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From soil health to agricultural productivity: The critical role of soil constraint management

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ABSTRACT

Soil constraints significantly impact agricultural productivity and food security by affecting soil health and crop yields. This study provides a comprehensive global bibliometric analysis of global research on soil physical, chemical and biological constraints, utilizing R, VOSviewer, and Citespace. Global publications totaled 1,418 showing a significant increase in output since the early 2000 s, with Australia and the United States leading in research contributions. The top journals accounted for 13.13% of the total publications, with major contributions from institutions in Australia, the United States and China. Key research themes identified include the impact of climate change, nutrient management, and crop-specific responses to soil constraints. Moreover, the analysis showed a shift towards advanced scientific techniques and technologies in recent years, such as molecular biology, proteomics, and remote sensing, which reflects the evolving focus of soil constraint research. The studies in the 2000 s primarily focused on traditional soil management practices and the identification of basic nutrient deficiencies. However, the recent shift towards advanced methodologies highlights an evolving focus on precise, high-resolution techniques for understanding and mitigating soil constraints. Despite these advancements, potential gaps remain in the integration of these technologies into practical soil management strategies, and in addressing regional differences in soil constraints. Our study emphasizes the importance of continued international collaboration and the integration of innovative methodologies to address the complex challenges of soil management. The future research should further support the realization of the global Sustainable Development Goals (SDGs) by adopting scientific soil management measures, applying appropriate fertilizers, improving soil structure, reducing soil pollution and erosion, and enhancing agricultural sustainability and food security.

1. Introduction

Soil constraints refer to various physical, chemical, and biological limitations that adversely affect environmental sustainability, plant growth and agricultural productivity (Naorem et al., 2023). Globally, soil constraints are becoming increasingly acute, especially in areas with intensive agricultural land use (Ahmad et al., 2020; Xie et al., 2020). The continuing increase in global population combined with the uncertainties in climate change and enhanced soil degradation poses a serious threat to food security (Smith et al., 2020). The Food and Agriculture Organization of the United Nations (FAO) estimates that about one-third of the world's land is experiencing varying degrees of degradation, affecting the livelihoods of more than 1.5 billion people (Bardgett et al., 2021; Pani, 2020). These constraints include soil compaction, waterlogging, erosion, poor soil structure, sodicity, salinity, acidity, nutrient deficiencies, pests, and soil-borne diseases (Naorem et al., 2023) (Fig. 1). Addressing these soil constraints is crucial for ensuring sustainable agricultural practices, food security, and

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environmental sustainability, especially in the context of a growing global population and climate change.

Soil constraints could have significant negative effect on agricultural productivity and environmental health. Historical literature reveals that the global research hotpots on soil constraints mainly focus on soil compaction and salinisation (Rodrigo-Comino et al., 2020). However, the types of soil limitation and the research focus differ significantly across regions. For instance, studies indicate that soil compaction problems in North America and Europe are mainly due to the extensive use of heavy agricultural machinery (Lindstrom and Voorhees, 1994; Lipiec et al., 2003; Sonderegger and Pfister, 2021), which leads to the destruction of soil structure and decreases of soil porosity, limiting the root growth and water infiltration, and leading to decreased crop yields and increased erosion susceptibility (Nawaz et al., 2013; Shaheb et al., 2021). Similarly, soil acidification is a serious problem in Asia and Africa, often caused by excessive use of nitrogenous fertilizers (Butterly et al., 2022; Hicks et al., 2008; Juo et al., 1995), which could lead to toxic levels of aluminum and manganese, and reduced nutrient availability (Bouwman et al., 2002; Sumner and Noble, 2003; Yadav et al., 2020). In Australia, research has also focused on soil degradation due to drought (Singh, 2022). Soil salinization, common in arid and semi-arid regions, severely limits crop growth and productivity due to the accumulation of soluble salts (Hailu and Mehari, 2021). In Latin America, soil erosion and heavy metal pollution are major research themes (Alves Peixoto and Jadán-Piedra, 2022). Heavy metal contamination poses serious risks to food safety and human health, as toxic metals can accumulate in crops and enter the food chain (Kumar et al., 2019).

Significant progress has been made in understanding and managing soil constraints. Soil compaction due to physical constraints reduces soil porosity, limiting root growth and water and nutrient anailability, resulting in reduced crop yields (Hamza and Anderson, 2005; Shah et al., 2017). The challenge in addressing this issue is to find economically viable ways to increase soil porosity and remove the compacting layer to alleviate compaction, such as using deep tillage or applying organic matter to improve soil structure (Sale et al. 2021). Chemical limitations include soil acidity, salinity, and nutrient deficiency (Athanase et al., 2013; Bolan et al., 2023). These problems directly affect the nutrient absorption and growth of crops. The main challenge in addressing chemical limitations is how to accurately formulate fertilizer programs, particularly N fertilizers, to minimize soil acidification, while avoiding the environmental pollution, such as nitrate leaching loss and greenhouse gas emissions, caused by excessive fertilization. Soil organic matter is a major source of plant nutrients and an important component of soil structure and health (Abdulraheem et al., 2023; Sahbeni et al., 2023). Biological limitations include soil-borne diseases caused by pathogens, declining microbial diversity, and low organic matter content, which reduce nutrient cycling and hinder plant growth (Sinton et al., 2022; Tripathi et al., 2020). The challenge of increasing soil organic matter is how to continuously add organic matter, such as through compost or manure, while also improving microbial activity for long-term soil health benefits.

Recent advancements in remote sensing and precision agriculture have provided innovative tools for managing soil constraints (Li and et al., 2023; Tziolas, 2021). Unmanned aerial vehicles (UAVs) and satellite imagery enable high-precision monitoring of soil health parameters such as soil temperature, moisture, vegetation index, soil organic matter, and land use and cover, which provide real-time data for targeted interventions (Tsouros et al., 2019). Furthermore, integrated soil

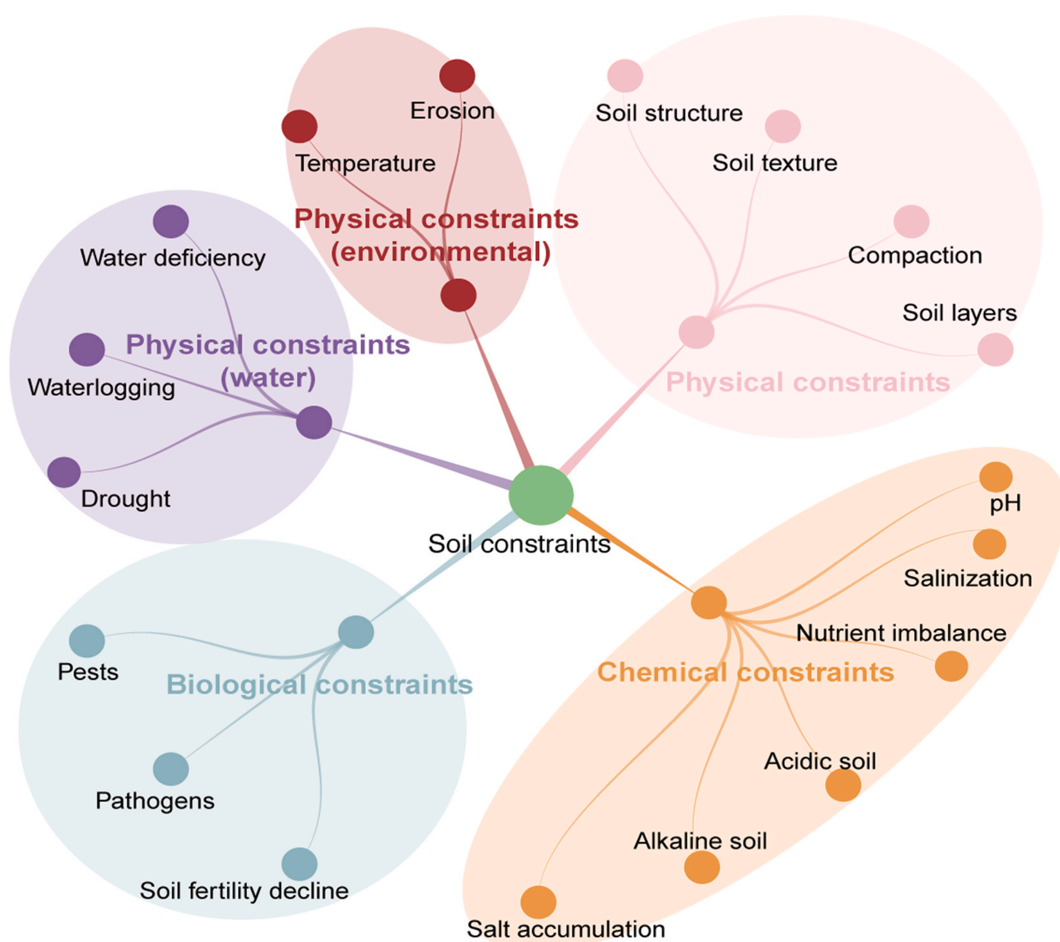

Fig. 1. Classification maps of soil constraints include physical constraints (soil structure, environment, and water), chemical constraints, and biological constraints.

management practices that combine physical, chemical, and biological strategies have shown promise in addressing multiple soil constraints simultaneously (Naorem et al., 2023).

