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Bibliometric Insights into Pearl Millet-based Cropping Systems and Soil Health Research: A Comprehensive Analysis (2000–2023)

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ABSTRACT

This article presents a comprehensive bibliometric analysis of studies conducted on pearl millet–based cropping systems and soil health from 2000 to 2023, utilizing the Scopus database. Pearl millet, a significant cereal crop globally, is known for its resilience in arid and semi–arid conditions. The cultivation of pearl millet spans over 30 million hectares worldwide, with India contributing significantly to its acreage. The study examines the impact of pearl millet production in rainfed and arid regions on soil health under conservation agriculture (CA) practices. The bibliometric analysis employs rigorous methodologies, including Bradford's Law, fractionalized articles, and thematic mapping. It reveals the evolution of scientific output, citation patterns, and collaborative networks. Findings indicate a steady growth in scientific production related to pearl millet research, with a notable surge in recent years. The average citations per year exhibit fluctuating trends, emphasizing the need for continued exploration. We found that there is limited research in the area of pearl millet–based cropping system in relation with soil health. Brazil, USA and India are the top three countries conducting research on this area. CA under degraded soils with pearl millet is still unexplored area of research. It also found that in last one decade (2011–2022), scientists are working in this area has been increased as per number of documents published as citations received during this period on the given topic. Pearl millet-based cropping systems, integrated with CA practices such as zero tillage, residue incorporation, and deficit irrigation, offer a sustainable and climate-resilient solution for addressing soil salinity challenges while enhancing soil health, water use efficiency, and nutritional security in arid and semi-arid regions. The study concludes by identifying research gaps, emphasizing the need for further investigations into the advantages of pearl millet–based cropping systems, their impact on soil health, and the development of production systems for degraded soils. Despite limitations related to the temporal scope, database constraints, and language bias, the study contributes valuable insights into the dynamic field of pearl millet research, guiding future endeavours and fostering collaboration among researchers, policymakers, and practitioners.

Keywords: Pearl millet–based cropping systems, Bibliometric analysis, Soil health, Thematic mapping

Introduction

Pearl millet (*Pennisetum glaucum*) ranks as the sixth most important global cereal crop, cultivated on over 30 million hectares in arid and semi–arid regions, following rice, wheat, maize, barley, and sorghum (Satyavathi *et al.,* 2021). In India, pearl millet covers ~6.93 million hectares, yielding an average production of 8.61 metric tons and a productivity of 1.2 t ha^{-1}. Rajasthan, Maharashtra, Gujarat, Uttar Pradesh, and Haryana collectively contribute 90% to the total pearl millet acreage in the country (Naorem *et al.,* 2023).

Arid and semi-arid regions are characterized by harsh agroclimatic conditions, including erratic and limited rainfall, elevated temperatures, high evapotranspiration rates, irrigation-induced salinity and sodicity, and nutrient-poor sandy soils. These constraints pose significant challenges to achieving economically viable crop yields in most agricultural systems (Engel *et al.,* 2017; Manna *et* *al.,* 2003; Srinivasarao *et al.,* 2014; Dhawi, 2023). Pearl millet (*Pennisetum glaucum*), however, exhibits remarkable adaptability to such challenging environments owing to its C4 photosynthetic pathway, high photosynthetic efficiency, exceptional dry matter production, and deep-rooting system, thereby qualifying it as a climate-resilient crop (Satyavathi *et al.,* 2021). Unlike rice, whose productivity declines at salinity levels exceeding 3 dS m^{-1}, pearl millet can sustain growth under salinity conditions greater than 12 dS m^{-1} (Babele *et al.,* 2022).

While agronomic interventions have traditionally focused on ameliorating surface salinity, addressing subsurface salinity remains a formidable challenge. Recent innovations have demonstrated promising results in highly saline environments. Neha *et al.* (2025) employed cut-soiler technology combined with residue incorporation to create shallow subsurface drainage systems, effectively reducing salinity levels. This approach resulted in pearl millet yield improvements exceeding 25%, even under saline irrigation conditions. Nevertheless, prolonged exposure to high salinity or sodicity continues to impair crop growth, and continuous monoculture without appropriate soil management practices can lead to soil health degradation. Therefore, integrating pearl millet into diversified cropping systems with suitable agronomic practices and rotations is essential for maintaining or restoring soil microbial diversity, enhancing organic carbon sequestration, and improving soil nutrient status, including nitrogen, phosphorus, potassium, sulfur, and essential micronutrients.

Global estimates indicate that salt-affected soils currently span 1381 million hectares, representing 10.7% of the world's cropland area (FAO, 2024). In northwest India's arid regions, pearl millet-wheat and pearl millet-mustard cropping sequences have emerged as dominant systems, replacing the traditional rice-wheat rotation (Ankit *et al.,* 2024). These pearl millet-based systems depend on residual soil moisture and exhibit inherent salinity tolerance, making them particularly well-suited to resource-constrained environments. Extensive research has documented the sustainability and economic viability of pearl millet-based cropping systems across India and globally, especially under rainfed and water-limited conditions (Álvaro-Fuentes *et al.,* 2021; Saxena *et al.,* 2005; Srinivasarao *et al.,* 2014; Tetarwal *et al.,* 2011).

Recent advances in water-saving technologies and conservation agriculture have further enhanced the performance of these systems. Deficit irrigation at 60% of crop water requirement for wheat, coupled with rice straw mulching under zero tillage and reduced tillage regimes, significantly improved soil quality index values following both pearl millet and wheat harvests. These integrated practices demonstrated substantial benefits in conserving soil quality, reducing freshwater irrigation demand, and enhancing soil moisture retention (Soni *et al.,* 2021, 2023). Beyond agronomic advantages, pearl millet offers exceptional nutritional value, being rich in protein and micronutrients while remaining naturally gluten-free, thereby contributing to nutritional security in vulnerable populations. The combination of stress tolerance, low input requirements, and consistent productivity under adverse conditions underscores pearl millet's strategic importance for sustainable agriculture (Satyavathi *et al.,* 2021). Reflecting this growing recognition, the International Year of Millets declaration in 2023 has catalyzed intensified research and development initiatives focused on promoting millet conservation, cultivation, and consumption worldwide (Naorem *et al.,* 2023).

Pearl millet-based cropping systems, when integrated with conservation agriculture (CA) practices, offer a promising approach to enhance pearl millet production in rainfed and arid regions (Choudhary *et al.,* 2019). CA characterized by minimal soil disturbance, permanent soil cover, practicing diversified crop rotations, cover cropping proves particularly advantageous for pearl millet cultivation in challenging environments. The reduction of soil disturbance preserves soil structure breakdown and enhances moisture retention which are the critical factors in the regions with limited water availability. Permanent soil cover, achieved through methods such as mulching or cover cropping, mitigates soil erosion, conserving moisture and additionally moderate soil temperature based on the hot summer and cold winter in environment. Diversified crop rotations, when integrated with pearl millet, disrupt disease and pest cycles while optimizing nutrient utilization (Bhan and Behera, 2014; Chaudhary *et al.,* 2023; Farooq and Siddique, 2015; Pratibha *et al.,* 2022). CA has garnered substantial attention for its potential to improve soil health, boost crop productivity, and alleviate the impacts of climate change (Bana *et al.,* 2023; Faiz *et al.,* 2022). So, taking into consideration of increasing extent of degraded soils, it's imperative to understand the research trends related to pearl millet cultivation and its effect on soil health is necessary. We have used bibliometric analysis for systematically examining scientific literature, and established a pivotal role in elucidating research trends, knowledge gaps, and the implications of pearl millet–based cropping systems for soil health.

