)	19				
physicochemical property	15				
soil test	13				
metal	11				
Sub Total	**515**				
Sub 4—Environmental Impact and Experimentation		Sub 4—Environmental Impact and Geographic Focus		Sub 4—Geographic and Long-Term Impact	
field experiment	214	agro ecosystem (19)	19	semi-arid region	15
randomized block design	39	glyphosate (10)	10	fold	15
greenhouse gas emission	31	asia (15)	15	profile	47
positive correlation	16	gangetic plains (18)	18	long-term impact	11
Sub Total	**300**	**Sub Total**	**62**	**Sub Total**	**88**
		Total	**2711**	**Total**	**1448**
Sub 5—Agriculture and Sustainability					
sustainable agriculture	32				
food security	16				
Sub Total	**48**				
Sub 6—Specific Location and Study					
delhi	12				
Sub Total	**12**				
Total	**2953**				

Bold values indicate the total term frequency within each subgroup/Total cluster.

- **Subgroup 4—Environmental Impact and Geographic Focus:** This subgroup explores the broader environmental implications and regional contexts of soil health research. It includes terms related to areas like the Gangetic plains and practices such as glyphosate use. Researchers aim to address geographic-specific challenges and long-term environmental impacts of agricultural practices.

Finally, the blue term cluster, containing 30 terms, deals with Microbial Ecology and Soil Health (Figure 2A). This cluster centers on soil microbial communities and their critical role in soil health. It explores key topics such as soil enzyme activity, microbial diversity, and the interplay between microbial communities and agricultural management practices. This cluster highlights the growing acknowledgment of soil biology's contributions to soil health, contrasting with earlier research that often neglected these microbial influences.

We can partition this cluster into four subgroups:

- **Subgroup 1—Microbial Activity and Soil Communities:** This subgroup focuses on the intricate world of soil microorganisms. It encompasses terms related to various microbial activities and communities found within soil ecosystems. Researchers in this field explore soil enzyme activity, bacterial and fungal communities, and the presence of organisms like actinomycetes and arbuscular mycorrhizal fungi. Understanding these microorganisms and their functions is crucial for assessing soil health and its impact on plant growth and environmental sustainability.

- **Subgroup 2—Agricultural Practices and Soil Management:** This subgroup delves into the realm of agricultural practices and management strategies. It includes terms related to different agricultural systems, practices, and their sustainability. Researchers in this area explore topics such as agricultural management techniques, organic and conventional farming methods, irrigation practices, and pesticide usage. The aim is to optimize agricultural systems for improved crop yields, resource efficiency, and reduced environmental impact.
- **Subgroup 3—Soil Health and Nutrient Content:** Within this subgroup, the emphasis is on soil health and its essential components. It encompasses terms related to soil nutrients, organic matter content, and indicators of soil health improvement. Researchers study factors like soil respiration, degradation, and the influence of organic inputs on soil quality. This subgroup is vital for sustainable agriculture practices, as it helps in maintaining and enhancing the long-term fertility and productivity of agricultural soils.
- **Subgroup 4—Geographic and Long-Term Impact:** The final subgroup focuses on the broader context of the research, considering geographical factors and the long-term consequences of various agricultural and environmental practices. Terms within this subgroup encompass regions like semi-arid areas, profiles of soil composition, and studies assessing the lasting impact of agricultural interventions. Researchers in this field seek to explore how geographic factors and extended timeframes can affect soil health and agricultural sustainability (Table 1).

In Figure 2B, we present the evolution of key research terms within the co-occurrence network from 1996 to 2021, with a particular focus on the 2015–2018 period. This timeframe represents a critical transition in soil health research, as indicated by our previous analysis (6). During these years, there was a noticeable shift toward biological indicators (e.g., microbial communities, enzyme activities) and sustainable agricultural practices (e.g., cover crops, residue management). This shift coincided with the emergence of policy frameworks such as the Global Soil Partnership, also the EU Soil Strategy, the UN Sustainable Development Goals (SDGs), and the FAO's Status of the World's Soil Resources report, alongside technological advancements that influenced research directions.

