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REVIEW

Mapping soil health research in the Brazilian Semiarid region: a bibliometric approach

Antonio Yan Viana Lima[1,2], Maurício Roberto Cherubin[2,3], Lucas Tadeu Greschuk[2], Gabriel de Almeida Mori Muniz[2], Douglas Monteiro Cavalcante[2] and Arthur Prudêncio de Araujo Pereira[1]

[1]Department of Soil Science, Federal University of Ceará, Fortaleza, Ceará, Brazil, [2]Department of Soil Science, Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil and [3]University of São Paulo, Center for Carbon Research in Tropical Agriculture (CCARBON), Piracicaba, SP, Brazil
Corresponding author: Antonio Yan Viana Lima; Email: yanviana@usp.br

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Summary
Bibliometric research illuminates the scientific development of soil health (SH) studies in the Brazilian Semiarid, which are crucial for sustainable agriculture and mitigating climate change impacts. However, research trends on SH in the Brazilian Semiarid are still not well understood. This study aimed to illustrate how SH has been addressed in research concerning the Brazilian Semiarid. Terms such as 'soil health,' 'soil quality,' 'biological quality,' 'chemical quality,' 'physical quality,' as well as 'Caatinga,' 'Brazilian Semiarid,' and 'Brazilian Northeast' were searched in the Scopus® database. Bibliometric parameters were catalogued by the number of publications per year, most cited articles, primary institutions, main journals, and keyword frequency. The articles were evaluated based on the examination of chemical, physical, and biological indicators, and a similarity test was conducted to group articles according to these indicators. The bibliometric analysis reveals a significant increase in scientific output since 2020. Embrapa research centres contribute significantly to this expanding body of knowledge, with the leading journal 'Revista Caatinga' reflecting a specialized focus on the region's unique challenges. The most evaluated indicators were pH, soil organic carbon, P, Ca^{2+}, Mg^{2+}, K^{+}, and bulk density, but the prevalence of biological indicators, such as soil organic carbon (SOC), activity of enzymes such as alkaline and acid phosphatase, and ß-glucosidase, microbial activity, and soil fauna, underscores key research themes. These findings highlight the practical implications of SH research, but while increased research is commendable and increasingly necessary, studies are still scarce. Increased research is vital for the development of strategies that contribute to the long-term sustainability of the Brazilian Semiarid region.

Keywords: bibliometric review; soil quality; soil health indicators; Caatinga; drylands

Introduction

The Brazilian Semiarid, covering ~12% of Brazil's territory, has emerged as an outstanding region in the global context due to the uniqueness of its climatic and environmental characteristics (Brazil, 2021a). An area of 70 500 km^2 in Brazil is now unsuitable for agriculture due to the low productivity of natural resources, affecting both human and animal life (Brazil, 2021b). The Caatinga biome, which dominates the Brazilian Semiarid region, faces challenges from low annual precipitation (<800 mm), high solar radiation (2800 hours), temperature ranges of 23–27°C, and high evaporation rates (2000 mm) (Brazil, 2021a). The average relative humidity is around 50%, further disrupting the biome's ecological balance (Moura *et al.*, 2019).

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The Caatinga biome is characterized by vegetation and remarkable biodiversity adapted to extreme climatic conditions of arid and semiarid environments (Brazil, 2021b). The semiarid environment is not only home to unique ecosystems, but also faces significant threats, such as soil degradation due to anthropogenic activities, including overgrazing and the extensive burn and removal of native vegetation (Brazil, 2021b). Studies indicate a worrying reduction of 57% in the natural areas of the Caatinga biome, which has only 1% of its area protected and increasing livestock expansion (Brazil, 2021b), highlighting the pressing need for monitoring strategies and sustainable interventions to preserve the integrity of these critical ecosystems.

Soil health (SH) can be defined as the ability of the soil to function, interacting with the external environment for the benefit of sustainable animal and plant production (Doran and Parkin, 1994). SH goes beyond increasing agricultural productivity, contributing significantly to various ecosystem services, such as water quality, and human health, and mitigating the impacts of climate change (Karlen *et al.* 1997; Lehmann *et al.* 2020; Cherubin *et al.* 2021). Given the growing demand for inputs in the agricultural and industrial sectors due to the increase in the world's population, the study of SH becomes imperative for the establishment of sustainable agricultural systems (Cherubin *et al.*, 2016). In Brazil, this scenario is even more challenging in the drylands, where high soil degradation and the advance of climate change represent a major obstacle to agricultural sustainability.

Environmental vulnerability in the Brazilian Semiarid region is aggravated by practices such as intensive agricultural use and changes in soil cover, which have significant impacts on soil microbial communities and biogeochemical cycles (Ribeiro *et al.*, 2016; Lacerda-Júnior *et al.*, 2019). Livestock, considered an important source of greenhouse gas emissions, contributes to environmental degradation, especially through overgrazing associated with the removal of native vegetation of Brazilian Semiarid (Ribeiro *et al.*, 2016; Pereira *et al.*, 2021; Araújo *et al.*, 2024; Lima *et al.*, 2024). The predominant practice of slash-and-burn to introduce annual crops or pastures represents a significant agent of environmental change and degradation, leading to a decline in SH and changes in physical, chemical, and biological properties (Ferreira *et al.*, 2016; Rousseau *et al.*, 2022). In addition, studies indicate a substantial reduction in soil carbon in conventional systems, highlighting the negative effects of these practices on environmental sustainability in the Brazilian Semiarid region (Medeiros *et al.*, 2020; Tonucci *et al.*, 2023).

The study of SH in the Brazilian Semiarid is crucial for improving agricultural productivity and addressing challenges like soil degradation and climate change, but the research dynamics and trends in this area remain poorly understood. Thus, bibliometric analysis provides a quantitative view of research trends and patterns (Sellami and Terribile, 2023; Cancian *et al.*, 2018). It also allows for the visualization of collaboration networks and citation patterns (Bezak *et al.*, 2021), highlighting research gaps and opportunities. This method is ideal for exploring SH research, especially in specific regions such as the Brazilian Semiarid region.

This bibliometric study aims to explore how SH has been evaluated within research concerning Brazil's Semiarid region. By utilizing data from the Scopus® database, the study intends to identify prevailing research trends on SH in this specific geographical context. Moreover, it aims to identify the main soil indicators studied and their relationships with research, thus identifying and offering valuable insights for future investigations.

Material and methods

The bibliographic search was performed using a combination of search terms considering all the databases of the Scopus® platform (https://www.scopus.com/), conducted in February 2024 (Fig. 1). The search was performed using the 'Documents' field, which considers the 'Article title', 'Abstract' and 'Keywords' of a record. The advanced search for papers selection was done through

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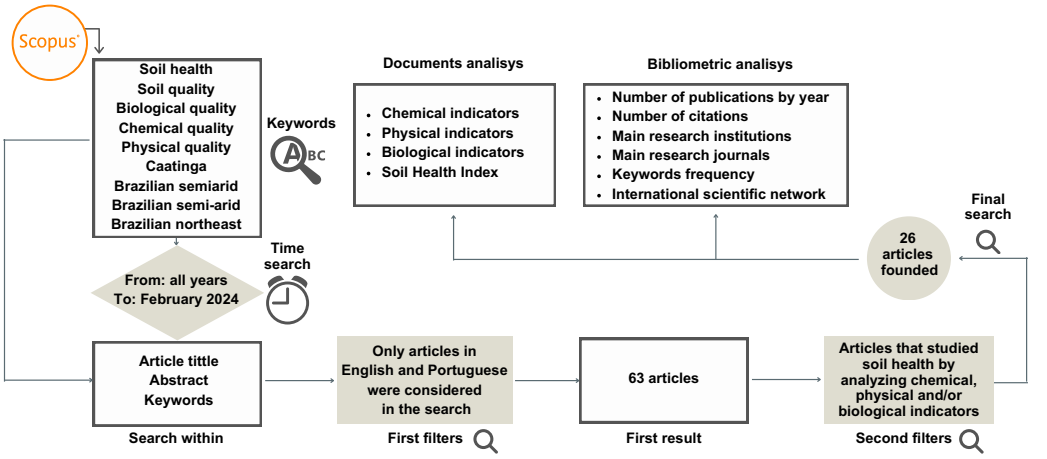

Figure 1. Main steps used for screening and evaluation of soil health manuscripts in Brazilian Semiarid.

the search command 'Search documents' using the terms and keywords ('soil health' OR 'soil quality' OR 'biological quality' OR 'chemical quality' OR 'physical quality' AND 'Caatinga' OR 'Brazilian semiarid' OR 'Brazilian semi-arid' OR 'Brazilian northeast'). Only articles and publications in English and Portuguese were considered resulting in 63 articles found in this first search.