This analytical approach entails a rigorous quantitative assessment of scientific publications, citation patterns, and collaborative networks, offering multifaceted advantages. Firstly, it is an effective tool for identifying emerging research frontiers, discerning prevalent topics of inquiry, and pinpointing areas where knowledge remains deficient, enabling researchers to strategically direct their investigations. Secondly, bibliometric indices, including citation counts and the h-index, serve as robust metrics for quantifying the impact and scholarly quality of scientific publications, facilitating the comprehensive evaluation of researchers, academic institutions, and funding bodies in terms of research influence and productivity. Consequently, bibliometric analysis emerges as an indispensable instrument for evidence-based decision-making and strategic planning in the domain of CA research (Bhattacharjee *et al.,* 2023). Additionally, bibliometric analysis facilitates the identification of key stakeholders and their contributions to the field. This information can be utilized to foster collaborations between scientists, policymakers, and farmers, leading to the development and implementation of sustainable agricultural practices (Hu *et al.,* 2022). By disseminating the findings of the bibliometric analysis, awareness can be raised among stakeholders about the importance of pearl millet–based cropping systems and its impact on soil health, encouraging the adoption of these practices on a larger scale.

Methodology

The bibliometric research methodology employed in this study involved a series of sequential steps. Firstly, access to the Scopus database (https://www.scopus.com/search) was secured. Subsequently, the obtained results underwent rigorous filtering to refine the dataset. For example, we filtered time span limited to 2000 to 2023, key words are limited to Pearl millet, soil health, conservation agriculture etc. Following this, a systematic query was executed within the Scopus platform to retrieve relevant scientific literature. Once the data were retrieved, a series of data extraction and processing procedures was undertaken to ensure accuracy and consistency. Subsequently, the compiled dataset underwent comprehensive analysis and visualization using established bibliometric techniques and the R software. It is essential to note that the primary objective of this study was to employ bibliometric techniques to scrutinize the body of literature concerning soil health and CA within the context of pearl millet-based cropping systems. The execution of the bibliometric study adhered to a meticulously planned two-step process designed to ensure rigor and reproducibility.

Step 1: Assessing and filtering Scopus database on September 24, 2023, the Scopus database was assessed. A search for relevant literature related to pearl millet research under CA yielded 171 sources. Subsequently, the timeframe was filtered from 2000 to 2023, resulting in 153 sources, comprising 131 sources in English, 32 in Portuguese, and 1 in Spanish. Finally, the results were filtered for the "English" language, yielding 131 relevant sources, which were included in this study for further evaluation. The final search query is presented here:

(TITLE"ABS"KEY ("Pearl Millet") AND TITLE"ABS"KEY ("Conservation agriculture") OR TITLE"ABS"KEY ("No"Till") OR TITLE"ABS"KEY ("Crop rotation")) AND PUBYEAR > 1999 AND PUBYEAR < 2024)

The metadata were exported in two formats: CSV files and tab–delimited files. Subsequently, the unprocessed raw files were imported into the R software environment, where a suite of custom codes was executed. These codes, utilizing the capabilities of the R–package bibliometrix, were designed to meticulously clean and preprocess the data, adhering to established methodologies (Aria and Cuccurullo, 2017).

Employing bibliometric methodologies and leveraging R software, specifically the bibliometrix package, a comprehensive analysis of the dataset was conducted to uncover intricate patterns and emerging trends within the domain of pearl millet research. Subsequently, the capabilities of VosViewer (Van Eck and Waltman, 2017), a dedicated software tool for constructing and visualizing bibliometric networks, were harnessed to generate a range of visual representations.

Numerous key parameters were scrutinized, encompassing annual scientific output, average citations per year, the three-field plot, relevant information sources, the application of Bradford's Law, source dynamics, identification of the most influential authors (with an emphasis on fractionalized articles), prominent affiliations, highly cited documents on a global scale, frequently occurring keywords, trending topics and thematic mapping.

Of notable importance, Bradford's Law (Brookes, 1969) was invoked as a bibliometric principle to elucidate the distribution of information sources within the selected field, providing insights into the concentration of research output. Additionally, the concept of fractionalized articles was applied, where publications featuring multiple authors were systematically fractionalized based on their individual contributions to the publication. This fractionalization approach allows for a more precise representation of an author's research productivity and influence within the field, particularly when assessing their contribution to collaborative publications involving multiple authors.

Results

A comprehensive overview of the gathered document data, aiming to assess the landscape of research on pearl millet–based cropping systems under CA (Table 1). The time span the period from 2000 to 2023 and originate from diverse sources, including journals and books. A meticulous analysis of 131 documents reveals a modest annual growth rate of 0.8%, indicating a measured expansion of research efforts in this specific domain over the past two decades. The mean age of documents is 8.5 years, with an average citation count of 23.7 per document. This suggests that investigations into pearl millet under CA are firmly established and widely acknowledged, with substantial references to earlier works.

Table 1. Main contents of the collected sources

Description	Results
Timespan	2000:2023
Sources (Journals, Books, *etc.*)	82
Documents	131
Annual growth rate, %	0.8
Document average age	8.5
Average citations per doc	23.7
References	5658
Document contents	
keywords plus (id)	761
author's keywords (de)	434
Authors	
Authors	527
Authors of single-authored docs	2
Authors collaboration	
Single–authored Docs	2
Co–authors Per Doc	5.3
International Co–Authorships %	32.8
Document types	
article	122
book chapter	2
conference paper	4
review	3

The references section, encompassing 5658 citations, emphasizes the broad spectrum of topics within this field of study. Document content analysis identified 761 keywords plus (ID) and 434 author's keywords (DE). The authorship landscape involves 527 contributors, with only 2 engaging in single–authored documents. Examination of collaboration patterns indicates

2 single–authored documents, averaging 5.34 co–authors per document. Notably, 32.8% of co–authorships represent international collaborations, signifying a moderate degree of global cooperation in this research domain. These findings emphasize the collaborative and international nature of pearl millet research, leveraging expertise and resources from diverse origins. Regarding document types, the majority consist of articles (122), with fewer contributions from book chapters (2), conference papers (4), and reviews (3), highlighting a notable scarcity of reviews within this research field (Table 1).

Annual scientific production

This study aimed to analyse the annual scientific production on CA under pearl millet from 2000 to 2023 to identify trends and patterns over time. Relatively stable scientific production in the early 2000s, with an average of 3.3 publications per year between 2000 and 2010 (Fig. 1). However, there was a significant increase in scientific production from 2011 to 2022, with the number of publications nearly doubling to an average of 7.3 per year. These findings suggest that pearl millet research under CA has undergone consistent growth in scientific production over the past two decades, with a notable surge in recent years. This upturn could be attributed to various factors, including increased funding, heightened interest in the subject matter, or advancements in technology facilitating easier access to research. The implications of these findings are valuable for informing future research endeavours and gaining insights into the progress and advancement of pearl millet research under CA.

Average citations per year

The average citations per year for pearl millet research under CA were analyzed from 2000 to 2023 to identify trends and patterns over time (Fig. 2). The data exhibited a general trend of increasing citations per year from 2000 to 2005, followed by a sharp increase until 2009, after which it gradually decreased in subsequent years. In 2005, the average citations per article were at their lowest, reaching 0.35, and steadily increased to a peak of 6.27 in 2009. However, post 2010, the average citations per article began to decline, reaching a low of 0.33 in 2023.