Before 2015 (Purple cluster), research was predominantly centered around traditional agricultural practices, with a strong emphasis on manure, organic fertilizers, and crop-specific studies, particularly focusing on Oryza sativa (rice). Topics such as microbial biomass carbon and soil organic carbon were central, reflecting a deep interest in soil health and organic matter management. There was also significant attention on sustainable farming practices, as indicated by studies on soil quality indexes and the use of farmyard manure, especially in the context of rice cultivation in Delhi's sandy loam soils. Additionally, research explored the potential of organic fertilizers and green manure as environmentally friendly alternatives within the rice-wheat cropping system, alongside efforts to optimize fertilization rates.

Between 2015 and 2018 (Soft green cluster), we observed a noticeable shift in research focus. During this period, the field began to reinforce previous work on organic carbon and tillage, with an increased emphasis on field experiments to validate these practices in real-world conditions. This period marked a transition towards more holistic and integrated strategies for soil management. Research expanded to cover topics like organic manure and integrated nutrient management, highlighting a growing awareness of balanced nutrient management practices. Studies also diversified to include crops like soybean and began to explore the impacts of tillage, reflecting an expansion in cultivation techniques and crop focus. The deeper investigation into soil organic carbon and total organic carbon during this time indicated a stronger emphasis on understanding soil carbon dynamics in agricultural systems.

After 2018 (Fresh green and yellow cluster), the research landscape expanded further, incorporating a very strong component of soil biological analysis in soil health, particularly focusing on bacterial communities, enzyme activities, and more advanced soil management practices, such as the use of cover crops. This period was characterized by a broadening of the research scope to include a wide array of topics related to soil health, sustainability, and agricultural productivity. There was also a strong focus on residue management and the study of microbial communities, reflecting growing concerns about maintaining soil quality and mitigating environmental degradation. Additionally, long-term studies became more prominent, underscoring the importance of sustainable agricultural systems. The investigation into carbon-related parameters, such as dehydrogenase activity and soil fertility, deepened, highlighting the critical role of carbon in maintaining soil health. Research also diversified into exploring different crop varieties, yield optimization, and mulching practices, alongside a greater emphasis on rigorous experimental design and statistical analysis to ensure the reliability of findings.

Overall, the research evolution over time reflects a transition from studies that focused narrowly on impacts and optimization of agricultural management practices to broader studies in the context of environmental impacts and overall sustainability. This progression signifies a commitment to enhancing agricultural productivity while preserving soil health and ecosystem integrity in agricultural systems.

3.2 Co-cited reference network

The co-citation network encompassed a total of 51,829 cited references associated with 984 academic studies on soil health spanning from 1996 to 2021. This network featured 1,976 nodes representing individual references and 6,306 links denoting their co-citation relationships. A listing of the top 8 most frequently cited references is provided in Table 2. A detailed analysis of these highly cited references reveals several notable findings. Notably, the review by Karlen et al. (24), titled "Soil Quality: A Concept, Definition, and

TABLE 2 The top 8 references with centrality value.

Citation Counts	Centrality	Year	References (1st author)
23	0.03 (34)	1997	Karlen et al. (24)
20	0.01 (75)	2002	Six et al. (25)
18	0.01 (98)	2000	Six et al. (26)
18	0.00 (160)	2003	Weil et al. (27)
17	0.00 (162)	1969	Tabatabai and Bremner (28)
17	0.04 (169)	2015	Hartmann et al. (29)
13	0.00 (171)	2015	Mbuthia et al. (30)
12	0.00 (173)	1988	Kandeler and Gerber (31)

Rank number in parentheses.

Framework for Evaluation," stands out with 23 citations, a significant burst occurrence of 5, and a substantial Sigma value of 1.14. This makes it the most frequently cited reference in the selected soil health studies. The second most cited work is the review by Six et al. (25), titled "Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils," which has received 20 citations. The third position is shared by two articles: "Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture" by Six et al. (26), and "Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use" by Weil et al. (27), each garnering 18 citations in soil health research.