The 63 articles found were then thoroughly analysed and those that studied SH through the analysis of chemical, physical, and/or biological indicators were filtered out. Articles that only mentioned soil health or soil quality, but did not evaluate soil functionality, were disregarded. After the second filtering, 26 articles were found within the scope of this research (Fig. 2). The files were downloaded in .csv and processed in the field 'Analyse search results' in the Scopus® platform, being later exported to Microsoft Office Excel (v. 2021) and VOSviewer (v. 1.6.17) software Van Eck and Waltman (2010) available at (https://www.vosviewer.com/). The following bibliometric parameters were analysed: i) the number of publications by year, ii) most cited articles, iii) main institutions, iv) main journals, and v) frequency of keywords. The articles were evaluated according to the following criteria: i) identification of chemical, ii) physical, and iii) biological indicators studied in the articles, and the use of vi) SH index.

In this study, maps were formed representing the link between keywords that contribute the most research, showing the existing relationship within each group by forming individual clusters. Each group of clusters represented by the same colour shows the strongest network of cooperation between them. In the clustering maps, each word is identified by a rectangle, where the size of the rectangle represents the frequency of the record of that word. Words with greater registration have a larger size than words registered with less frequency. In the case of the map of countries, the group of countries that presented co-authored publications has the same colour.

The maps obtained from VOSviewer are based on co-occurrence matrices, this being a three-step process: i) a co-occurrence matrix is used to calculate a similarity matrix, which ii) will be applied to VOS mapping technique to construct a map, and finally, iii) the map is translated, rotated, and reflected, thus giving rise to the VOSviewer maps (Van Eck and Waltman, 2010). The data extracted by VOSviewer allows reflecting on the state of the art of a given subject by generating knowledge maps from co-occurrence and co-citation analyses, allowing, for example, identification of gaps in knowledge as well as critical points in a research area (Van Eck and Waltman 2010).

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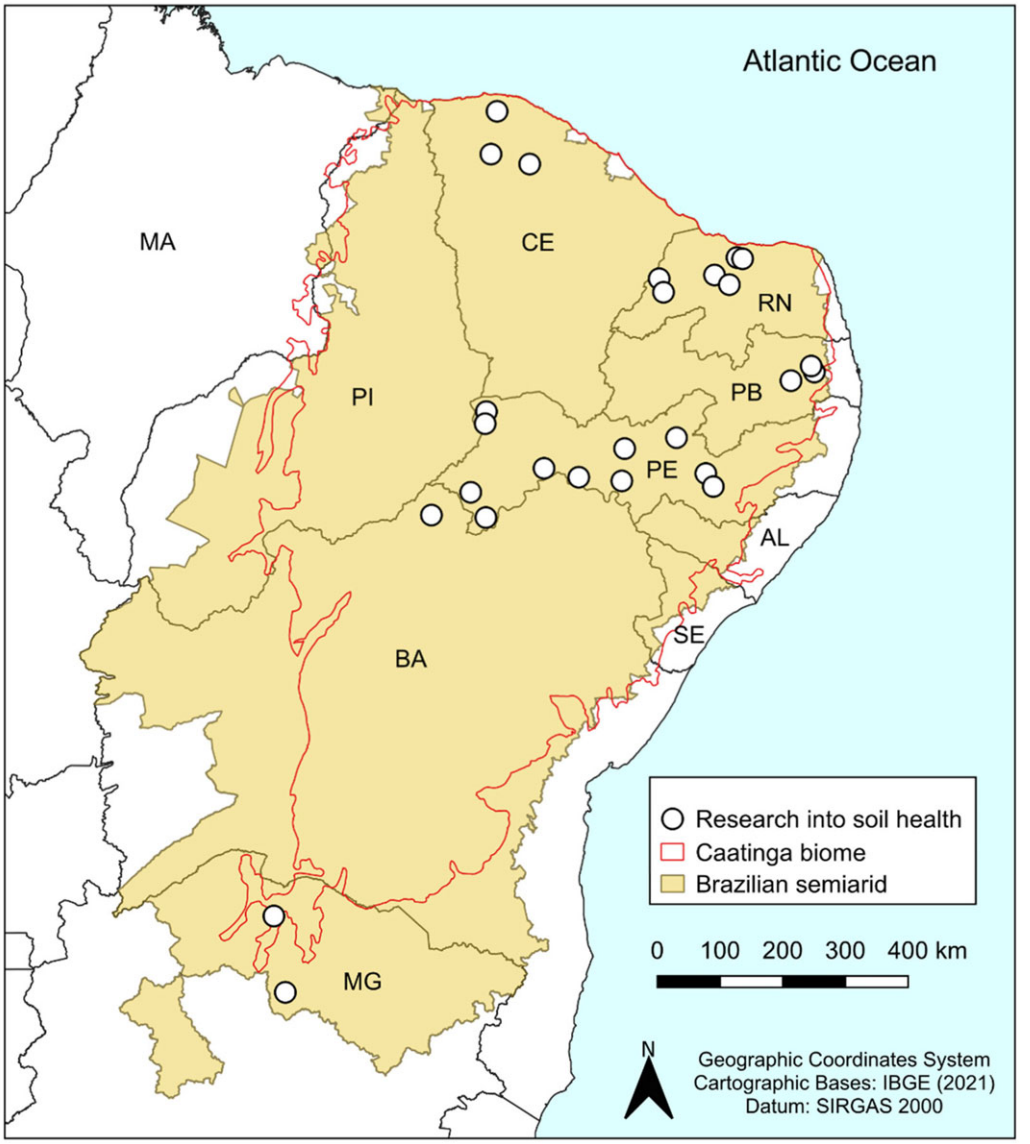

Figure 2. Representation of soil health studies in the Brazilian Semiarid and Caatinga biome delimitation (n = 26). The map was drawn with QGIS (v. 3.34.1).

Agglomerative hierarchical clustering of the articles was conducted through a similarity test to group the articles based on their chemical, physical, and biological indicators, using the statistical software XLSTAT (version 2023.3) (Lumivero, 2024). Following the principles established by clustering techniques such as the k-means or hierarchical algorithm, we sought to identify underlying patterns in the datasets of the reviewed articles. This approach aims to group articles that share significant similarities in terms of soil health indicators, highlighting differences or relationships between the formed groups. For the analysis of correlation between variables and factors, we explored the interactions among the chemical, physical, and biological indicators to identify patterns of association among the different indicators.

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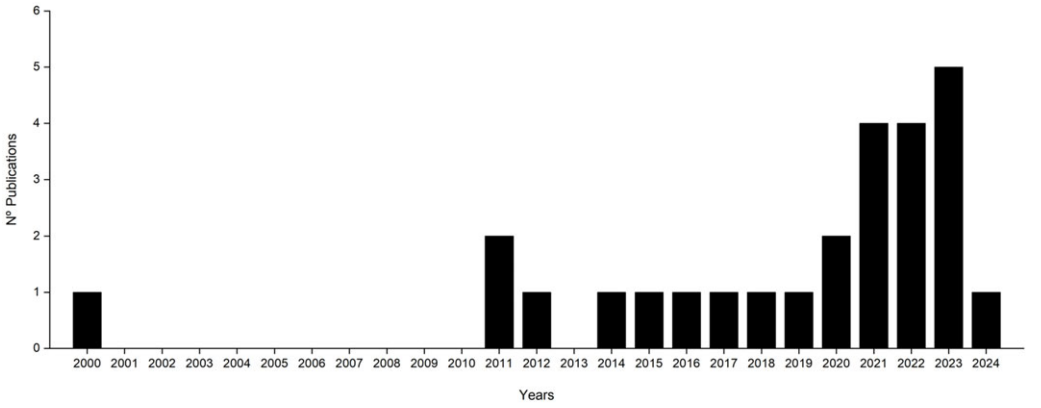

Figure 3. Number of publications by year on soil health in Brazilian Semiarid.

Results

Bibliometric analysis

In recent decades, research into SH in the Brazilian Semiarid region has undergone a notable evolution, with more than 60% of research published between 2020 and February 2024. (Fig. 3). Initially, from 2000 to 2010, scientific production in this area was minimal, with a slight increase in 2011 with two publications. There was a consistent output of at least one article per year, except in 2013. Year 2020 marked a significant turning point, with the number of publications doubling to two. This growth continued in 2021 and 2022, with four additional publications each year compared to the previous year. The upward trend reached its peak in 2023, with five publications. Data for 2024 are limited to articles published up to February.

Analysing the six most cited articles, we observed a variation in the number of citations per year, reflecting their relevance over time (Table 1). The most cited study, 'Land quality changes following the conversion of the natural vegetation into silvo-pastoral systems in semi-arid NE Brazil,' authored by Wick *et al.* (2000) in the journal Plant and Soil, accumulated 49 citations over the years, with an average of approximately 2 citations per year. The second most cited article, 'Soil biochemistry and microbial activity in vineyards under conventional and organic management at Northeast Brazil' by Freitas *et al.* (2011) in the journal Scientia Agricola, recorded 35 citations in total, resulting in an average of about 2.5 citations per year. Next, the study 'Plant-type dependent changes in arbuscular mycorrhizal communities as soil quality indicator in semi-arid Brazil,' published in the journal Ecological Indicators by Pagano *et al.* (2011), accumulated 28 citations, resulting in a similar average of 2 citations per year.