The three–field plot, illustrating the top ten countries, top ten keywords, and sources, offers a comprehensive visualization of the most significant contributors in pearl millet research under CA from 2000 to 2023 (Fig. 3). This versatile analytical tool in bibliometrics simultaneously visualizes relationships between countries, keywords, and sources within a specific research domain. The horizontal axis represents countries

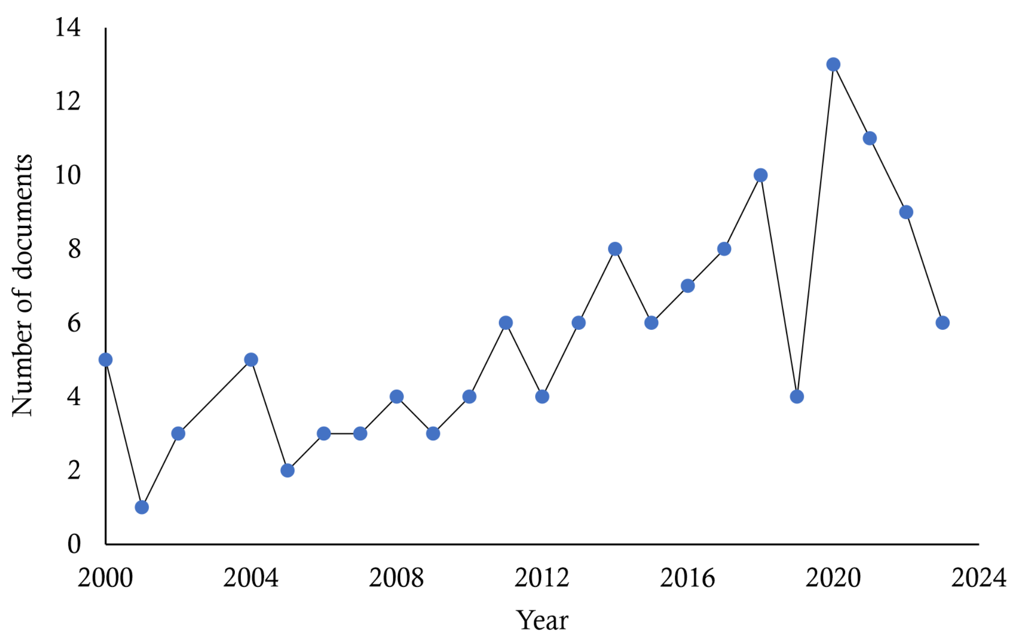


Fig. 1 Annual scientific production

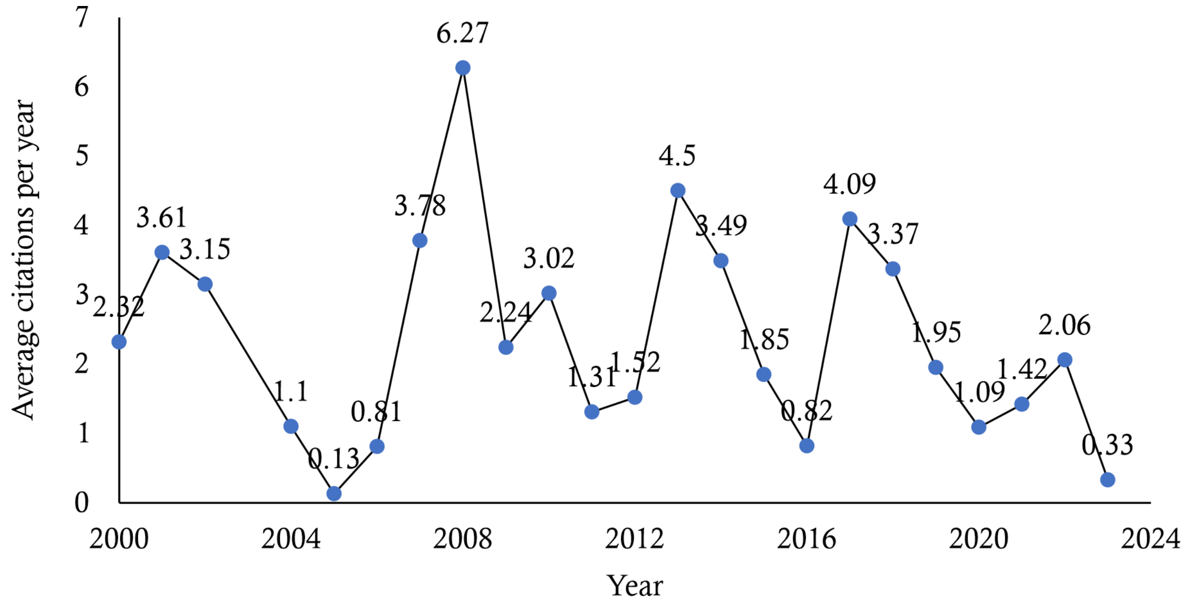


Fig. 2 Average citations per year for pearl millet-based cropping systems under conservation agriculture and soil health from 2000–2023

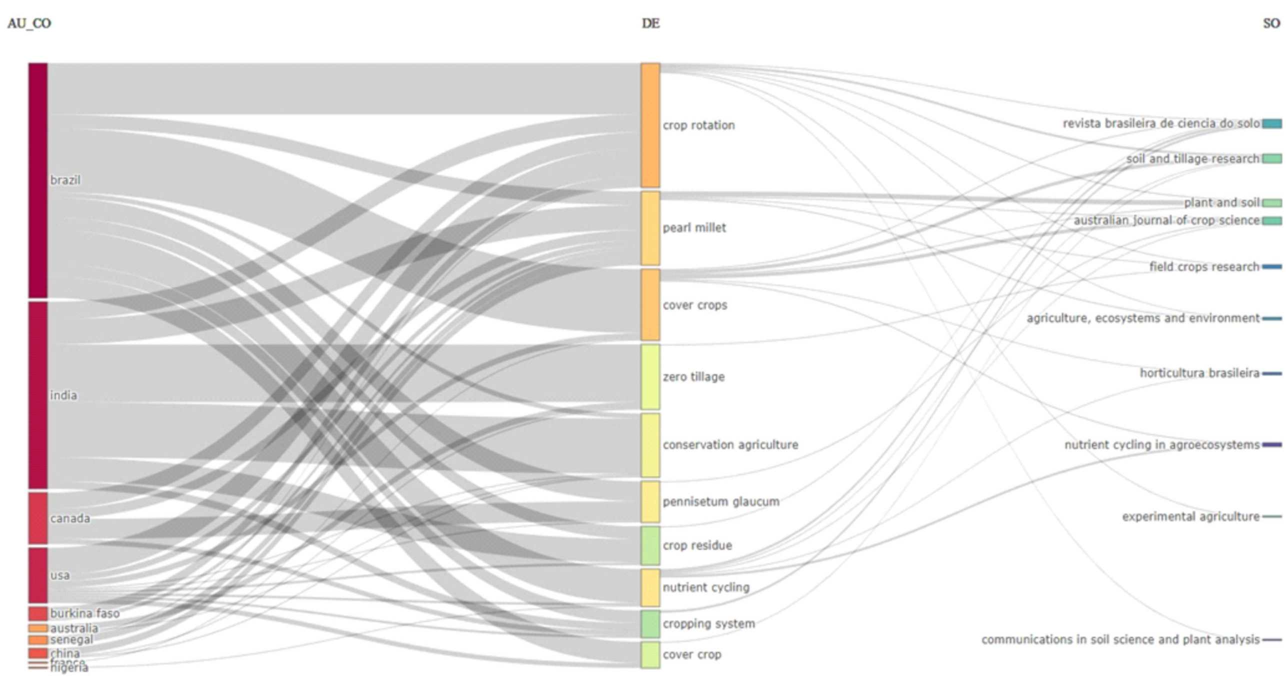


Fig. 3 Three–field plot of pearl millet–based cropping system research connecting top 10 countries, authors keywords and most relevant sources

or regions, showcasing the geographical distribution of research contributions. The vertical axis signifies keywords or topics, highlighting the prevalence and relevance of specific research themes. The third dimension, depicted as the size or color of data points, corresponds to sources or publications, elucidating the influence and impact of particular journals, institutions, or research outlets. Three–field plots provide a holistic view of the global research landscape, enabling stakeholders to discern trends, collaborations, and knowledge dissemination patterns across nations, topics, and publication sources, thereby facilitating informed decision–making and strategic research planning. This three–plot shows that Brazil, India and Canada are top three countries published research papers on the topic of pearl millet, while top three key words are crop rotation, pearl millet