Within the co-cited reference network, 35 distinct fields of research within the domain of soil health were delineated (Figure 3). Figure 3 provides a visual representation of the 12 most prominent clusters, whereas a comprehensive compilation of metrics encompassing cluster size, silhouette values, and the mean duration (in years) of each cluster, systematically derived for all 35 clusters, is available within the Table 3. The modularity Q value was 0.878, signifying a reasonably effective division of the network into loosely interconnected clusters. The silhouette value (S), which was 0.948, indicates that, on average, these clusters exhibit a high degree of homogeneity (Figure 3). It is noteworthy that the major clusters identified within the co-cited reference network demonstrate a relatively high level of homogeneity (Table 3). Cluster #0, denoted as "conservation agriculture and soil biology," emerges as the most extensive cluster, encompassing 166 nodes. This cluster has a silhouette score of 0.738, indicative of a heterogeneous cluster aggregating diverse soil health citations. The average publication year of references within this cluster is 2004. In a similar vein, cluster #1, designated as "soil amendment and soil biota," comprises 131 nodes and has a high silhouette score of 0.878. The references within this cluster, on average, possess a publication year of 2008. Cluster #2, referred to as "biofertilizers" stands as the third largest cluster, with 96 nodes and a high silhouette score of 0.958. The references within this cluster were, on average, published in 1995. Where a cluster has a high silhouette score this describes a well-defined and homogeneous scientific community—perhaps better as—network of researchers most often quoting each other.

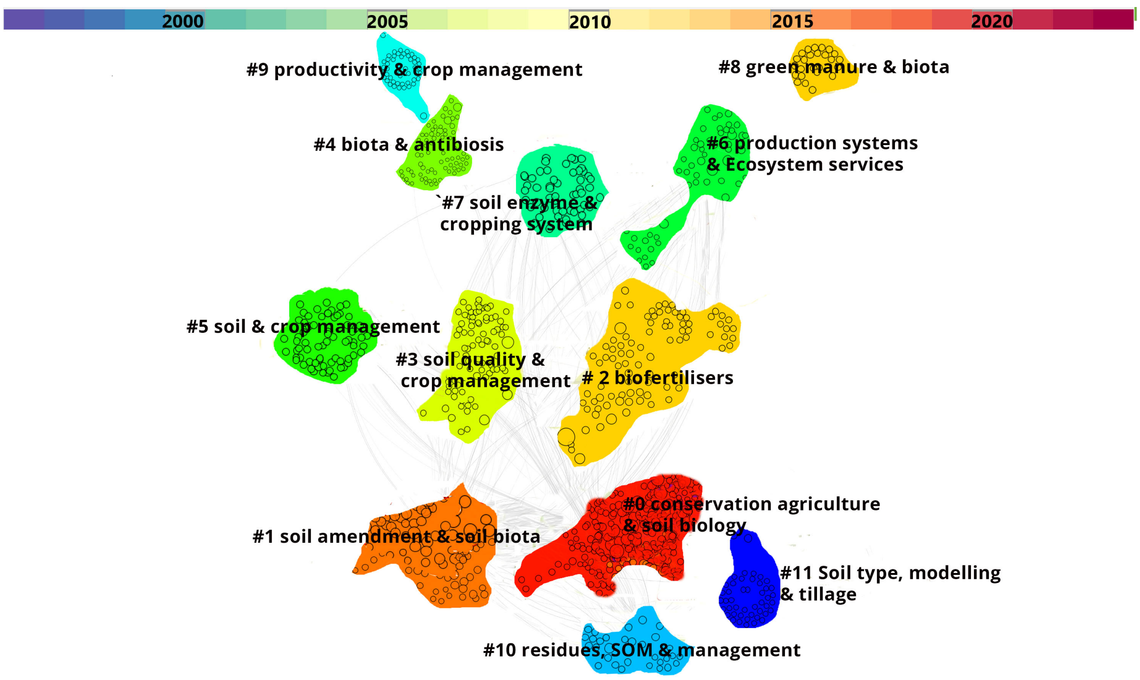

FIGURE 3
Co-cited reference network in soil health research topic (1996–2021) with cluster labels. Legend: Node: represents reference articles (node size based on the total citation of the references); Colors: represent the temporal orders of co-occurrence links between reference articles. Modularity Q index=0.878, mean silhouette score (S)=0.948. Source: CiteSpace (Configuration: LRF=3, LBY=−1, e=1.0, g-index (k=50). Network=1976 references and 6306 co-citation links).

TABLE 3 Co-cited reference cluster in soil health research from 1996 to 2021.