The fourth most cited article, 'Carbon in humic fractions of organic matter in soil treated with organic composts under mango cultivation' by Silva *et al.* (2016) in the journal Revista Brasileira de Ciência do Solo, registered 18 citations, resulting in an average of 2 citations per year. The fifth and sixth most cited articles, 'Physical soil quality indicators for environmental assessment and agricultural potential of Oxisols under different land uses in the Araripe Plateau, Brazil' by Cavalcante *et al.* (2021), and 'Effect of land use and seasonality on nematode faunal structure and ecosystem functions in the Caatinga dry forest' by Silva *et al.* (2021) in the journals Soil and Tillage Research and European Journal of Soil Biology, respectively, accumulated 12 citations each, resulting in an average of 3 citations per year.

The analysis of the main institutions reveals a significant contribution from Embrapa research centres and Universities/Research Institutions located in the Northeast region (Table 2). Embrapa and the Federal Rural University of Pernambuco lead equally, each contributing 8 articles, accounting for 31% of the total articles analysed. Next, the Federal Rural University of the

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Table 1. Articles on soil health ranked by the number of citations in Brazilian Semiarid

Paper	Title	Cited by	Year	Authors	Journal	Citations by year
P1	Land quality changes following the conversion of the natural vegetation into silvo-pastoral systems in semi-arid NE Brazil	49	2000	Wick B. *et al.*	Plant and Soil	2
P2	Soil biochemistry and microbial activity in vineyards under conventional and organic management at Northeast Brazil	35	2011	Freitas N.O. *et al.*	Scientia Agricola	2,5
P3	Plant-type dependent changes in arbuscular mycorrhizal communities as soil quality indicator in semi-arid Brazil	28	2011	Pagano M.C. *et al.*	Ecological Indicators	2
P4	Carbon in humic fractions of organic matter in soil treated with organic composts under mango cultivation	18	2016	Silva J.R. *et al*	Rev. Bras. de Ciencia do Solo	2
P5	Physical soil quality indicators for environmental assessment and agricultural potential of Oxisols under different land uses in the Araripe Plateau, Brazil	12	2021	Cavalcante D.M. *et al.*	Soil and Tillage Research	3
P6	Effect of land use and seasonality on nematode faunal structure and ecosystem functions in the Caatinga dry forest	12	2021	Silva J.V.C.D.L. *et al.*	European Journal of Soil Biology	3
P7	Soil fauna as bioindicator of recovery of degraded areas in the Caatinga biome	12	2017	Lima K.D.R. *et al.*	Revista Caatinga	1,5
P8	Mycorrhizal *Atriplex nummularia* promote revegetation and shifts in microbial properties in saline Brazilian soil	10	2020	Leite M.C.B.S. *et al.*	Applied Soil Ecology	2
P9	Indices of chemical quality of soil in areas cultivated with irrigated papaya	6	2015	Morais E.R.C. *et al.*	Rev. Bras. de Engenharia Agricola e Ambiental	0,6
P10	Soil enzymatic activities in areas with stages and management of forest regeneration from Caatinga	5	2018	Silva A.E.O. *et al.*	Revista Caatinga	0,7
P11	Agroforestry system improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid region	5	2023	Tonucci R.G. *et al.*	Rev. Bras. de Ciencia do Solo	2,5
P12	Soil quality under irrigated banana and its relationship with areas of 'Caatinga'	5	2014	Morais E.R.C. *et al.*	Rev. Bras. de Engenharia Agricola e Ambiental	0,5
P13	Effects of cropping systems and management of savanna through the analysis of chemical indicators of soil quality in agricultural production in Apodi. RN	5	2012	Lira R.B. *et al.*	Revista Caatinga	0,4
P14	Effects of land use changes on the potential for soil to contribute phosphorus loads in watersheds	3	2023	Cunha G.K.G. *et al.*	Environmental Development	1,5
P15	Soil carbon and nitrogen stocks under agrosilvopastoral systems with different arrangements in a transition area between Cerrado and Caatinga biomes in Brazil	3	2022	Freitas I.C.D. *et al.*	Agronomy	1
P16	Total and particulate contents and vertical stratification of organic carbon in agroforestry system in caatinga	2	2021	Iwata B.D.F. *et al.*	Revista Caatinga	0,5

(*Continued*)

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Table 1. (*Continued*)

Paper	Title	Cited by	Year	Authors	Journal	Citations by year
P17	Enzymatic activity of caatinga biome with and without anthropic action	2	2020	Cavalcante W.F. *et al.*	Revista Caatinga	0,4
P18	Multivariate analysis of chemical and physical attributes of quartzipsamments under different agricultural uses	2	2019	Arcoverde S.N.S. *et al.*	Engenharia Agricola	0,3
P19	Grazing exclusion restores soil health in Brazilian drylands under desertification process	1	2024	Lima A.Y.V. *et al.*	Applied Soil Ecology	1
P20	Soil physical-chemical traits and soil quality index in a tropical Cambisol as influenced by land uses and soil depth at Apodi plateau, northeastern Brazil	1	2023	Gondim J.E.F. *et al.*	International Journal of Plant Production	0,5
P21	Fertility, carbon stock, and aggregate stability of an Alfisol under integrated farming systems	1	2021	Silva P.L.F. *et al.*	Pesquisa Agropecuaria Tropical	0,3
P22	Impact of deforestation on the soil physical and chemical attributes, and humic fraction of organic matter in dry environments in Brazil	1	2022	Rezende J.S. *et al.*	IForest	0,3
P23	Structuring of the epigeal fauna in restoration of Brazilian Semiarid forest in the short term	0	2022	Gomes J.M. *et al.*	Soil Research	0
P24	Crop systems' influence on soil fauna community in the Brazilian northeast	0	2022	Silva S.I.A. *et al.*	Ciencia Florestal	0
P25	Nematodes as bioindicators of soil health in different land uses in the São Francisco River Valley, Brazil	0	2023	Caixeta L.B. *et al.*	Nematology	0
P26	Soil health in an integrated production system in a Brazilian Semiarid region	0	2023	Brito Neto J.F. *et al.*	Land	0

Semi-Arid and the Federal University of Paraíba appear with 5 articles, corresponding to 19% each, followed by the Federal University of Pernambuco (12%). Additionally, institutions such as the Federal Institute of Piauí, Federal Rural University of Rio de Janeiro, Federal University of Ceará, Federal University of Minas Gerais, State University of Maringá, and State University of Piauí, all with 2 articles each, also contribute to the research on SH in the Brazilian Semiarid region.

The main journals publishing research on SH in the Brazilian Semiarid region are Brazilian (Table 3). The 'Revista Caatinga' leads with 5 publications, representing 19% of the total. Next, we have three journals with 2 publications each, contributing 8% each: 'Applied Soil Ecology,' 'Revista Brasileira de Engenharia Agrícola e Ambiental,' and 'Revista Brasileira de Ciência do Solo.' The keywords reveal a variety of themes and areas of interest in the study of SH in the Brazilian Semiarid region (Fig. 4). 'Soil quality' emerges as the most recurrent term, with 18 citations, followed by 'Semiarid,' which is mentioned 15 times. 'Caatinga' emerges as one of the most frequently mentioned words, with 9 citations. Other commonly addressed topics include 'Semiarid' (7 citations), 'Arbuscular mycorrhizal fungi' (6 citations), and 'Land use change' (6 citations). The analysis of international participation reveals that Brazil is the most prominent country, with 26 articles. In second place, the USA contributed 2 articles, while Argentina, Canada, and India had a contribution of 1 article each. Other countries did not appear in this search.