These studies stress the diversity and complexity of soil constraints but also highlight several challenges and limitations in research methodologies, regional distribution, and interdisciplinary integration. Firstly, existing studies are predominantly concentrated in specific regions and environmental conditions (Alotaibi et al., 2023; Kumar et al., 2022; Rao et al., 2023), lacking a systematic global perspective. Secondly, while soil constraint research involves multiple disciplines, the integration and collaboration between different fields remain insufficient. Lastly, although many studies propose management strategies to improve soil health, their effectiveness across different regions and practical applications requires further evaluation (Dey et al., 2024; Ryan et al., 2013; Saleem et al., 2023). Despite these advancements, several gaps persist in the current research landscape.

By systematically reviewing and evaluating the current status and development trends of global research on soil constraints, this study offers a comprehensive landscape to the academic community and policymakers. Identifying major contributors and emerging research topics can promote further research in key areas and provide scientific evidence for policymaking to support sustainable agriculture and environmental protection. In the context of global climate change and food security challenges, understanding the status and trends of soil constraint research is crucial for developing effective soil management and improvement strategies.

2. Material and methods

2.1. Data collection and screening

To systematically evaluate the current status and development trends of global research on soil constraints, this study utilized the Web of Science database (core collection). This database encompasses a wide range of peer-reviewed academic journal articles, providing comprehensive support for literature data. The literature search covered all publication years to ensure data comprehensiveness and representativeness, with the language restricted to English. The analysis strategy was based on a combination of keywords and Boolean operators to ensure the inclusion of all relevant studies on soil constraints. The primary keywords included but were not limited to soil constraints, compaction, sodicity, alkalinity, salinity, heavy metal pollution, nutrient deficiency and structure. During this course, the specific search query utilized the "TS" field tag in the Web of Science database, which allows for searching terms across the title, abstract, author keywords, and Keywords Plus. The query was designed as follows (TS = ("compaction" OR "erosion" OR "acidity" OR "salinization" OR "salinity" OR "heavy metal" OR "nutrient deficiency" OR "alkalinity" OR "sodicity" OR "nutrient deficiencies" OR "surface seal*" OR "waterlogg*" OR "nutrient toxicity" OR "Soil borne disease*" OR "soil fertility decline" OR "subsurface hardening" OR "high soil density") and TS = ("cropland*" OR "cropping system*" OR "agricultur* management" OR "sustainable agricultur*" OR "soil management" OR "soil management practice*" OR "agro-ecosystem*" OR "crop" OR "field crop*" OR "farmland" OR "yield") NOT TS = ("grassland" OR "forest" OR "incubation" OR "ocean" OR "costal") and TS = ("soil" OR "subsoil") and TS = ("constraint*" OR "limation*").

To ensure the relevance and quality of the literature, the study established the following inclusion and exclusion criteria: i) original research and review articles related to soil constraints published in peer-reviewed journals were included, ii) studies unrelated to soil constraints, iii) book chapters, editorials, conference papers, and commentaries, were excluded (Fig. 2). After retrieving the literature, EndNote software was used to manage the references and remove duplicates. For each included study, the following information was extracted: authors, title, journal, publication year, institutions, country, keywords, and abstract.

2.2. The analysis of bibliometrics

The bibliometric analysis employed a comprehensive approach using multiple tools to ensure a thorough understanding of the global research landscape on soil constraints. Firstly, the Bibliometrix package in R was a powerful tool designed for bibliometric analysis. Bibliometrix is capable of handling a large volume of literature data and generating extensive analytical results and visualizations (Derviş, 2020). Additionally, VOSviewer software was used to create scientific knowledge

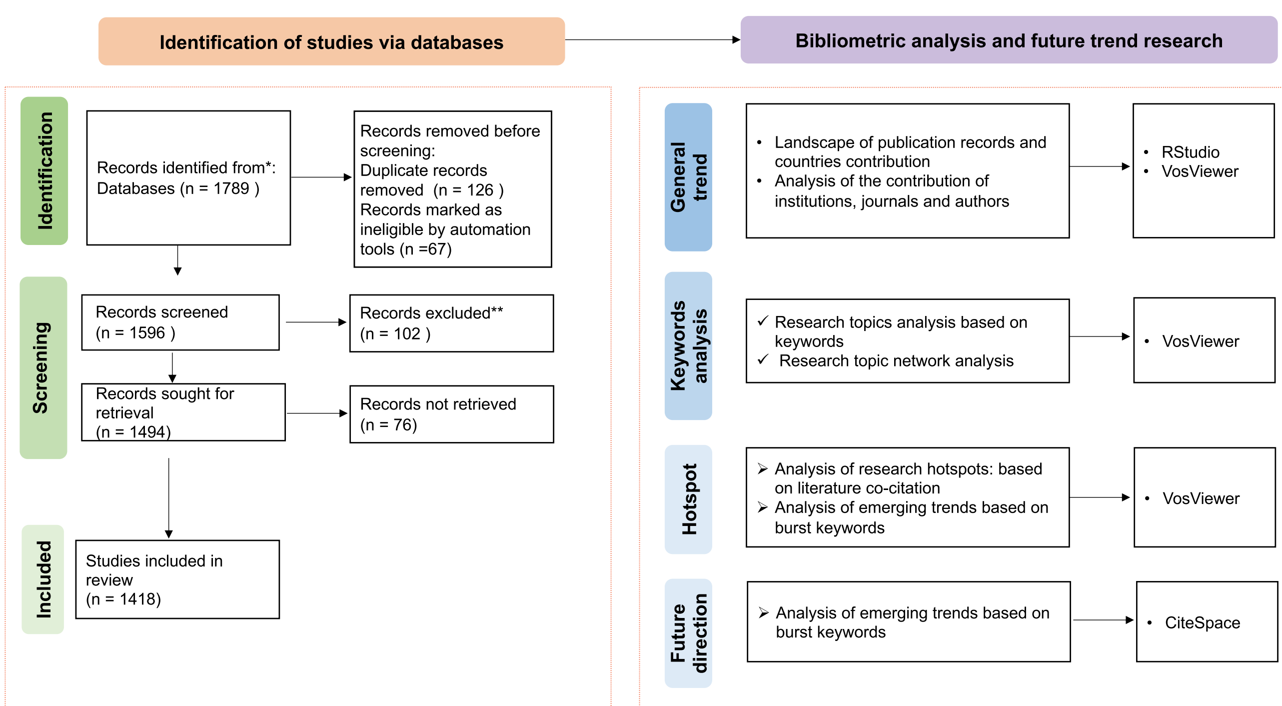

Fig. 2. Literature search, exclusion and bibliometrics analsyis process.

maps. It facilitated the analysis of citation relationships between documents and the evolution of research themes (van Eck and Waltman, 2010; Van Eck and Waltman, 2017; Li et al., 2022a; Li et al., 2022c). In VOSviewer, there is one indicator need to be focused, which is total link strength (TLS), TLS represents the cumulative strength of co-occurrence relationships for a keyword, calculated by summing the co-occurrence frequencies of the keyword with all others in the network, indicating its centrality and importance within the research field. CiteSpace was employed to detect and analyze burst terms, identifying the most influential and emerging topics within the field. Using its citation burst detection algorithm, CiteSpace calculates the sudden rise in a term's usage frequency within specific timeframes, marking terms with rapid and statistically significant increases as "burst terms". This analysis revealed keywords that experienced notable citation surges, highlighting periods of intensified research focus and providing insights into evolving research trends (Li et al., 2022b; Li et al., 2021b). This comprehensive methodological approach integrates Bibliometrix, VOSviewer, and CiteSpace to thoroughly assess global research trends on soil constraints. It provides valuable insights for researchers, policymakers, and practitioners striving towards sustainable soil management and agricultural productivity.

3. Results and Discussion

3.1. Landscape of publication records and contribution of countries

Annual publication counts display a significant exponential increase from 1973 to 2024 (include some gap years), particularly from the early 2000 s onwards. This growth reflects heightened global awareness of soil health and its importance for agricultural productivity and sustainability (Yang et al., 2020). Peaks in local citation scores (LCS) during 2003–2007 and 2010–2015 align with the publication of influential studies addressing soil constraints and management practices, such as Dang et al. (2006a) and Rengasamy (2002). The LCS, represented by the orange line with dots, exhibits high variability over the years, peaking notably in the periods of 2003–2007 and 2010–2015, but generally increasing in alignment with publication records (Fig. 3**a**).

Geographic distribution reveals that research output is concentrated in a few key regions. The highest number of publications (221–270) originate from Australia and the United States, shown in the darkest blue shades. East Asia (notably China) and western Europe (including Germany, France, and UK) also contribute significantly, with publication counts ranging from 121 to 220. These regions are pivotal hubs of academic and research activities, highlighting their substantial contributions to global scientific literature (Fig. 3**b**). Australia's significant contribution is closely linked to its research focus on sodic soils, salinity, and subsoil constraints, which impact over 60% of its cropping regions (Rengasamy, 2002; Dang et al., 2006a).

Longitudinal analysis of publication records from different countries demonstrates varying growth patterns. Australia, indicated by a solid line, leads with the steepest increase in publication numbers, surpassing 300 records by 2024. This growth is supported by robust government funding and a strategic focus on soil management challenges, particularly in dryland farming regions (Adcock et al., 2007). Other countries, such as China, US, India, and the UK, also exhibit significant upward trends, indicating robust growth in their research outputs. European countries like Germany, France, and Italy have shown a consistent growth but at a slower rate compared to Australia and China (Fig. 3**c**).