Cluster ID	Size	Silhouette	Mean (year)	Cluster label (combined)	Representative article in the cluster (highest citation frequency)	Most representative cited references in the cluster
0	166	0.738	2004	conservation agriculture & soil biology	Chahal et al. (32)	1—Six et al. (25), 2—Doran and Zeiss (1), 3—Tabatabai and Bremner (28)
1	131	0.878	2008	soil amendment & soil biota	Urra et al. (33)	1—Weil et al. (27), 2—Hartmann et al. (29), 3—Fierer et al. (34)
2	96	0.958	1995	biofertilizers	Kalra et al. (35)	1—Jackson (36), 2—Gomez and Gomez (37), 3—Karlen et al. (24)
3	78	0.968	1994	soil quality & crop management	Buman et al. (38)	1—Loria et al. (39), 2—Peet (40), 3—Janvier et al. (41)
4	71	1	1988	biota & antibiosis	Sturz et al. (42)	1—Andrews et al. (43), 2—Doran (44), 3—Alatalo (45)
5	71	0.997	1997	soil & crop management	Berkelmans et al. (46)	1—Bongers (47), 2—Bongers and Bongers (48), 3—Ferris et al. (49)
6	56	0.924	2000	production systems & Ecosystem services	Sihi et al. (50)	1—Lal (51), 2—Burns et al. (52), 3—Walkley and Black (53)
7	54	1	1991	soil enzyme & cropping system	Dodor and Tabatabai (54)	1—Anderson and Domsch (55), 2—Jenkinson (56), 3—Bristow and Jarvis (57)
8	54	1	1986	green manure & biota	Manici et al. (58)	1—Grünwald et al. (59), 2—Van Os et al. (60), 3—De Weger et al. (61)
9	49	0.986	1990	productivity & crop management	Carter et al. (62)	1-Carter (63), 2-Sturz and Christie (64), 3—Kimpinski et al. (65)
10	49	0.918	2003	residues, SOM & management	Desrochers et al. (66)	1—Casida et al. (67),2—Paustian et al. (68), 3—Minasny et al. (69)
11	46	0.989	1996	soil type, modelling & tillage	Carvalho Leite et al. (70)	1—Cambardella and Elliott (71), 2—Sinsabaugh et al. (72), 3—Joergensen and Mueller (73)
12	44	0.98	1993	soil tillage & soil biology	Alvear et al. (74)	1—Angers et al. (75), 2—Badri and Vivanco (76), 3—Doran (77)
13	44	0.899	2002	soil tillage & soil management	Acosta-Martínez and Cotton (78)	1—Six et al. (26), 2—Brookes et al. (79), 3—Bossio et al. (80)
14	43	1	1990	Carbon & cropping system	Shrestha et al. (81)	1—Cassman et al. (82), 2—Korschens (83), 3—Paustin et al. (84)
15	38	1	1986	mulch & cropping system	Rosemeyer et al. (85)	1—Andrén et al. (86), 2—Kettler (87), 3—Abawi (88)
16	34	1	1985	fertilizers, farm management & microbiota	Narula et al. (89)	1—Schinner and Sonnleitner (90), 2—Kumar and Narula (91)
17	32	0.962	2004	yield & soil health indicators	Sainju et al. (92)	1-Culman et al. (93), 2—Tabatabai (94), 3—Roper et al. (95)
18	31	0.943	2002	conservation tillage	Tillman et al. (96)	1—Vance et al. (97), 2—Karlen et al. (98), 3—Hoyt et al. (99)
19	29	1	1988	microorganisms & soil management	Entry et al. (100)	1 -McGill et al. (101), 2—Boquet and Dabney (102), 3—Anderson and Domsch (103)
20	28	1	1989	production systems	Wells et al. (104)	1—Varvel (105), 2—Robinson and Sharpley (106), 3—Chan and Heenan (107)
21	28	0.997	1995	crop management & aggregate stability	Wright and Anderson (108)	1-Wright and Upadhyaya (109), 2—Oades (110), 3—Sainju et al. (111)
22	28	0.989	1992	yield & crop management	Yadav et al. (112)	1—Timsina and Connor (113), 2—Yadav (114), 3—Aggarwal et al. (115)

(Continued)