Soil health indicators evaluation

The analyses of SH indicators in the Brazilian Semiarid region reveal a predominance of biological indicators, present in 88% of publications (23). Chemical indicators were studied in 81% of the

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Table 2. Institutions responsible for the highest number of publications on soil health in Brazilian Semiarid (n = 26)

Institution (Country)	Articles	%
Embrapa (Brazil)	8	31
Federal Rural University of Pernambuco (Brazil)	8	31
Federal Rural University of the Semi-Arid (Brazil)	5	19
Federal University of Paraíba (Brazil)	5	19
Federal University of Pernambuco (Brazil)	3	12
Federal Institute of Piauí (Brazil)	2	8
Federal Rural University of Rio de Janeiro (Brazil)	2	8
Federal University of Ceará (Brazil)	2	8
Federal University of Minas Gerais (Brazil)	2	8
State University of Maringá (Brazil)	2	8
State University of Piauí (Brazil)	2	8

Table 3. Top 10 journals ranked by the number of publications on soil health in Brazilian Semiarid (n = 26)

Journals	Publications
Revista Caatinga	5
Applied Soil Ecology	2
Revista Brasileira de Engenharia Agrícola e Ambiental	2
Revista Brasileira de Ciência do Solo	2
Plant and Soil	1
Soil and Tillage Research	1
Soil Research	1
Environmental Development	1
Scientia Agricola	1
International Journal of Plant Production	1
Agronomy	1
Pesquisa Agropecuária Tropical	1
Ciência Florestal	1
Engenharia Agrícola	1
European Journal of Soil Biology	1
IForest	1
Nematology	1
Ecological Indicators	1
Land	1

articles (21), followed by physical indicators, present in 46% of the research (12). The SH index was used in only 23% of the studies analysed (6). Soil pH was the most used chemical indicator, appearing in 15 of the 26 articles (Fig. 5). Next, elements such as P, Ca^{2+}, K^{+}, and Mg^{2+} were mentioned in 14 articles. Sodium was mentioned in 11 articles, while exchangeable acidity (H + Al) was addressed in 8 articles. Nitrogen was used in 6 articles, while electrical conductivity (EC) in 5, and Al3+ in 4 articles. Metallic elements such as Pb^{2+}, Ni^{2+}, Cd^{2+}, Mn^{2+}, and Fe^{2+} were less frequently studied, appearing in only 2 articles each. Finally, S, Cu^{2+}, and Zn^{2+} were mentioned in only one article each.

Among the physical indicators of SH, bulk density was the most frequently evaluated, appearing in 9 out of 26 studies analysed (Fig. 5). Soil porosity was examined in 7 articles. Soil aggregate stability was assessed in 3 articles, while soil moisture in 2 articles. Hydraulic conductivity and penetration resistance were studied only once. Among the biological indicators, soil organic carbon was the most frequently evaluated indicator, appearing in 20 out of 26 studies analysed (Fig. 5). Next, a variety of enzymes and biological components, such as alkaline and acid phosphatases, β-glucosidase, microorganisms such as arbuscular mycorrhizal fungi, soil microbial biomass, soil fauna, humic, and fulvic acids, were quantified in 3 articles each. Soil proteins related to glomalin, nematodes, humin, arylsulfatase, urease, and basal respiration were studied in 2 articles each. DNA-based methodologies were mentioned in only one article.

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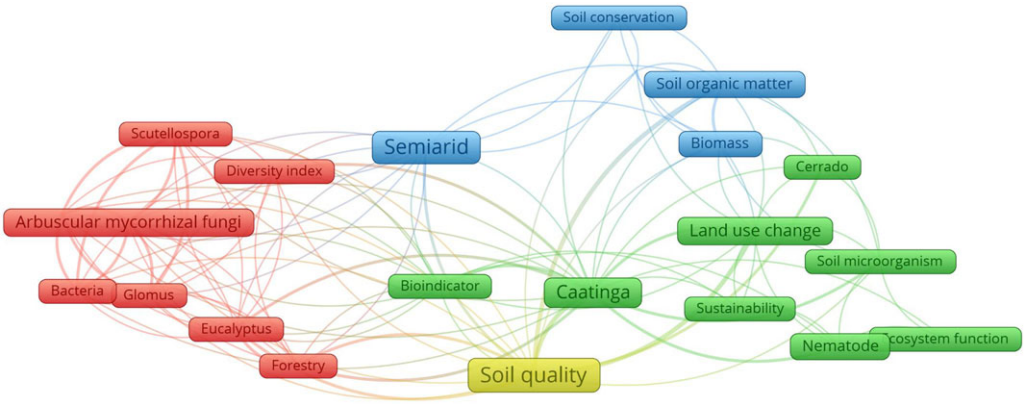

Figure 4. Bibliometric map of the frequency of keywords used in research on Soil Health in the Brazilian Semiarid. Each group of clusters represented by the same colour shows the strongest use of keywords in a specific theme.

The variable/factor correlations show a positive correlation between Cd^{2+}, Pb^{2+}, Ni^{2+}, Fe^{2+}, and Mn^{2+} (0.535), Cu^{2+} and Zn^{2+} (0.359), and P and K^{+} (0.614) (Fig. 6). Additionally, we found correlations between pH and Ca^{2+} (−0.460) and pH and Mg^{2+} (−0.461). Regarding biological activity indicators, we observed a positive correlation between alkaline phosphatase (ALKP), acid phosphatase (ACIP), and soil fauna (FAUNA) (0.567). Lastly, we identified complex correlations between moisture content (MOIST), humin (HUM), fulvic acids (FAC), and humic acids (HAC), as well as between basal respiration (BRESP), microbial biomass carbon (MBC), and arbuscular mycorrhizal fungi (AMF). There were no correlations between the physical indicators.

The results of the similarity test indicate that the articles were grouped into seven distinct classes (Table 4). The number of articles in each cluster varies, with some clusters containing more articles than others, such as cluster 1 which grouped 14 articles, while clusters 3, 5, and 7 grouped one article each. The variance within the cluster also varies, with some clusters showing greater variability among the grouped objects (clusters 1 and 2), while others have zero variance (clusters 3, 5, and 7).

Discussion

The evolution of SH research in the Brazilian Semiarid region has been influenced by various factors. Conversion of native vegetation into agricultural and pasture systems in Brazilian drylands, as highlighted by MapBiomas (2021), exacerbates the already alarming loss of biodiversity, with approximately 53.5% of its native vegetation already degraded. The accelerated growth of agricultural areas (1,456%) and pastures (48%) between 1985 and 2020 underscores the ongoing degradation of Brazilian drylands (MapBiomas, 2021).

The effects of land use changes on the biomes of the Brazilian Semiarid region have led to a significant alteration in soil characteristics, such as reduced moisture (Queiroz *et al.*, 2020), alteration in the stocks of C, N, and P (Gava *et al.*, 2021), as well as changes in soil properties and microclimate (Silva *et al.*, 2020), and microbial diversity (Pereira *et al.*, 2021). Thus, the conservation of native species and prevention of deforestation, typically caused by agricultural activities (Sieber *et al.*, 2011), is essential. Equally crucial is understanding the impact of climate change on soil organic carbon stocks (Maia *et al.*, 2019; Medeiros *et al.*, 2021).

Notably, there has been a significant increase in scientific production in this area. Initially, between 2000 and 2010, scientific output was minimal. However, there was a gradual increase from 2011 onwards, with at least one article published per year, except in 2013. The turning point

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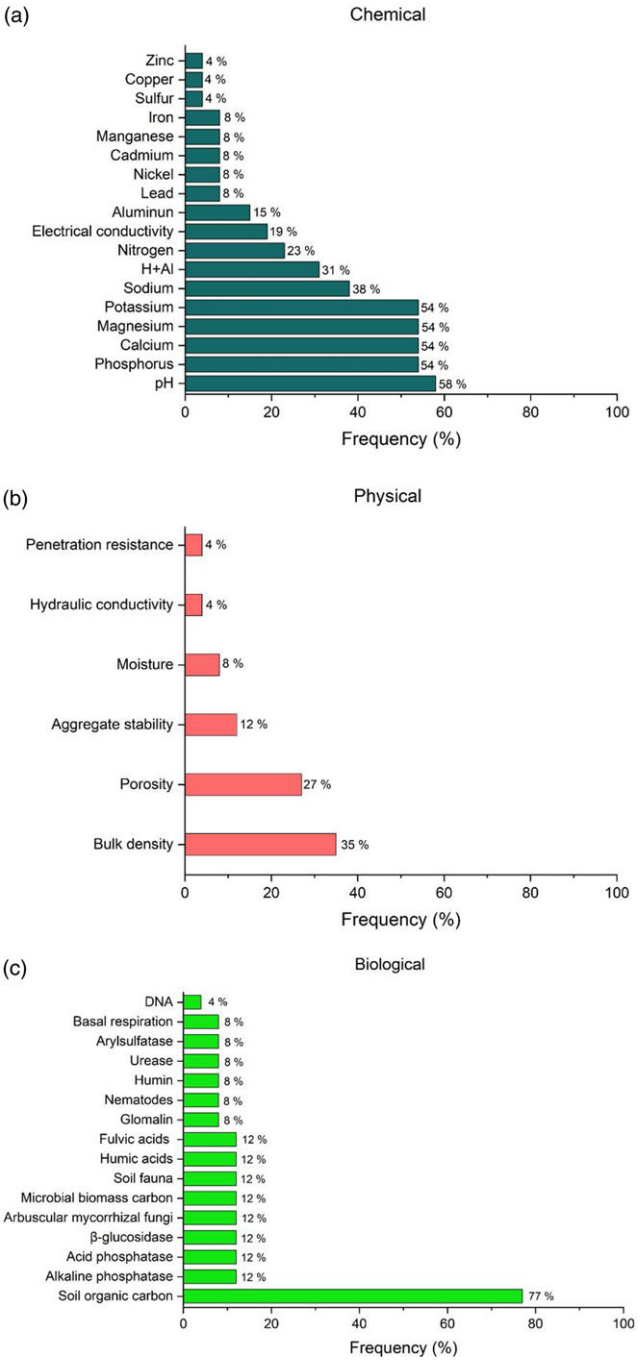