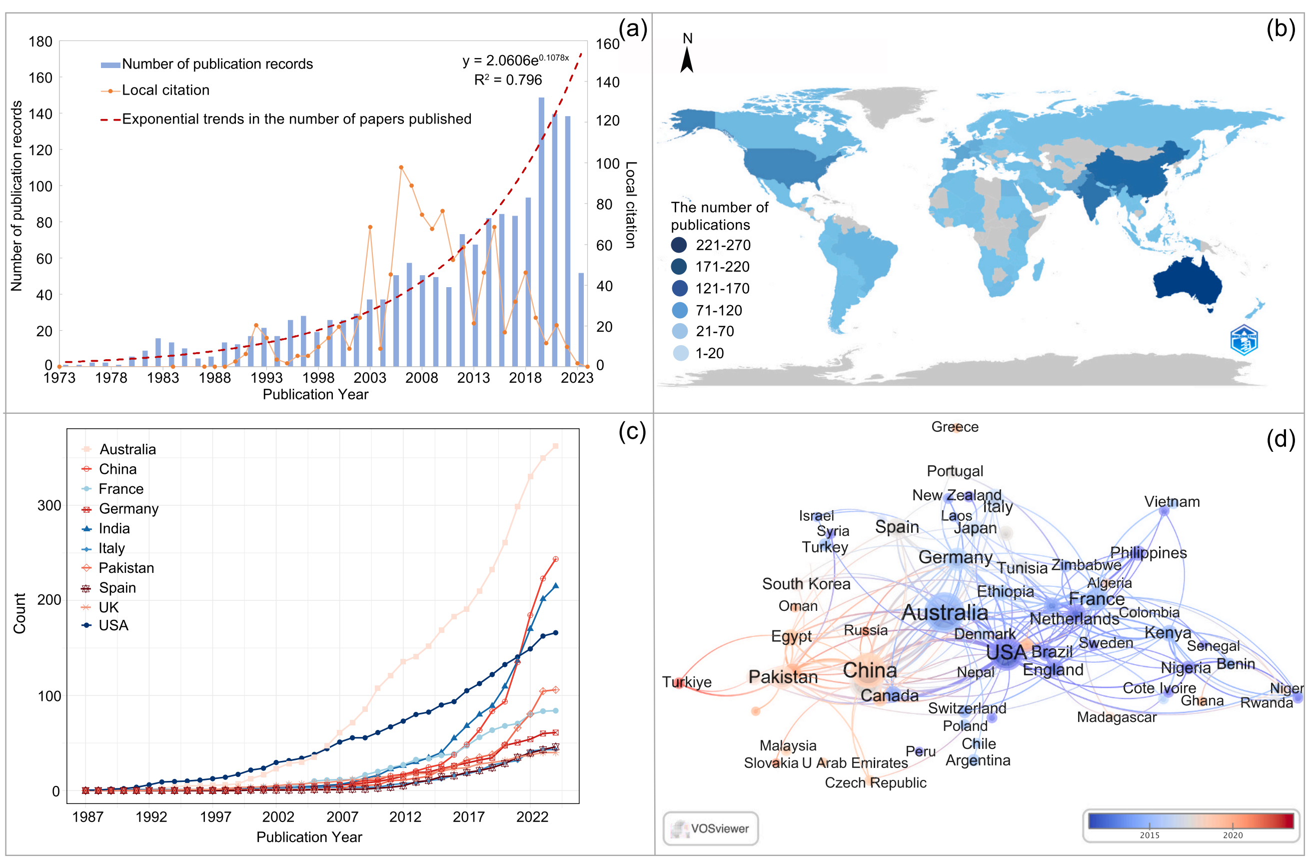

Fig. 3. Trends in publication records and local citations over time (a). Global distribution map of publications by country (b). Publication records over time for the top 10 countries (c). International collaboration network (d) within the research studies of soil constraints. The size of the bubbles represents the number of articles, with larger bubbles indicating more articles published in that country. The color of the bubbles represents the number of citations, with deeper colors indicating higher citation counts.

Network analysis of international collaboration highlights the interconnected nature of global research efforts. Major nodes such as Australia, US, and China stand out, reflecting their central roles in international collaborations. The thickness of the connecting lines indicates the strength and frequency of collaborative efforts, with Australia-China and US-China partnerships being particularly notable. These collaborations have led to advancements in addressing global challenges, such as subsoil salinity and conservation agriculture in regions like Sub-Saharan Africa and Southeast Asia (Giller et al., 2009; Rengasamy, 2006). The color gradient from blue to red illustrates the temporal shift in collaborations, with blue representing collaborations up to 2015 and red indicating more recent partnerships (2020 onwards). This trend demonstrates increasing collaboration over time, especially among leading research nations, fostering a more integrated global research community (Fig. 3**d)**.

3.2. Analysis of the contribution of institutions, journals and authors

The top 10 Web of Science categories in soil science research are depicted in Fig. 4**a**. "Plant sciences" and "agronom" are the predominant categories, accounting for 24.74% and 20.15% of the total records, respectively. Other significant categories include "environmental sciences" (14.86%), "soil science" (14.35%), and "agriculture multidisciplinary" (8.45%). The analysis of publication journals demonstrates a wide distribution of research outputs, with significant contributions in the fields of plant science, soil science, and related areas (Fig. 4**b**). The top five journals, including *Field Crops Research*, *Plant and Soil*, *Frontiers in Plant Science*, *Soil and Tillage Research*, and *Agriculture, Ecosystems & Environment* – account for 13.13% of the total publications, highlighting their status as flagship journals in the field (Fig. 4**b**). The network analysis reveals that research institutions are predominantly concentrated in Australia, with notable universities such as the University of Adelaide, the University of Western Australia, the University of Queensland, Murdoch University, and La Trobe University forming key nodes in the collaboration network (Fig. 4**c**). Additionally, US Department of Agriculture (USDA) and institutions in India are prominent players. The robust collaboration between these institutions is indicated by the thick connecting lines. Emerging research institutions in China, marked in red, represent new contributors to the field. The color gradient represents the timeline of collaborations from 2010 to 2020, with Australia, US, and China as central nodes in the network. Author analysis indicates that scholars from Australian research institutions lead the field. The top prolific authors include Y.P. Dang, R.C. Dalal and N.W. Menzies from the University of Queensland, R.D. Armstrong from Agriculture Victoria, and C. Tang and P.W.G. Sale from La Trobe University, S. Shabala from the University of Tasmania, and S.H.M. Kadambot from the University of Westtern Australia (Fig. 4**d**). Their publication output has significantly increased since 2006, suggesting a rise in research activity and output in recent years. Additionally, two authors, R. Lal in 2015 and L. Van Zwieten in 2021, stand out for their high single-year citation counts, indicating significant impact of their publications during those years.

3.3. Analysis of research topics based on keywords

3.3.1. High-frequency keywords

The keyword frequency analysis depicted in Fig. 5 highlights the prevalent themes in soil constraints. "Salinity" emerges as the most frequent keyword, appearing 130 times (12%), emphasizing its critical importance in soil constraint studies and aligning with high-citation

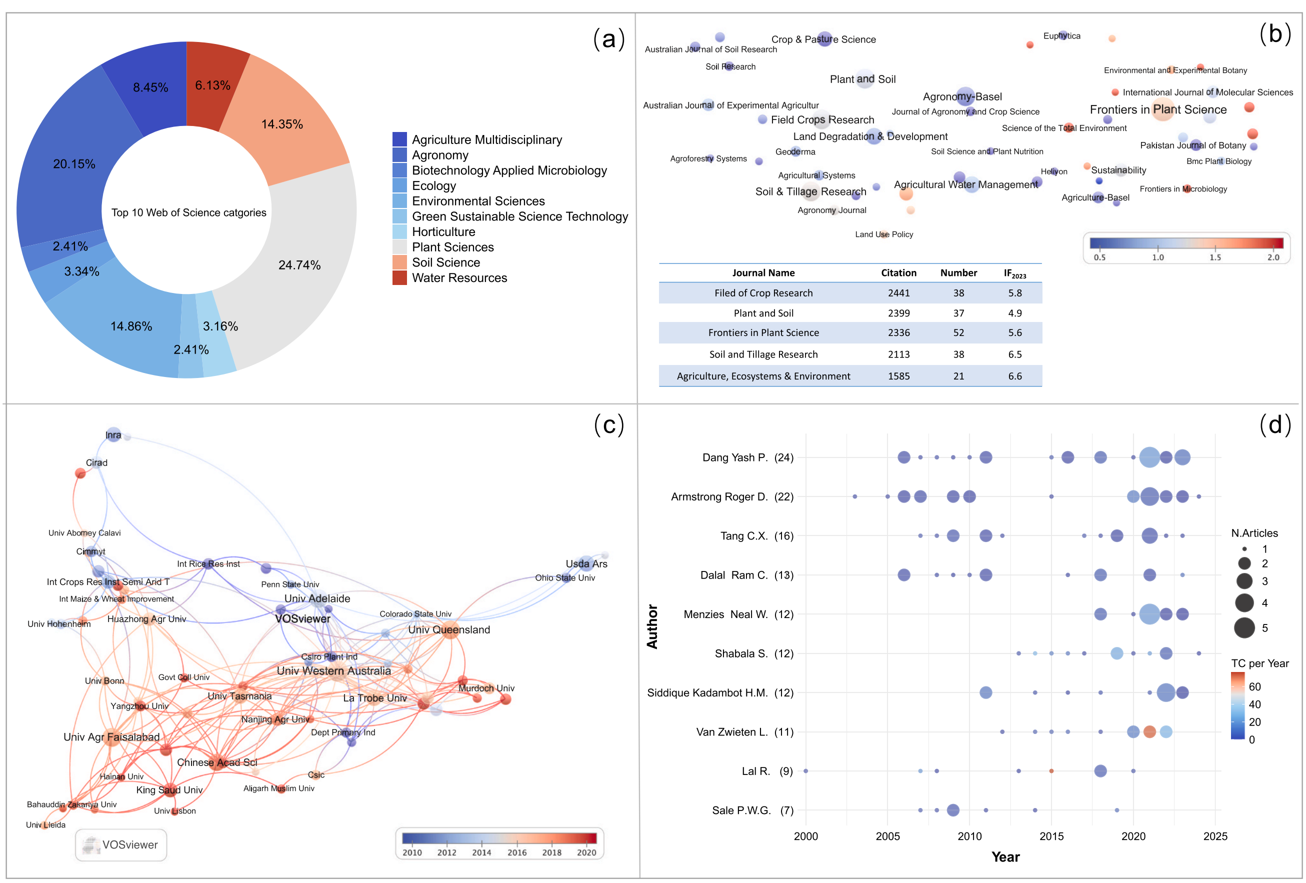

Fig. 4. Top 10 web of sciences categories (a). The most cited journals (b). The legend indicates that the range of 0.5–2.0 represents the average number of normalized citations (avg. norm citation); The collaboration network of international research institutes (c). In the legend, 2010–2020 represents average publication year. Main study authors and publication and citation characteristics over time (d), within the research studies of soil constraints.