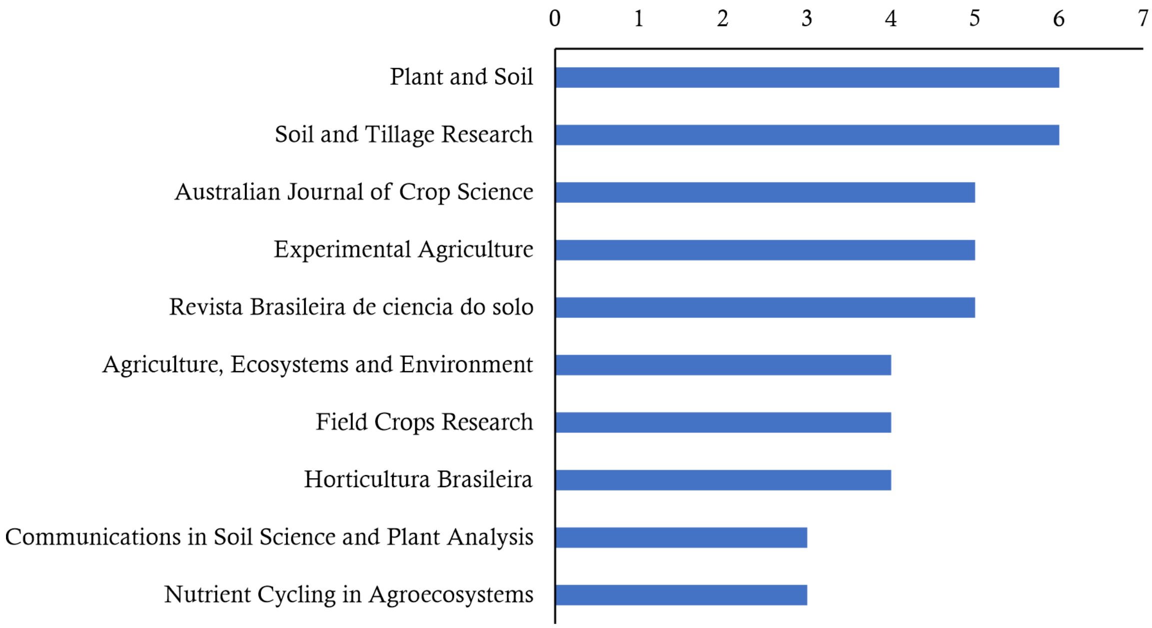


Fig. 4 Most relevant sources publishing research papers on pearl millet–based cropping systems under CA and its effect on soil health

and cover crops and the top three journals are *The Revista Brasileira de Ciência do Solo (RBCS),* Soil and Tillage Research and Plant and Soil. The three–plot clearly showed the major countries having focus on pearl millet-based cropping systems for improving soil health but research work is mostly concentrated on fine–tuning cropping system through crop rotation, the research work related to pearl millet–based cropping systems under CA or problematic soil is still less explored.

Relevant sources

The most relevant sources publishing research papers in the area of soil health under pearl millet–based cropping systems (Fig. 4). The maximum number of research papers is being published in "Plant and Soil" and "Soil and Tillage Research" journals, both contributing 6 publications each. Following these journals, the "Australian Journal of Crop Science," "Experimental Agriculture," and "Revista Brasileira De Ciencia Do Solo" have published 5 papers each. Subsequently, "Agriculture, Ecosystems and Environment," "Field Crops Research," and "Horticultura Brasileria" have contributed 3 papers each related to pearl millet and soil health in the last three decades. The number of publications on this topic is relatively low, emphasizing the need for increased attention from scientists to develop a better understanding of soil health under pearl millet–based cropping systems across various agro–ecologies and soil conditions.

The h–index, which is based on the number of publications in a journal on a particular topic and the number of citations those publications receive (Table 2). For example, the h–index of 5 for "Plant and Soil" and "Soil and Tillage Research" indicates that these journals have at least 5 papers with 5 citations on a particular subject. The h–index serves as a useful tool to gauge the overall impact of a researcher's

Table 2. H–Index and total citations (TC) in journals for pearl millet–based cropping systems under conservation agriculture research

Journals	H index	TC
Plant and Soil	5	228
Soil and Tillage Research	5	386
Experimental Agriculture	4	135
Field Crops Research	4	166
Revista Brasileira De Ciencia Do Solo	4	62
Agriculture, Ecosystems and Environment	3	262
Australian Journal of Crop Science	3	26
Nutrient Cycling in Agroecosystems	3	54
Soil Use and Management	3	111
Agricultural Water Management	2	15

contribution to their field, considering both the quantity and quality of their work. The table also presents the total number of citations incurred in journals, with the highest citations in "Soil and Tillage Research" journal (386), followed by "Agriculture, Ecosystems and Environment" (262) and then "Plant and Soil" (228).

Observing the total citations in this specific area of pearl millet–based cropping systems and soil health, it is noted that the field does not yet have a substantial number of citations. This indicates that it is a relatively new area of research, with scientists evolving newer insights in this field over the past few decades.

Analysis of authors

The analysis of authors is a crucial aspect of bibliometric analysis, and the total number of authors on this particular topic is counted as 527. However, not all authors are equally productive. The productivity of authors is estimated using Lokta's law, a classical procedure in bibliometrics that describes the frequency of publication by an author in a given field (Pao *et al.,* 1985). Generally, only a few authors produce more documents, while a large pool of authors contributes very few documents. The portrayal of Lokta's law in Fig. 5 indicates that 82.7% of the authors have produced only one document, 11.0% of the authors produced 2 documents, and 0.2% of the authors have produced 20 documents. There is only one author who has published 20 articles.

Top ten most prominent authors who significantly contributed to publications on pearl millet–based cropping systems (Table 3). Rosolem, C.A. had the highest number of publications (20), followed by Calonego, J.C. (11); Crusicol, C.A.G. (7); Rigon, J.P.G. (7); Bana, R.S; Cora, J.E.; and Lal, R., each having 5 publications. Besides this, Table 3 presents two metrics: h–index and m–index for ranking authors, in addition to the number of publications. The m–index takes into account both the number of publications and the number of citations. For example, if an author has an m–index of 10, it means that among his top 10 papers, the paper with the most citations has been cited at least 10 times. Rosolem, C.A. of São Paulo State University, Brazil, has the highest number of publications (20) and total citations (659), with an h–index of 11 and an m–index of 0.5. Similarly, the citations matrix for other authors is also mentioned in Table 3, showing the general trend that a higher number of publications yield higher citations and a higher h–index.