Figure 5. Chemical, physical, and biological indicators used in soil health studies in the Brazilian Semiarid (n = 26).

occurred in 2020 when the number of publications doubled, and this growth continued in the subsequent years, reaching its peak in 2023. This upward trend suggests a growing interest and recognition of the importance of SH in the Brazilian Semiarid region, possibly driven by environmental and agricultural concerns (e.g., soil degradation and climate changes). This growth

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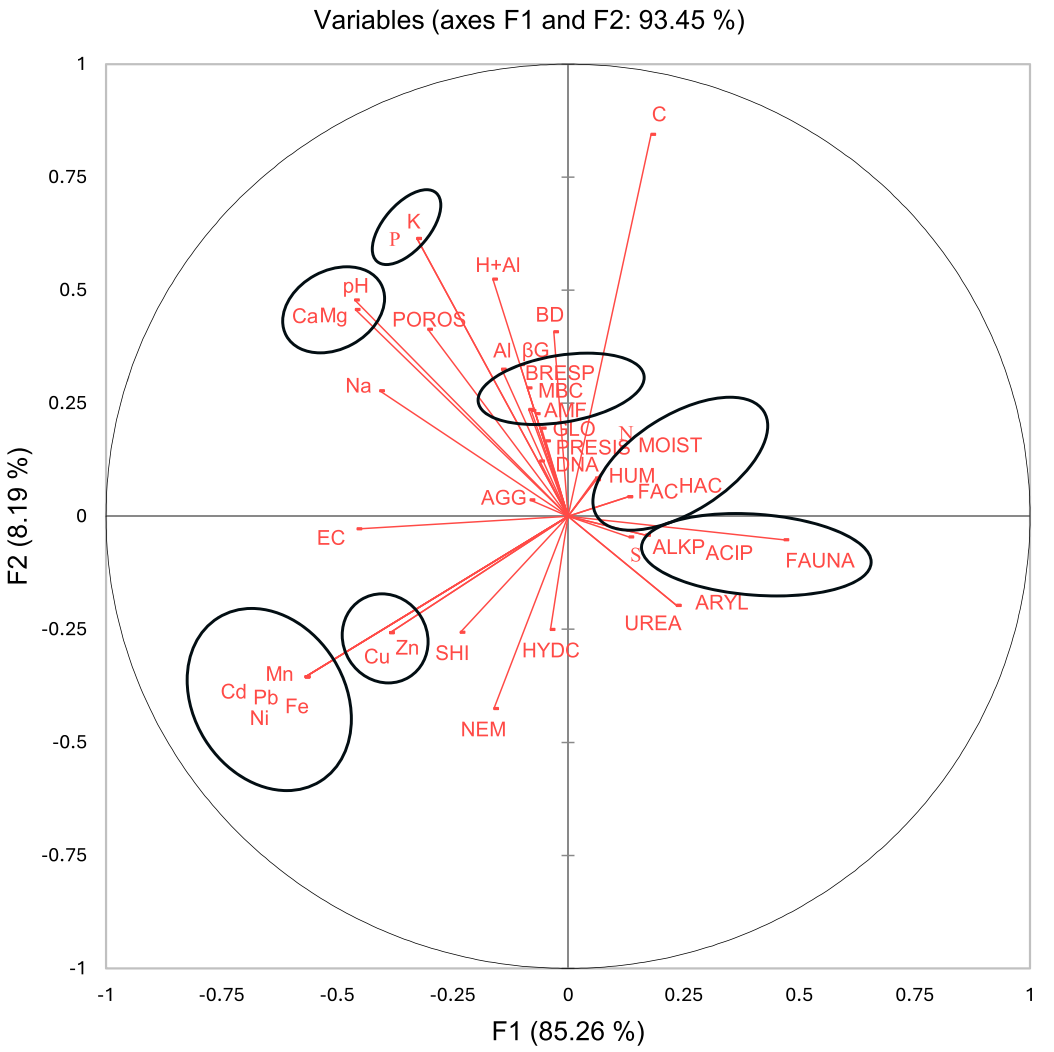

Figure 6. Variable/factor correlations of chemical, physical, and biological indicators used in soil health studies in the Brazilian Semiarid.

Note: pH (hydrogenionic potential), P (phosphorus), Al (aluminium), Ca (calcium), Mg (magnesium), K (potassium), Na (sodium), H + Al (potential acidity), N (nitrogen), EC (electrical conductivity), Zn (zinc), Cu (copper), Pb (lead), Ni (nickel), Cd (cadmium), Mn (manganese), Fe (iron), S (sulphur), BD (bulk soil density), POROS (porosity), AGG (soil aggregate stability), MOIST (moisture), HYDC (hydraulic conductivity), PRESIS (penetration resistance), C (soil organic carbon), ALKP (alkaline phosphatase), ACIP (acid phosphatase), ARYL (arylsulfatase), UREA (urease), βG (β-glucosidase), AMF (arbuscular mycorrhizal fungi), MBC (microbial biomass carbon), FAUNA (soil fauna), HAC (humic acids), FAC (fulvic acids), GLO (glomalin), NEM (nematodes), HUM (humin), BRESP (basal respiration), DNA, SHI (soil health index).

in recent years follows the national trend, as shown by Simon *et al.* (2022), where between 2014 and 2021 there was a linear growth in publications in Brazil.

The findings from Wick *et al.* (2000), Freitas *et al.* (2011), and Pagano *et al.* (2011) emphasize the intricate relationship between SH and microbial communities in semi-arid regions like Brazil. Their research highlights the profound impact of land conversion and management on soil biochemistry and microbial activity, underscoring the imperative for adopting sustainable land use practices to preserve soil health. Moreover, Pagano *et al.* (2011) specifically shed light on the potential of AMF as an indicator of SH improvement due to their fundamental role in soil

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Table 4. Similarity test results for grouping articles based on chemical, physical, and biological indicators on soil health in Brazilian Semiarid

Class	1	2	3	4	5	6	7
Number of objects by cluster	14	5	1	2	1	2	1
Sum of weights	14	5	1	2	1	2	1
Within-cluster variance	4.429	3.200	0.000	2.000	0.000	1.500	0.000
Minimum distance to centroid	1.266	1.114	0.000	1.000	0.000	0.866	0.000
Average distance from centroid	1.988	1.540	0.000	1.000	0.000	0.866	0.000
Maximum distance from centroid	2.678	2.245	0.000	1.000	0.000	0.866	0.000
	P1	P4	P5	P9	P10	P23	P25
	P2	P6		P12		P24	
	P3	P11					
	P7	P15					
	P8	P16					
	P13						
	P14						
	P17						
	P18						
	P19						
	P20						
	P21						
	P22						
	P26						

aggregation, nutrient cycle, and plant nutrition, suggesting avenues for leveraging microbial indicators to assess and monitor SH in Semiarid regions.

The research on SH in the Brazilian Semiarid region is significantly shaped by Embrapa research centres and northeastern educational institutions, particularly the Federal Rural University of Pernambuco, the Federal Rural University of the Semi-Arid, and the Federal University of Paraíba. Embrapa, as the main agricultural research institution, plays a crucial role in this context, with a focus on open access to scientific information and strategic planning (**Leite 2009). It's important to consider the low number of institutions outside the Northeastern Region of Brazil participating in research projects on the topic. While the significant presence of Northeastern Institutions demonstrates interest in local studies, it also indicates that partnerships between educational institutions across the country are still incipient regarding studies on SH in the Brazilian Semiarid region.

The SH research in the Brazilian Semiarid is predominantly domestic, conducted by local institutions (Universities and Research Institutions) and published in local (Revista Caatinga and 'Revista Brasileira de Engenharia Agrícola e Ambiental') and national (e.g., 'Revista Brasileira de Ciência do Solo') journals. This endogenous scientific scenario probably explains the small number of publication and the reduced interest of research from other regions of Brazil, and international collaborations. However, the intense promotion of global agendas in the last couple years, such combat to desertification and climate changes, national and international interest for drylands has raised, and it expected an expansion and internationalization of SH research in the Brazilian Semiarid.

Despite the increasing number of studies, the geographic distribution of research on SH in the Brazilian Semiarid is not homogeneous, leaving entire states without data on the health of their soils, such as Piauí, Sergipe, and Alagoas (Fig. 2). Even in states where research has been conducted, this number ends up being very low, as is the case of Bahia, which, despite being the largest state in the Northeast and one of the largest in Brazil, has only one study on SH.