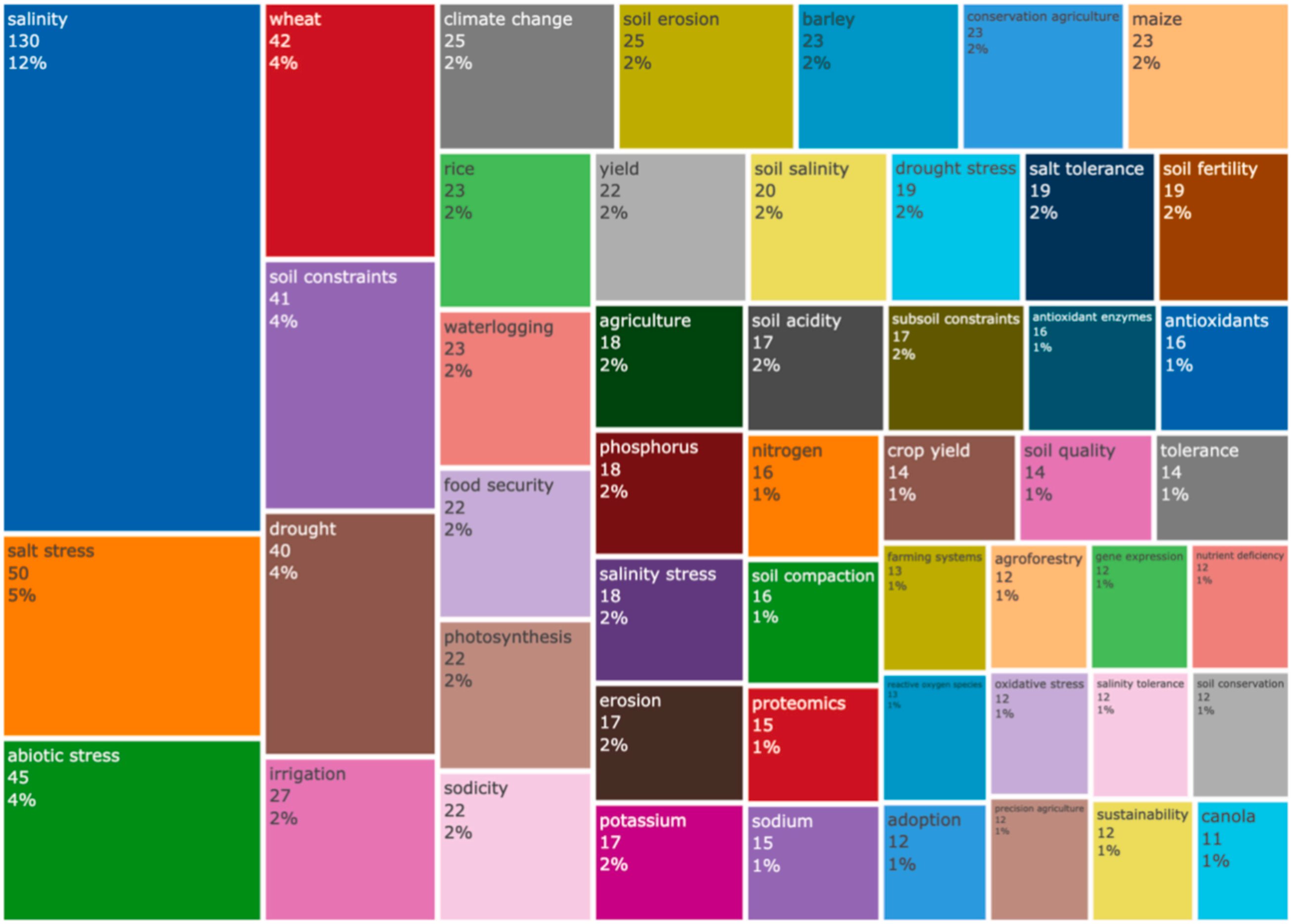

Fig. 5. The distribution of high-frequency of keywords.

studies such as Rengasamy (2006), which highlighted salinity as a major challenge in Australian soils. Other prominent keywords include "wheat" (42 occurrences, 4%), reflecting the crop's significance in agricultural research, and "climate change" (35 occurrences, 3%), indicating its impact on soil health and productivity. "Soil erosion" and "barley" each occur 28 times (3%), and "maize" appears 23 times (2%), showcasing the relevance of these crops and issues in soil science. Keywords like "soil fertility", "soil tolerance", and "antioxidants", each appearing 22 times (2%), suggest their importance in maintaining soil health and plant productivity. These keywords reflect a shift from traditional soil management to more targeted research addressing climate adaptation and abiotic stress responses. Additionally, "soil constraints" (24 occurrences, 2%), "drought" (40 occurrences, 4%), "waterlogging" (19 occurrences, 2%), and "agriculture" (19 occurrences, 2%) highlight the diverse challenges and areas of focus within soil constraint research. "Phosphorus" (17 occurrences, 2%) emphasizes its role in soil fertility and plant nutrition, while "nitrogen" (16 occurrences, 2%) stresses its significance in crop growth. Keywords related to soil and plant stress, such as "salt stress" (50 occurrences, 5%) and "abiotic stress" (43 occurrences, 4%) emphasize a research focus on stress tolerance mechanisms, as reflected in studies of reactive oxygen species and antioxidant enzymes (Ullah et al., 2023).

3.3.2. Thematic structured analysis

The analysis of keyword relationships through a structural map reveals key topics and distributed in two dimensions and clustered by similarity (Fig. 6). The clusters indicate four main topics for soil and crop research. First, abiotic stress and crop tolerance (blue cluster) are focuses on abiotic stress factors such as drought, salinity, and oxidative stress, with key terms including antioxidant enzymes, gene expression, proteomics, salinity stress, and stress tolerance mechanisms in crops like tomato and rice. Second, soil health and conservation (yellow cluster) encompass soil erosion, soil conservation, soil compaction, soil quality, crop yield, and soil acidity, highlighting research dedicated to enhancing soil health and implementing conservation practices to sustain agricultural productivity. Such practices align with conservation agriculture principles, as shown in Giller et al. (2009). Third, nutrient management (green cluster) concentrates essential nutrients like N and P, emphasizing research on nutrient management and its effects on crop growth and soil health. fourth, sodium and crop species (red cluster) center around specific crop species like barley, wheat, and canola, and elements like sodium and potassium, focusing on the impact of these elements on crop growth and productivity. Additionally, the map includes an isolated topic on oxidative stress (pink cluster) indicates specialized studies on plant stress mechanisms, focusing on enzymes, proteomics, and gene expression. These clusters reflect interconnected themes, with recent studies increasingly exploring advanced techniques such as genomics and molecular biology to address soil constraints (Jurado et al., 2024).

3.4. Research topic network analysis

The co-occurrence analysis of author keywords in the field of soil constraint research is shown in Fig. 7. The nodes in the graph represent the keywords, and the lines connecting the nodes indicate the frequency with which these keywords co-occur in the literature. The color of the nodes corresponds to the specific research cluster they belong to, highlighting different thematic areas within soil constraint research.