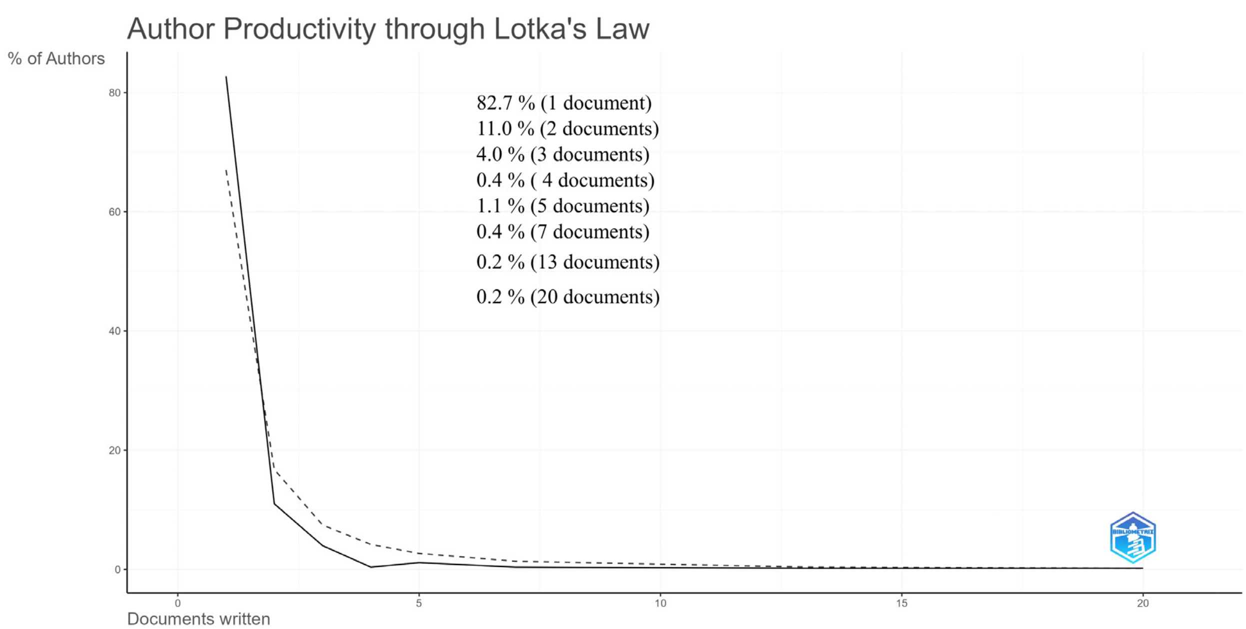


Fig. 5 Productivity of authors as per Lokta's law

Table 3. Top 10 authors contributing to publications on pearl millet-based cropping systems

Rank	Name of Author	Affliation	h_index	m_index	Total citations	No. of publications
1	Rosolem C	São Paulo State University, Brazil	11	0.5	659	20
2	Calonego J	UNESP, São Paulo State University, Brazil	9	0.643	373	13
3	Crusciol C	UNESP, São Paulo State University, Brazil	6	0.3	214	7
4	Corá J	UNESP, São Paulo State University, Brazil	5	0.333	108	5
5	Lal R	Ohio State University, USA	5	0.455	342	5
6	Rigon J	UNESP, São Paulo State University, Brazil	5	0.714	173	7
7	Bana R.S.	Indian Agricultural Reseach Instiute, India	4	0.571	94	5
8	Bationo A	IFDC-Afrique, Togo	4	0.167	295	4
9	Yadav A	Eternal University, India	4	0.308	64	5
10	Chhokar R.S.	Indian Institute of Wheat and Barley Research, India	3	0.231	57	3

Therefore, considering the number of publications as a measure of an author's influence in a particular field is the simplest way of measuring their contribution to that field. However, in some cases, authors in their early career whose scientific trajectory is still in the growth stage may have fewer publications (Montalvan-Burbano *et al.,* 2020).

Analysis of documents

The top 10 most cited documents are depicted in Table 4, which had a great role in the development and evolution of this topic over the year. The highest cited documents in pearl millet–based cropping systems and soil health is titled as "Alternative soil quality indices for evaluating the

Table 4. Top 10 most cited documents

Reference	Title of paper	Total Citations	TC per year	Norm-alized TC
Masto R, 2008, Environ Monit Assess	Alternative soil quality indices for evaluating the effect of intensive cropping, fertilisation and manuring for 31 years in the semi-arid soils of India	214	13.38	2.13
Masto R, 2007, Agric Ecosyst Environ	Soil quality response to long-term nutrient and crop management on a semi-arid Inceptisol	181	10.65	2.81
Srinivasarao C, 2014, Land Degrad Dev	Long term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet cluster bean castor rotation in Western India	159	15.90	4.56
Rosolem C, 2002, Soil Tillage Res	Root growth and nutrient accumulation in cover crops as affected by soil compaction	130	5.91	1.88
Calonego Jc, 2017, Eur J Agron	Soil compaction management and soybean yield with cover crops under no-till and occasional chiseling	117	16.71	4.09
Senthilvel S, 2008, Bmc Plant Biol	Development and mapping of Simple Sequence Repeat markers for pearl millet from data mining of Expressed Sequence Tags	111	6.94	1.11
Bagayoko M, 2000, Plant Soil	Cereal/legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes	110	4.58	1.97
Calonego J, 2010, Eur J Agron	Soybean root growth and yield in rotation with cover crops under chiseling and no-till	107	7.64	2.53
Srinivasarao C, 2013, Adv Agron	Sustainable Management of Soils of Dryland Ecosystems of India for Enhancing Agronomic Productivity and Sequestering Carbon	106	9.64	2.14
Singh G, 2018, Soil Tillage Res	Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains	90	15.00	4.46