TABLE 3 Continued

Cluster ID	Size	Silhouette	Mean (year)	Cluster label (combined)	Representative article in the cluster (highest citation frequency)	Most representative cited references in the cluster
23	27	1	1991	intercropping system	Hulugalle et al. (116)	1—McGarity et al. (117), 2—Little et al. (118), 3—Reuter and Walker (119)
24	25	1	1984	cropping system & compost	Jeyabal and Kuppuswamy (120)	1—Senapati and Dash (121), 2—Walkley and Black (53), 3—Sharma and Mittra (122)
25	25	0.967	1999	SOC & conservation agriculture	Kumar and Babalad (123)	1—West and Post (124), 2—Lal (51), 3—Jackson (36)
26	25	1	1990	cropping system & SOM	Ramesh and Chandrasekaran (125)	1—van Veen et al. (126), 2—Vityakon et al. (127)
27	21	1	1988	wastewater	Hayat et al. (128)	1—McGrath and Lane (129), 2—Ahmad and Yadava (130), 3—Summers and Silver (131)
28	20	0.992	1991	nutrient management & soil type	Shukla et al. (132)	1—Cochran and Cox (133), 2—Agrawal and Mohan Singh (134), 3—Beri et al. (135)
29	19	0.967	2010	Great Plain & SOM	Nash et al. (136)	1—Holland (137), 2—Lehmann and Kleber (138), 3—Gauch et al. (139)
30	15	1	1988	microbiota & plant disease	Rousseau et al. (140)	1—Barrett et al. (141)
31	14	1	1993	soil fauna & fertilizers	Nkem et al. (142)	1—Burr (143), 2—Hulugalle et al. (144), 3—Isbell (145)
32	12	1	1996	compost & plant biomass	Das et al. (146)	1—Kolawole et al. (147), 2—Baca et al. (148), 3—Bujarbaruah (149)
33	11	1	1986	sludge	Kayikcioglu and Delibacak (150)	1—Bandick and Dick (151), 2—Vance et al. (97), 3—Keeney (152)
34	10	1	1995	winter vegetable & nutrient management	Dass et al. (153)	1—Atiyeh et al. (154), 2—Baskar (155), 3—Srivastava et al. (156)
35	10	0.999	2009	fertilizers & organic residues	Baruah et al. (157)	1—Van Groenigen et al. (158), 2—Ma et al. (159), 3—Mosier et al. (160)

It is of special interest to highlight those topics such as “modelling”, “soil types” (then pedology) which, although key topics within the broader field of soil science research, have as yet made little contribution to soil health citations. In fact, Figure 3 shows the occurrence of the small cluster 11 (high silhouette)—apparently of limited importance—on soil type, modelling and tillage. This is a notable gap, as this cluster could strongly contribute to the quantification of soil ecosystem services strongly required by soil policies.

Another interesting finding is the analysis of the small cluster 8 on green manure and biota which has both has the highest silhouette (value 1) and almost no connection with other clusters, thus likely depicting a rather closed community of scientists working very much within their own circle (Figure 3).

Furthermore, as depicted in Figure 4, the timeline view illustrates the temporal continuity and persistence of research developments over the years, thereby enriching our understanding of the evolution of the field. The analysis of these 12 clusters in soil health research conducted between 1996 and 2021 reveals distinct research aspects, evolving trends, and potential research gaps within the field. Notably, several clusters, including Cluster#0 “conservation agriculture and soil biology,” Cluster#1 “soil amendment and soil biota” and Cluster#2 “biofertilizers,” have emerged more prominently in last decade, particularly after 2015 (Figure 4). These clusters underscore contemporary the emphasis on sustainable agricultural practices, soil amendment strategies, the exploration of soil biota as pivotal components in soil health enhancement. This reflects a growing commitment to environmentally friendly agricultural practices, with a special focus on biologically mediated processes for soil improvement; often described by the term conservation or regenerative cropping.

In contrast, clusters such as Cluster#3 “soil quality and crop management” and Cluster#5 “soil and crop management” have demonstrated a consistent identity since 2005–2010 (Figure 4), highlighting sustained research interests in optimizing crop management practices while preserving soil quality. These clusters reflect a trend towards achieving a harmonious balance between agricultural productivity and soil health preservation.