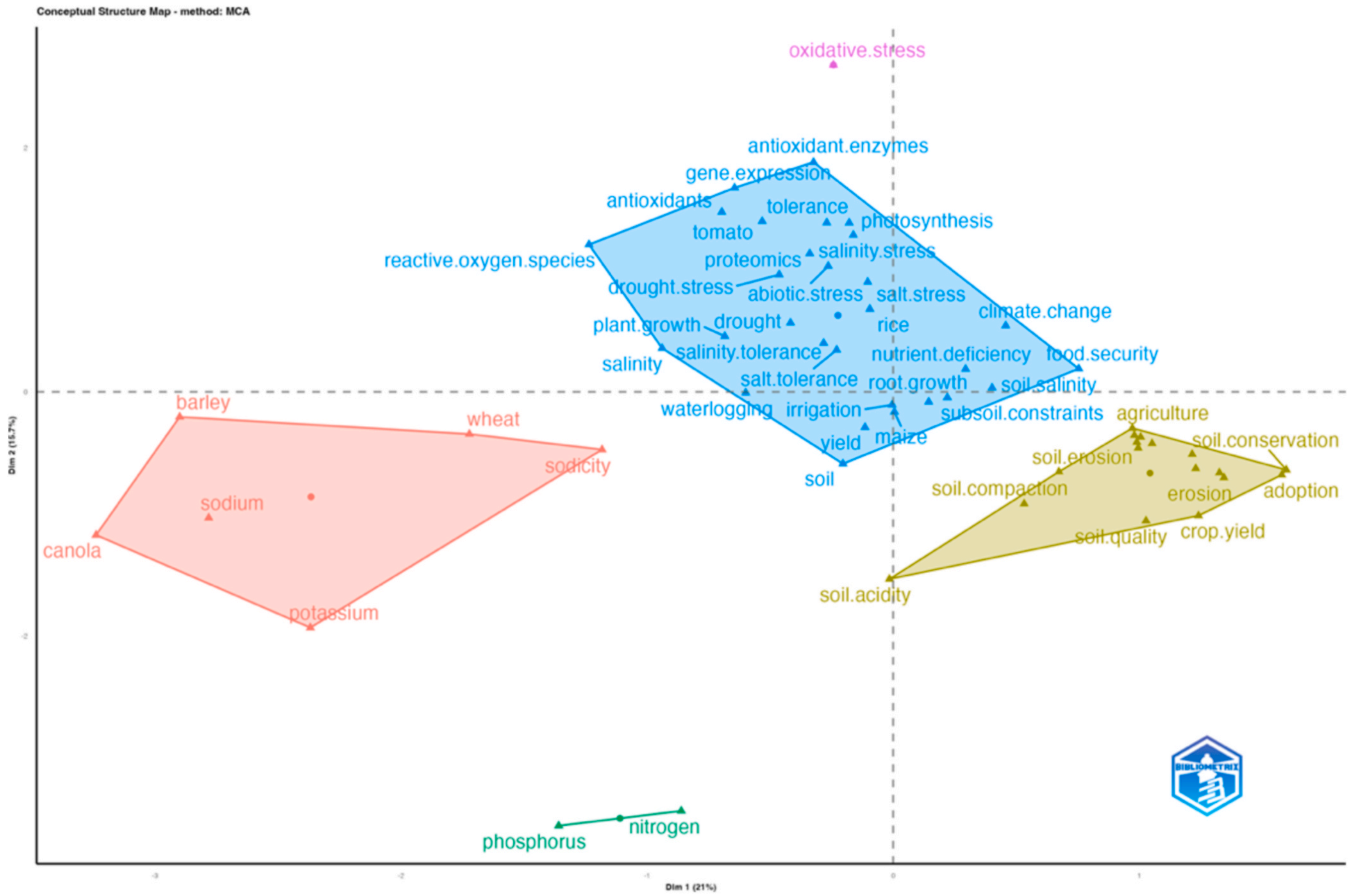

Fig. 6. Conceptual structure map with two dimensions showing the distribution of keywords for soil constraints research. Keywords with greater similarity are clustered closer together.

Additionally, the color gradient from blue to red indicates the average publication year of the documents associated with each keyword, with blue representing before 2016 and red representing after 2016.

The blue cluster is centered around the theme of climate change, comprising 55 keywords with a TLS of 80 and 39 connections. The top keywords in this cluster include "conservation agriculture", "fertilizer", "food security", "soil erosion", "cropping system", "erosion", "maize", "soil fertility", "crop productivity", and "soil organic carbon". This cluster emphasizes the intersection between climate change and soil management practices aimed at mitigating its impacts (Li et al., 2024a,b). The red cluster focuses on salinity, featuring 36 keywords with a significantly high TLS of 389 and 177 connections. The dominant keywords in this cluster are "salt stress", "drought", "rice", "antioxidant", "photosynthesis", "yield", "proteomics", "antioxidant enzyme", "halophyte", "oxidative stress", and "reactive oxygen species". The dominant keywords in this cluster indicate a focus on the impact of environmental stressors, such as salt stress and drought, on rice, particularly concerning its antioxidant mechanisms, photosynthesis, and yield. The light orange cluster is related to abiotic stress, including 29 keywords with a TLS of 116 and 55 connections. Key terms in this cluster are "plant growth", "growth", "heavy metal", "root", "quantitative trait loci", "legume", "tolerance", "arbuscular mycorrhiza", "cotton", and "genomics". This cluster highlights the broad range of abiotic stress factors affecting plant growth and the genetic and physiological mechanisms underlying stress tolerance. The very light blue cluster addresses sodic soil issues, with 28 keywords, a TLS of 77, and 30 connections. The primary keywords include "nitrogen", "subsoil constraint", "soil acidity", "phosphorus", "subsoil", "water use efficiency", "root growth", "aluminum", "breeding", and "cereal". This cluster focuses on soil chemical constraints and their impact on nutrient availability and plant growth. The light grey cluster is associated with irrigation, consisting of 21 keywords with a TLS of 72 and 46 connections. The main keywords are "waterlogging stress", "soil salinity", "management", "soil water", "soil amendment", "drainage", "precision agriculture", "soil degradation", "digital soil mapping", and "remote sensing". This cluster accentuates the importance of water management in mitigating soil constraints and enhancing soil health. The light blue cluster focuses on potassium-related research, including 14 keywords with a TLS of 48 and 18 connections. The notable keywords are "sodium", "soil compaction", "reactive oxygen species", "*Triticum aestivum*", "herbicide", "plant nutrition", "chloride", "silicon", "soil management", and "weeds". This cluster highlights the role of potassium and related nutrients in soil fertility and crop health. The deep blue cluster is centered on wheat, featuring 13 keywords with a TLS of 110 and 42 connections. Prominent keywords include "barley", "adaptation", "boron", "genotype", "canola", "Oryza sativa", "acid soil", "root architecture", "transpiration", and "water stress". This cluster emphasizes the genetic and environmental factors influencing wheat and related cereal crops (Table 1).

An important observation from the analysis is the temporal trend in keyword usage, indicated by the color gradient (Fig. 7). Keywords associated with early research (*e.g.*, "soil erosion", "fertilizer", and "maize") appear in blue, suggesting that foundational studies focused on traditional agricultural practices and basic soil management techniques. In contrast, keywords appearing in red (*e.g.*, "antioxidant enzyme", "proteomics", "genomics", and "remote sensing") represent more recent research trends (Jurado et al., 2024; Ullah, 2023). This shift indicates a growing interest in advanced scientific techniques and technologies, such as molecular biology and remote sensing, to address soil constraints (Das, 2021; Leo et al., 2023; Orton et al., 2022). Furthermore, the increasing prevalence of keywords related to "climate change" and

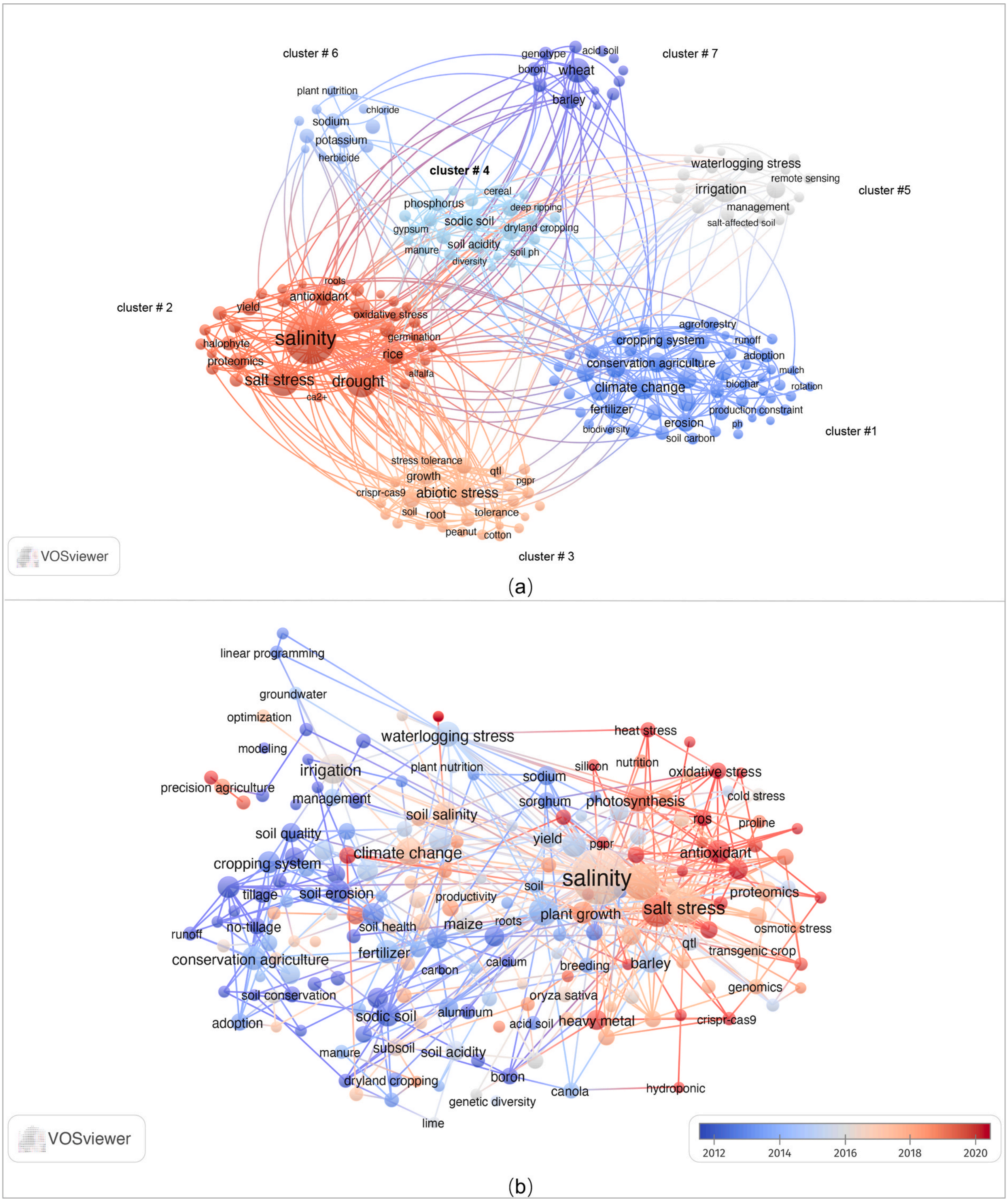

Fig. 7. Network of keywords based on the co-occurrence method (a); Evolution of keywords network for research on soil constraints (b). The nodes in the graph represent author keywords, and the connecting lines between the nodes indicate how often the literature in which these keywords are found is co-cited in the study. The color of the nodes corresponds to the research topic to which they belong.