effect of intensive cropping, fertilisation and manuring for 31 years in the semi–arid soils of India", which points out that long–term application of optimum inorganic fertilizers (NPK) and farmyard manure (FYM) resulted in higher soil quality ratings, with the best relationship between crop yield and a principal component analysis (PCA)–derived soil quality index, suggesting the sustainability of these practices over common soil management methods in India (Masto *et al.,* 2008). In another study by Masto *et al.* (2007), reported that the 31–year study on Inceptisols demonstrated that integrated NPK fertilizer and manure treatments significantly improved soil quality, as indicated by a soil quality index, emphasizing their sustain-ability over common fertilizer practices in India. The third most cited paper titled "Long–term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet–cluster bean–castor rotation in Western India" reported that despite the addition of 33.5 Mg ha^{-1} C inputs through crop residues and farmyard manure in an 18"year field experiment in western India, soil organic carbon (SOC) depletion by oxidation led to a net loss of 4.4 Mg C ha^{-1}, with the conjunctive use of chemical fertilizers and manure showing higher agronomic yields and reducing the rate of SOC depletion, emphasizing the importance of integrated management for sustaining soil productivity and carbon sequestration (Srinivasarao *et al.,* 2014). The fourth most cited research paper is "Root growth and nutrient accumulation in cover crops as affected by soil compaction" describing about crop rotation using cover crops with vigorous root systems, such as *Pennisetum americanum* L., could effectively manage soils with varying degrees of compaction, as demonstrated by higher shoot dry matter yield, root length density, and macronutrient accumulation, emphasizing its potential as a tool for tropical areas facing soil compaction challenges (Rosolem *et al.,* 2002). The next most cited document is "Soil compaction management and soybean yields with cover crops under no–till and occasional chiseling" having 117 citations and normalized citations index of 4.09 explaining about the study in Botucatu, Brazil, conducted under no-till, found that while the initial chiseling in 2003 provided short-term benefits in terms of increased soil macroporosity and soybean yields, the use of cover crops such as sunn hemp, forage sorghum, and pearl millet resulted in equal or better long-term improvements in soil structure, including increased macroporosity and decreased soil bulk density, with sunn hemp showing particular promise for enhancing soybean yields in clay soils (Calonego *et al.,* 2017). The next most cited document is "Development and mapping of Simple Sequence Repeat markers for pearl millet from data mining of Expressed Sequence Tags" having 111 citations. The study addressed the limited availability of co-dominant markers for pearl millet by developing 90 SSR markers based on expressed sequence tags, demonstrating their polymorphism and mapping potential, thus enhancing marker resources for pearl millet genetic improvement and breeding programs (Senthilvel *et al.,* 2008). The seventh most cited research paper is "Cereal/legume rotation effects on cereal growth in Sudano–Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes" explaining about field trials across Niger and Burkina Faso from 1996 to 1998, legume/cereal rotations, particularly with groundnut, significantly increased grain and total dry matter yields of cereals by elevating soil mineral nitrogen levels and promoting early arbuscular mycorrhizal infection, while the efficiency of legume species in suppressing nematode populations and enhancing plant-available nitrogen through nitrogen fixation played a role in the site-specific magnitude of these effects on nutrient-poor Sudano-Sahelian soils (Bagayoko *et al.,* 2000). The next most cited paper is "Soybean root growth and yield in rotation with cover crops under chiseling and no-till" having normalized citation of 2.53 empahized that crop rotations with triticale and pearl millet, having aggressive root systems, proved more effective than mechanical chiseling in mitigating the adverse impact of soil compaction on soybean yields in tropical soils. However, chiseling resulted in improved soil penetration and soybean yields in the first year (Calonego and Rosolem, 2010). Review article in Advances of Agronomy on the topic of "Sustainable Management of Soils of Dryland Ecosystems of India for Enhancing

Agronomic Productivity and Sequestering Carbon" explained about improving soil organic carbon (SOC) through integrated nutrient management practices, combining organic resources with chemical fertilizers, significantly enhances crop yields in rainfed areas of India (Srinivasarao *et al.,* 2013). These practices not only address the urgent need for increased productivity to meet growing food demands but also contribute to soil carbon sequestration, offering a win"win solution for food security and environmental sustainability. The tenth most cited paper titled "Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains" explained that in a rainfed system, crop residues exerted a positive influence on soil microbial activities, with the highest levels of soil glomalin and aggregate stability observed in residue-treated plots. Legume-based cropping demonstrated approximately 12% higher soil glomalin compared to a cereal-cereal system, and there was a positive correlation between aggregate stability and glomalin content. Additionally, both the presence of crop residues and crop rotation had beneficial effects on microbial biomass carbon and labile carbon in the soil (Singh *et al.,* 2018).

Analysis of countries

The distribution of publications across different countries in Fig. 6 reveals that Brazil leads with the maximum number of publications (n = 59), constituting a significant 45% of the total publications included in the study. The second position in terms of the number of publications is held by the USA (n = 35), followed closely by India (n = 34), contributing to approximately 25-26% of the total publications. Other countries on the list, including Canada, Niger, Burkina Faso, Germany, Mali, Australia, and France, each have less than 10 publications.

This distribution underscores the increasing popularity and acceptability of the research topic, indicating a global interest in pearl millet-based cropping systems and soil health. The collaborative network among countries is robust, with Brazil, the USA, and India emerging as central countries with strong connections not only with each other but also with various other regions