The high frequency of the term 'Soil quality' indicates that researchers are interested in understanding and improving SH in the region, which can involve issues such as fertility, land use changes, and the recovery of degraded areas. The prominence of 'Semiarid' and 'Caatinga' suggests

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that there is a particular focus on understanding the challenges and opportunities associated with the Semiarid climate and the Caatinga biome. Additionally, themes such as 'arbuscular mycorrhizal fungi' and 'land use change' indicate specific areas of research, such as the influence of soil organisms on plant health and the effects of land use change on biodiversity and SH.

A review of SH indicators in the Brazilian Semiarid region reveals a focus on biological indicators, particularly soil organic carbon (SOC), which was the most frequently studied. The conversion of natural vegetation into silvo-pastoral systems in Brazilian Semiarid has been found to significantly impact SH, with preserved native trees maintaining higher nutrient and organic matter levels than grass or introduced tree species (Wick *et al.*, 2000). This is further supported by the finding that the conversion of forests into successional areas can decrease soil carbon stocks and microbial biomass (Santos *et al.*, 2018). However, the introduction of mycorrhizal *Atriplex nummularia* has been shown to promote revegetation and shift microbial properties in saline Brazilian soil (Pagano *et al.*, 2011, Leite *et al.*, 2020). Additionally, grazing exclusion has been found to restore SH in Brazilian drylands undergoing desertification mainly through microbiological restoration (Lima *et al.*, 2024).

A range of chemical indicators have been studied in the context of SH. Arcoverde *et al.* (2019) used multivariate analysis to assess the quality of Quartzipsamments under different agricultural uses, identifying the role of fertility in improving SH. A series of studies have explored the impact of different agricultural practices on SH in Brazil. Morais *et al.* (2015) found that phosphorus and pH levels increased in areas cultivated with papaya, negatively affecting the quality of soil in these areas, with a significant decrease in environmental quality index over time. Similarly, Morais *et al.* (2014) observed that over time, the Environmental Quality Index declined due to cultivation, mainly influenced by factors like EC, Na^{+}, Pb^{2+}, and Ni^{2+}. However, improvements were observed in the environmental quality concerning Ca^{2+}, K^{+}, Zn^{2+}, and Fe^{2+}.

A range of physical indicators have been evaluated in studies on SH, with bulk density and porosity being the most frequently examined. These indicators are significantly affected by deforestation and different agricultural uses. Deforestation and land use change in dry environments in Brazil have been found to significantly impact SH, with degraded native vegetation and agricultural uses leading to lower soil fertility, organic carbon, and humic fractions. Rezende *et al.* (2022) found that the increase in soil bulk density in disturbed native vegetation areas was attributed to a reduction in soil porosity, particularly macroporosity. Gondim *et al* (2023) suggested that land use practices such as monocropping systems can have varied effects on soil bulk density. In their findings, compared to conventional farming methods, both agroecological and fruticulture farming systems led to significant increases in bulk density, with respective increases of 11.5% and 13.6% observed at a soil depth of 15–25 cm.

Cavalcante *et al.* (2021) formulated a soil quality index (SQI) framework using principal component analysis and linear model, with methodologies inspired by Karlen and Stott (1994) and Brejda *et al.* (2000). This approach was applied to assess the impacts of different management systems and evaluate the alternative use of Eucalyptus to reduce the impact of deforestation of the Caatinga, for use in charcoal kilns and calcination to produce limestone and gypsum in the Araripe region. Lima *et al.* (2024) used the Soil Management Assessment Framework (SMAF) to evaluate SH in areas of native Caatinga vegetation, degraded by overgrazing, and restored by grazing exclusion in the Irauçuba Desertification Nucleus, state of Ceará. In this study, the SH index showed that restored areas in the Caatinga can achieve levels of SH similar to those found in native Caatinga vegetation. Gondim *et al.* (2023) utilized the model introduced by Karlen and Stott (1994) to construct a SQI incorporating the mean values of various soil physical and chemical traits. The SQI model was developed based on data from soil depths ranging from 0 to 25 cm. The main model employed important functions like water supply and storage, root growth, nutrient cycling, and soil conservation.

The correlation between soil pH and Ca^{2+} and Mg^{2+}, and between P and K^{+}, suggests that these are often discussed together in the reviewed studies. This may reflect a shared interest in

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understanding how soil acidity affects the availability of these important minerals for plant growth in the context of the Brazilian Semiarid region. The correlations between Cd^{2+}, Pb^{2+}, Ni^{2+}, Fe^{2+}, and Mn^{2+} (evaluated in two articles), and between Cu^{2+} and Zn^{2+} (evaluated in one article) may indicate a common concern regarding the presence of these elements in the soil related to contamination or availability. Correlations between biological activity, such as alkaline and acid phosphatase activity, and soil fauna suggest a collective interest in understanding the dynamics of soil life and its role in maintaining soil health in the semi-arid environment (Hågvar, 1994).

Correlations between soil moisture and biological indicators (basal respiration, microbial biomass carbon, and arbuscular mycorrhizal fungi) indicate that water and soil microbiota are closely linked and can influence each other in soil health (Gehring, 2017). The lack of correlations between the other evaluated physical indicators may indicate that, while these factors are important individually, their relationship with other factors (chemical, biological) may be less direct or more complex.

Assessing SH in semi-arid regions requires consideration of specific indicators that are sensitive to local conditions. Key indicators such as SOM, pH, and bulk density reflect the challenges of low precipitation and soil degradation in semi-arid areas (Ghimire *et al.*, 2023). SOM is particularly crucial for water retention in water-limited environments (Allen *et al.*, 2011). Biological indicators such as microbial biomass and enzyme activity, dependent on SOM, show rapid responses to management changes (Lima *et al.*, 2024). Comparing the Brazilian findings with other semi-arid regions, similar challenges of low SOM and low fertility are observed (Ghimire *et al.*, 2023). However, specific indicators may vary based on local conditions. Grazing exclusion and conservation practices can improve SH in Brazilian drylands (Lima *et al.*, 2024), showing positive variations, mainly in bulk density and SOM.

The absence of more DNA-based analyses in SH studies in the Brazilian Semiarid region is a significant gap that needs to be addressed. While our study highlighted the importance of SH indicators, the lack of comprehensive soil data in these studies is concerning. This study emphasizes the role of soil biology and the need for advanced assessment methods, such as RNA and DNA-based analysis, in the evaluation of SH in the understanding of gene expression and important functions of microorganisms in Brazilian Semiarid soils. Thus, future research should prioritize the inclusion of RNA and DNA-based analyses to provide a more comprehensive understanding of SH.

In 2022 was created the Caatinga Microbiome Initiative, an interinstitutional initiative involving more than 20 professors and researchers from Brazil and abroad, with the aim of studying the Caatinga microbiome and its relationship with soil health. In addition, the Brazilian Soil Health Partnership, coordinated by Center for Carbon Research in Agriculture (CCARBON) of University of São Paulo, was just launched (April 2024). This alliance aims to promote a national SH agenda through the pillars 'Research, Innovation and Dissemination', enabling connections between scientists (50 researchers from all regions and multiple institutions), producers, and stakeholders. Both initiatives are good examples of the recent scientific organization of the SH agenda in Brazil, which will potentially boost studies in Brazilian drylands in the coming decades.

Advancing SH research in the Brazilian Semiarid requires continuous investment in infrastructure, funding, and training, alongside greater collaboration between institutions and the private sector, and the adoption of participatory approaches to develop sustainable agricultural practices that benefit local communities. Initiatives such as the Caatinga Microbiome Initiative and the Brazilian Partnership for Soil Health marks a milestone in the study of SH in Brazil, particularly in the Semiarid region, making it a national priority in the context of active climate change. Tools like SMAF have proven efficient for soil analysis (Lima *et al.*, 2024) and are widely used in Brazilian laboratories. The KIT SOHMA (Schiebelbein and Cherubin, 2024) is another low-cost and accessible tool that allows producers to monitor soil in agricultural areas. These tools can guide decision-makers in developing public policies to recover degraded areas or maintain SH

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in farming areas. Monitoring and restoring SH in the Semiarid helps mitigate poverty and improve quality of life, enabling farmers to sustain their livelihoods.

Conclusions

The study of SH in the Brazilian Semiarid region reflects a multifaceted understanding of the region's environmental dynamics, shaped by factors such as land use changes, climate variability, and biodiversity conservation efforts. It is important to highlight the limitations of the study, such as the dependence on a single database (Scopus) and the fact that some works on SH, published or not yet published (such as theses and dissertations) in Portuguese, may not have been widely cited, which impacts their detection in the survey carried out. As research on SH continues to grow, propelled by both national and international collaborations that need to be better grounded, it becomes increasingly evident that SH plays a crucial role in addressing the challenges posed by climate change and sustainable land management. By employing innovative methodologies and focusing on key indicators, such as SOC, pH, bulk density, porosity, and chemical composition like Ca^{2+}, Mg^{2+}, P, Na^{+}, and K^{+}, researchers are striving to develop comprehensive strategies for preserving soil fertility, enhancing agricultural productivity, and fostering ecosystem resilience in the unique context of the Brazilian Semiarid region. Through ongoing interdisciplinary efforts and knowledge sharing, it is hoped that these endeavours will contribute to the long-term sustainability and prosperity of the region's ecosystems and communities.