"abiotic stress" highlights the research community's response to global environmental challenges and the need for sustainable agricultural practices (Dang et al., 2006b, 2011; Orton, 2018).

In the thematic structured analysis and research topic network analysis, different software was employed to analyze clusters of related studies. Fig. 6 presents a conceptual structure map, clustering keywords based on their thematic similarity and spatial distribution along conceptual dimensions. In contrast, Fig. 7 illustrates the co-occurrence strength and temporal evolution of research topics, offering insights into the dynamic connections between keywords over time. Together, these analyses provide complementary perspectives on the structure and evolution of research themes.

3.5. *Analysis of research hotspots: Based on literature co-citation*

The research hotspots discussed in this section are presented in Fig. 8, which illustrates the literature co-citation network clusters and their thematic focus. The document co-citation results revealed three

Table 1
Identified clusters of keywords.

Rank	Color	Cluster	M	O	TLS	L	Top 10 keywords
1	Blue	Climate change	55	55	80	39	Conservation agriculture, fertilizer, food security, soil erosion, cropping system, erosion, maize, soil fertility, crop productivity, soil organic carbon
2	Red	Salinity	36	127	389	177	Salt stress, drought, rice, antioxidant, photosynthesis, yield, proteomics, antioxidant enzyme, halophyte, oxidative stress, reactive oxygen species (ros)
3	Light orange	Abiotic stress	29	65	116	55	Plant growth, growth, heavy metal, root, quantitative trait loci (qlt), legume, tolerance, arbuscular mycorrhiza, cotton, genomics
4	Very light blue	Sodic soil	28	42	77	30	Nitrogen, subsoil constraint, soil acidity, phosphorus, subsoil, water use efficiency, root growth, aluminum, breeding, cereal
5	Light grey	Irrigation	21	41	72	46	Waterlogging stress, soil salinity, management, soil water, soil amendment, drainage, precision agriculture, soil degradation, digital soil mapping, remote sensing
6	Light blue	Potassium	14	34	48	18	Sodium, soil compaction, reactive oxygen species, triticum aestivum, herbicide, plant nutrition, chloride, silicon, soil management, weeds
7	Deep blue	Wheat	13	65	110	42	Barley, adaptation, boron, genotype, canola, oryza sativa, acid soil, root architecture, transpiration, water stress

M: member of cluster; O: occurrence; TLs: total link strength; L: link strength.

distinct clusters in the study of soil constraints. Cluster 1 focuses on soil chemistry and salinity management, encompassing foundational research and practical guidelines for diagnosing and improving saline and alkaline soils. Key contributions include Walkley and Black (1934), Richards (1954), Maas and Hoffman (1977), and Rengasamy (2002, 2006), which highlight the importance of understanding soil chemistry and implementing effective management practices to enhance soil health and crop productivity. Cluster 2 addresses plant physiology and stress response, exploring the physiological and molecular mechanisms underlying plant tolerance to environmental stresses such as salinity and drought. Significant studies by Greenway and Munns (1980), Munns (2002, 2005), Munns and Tester (2008), Zhu (2001, 2002), Flowers (2004), and Flowers and Colmer (2008) emphasize the development of stress-tolerant crop varieties through genetic approaches and plant breeding strategies. Cluster 3 centers on analytical methods and biochemical assays, with seminal works by Arnon (1949), Heath and Packer (1968), and Bradford (1976) that provide essential techniques for studying soil and plant biochemistry. These clusters collectively form a comprehensive framework for understanding and managing soil constraints, integrating soil science, plant physiology, and analytical chemistry to improve agricultural productivity.

3.6. Analysis of emerging trends based on burst keywords

The keywords of high frequency and central relevance emerged prominently in different stages. These terms alone fail to fully convey the shifts in research focus over time (Fig. 9). To address this, citation burst analysis was employed, which is critical for elucidating the dynamics of research interests by monitoring the surges in specific keywords within given timeframes. The top 30 keywords that experienced the most significant bursts in citations reveal a discernible evolution in the thematic concentration of research on soil constraints from 1973 to 2024 (Fig. 9). The analysis of keywords over time reveals distinct phases in the research focus on soil constraints, each marked by evolving priorities and emerging trends. The time periods were determined based on the temporal distribution of keyword bursts identified by the citation burst detection algorithm, which highlights periods of intensified scholarly attention to specific topics by the algorithm in CiteSpace.

(1) Early focus (1973–1995)

In the early period, research was heavily centered on understanding and managing soil erosion, as indicated by the keyword "erosion response units" (1973–2013), highlighting its critical role in soil constraint research. "Organic matter" (1973–2010) was another major focus, emphasizing its importance in maintaining soil health and fertility (Morgan, 2004; Probert and Keating, 2000). Studies during this time also explored integrated approaches to soil management, as evidenced by the keyword "systems" (1973–2001).

(2) Mid period (1996–2010)

The mid period showed a shift towards more specific and technical aspects of soil and crop management (Pagès et al., 2013; Piikki et al., 2015; Pywell, 2007; Singh and Dwivedi, 2006). "Nitrogen fertility" (1996–2012) marked a significant area of investigation, exploring the impact of nitrogen on soil productivity and crop yields. "Management zones" (1996–2006) became a prominent topic, reflecting the emphasis on optimizing soil and crop management through the creation and management of specific zones within agricultural fields. The development and use of "model" (1998–2009) to simulate and predict soil behavior and responses to various treatments gained attraction. Water management, represented by the keyword "water" (1999–2011), and studies on specific crops like "barley/alfalfa" (2001–2011), were also critical areas of research. Other notable keywords include "root growth" (2002–2008), "sodicity" (2003–2007), and "tillering dynamic" (2005–2012), indicating a focus on root development, soil sodicity, and crop tillering dynamics, respectively. Strategies for managing soil fertility, as shown by the keyword "soil fertility management" (2005–2011), continued to be a significant area of research.

(3) Recent trends (2011–2024)

In recent years, research has continued to address soil erosion ("soil erosion", 2009–2017) while also exploring new areas and approaches.

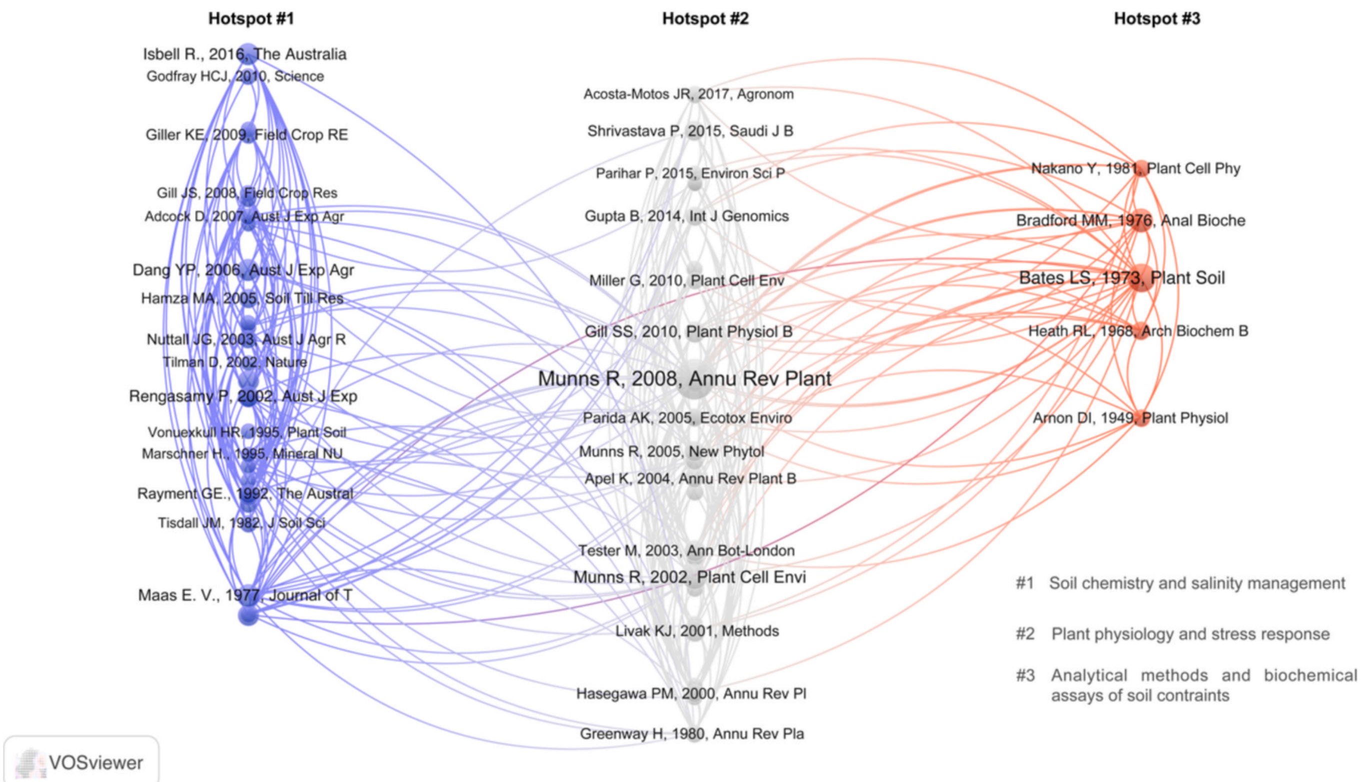

Fig. 8. The co-citation network map of the literature. The nodes in the graph represent individual studies, and the connecting lines between the nodes indicate the frequency with which these studies are co-cited. The color of the nodes corresponds to the research hotspot to which they belong.