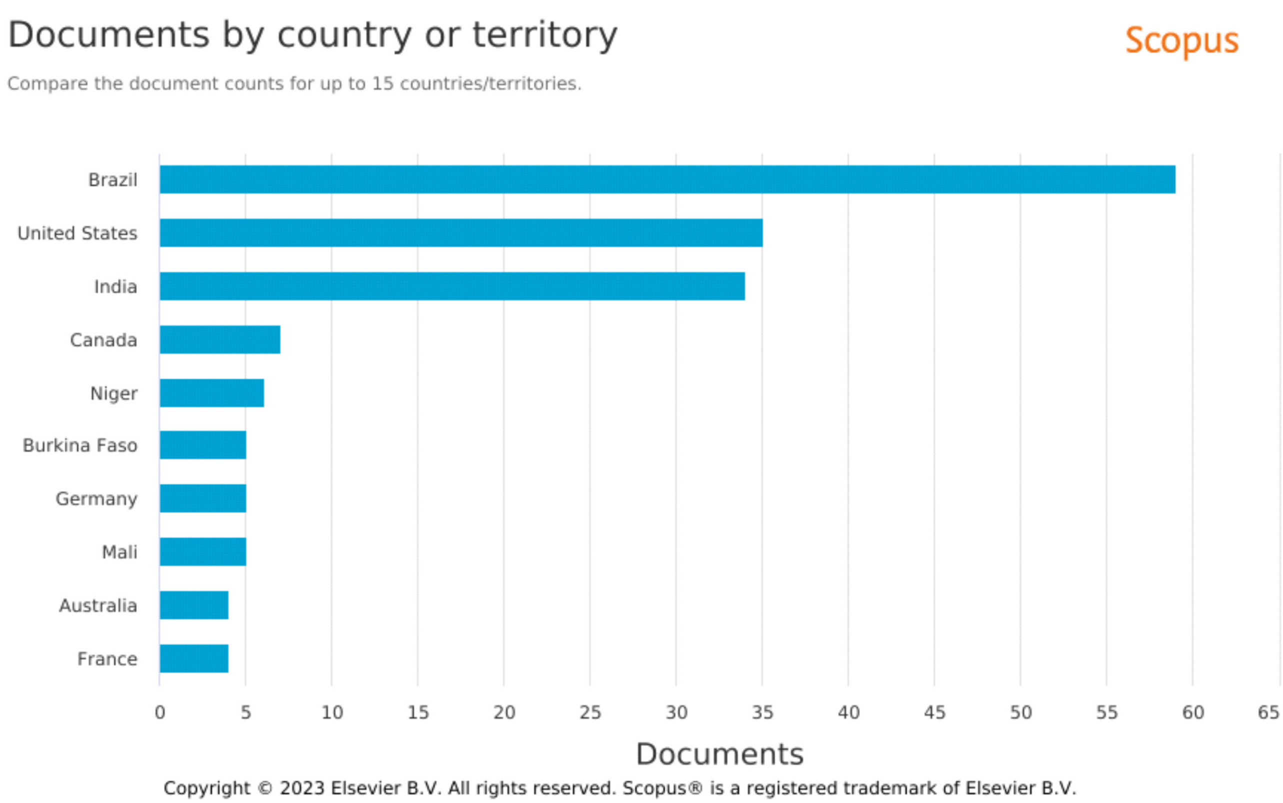


Fig. 6 Top 10 countries with highest number of documents

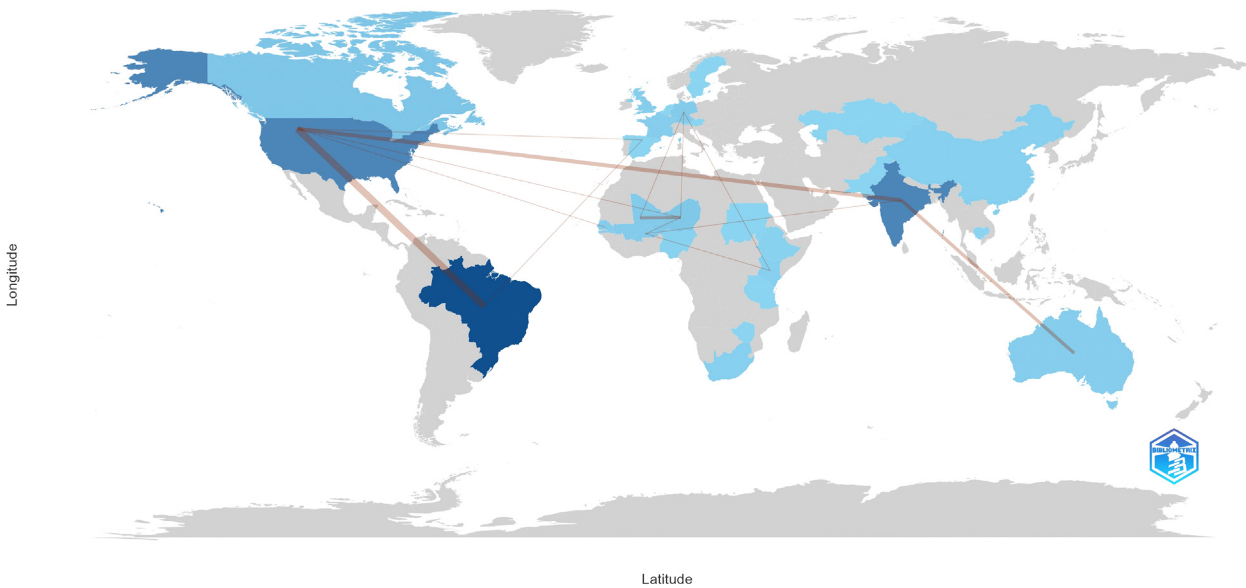
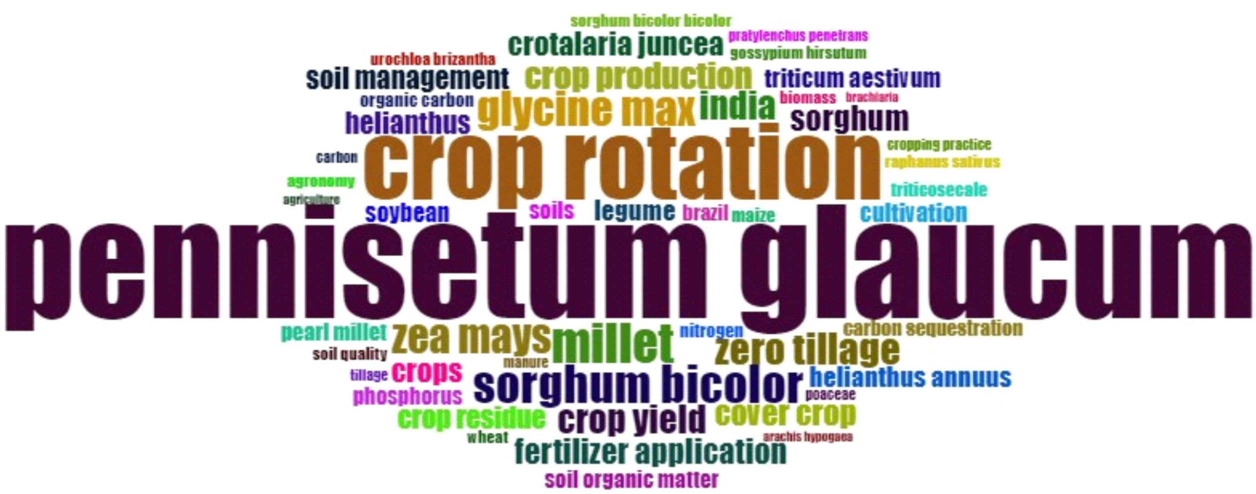


Fig. 7 Country collaborative map for pearl millet-based cropping systems research under conservation agriculture

worldwide. India, in particular, exhibits a strong collaborative network with the USA and Australia, while the USA engages in broad collaborations with India, Brazil, as well as several European and African countries. This inter-connectedness highlights the global reach and collaborative nature of research in the field of pearl millet-based cropping systems and soil health (Fig. 7).

Analysis of keywords

The most prevalent keywords related to pearl millet"based cropping systems and soil health. The analysis reveals that "pearl millet (*Pennisetum glaucam*)" is the most frequently occurring keyword, appearing 71 times, followed by "crop rotation" (48) and "millet" (25) (Fig. 8). Notably, keywords such as "*Sorghum bicolor*," "*Glycine max*," "*Zea mays*," "crop yield," and "India" indicate the



Words	Occurrences	Words	Occurrences	Words	Occurrences
Pennisetum glaucum	71	crop rotation	48	millet	25
Sorghum bicolor	24	*Glycine max*	22	*Zea mays*	21
zero tillage	20	crop yield	18	India	18
crop production	17				

Fig. 8 Word cloud of keywords published under pearl millet, soil health and cropping systems titles

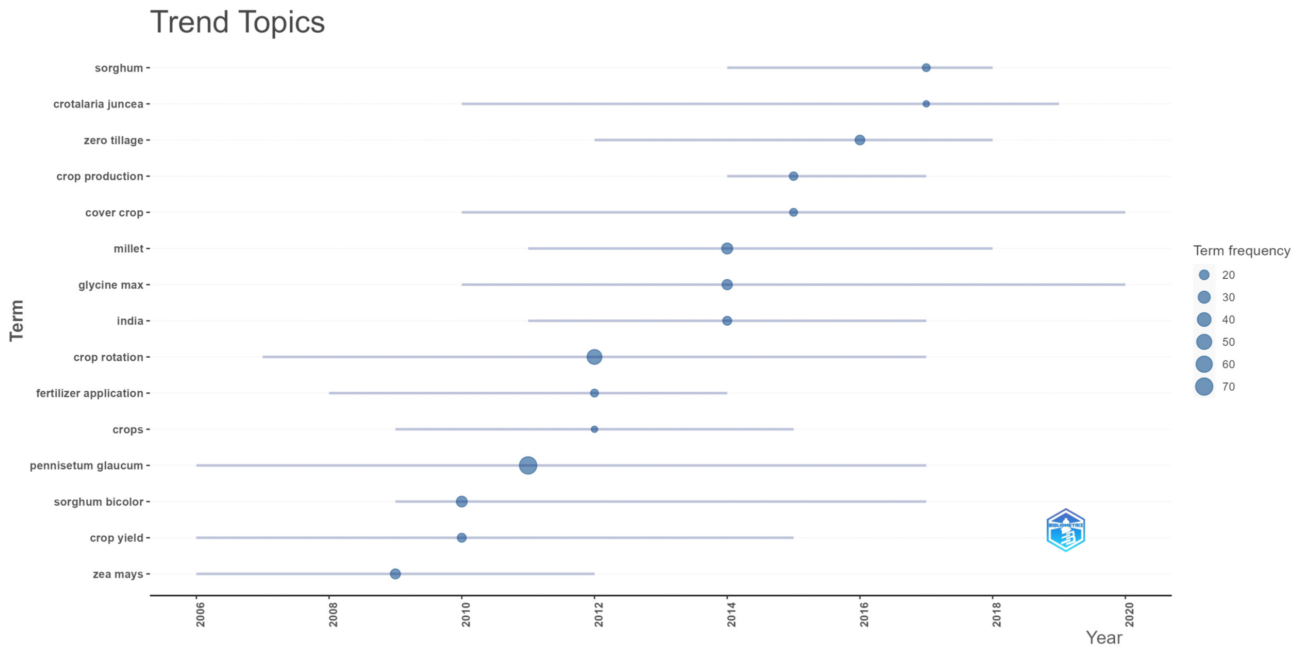


Fig. 9 Trending topics over period of time

central focus of Indian scientists on coarse cereal research.