However, some clusters, such as Cluster#4 “biota and antibiosis,” Cluster#7 “soil enzyme and cropping system,” Cluster#9 “productivity and crop management,” and Cluster#11 “soil type, modeling and tillage,” had an established research identity before 2005 (Figure 4). These clusters encompass critical aspects of soil health research, including the interactions between soil biota that

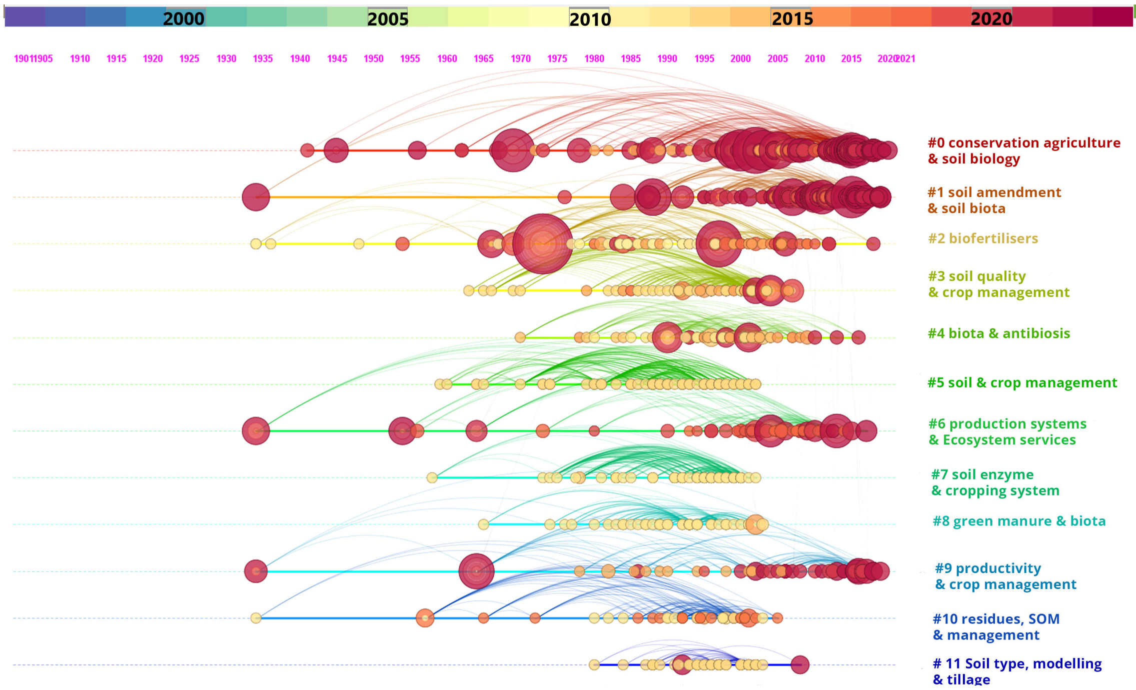

FIGURE 4
Timeline view of clustered co-cited references in soil health research topic. Legend: Node: represents reference articles (node size based on the total citation of the references); Straight lines: represent the cluster of references based on the clustering algorithm in CiteSpace; Colors: represent the temporal orders of co-occurrence links between reference articles; Curved lines: the time periods of cited reference articles. Modularity Q index=0.878, mean silhouette score (S)=0.948. Source: CiteSpace [Configuration: LRF=3, LBY=–1, e=1.0, g-index (k=50). Network=1976 references and 6306 co-citation links].

TABLE 4 The top 11 references with the highest citation bursts.

Citation Counts	Burst strength	BurstBegin	BurstEnd	Centrality	Sigma	References (1st author)	DOI	Cluster
17 (7)	6.17 (2)	2019	2021	0.00 (160)	1.00 (124)	Tabatabai and Bremner (28)	10.1016/0038-0717(69)90012-1	0
23 (3)	5.00 (4)	2016	2019	0.03 (34)	1.14 (5)	Karlen et al. (98)	10.2136/sssaj1997.03615995006100010001x	2
13 (9)	4.71 (5)	2019	2021	0.00 (161)	1.00 (125)	Mbuthia et al. (30)	10.1016/j.soilbio.2015.06.016	0
18 (5)	4.44 (6)	2019	2021	0.00 (162)	1.01 (12)	Weil et al. (27)	10.1079/ajaa2003003	1
8 (11)	4.12 (7)	2016	2018	0.02 (54)	1.08 (6)	Six et al. (161)	10.2136/sssaj1999.6351350x	0
12 (10)	4.00 (8)	2020	2021	0.00 (163)	1.02 (11)	Kandeler and Gerber (31)	10.1007/bf00257924	1
17 (8)	3.93 (9)	2017	2021	0.04 (19)	1.16 (4)	Hartmann et al. (29)	10.1038/ismej.2014.210	1
18 (6)	3.75 (10)	2019	2021	0.01 (98)	1.03 (8)	Six et al. (26)	10.1016/s0038-0717(00)00179-6	13
20 (4)	3.63 (11)	2016	2021	0.01 (75)	1.03 (9)	Six et al. (25)	10.1023/A:1016125726789	0
8 (12)	3.55 (12)	2014	2018	0.02 (48)	1.08 (7)	West and Post (124)	10.2136/sssaj2002.1930	25
6 (13)	3.45 (13)	2014	2016	0.08 (6)	1.30 (2)	Karlen et al. (98)	10.1016/j.still.2013.05.013	18