Conservation efforts are highlighted by the keyword "conservation reserve program" (2010–2013), and the examination of different "land-use systems" (2010–2011) and their impacts on soil conditions has gained importance. Studies on various "farming systems" (2011–2014) and the role of "carbon credits" (2012–2016) have emerged, highlighting their significance in mitigating climate change and promoting sustainable soil management practices. There has been a regional focus on "sub-saharan africa" (2012–2015) and efforts to "identification" (2013–2017) of specific soil constraints. The exploration of "biofuels" (2015–2017) and the role of "salicylic acid" (2015–2017) in soil and plant health are noteworthy. More recently, interest has shifted towards "antioxidants" (2020–2024), "salinity stress" (2022–2024), and "traits" (2022–2024) related to plant resilience. Emerging topics include the application of "nanotechnology" (2023–2024) in soil management and studies on "oxidative stress tolerance" (2023–2024) and "seed germination" (2023–2024) in relation to soil constraints (Kumari et al., 2024; Mann, 2024).

3.7. Impacts and management of different soil constraint types

The physical constraints and chemical constraints are the focus of our research hotspots and research themes (Fig. 9). Physical and chemical constraints were identified as key research focuses on Fig. 9 through the frequency and clustering of keywords related to challenges such as erosion, salinity, acidity, and nutrient deficiencies, reflecting their prominence in the field of soil constraint research. By summarizing the impacts and management strategies for physical, chemical, and biological constraints, this section underscores their contribution to advancing soil research hotspots and guiding innovative solutions for sustainable land management.

3.7.1. Soil physical constraints

Soil erosion, compaction and waterlogging are common physical constraints on agricultural land worldwide. Soil erosion significantly impacts crop productivity by removing the nutrient-rich topsoil layer, leading to reduced soil fertility and water-holding capacity (Lal, 2001; Morgan, 2009). This degradation limits the growth and yield of crops, making soil erosion a critical constraint in sustainable agriculture (Morgan, 2009). Effective management practices, such as contour farming, cover cropping, and conservation tillage, are essential to mitigate the adverse effects of soil erosion and maintain soil health.

Soil compaction leads to reduced soil porosity, hindering root growth and the absorption of water and nutrients by crops (Obour and Ugarte, 2021). Soil compaction is particularly prominent in areas with widespread mechanized farming. To alleviate soil compaction, deep plowing and improved mechanical operations are common measures. Additionally, Cooper et al. (2020) found that improving farming practices, such as reducing the use of heavy machinery and promoting conservation tillage, can effectively reduce soil compaction.

Research indicates that excessive water could lead to root oxygen deficiency, affecting crop growth (Akhtar and Nazir, 2013; Rane et al., 2021). Effective management of waterlogging issues could be achieved by constructing efficient drainage systems and planting water-tolerant crops (Chhabra and Chhabra, 2021). Raised beds are commonly used to improve soil aeration and drainage, promoting root health and crop productivity. In some low-lying areas, constructing underground drainage systems and improving surface drainage facilities can significantly enhance soil drainage performance, promoting healthy crop growth.

3.7.2. Chemical constraints

Soil salinization is a severe problem in many agricultural regions worldwide, particularly in arid and semi-arid areas where soil chemical constraints are more common. The total area of salt-affected soils is 17 million km^2, but the greatest potential for saline agriculture lies in saline soils with an electrical conductivity in the saturation extract above 4 dS/m in non-depleted water basins, totaling 2 million km^2 (Negacz et al., 2022). The high salinity levels inhibit the absorption of water and

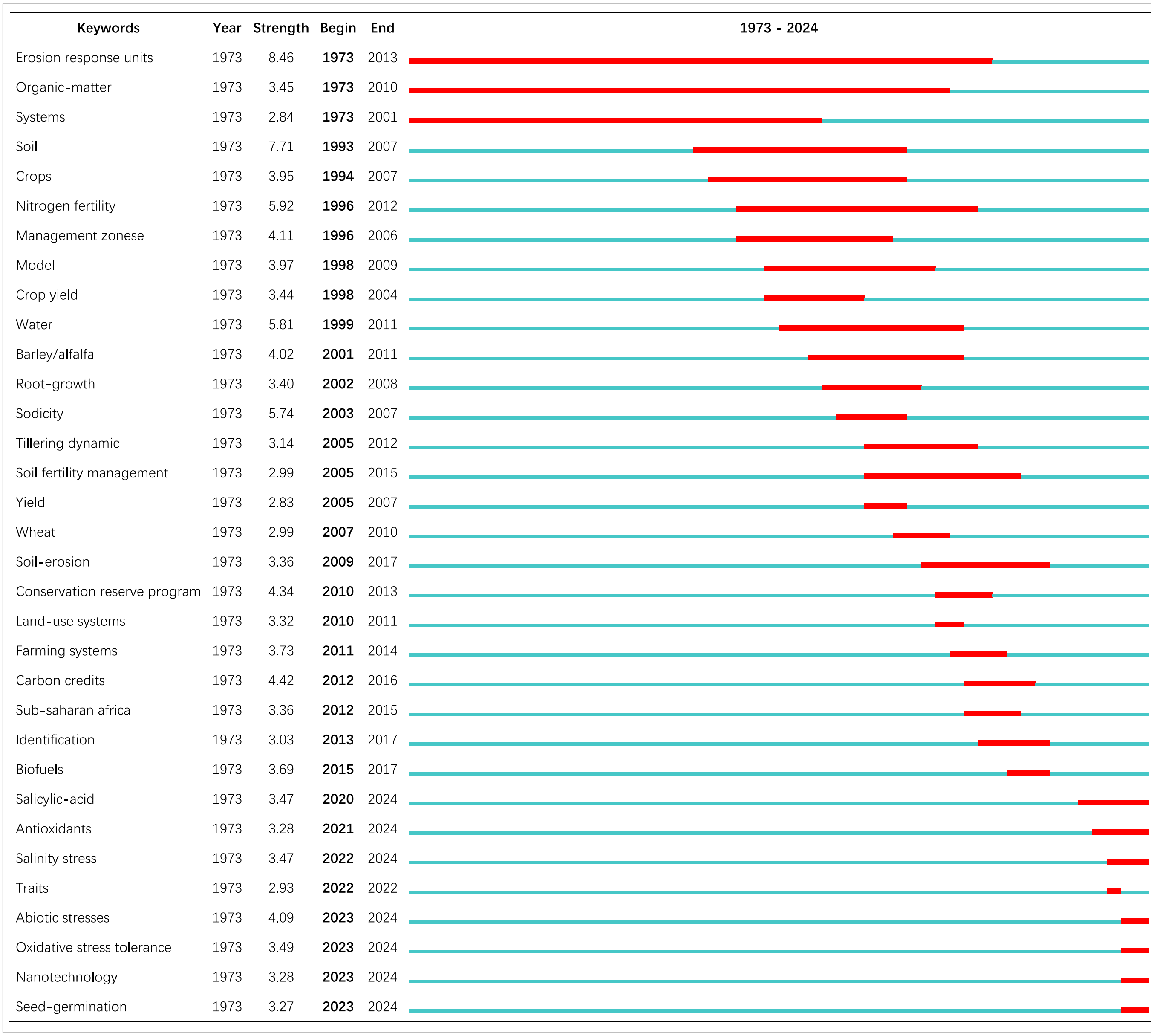

Fig. 9. Top 30 Keywords with the strongest citation bursts. Begin and end denote the start and end years of the keyword as a frontier, and strength denotes the emergence strength. The red line represents the specific ephemeral stage at which the keyword became a hotspot of academic research. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

nutrients by plants, which can lead to crop death in severe cases (Etikala et al., 2021). Soil salinization can be effectively managed through the use of ameliorants, improved irrigation methods, and the cultivation of salt-tolerant crops (Devkota et al., 2022; Hayat et al., 2020). Hayat et al. (2020) proposed the potential of sustainable saline agriculture based on phytoremediation techniques involving the genus *Pennisetum* (Poaceae). The use of gypsum as an ameliorant and freshwater irrigation can effectively reduce soil salinity in the rooting zone and increase crop yields (Negacz et al., 2022).

Soil acidification and heavy metal contamination are two significant chemical constraints in soils. Soil acidification can lead to nutrient loss and heavy metal release, affecting crop health and growth (Yadav et al., 2020). Application of liming materials is a common method to neutralize soil acidity, effectively increasing soil pH and nutrient availability. Daba et al. (2021) showed that the application of lime and organic fertilizers could significantly increase the pH of wheat-maize rotationsystem in red soils and improve the crop growth environment. Aluminum (Al) and manganese (Mn) toxicities in acid soils can severely affect root development and function, reducing water and nutrient uptake. High concentrations of Al can disrupt cell division and elongation, while excess Mn can interfere with various physiological processes, including photosynthesis and enzyme activity. Addressing these toxicities is crucial for ensuring healthy crop growth in acidic soils.