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References

Allen, D.E., Singh, B.P. and Dalal, R.C. (2011) Soil health indicators under climate change: A review of current knowledge. In Singh, B., Cowie, A. and K. Chan (eds.), *Soil Health and Climate Change*. Springer, p. 29. https://doi.org/10.1007/978-3-642-20256-8_2

Araújo, A.S.F., Medeiros, E.V., Costa, D.P., Pereira, A.P.A. and Mendes, L.W. (2024) From desertification to restoration in the Brazilian semiarid region: unveiling the potential of land restoration on soil microbial properties. *Journal of Environmental Management* **351**, 119746. https://doi.org/10.1016/j.jenvman.2023.119746

Arcoverde, S.N.S., Cortez, J.W., Olszevski, N., Salviano, A.M. and Giongo, V. (2019) Multivariate analysis of chemical and physical attributes of quartzipsamments under different agricultural uses. *Engenharia Agrícola* **39**, 457–465. https://doi.org/10.1590/1809-4430-Eng. Agric.v39n4p457-465/2019

Bezak, N., Mikoš, M., Borrelli, P., Alewell, C., Alvarez, P., Anache, J.A.A., Baartman, J., Ballabio, C., Biddoccu, M., Cerdà, A., Chalise, D., Chen, S., Chen, W., De Girolamo, A.M., Gessesse, G.D., Deumlich, D., Diodato, N., Efthimiou, N., Erpul, G., … **Panagos, P.** (2021) Soil erosion modelling: a bibliometric analysis. *Environmental Research* **197**, 111087. https://doi.org/10.1016/j.envres.2021.111087

Brasil (2021a) *Delimitação do Semiárido*. Superintendência do Desenvolvimento do Nordeste – SUDENE. Available at https://www.gov.br/sudene/pt-br/centrais-deconteudo/02semiaridorelatorionv.pdf (accessed 16 February 2024).

Brasil (2021b) *Quarta Comunicação Nacional do Brasil à Convenção-Quadro das Nações Unidas sobre Mudança do Clima*. Setor Uso da Terra, Mudança do Uso da Terra e Florestas. MCT, Brasília. Available at https://antigo.mctic.gov.br/mctic/export/sites/institucional/arquivos/SIRENE/Comunicacoes-Nacionais-do-Brasil-a-UNFCCC/2020_12_22_4CN_v5_PORT_publicada.pdf (accessed on 16 February 2024).

Brejda, J.J., Moorman, T.B., Karlen, D.L. and Dao, T.H. (2000) Identification of regional soil quality factors and indicators: I. Central and Southern High Plains. *Soil Science Society of America Journal* **64**, 2115–2124.

Cancian, L.C., Dalmolin, R.S.D. and Caten, A.T. (2018) Bibliometric analysis for pattern exploration in worldwide digital soil mapping publications. *Anais Da Academia Brasileira De Ciências* **90**, 3911–3923. https://doi.org/10.1590/0001-3765201820180423

Cavalcante, D.M., Silva, A.P.F., Almeida, B.G., Freire, F.J., Silva, T.H.S. and Cavalcante, F.M.S. (2021) Physical soil quality indicators for environmental assessment and agricultural potential of Oxisols under different land uses in the Araripe Plateau, Brazil. *Soil and Tillage Research* **209**, 104951. https://doi.org/10.1016/j.still.2021.104951

Cherubin, M.R., Bordonal, R.O., Castioni, G.A., Guimarães, E.M., Lisboa, I.P., Moraes, L.A.A., Menandro, L.M.S., Tenelli, S., Cerri, C.E.P., Karlen, D.L. and Carvalho, J.L.N. (2021) Soil health response to sugarcane straw removal in Brazil. *Industrial Crops and Products* **163**, 113315. https://doi.org/10.1016/j.indcrop.2021.113315

Cherubin, M.R., Karlen, D.L., Franco, A.L.C., Cerri, C.E.P., Tormena, C.A. and Cerri, C.E. (2016) A soil management assessment framework (SMAF) evaluation of Brazilian sugarcane expansion on soil quality. *Soil Science Society of America Journal* **80**, 215–226. https://doi:10.2136/sssaj2015.09.0328

Doran, J.W. and Parkin, T.B. (1994) Defining and assessing soil quality. In Doran, J.W., Coleman, D.C., Bezdicek, D.F. and Stewart, B.A. (eds.), *Defining Soil Quality for a Sustainable Environment*. USA. https://doi.org/10.2136/sssaspecpub35.c1

Ferreira, A.C.C., Leite, L.F.C., Araújo, A.S.F. and Eisenhauer, N. (2016) Land-use type effects on soil organic carbon and microbial properties in a semi-arid region of Northeast Brazil. *Land Degradation & Development* **27**, 171–178. https://doi.org/10.1002/ldr.2282

Freitas, N.O., Yano-Melo, A.M., Silva, F.S.B., Melo, N.F. and Maia, L.C. (2011) Soil biochemistry and microbial activity in vineyards under conventional and organic management at Northeast Brazil. *Scientia Agricola* **68**, 223–229. https://doi.org/10.1590/S0103-90162011000200013

Gava, C., Giongo, V., Signor, D. and Fernandes-Júnior, P. (2021) Land-use change alters the stocks of carbon, nitrogen, and phosphorus in a Haplic Cambisol in the Brazilian semi-arid region. *Soil Use and Management* **38**, 953–963. https://doi.org/10.1111/sum.12716

Gehring, C.A. (2017) Introduction: Mycorrhizas and soil structure, moisture, and salinity. In Johnson, C., Gehring, C. and Jansa, J. (eds.), *Mycorrhizal Mediation of Soil*. Elsevier, pp. 235–240. https://doi.org/10.1016/B978-0-12-804312-7.00013-9

Ghimire, R., Thapa, V.R., Acosta-Martinez, V., Schipanski, M., Slaughter, L.C., Fonte, S.J., Shukla, M.K., Bista, P., Angadi, S.V. and Mikha, M.M. (2023) Soil health assessment and management framework for water-limited environments: examples from the Great Plains of the USA. *Soil Systems* **7**, 22. https://doi.org/10.3390/soilsystems7010022

Gondim, J.E.F., Souza, T., Portela, J.C., Santos, D., Nascimento, G.S. and Silva, L.J.R. (2023) Soil physical-chemical traits and soil quality index in a tropical Cambisol as influenced by land uses and soil depth at Apodi Plateau, Northeastern Brazil. *International Journal of Plant Production* **17**, 491–501. https://doi.org/10.1007/s42106-023-00256-1

Hågvar, S. (1994) Soil biology: soil animals and soil acidity. In Abrahamsen, G., Stuanes, A.O. and Tveite, B. (eds.), *Long-Term Experiments with Acid Rain in Norwegian Forest Ecosystems*. Ecological Studies. New York, USA: Springer, p. 104. https://doi.org/10.1007/978-1-4612-2604-8_5

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F. and Schuman, G.E. (1997) Soil quality: a concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal* **61**, 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x

Karlen, D.L. and Stott, E. (1994) A framework for evaluating physical and chemical indicators of soil quality. In Doran, J.W. (ed.), *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America Journal, pp. 53–72. https://doi.org/10.2136/sssaspecpub35.c4

Lacerda-Júnior, G.V., Noronha, M.F., Cabral, L., Delforno, T.P., de Sousa, S.T.P., Fernandes-Júnior, P.I., Melo, I.S. and Oliveira, V.M. (2019) Land use and seasonal effects on the soil microbiome of a Brazilian dry forest. *Frontiers in Microbiology* **10**, 648. https://doi.org/10.3389/fmicb.2019.00648

Lehmann, J., Bossio, D.A., Kögel-Knabner, I. and Rilling, M.C. (2020) The concept and future prospects of soil health. *Nature Reviews Earth & Environment* **1**, 544–553. https://doi.org/10.1038/s43017-020-0080-8

Leite, F.C.L., Bertin, P.R.B., Vacari, I., Simão, V.P.M. and Visoli, M.C. (2009) Implementação de estratégias de acesso aberto em uma instituição de pesquisa de grande porte na área de agricultura: a experiência da Embrapa. In *Reunión De La Asociación Interamericana De Bibliotecarios, Documentalistas Y Especialistas Em Información Agrícola*. Lima, Peru.