Rank number in parentheses.

agricultural practices, and modelling approaches, may benefit from a reassessment and integration of contemporary knowledge and methodologies to address evolving agricultural and environmental challenges. Again, cluster 11 including soil type and modelling, depicts a low-profile scenario with a consistent but still rather small number of total citations.

In summary, the research landscape in soil health encompasses a diverse array of topics, ranging from conservation agriculture to biotic interactions and soil amendments. Trends indicate a persistent focus for soil health research on sustainable agricultural practices and the optimization of crop management strategies. To address potential research gaps, future investigations could focus on developing and testing innovative methodologies that offer more precise and comprehensive measurements of soil health. This might include new techniques for monitoring soil biological activity, nutrient cycling, and carbon sequestration. Additionally, research should examine the long-term impacts of conservation practices, such as cover cropping, reduced tillage, and organic amendments, to understand how these practices influence soil health over extended periods and across different environmental conditions. Moreover, there is a growing need to employ modelling strategies and modern pedology to quantify soil ecosystem services, such as carbon storage, water regulation, and biodiversity support. These efforts are increasingly needed to underpin soil policies that aim to promote sustainable land management. Integrating modelling techniques with field studies can help in predicting the outcomes of different management practices and in developing strategies that enhance soil health while supporting broader agroecosystem sustainability. It is crucial to ensure that soil health considerations are aligned with any policies to create more holistic and sustainable agricultural practices.

Table 4 provides detailed information about the top 11 references exhibiting robust citation bursts and offers a comprehensive analysis of their historical citation patterns. An in-depth analysis reveals that seven of the references with the highest citation bursts are primarily associated with the first three clusters: Cluster #0 (Conservation Agriculture & Soil Biology), Cluster #1 (Soil Amendments & Soil Biota), and Cluster #2 (Biofertilizers). These studies have played a pivotal role in shaping conceptual frameworks, experimental methodologies, and policy discussions on soil health. Notably, the reference by Tabatabai and Bremner (28), titled "Use of p-nitrophenyl phosphate for assay of soil phosphatase activity," stands out with the highest burst strength of 6.17. This work has been cited 17 times, particularly between 2019 and 2022. Tabatabai and Bremner (28) introduced a widely adopted method for assaying soil phosphatase activity, a key indicator of microbial health and nutrient cycling. This advancement has been integrated into many studies exploring soil enzyme activities and microbial responses to diverse management practices. Another influential reference, authored by Karlen et al. (24), demonstrates a burst strength of 5 and was consistently cited from 2016 to 2019, highlighting its lasting impact on scholarly discourse. Karlen et al. (24) established a foundational framework for defining and evaluating soil health, integrating soil quality indicators with agricultural productivity and ecosystem sustainability. This structured approach extended beyond basic chemical properties to assess soil function holistically, shaping subsequent research on soil health metrics and monitoring strategies. The third noteworthy reference is "Long-term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality," by Mbuthia et al. (30), with a burst strength of 4.71. Mbuthia et al. (30) significantly influenced soil health research by demonstrating how conservation practices, such as cover cropping and reduced tillage, affect microbial community dynamics over the long term. This study helped broaden the focus from agronomic outcomes to include soil biology and its interactions with management practices. Its emphasis on biological indicators, like microbial activity, bolstered their role in soil health assessments, contributing to the growing use of microbial and enzymatic markers in recent studies.

Additionally, the analysis reveals that scholars Six et al. has garnered three robust citation bursts for references concentrating on soil dynamics, particularly with respect to soil aggregates and organic matter. Their work has become a cornerstone for understanding soil carbon dynamics, influencing climate mitigation strategies and sustainable land management policies.