Heavy metal contamination poses significant threats to plant and human health. The soil around industrial and mining areas are heavily contaminated with heavy metals, requiring remediation using physical remediation, chemical and biological measures (Zhu et al., 2024). Due to simple structures and stable properties of heavy metals (Chaney et al., 1997), the most common and sustainable methods to remediate heavy metal pollution are phytoremediation and phyto-stabilization. Phytoextraction uses hyperaccumulator plants to absorb and accumulate heavy metals from the soil, reducing or even eliminating contamination. For example, *Pteris vittata*, an arsenic hyperaccumulator, can be used to remediate arsenic-contaminated soils (Xie et al., 2009). Phytostabilization involves using specific tolerant plants to immobilize heavy metals in the rhizosphere or root systems, reducing their mobility. For instance, naturally tolerant plants in mining areas can be used to remediate heavy metal-contaminated soils (Pérez-López et al., 2014). Additionally, certain specialized microorganisms can be used to reduce the activity and toxicity of heavy metals through metabolic processes, achieving soil remediation. For example, using hexavalent chromium-reducing bacteria to efficiently reduce hexavalent chromium in the soil can lower chromium toxicity and remediate chromium-contaminated soil (Smith and Gadd, 2000).

3.7.3. Biological constraints

Soil-borne diseases is the important biological constraints. The soil-borne diseases could affect crop health and reduce yields (Sinton et al., 2022). These diseases can be effectively managed through biological control, crop rotation, and increasing soil organic matter content. Declining soil fertility requires the use of organic fertilizers and improving the soil microbial environment to enhance soil health (Tripathi et al., 2020). Studies have shown that using organic fertilizers and compost can significantly increase soil organic matter content, improve soil structure, and enhance soil microbial diversity (Li et al., 2021a). Furthermore, planting cover crops and implementing diversified crop rotation systems can help reduce the occurrence of soil-borne diseases and improve soil health (Shah et al., 2021).

3.8. Quantification and management of soil constraints: Current practices and a way forward

3.8.1. Remote sensing and large-scale monitoring

In recent years, the development of remote sensing technology has opened up new possibilities for large-scale monitoring of soil constraints (Khanal et al., 2020; Wang et al., 2023). Remote sensing can monitor soil conditions over large areas with low cost and high efficiency, aiding in the identification and assessment of soil constraints (Akhtar et al., 2021). Studies have shown that satellite imagery and drone technology can monitor parameters such as soil moisture, salinity, and organic matter content, providing accurate soil health assessment data (Phang et al., 2023). In addition, remote sensing can be used to monitor soil erosion and compaction by analyzing soil surface features and vegetation cover, helping to identify areas of soil degradation (Borrelli et al., 2021). The application of these technologies provides powerful tools for soil management, supporting the development of scientific soil improvement and conservation measures.

3.8.2. Integrated strategies for managing soil constraints

Integrated management strategies are crucial for addressing soil constraints. Combining physical, chemical, and biological measures can comprehensively improve soil health (Ning et al., 2022). For compacted and acid soils, deep plowing and lime application can be employed simultaneously; for saline and heavy metal-contaminated soils, a combination of leaching, planting salt-tolerant crops, and phytoremediation techniques can be effective. Agronomic management is also an essential component of soil constraint management. Adjusting tillage methods, optimizing cropping patterns, and rational fertilization can significantly improve soil health and increase crop yields (Singh et al., 2018). In severely constrained areas, land use changes, such as converting farmland to pastures or forests, are also viable solutions (Hou et al., 2020).

Additionally, integrated management strategies include several key aspects: breaking up compacted soil layers through deep ripping and mechanical modification to increase soil porosity and improve root growth conditions (Obour and Ugarte, 2021); balanced fertilization by combining organic and inorganic fertilizers to ensure nutrient balance and enhance soil fertility (Raza et al., 2022). Strengthening water resource management by improving irrigation methods to reduce water waste and prevent soil salinization and water quality deterioration (Devkota et al., 2022). Improving vegetation cover and crop rotation systems by planting cover crops and implementing diverse crop rotations to reduce soil erosion and increase soil organic matter content (Chahal et al., 2021). These integrated approaches are essential for sustaining soil health and agricultural productivity as demostrated in Fig. 10.

3.8.3. Future direction and policy implication

Future research should focus on the development and application of innovative soil improvement technologies. The precision agriculture technologies and microbial remediation techniques hold significant potential for managing soil constraints (Akhtar et al., 2021; Bongiovanni and Lowenberg-DeBoer, 2004). Utilizing sensors and big data technology enable real-time monitoring of soil health, allowing for precise management practices and enhanced agricultural production efficiency (Bhat and Huang, 2021; Delgado et al., 2019). Interdisciplinary research and international collaboration are crucial for addressing global soil constraint issues. Effective management strategies require the integration of soil science, agricultural science, and environmental science, leveraging the knowledge and technologies from these fields. Policy support is essential for advancing soil constraint management. Governments and relevant institutions should increase funding for soil health research and management technologies, formulate and promote soil protection policies, and support farmers in implementing soil improvement measures. Providing financial subsidies and technical support can encourage farmers to adopt environmentally friendly farming practices and soil improvement technologies. Finally, enhancing public awareness and education on soil health is vital. Increasing societal recognition and concern for soil protection is an important practice for mitigating the influence of soil constraints and achieving sustainable agriculture.

4. Conclusion

This comprehensive bibliometric analysis elucidates the global trends, key research areas, and significant contributions in the research field of soil constraints. Our study highlights an exponential increase in publications since the early 2000 s, reflecting a growing global awareness of soil health's importance. Keyword analysis reveals major themes, including salinity, climate change, soil erosion, and nutrient management, with clusters of research topics focusing on mitigating abiotic stress, improving soil health, and optimizing nutrient management practices. Recent research trends highlight an increasing focus on conservation efforts, sustainable soil management practices, and the application of advanced technologies such as nanotechnology and remote sensing, reflecting evolving priorities driven by the need to address contemporary environmental challenges. The insights gained in this study will help researchers and policymakers prioritize efforts and allocate resources more effectively to mitigate soil constraints, enhancing agricultural productivity and sustainability worldwide.

CRediT authorship contribution statement

Tong Li: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Lizhen Cui:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Vilim Filipović:** Writing – review & editing. **Caixian Tang:** Writing – review & editing. **Yunru Lai:** Writing – review & editing. **Bernhard Wehr:** Writing – review & editing. **Xiufang Song:** Writing – review & editing. **Scott Chapman:** Writing – review & editing. **Hongdou Liu:** Writing – review & editing, Supervision, Software. **Ram C. Dalal:** Writing – review & editing. **Yash P. Dang:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition.

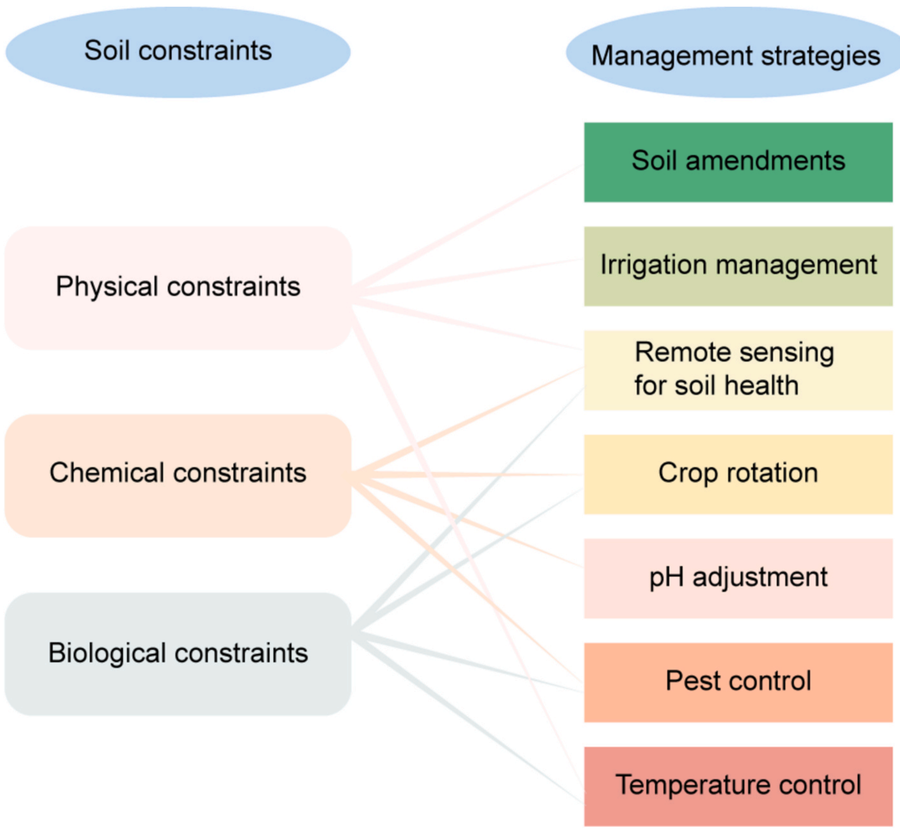

Fig. 10. The framework of soil constraints and integrated strategies for precision managing improve the soil quality.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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