Leite, M.C.B.S., Freire, M.B.G.S., Queiroz, J.V.J., Maia, L.C., Duda, G.P. and Medeiros, E.V. (2020) Mycorrhizal Atriplex nummularia promote revegetation and shifts in microbial properties in saline Brazilian soil. *Applied Soil Ecology* **153**, 103574. https://doi.org/10.1016/j.apsoil.2020.103574

https://doi.org/10.1017/S0014479724000243 Published online by Cambridge University Press

Lima, A.Y.V., Cherubin, M.R., Silva, D.F., Mota, J.C.A., Silva, F.G.M., Araújo, A.S.F., Melo, V.M.M., Verma, J.P. and Pereira, A.P.A. (2024) Grazing exclusion restores soil health in Brazilian drylands under desertification process. *Applied Soil Ecology* **193**, 105107. https://doi.org/10.1016/j.apsoil.2023.105107

Lumivero (2024) *XLSTAT Statistical (version 2023.3) and Data Analysis Solution*. Available at https://www.xlstat.com

Maia, S., Gonzaga, G., Silva, L., Lyra, G. and Gomes, T. (2019) Soil organic carbon temperature sensitivity of different soil types and land use systems in the Brazilian semi-arid region. *Soil Use and Management* **35**, 433–442. https://doi.org/10.1111/sum.12508

MapBiomas Project (2021) *Mapeamento Anual de Cobertura e Uso da Terra na Caatinga – Coleção 6*. Available at https://mapbiomas-brsite.s3.amazonaws.com/Fact_Sheet_CAATINGA_06102010_OKalta.pdf (accessed 10 May 2024).

Medeiros, A., Maia, S., Santos, T. and Gomes, T. (2021) Losses and gains of soil organic carbon in grasslands in the Brazilian semi-arid region. *Scientia Agricola* **78**, 20190076. https://doi.org/10.1590/1678-992x-2019-0076

Medeiros, A.S., Maia, S.M.F., Santos, T.C. and Gomes, T.C.A. (2020) Soil carbon losses in conventional farming systems due to land-use change in the Brazilian semi-arid region. *Agriculture, Ecosystems & Environment* **287**, 106690. https://doi.org/10.1016/j.agee.2019.106690

Morais, E.R.C., Maia, C.E., Gaudêncio, H.R.S.C. and Sousa, D.M.M. (2015) Indicadores da qualidade química do solo em áreas cultivadas com mamoeiro irrigado. *Revista Brasileira de Engenharia Agrícola e Ambiental* **19**, 587–591. https://doi.org/10.1590/1807-1929/agriambi.v19n6p587-591

Morais, E.R.C., Oliveira, A.A.S. and Maia, C.E. (2014) Qualidade do solo cultivado com banana irrigada e sua relação com áreas de caatinga. *Revista Brasileira de Engenharia Agrícola e Ambiental* **18**, 887–891. https://doi.org/10.1590/1807-1929/agriambi.v18n09p887-891

Moura, M.S.B., Espínola Sobrinho, J., Silva, T.G.F. and Souza, W.M. (2019) Aspectos meteorológicos do Semiárido brasileiro. In Ximenes, L.F., Silva, M.S.L. and Brito, L.T.L. (eds.), *Tecnologias de convivência com o Semiárido brasileiro*. Fortaleza, Brazil: Banco do Nordeste do Brasil 2, pp. 85–104. Available at https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1112124

Pagano, M.C., Utida, M.K., Gomes, E.A., Marriel, I.E., Cabello, M.N. and Scotti, M.R. (2011) Plant-type dependent changes in arbuscular mycorrhizal communities as soil quality indicator in semi-arid Brazil. *Ecological Indicators* **11**, 643–650. https://doi.org/10.1016/j.ecolind.2010.09.001

Pereira, A.P.A., Lima, L.A.L., Bezerra, W.M., Pereira, M.L., Normando, L.R.O., Mendes, L.W., Oliveira, J.G.B. de, Araújo, A.S.F. and Melo, V.M.M. (2021) Grazing exclusion regulates bacterial community in highly degraded semiarid soils from the Brazilian Caatinga biome. *Land Degradation and Development* **32**, 2210–2225. https://doi.org/10.1002/ldr.389347

Queiroz, M., Silva, T., Zolnier, S., Jardim, A., Souza, C., Júnior, G., Morais, J. and Souza, L. (2020) Spatial and temporal dynamics of soil moisture for surfaces with a change in land use in the semi-arid region of Brazil. *Catena* **188**, 104457. https://doi.org/10.1016/j.catena.2020.104457

Rezende, J.S., Freire, F.J., Araújo Filho, J.C., Freire, M.B.G.S, Almeida, B.G. and Santos, L.R.C. (2022) Impact of deforestation on the soil physical and chemical attributes, and humic fraction of organic matter in dry environments in Brazil. *iForest* **15**, 465–475. https://doi.org/10.3832/ifor4016-015

Ribeiro, K., Sousa-Neto, E.R., Carvalho, J.A., Lima, J.R.S., Menezes, R.S.C., Duarte-Neto, P.J., Guerra, G.S. and Ometto, J.P.H.B. (2016) Land cover changes and greenhouse gas emissions in two different soil covers in the Brazilian Caatinga. *Science of the Total Environment* **571**, 1048–1057. https://doi.org/10.1016/j.scitotenv.2016.07.095

Rousseau, G., Burgos-Guerrero, J., Hernández-García, L., Gómez-Cardozo, E., Triana, S., Medina, J., Silva, K. and Celentano, D. (2022) Potential of slash-and-mulch system with legumes to conserve soil attributes and macrofauna diversity in Eastern Amazon. *Pedobiologia* **95**, 150840. https://doi.org/10.1016/j.pedobi.2022.150840

Santos, U.J., Medeiros, E.V., Duda, G.P., Marques, M.C., Souza, E.S., Brossard, M. and Hammecker, C. (2018) Land use changes the soil carbon stocks, microbial biomass and fatty acid methyl ester (FAME) in Brazilian semiarid area. *Archives of Agronomy and Soil Science* **65**, 755–769. https://doi.org/10.1080/03650340.2018.1523544

Schiebelbein, B.E. and Cherubin, M.R. (2024) *Guia do usuário de campo do Kit SOHMA de saúde do solo*. Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz. https://doi.org/10.11606/9786587391557

Sellami, M.H. and Terribile, F. (2023) Research evolution on the impact of agronomic practices on soil health from 1996 to 2021: a bibliometric analysis. *Soil Systems* **7**, 78. https://doi.org/10.3390/soilsystems7030078

Sieber, S., Medeiros, P. and Albuquerque, U. (2011) Local perception of environmental change in a semi-arid area of Northeast Brazil: a new approach for the use of participatory methods at the level of family units. *Journal of Agricultural and Environmental Ethics* **24**, 511–531. https://doi.org/10.1007/S10806-010-9277-Z

Silva, J.R., Silva, D.J., Gava, C.A.T., Oliveira, T.C.T. and Freitas, M.S.C. (2016) Carbon in humic fractions of organic matter in soil treated with organic composts under mango cultivation. *Revista Brasileira de Ciência do Solo* **40**, 0150095. https://doi.org/10.1590/18069657rbcs20150095

Silva, J.V.C.L., Ferris, H., Cares, J.E. and Esteves, A.M. (2021) Effect of land use and seasonality on nematode faunal structure and ecosystem functions in the Caatinga dry forest. *European Journal of Soil Biology* **103**, 103296. https://doi.org/10.1016/j.ejsobi.2021.103296

https://doi.org/10.1017/S0014479724000243 Published online by Cambridge University Press

Silva, T., Queiroz, M., Zolnier, S., Souza, L., Souza, C., Moura, M., Araújo, G., Neto, A., Santos, T., Melo, A., Neto, J., Silva, M. and Alves, H. (2020) Soil properties and microclimate of two predominant landscapes in the Brazilian semiarid region: comparison between a seasonally dry tropical forest and a deforested area. *Soil and Tillage Research* **207**, 104852. https://doi.org/10.1016/j.still.2020.104852

Simon, C.P., Gomes, T.F., Pessoa, T.N., Soltangheisi, A., Bieluczyk, W., Camargo, P.B., Martinelli, L.A. and Cherubin, M.R. (2022) Soil quality literature in Brazil – a systematic review. *Revista Brasileira de Ciência do Solo* **46**, 0210103. https://doi.org/10.36783/18069657rbcs20210103

Tonucci, R.G., Vogado, R.F., Silva, R.D., Pompeu, R.C.F.F., Oda-Souza, M. and Souza, H.A. (2023) Agroforestry system improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid region. *Revista Brasileira de Ciência do Solo* **47**, 0220124. https://doi.org/10.36783/18069657rbcs20220124

Van Eck, N.J. and Waltman, L. (2010) Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **84**, 523–538. https://doi.org/10.1007/s11192-009-0146-3

Wick, B., Tiessen, H. and Menezes, R.S.C. (2000) Land quality changes following the conversion of the natural vegetation into silvo-pastoral systems in semi-arid NE Brazil. *Plant and Soil* **222**, 59–70. https://doi.org/10.1023/A:1004756416281

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