Furthermore, the reference authored by Hartmann et al. in 2015, titled "Distinct soil microbial diversity under long-term organic and conventional farming," emerges as the second highest in terms of sigma value. Their study provided empirical evidence of how long-term organic and conventional farming systems shape microbial diversity, supporting the argument that sustainable agricultural practices enhance soil microbiomes. This has had significant implications for agroecological research, encouraging further studies on microbiome-driven soil health improvements.

The results outlined above underscore certain limitations inherent in analyzing the top 11 references with the highest citation bursts. Notably, among these, several are methodological papers that have gained prominence not due to their direct contributions to soil health, but rather because of their widespread adoption in research methodologies. Other referenced papers focus primarily on defining soil health, and their extensive citation appears to stem less from their practical value in linking soil health to management practices and more from their conceptual scope. Among the 11 cited works, only a few—most notably Mbuthia et al. (30)—offer a truly integrative perspective on soil health, effectively bridging these dimensions.

4 Conclusions

This bibliometric analysis provides a comprehensive evaluation of the evolution of soil health research over the past two decades, identifying key research themes, influential publications, and emerging trends. Our findings indicate that soil health has transitioned from a concept primarily associated with agricultural productivity to a broader framework integrating ecosystem services, soil biodiversity, and sustainable land management. The increasing recognition of soil as a dynamic, living system underscores its critical role in ecosystem functionality, climate regulation, and agricultural resilience.

Despite significant advancements, notable research gaps persist, particularly in the long-term assessment of soil health indicators, the integration of soil microbiome studies, and the standardization of methodologies for assessing soil functions across diverse land uses. Furthermore, interdisciplinary collaboration remains insufficient, necessitating a more integrative approach that brings together soil scientists, agronomists, ecologists, environmental policymakers, and climate researchers. Addressing these gaps will require collaborative frameworks, such as linking agronomic experiments with soil-ecology modeling to quantify soil ecosystem services and develop evidence-based management practices. Additionally, leveraging big data analytics, artificial intelligence, and remote sensing can significantly enhance soil health monitoring, predictive modeling, and decision-making for both policymakers and practitioners.

Looking ahead, soil health research must be more explicitly integrated with global climate policies, conservation efforts, and sustainable agriculture initiatives. Given its essential role in carbon sequestration, water regulation, and nutrient cycling, soil health is increasingly recognized as a key component of climate change mitigation, ecosystem restoration, and land-use planning. Strengthening collaboration between researchers, policymakers, and land managers is essential to ensure that soil health considerations are embedded in agricultural best practices, legislative frameworks (e.g., EU Soil Strategy, Soil Monitoring Law), and international sustainability goals. Future research should also explore how soil health can support climate-resilient farming systems and contribute to global food security and ecosystem conservation.

While this study provides valuable insights, it has certain limitations. The reliance on bibliometric methods, though powerful, may not fully capture the complexity of research dynamics, particularly emerging trends that are underrepresented in the literature. Additionally, this study focuses on a specific time frame (1996–2021), which may not fully reflect the most recent advancements in the field. The exclusion of non-English publications and grey literature also limits the scope of the analysis, potentially overlooking significant contributions from non-English-speaking regions.

Despite these limitations, our analysis has revealed key trends and identified specific gaps in soil health research. To advance the field, future efforts should focus on: (i) applying modeling techniques and modern pedology to quantify soil ecosystem services, ensuring alignment with policy needs and sustainability frameworks; (ii) conducting long-term studies to assess the effects of conservation practices on soil health under varying climatic and land-use conditions; and (iii) fostering interdisciplinary collaboration to integrate soil health within broader environmental and climate policies.

In conclusion, while soil health remains a cornerstone of sustainable agriculture, its relevance is expanding into broader scientific, environmental, and policy frameworks. Advancing soil health research will require multidisciplinary collaboration, standardized methodologies, and integration into global governance strategies. Ensuring that soils continue to support agricultural productivity and ecological stability in the face of global change will demand innovative research, cross-sector cooperation, and policy engagement. Addressing the interactions between soil health, climate adaptation, and sustainability will be crucial for shaping new policies and agricultural strategies that extend beyond the agricultural sector, ensuring resilient food systems and ecosystems for future generations.

Author contributions

MS: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. MM: Writing – original draft, Writing – review & editing. FT: Conceptualization, Methodology, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was funded by the European Union's Horizon Europe research and innovation program, under Grant Agreement No. 101091010, Project BENCHMARKS.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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