The trending topic diagram in Fig. 9 illustrates the evolution of research topics in the field over the last three decades. Before 2010, the main topics of research were focused on "maize (*Zea mays*)" and "crop production." From 2010 to 2015, there was a shift towards diverse and interesting topics such as "*Pennisetum glaccum*," "millets," "crop yields," "fertilizer application," "crop rotation," "*Glycine max*," and "India." Post-2015, researchers show increased interest in topics like "zero"tillage," "sorghum," and "*Crotolaria juncea*," indicating ongoing exploration and the emergence of new areas of study related to pearl millet"based cropping systems and soil health. This dynamic evolution reflects the adaptability and responsiveness of scientific research to emerging trends and challenges in the field.

Thematic mapping

The authors of a study created a thematic map based on their keywords (Fig. 10). The map consists of four themes: niche, motor, and emerging and declining trends. The motor themes represent central and well"developed research themes, while the top-right quadrant showcases research areas that have been extensively studied. The motor themes include pearl millet, CA, cover crop, cropping systems, *Phaseoules valgaris*, and *Urochlora ruzzinensis*, which are the most trending topics among pearl millet researchers. The basic themes included zero-tillage, soil fertility, crop rotation, and cover cropping, which are related to integrated cropping systems and soil fertility. The niche area of research represents specialized and specific research within the domain of pearl millet-based cropping systems and soil health. It was found that N, P, soil organic matter, and its decomposition lie under the niche area of research for soil health maintenance under pearl millet"based cropping systems and soil health. Soil quality and soil compaction are the two emerging areas of research for pearl millet and soil health researchers. Thematic mapping is a useful tool for gaining insight into the current status of a research field and identifying future research areas. Therefore, through thematic mapping we can say that soil health or soil quality is the emerging area of research in the scientific community working with pearl millet–based production systems. Soil compaction has also got attention by research and under this physical hinderance pearl millet production has been taken to resolve this issue.

Implications

The current investigation into pearl millet–based cropping systems highlights several research gaps.

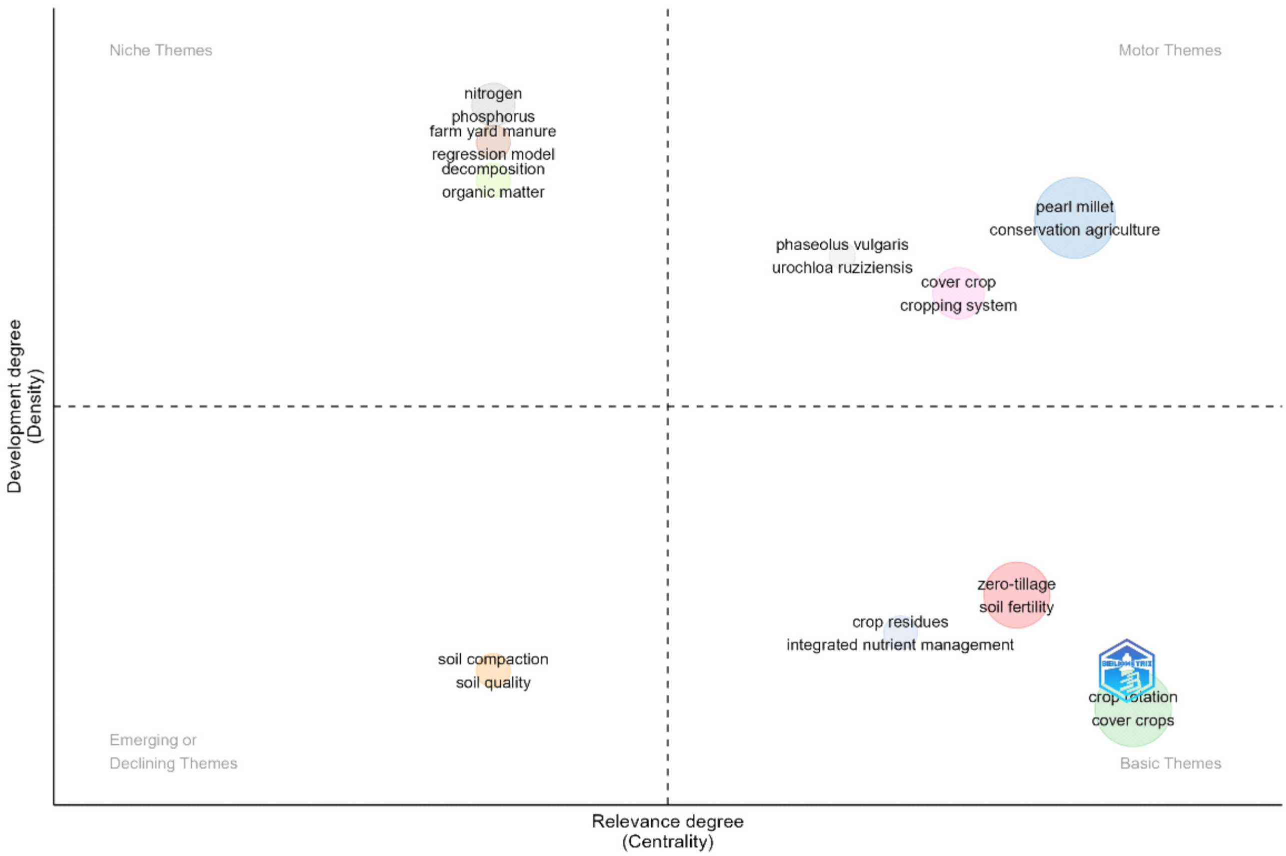


Fig. 10 Thematic map analysis of documents related pearl millet–based cropping systems and soil health

Firstly, there is a pressing need for further research to ascertain the comparative advantages of pearl millet–based cropping systems in contrast to other cropping systems. Over the past few decades, heightened emphasis has been placed on rice”wheat cropping systems in South Asian countries, driven by escalating population pressure, relegating millets to a secondary position. However, the global recognition of the significance of millets, marked by the declaration of 2023 as the International Year of Millets by the Food and Agriculture Organization (FAO), is expected to catalyze millet research, particularly focusing on pearl millet. Given its status as a major millet globally and its demonstrated resilience to climate change and abiotic stress, pearl millet is poised for increased attention and investigation.

Another intriguing avenue of research lies in understanding the impact of pearl millet–based cropping systems on soil health. Numerous researchers are actively exploring this domain, with many reporting positive effects of pearl millet–based cropping systems on both soil health and crop yield under rainfed conditions. However, substantial research is imperative to firmly establish whether pearl millet”based cropping systems possess carbon sequestration capabilities superior to other cropping systems. Lastly, the development of novel production systems for pearl millet, especially tailored for degraded and low”fertile soils with limited irrigation facilities or under rainfed conditions, emerges as a critical imperative. This strategic approach is vital for ensuring food security, particularly for economically disadvantaged farmers in Asian and African countries where millets form a major component of agricultural practices. The imperative is to devise innovative production systems that can uplift the agricultural productivity of pearl millet in challenging agroecological contexts such as areas associated with abiotic stress *viz.*, salinity, drought, heat stress, low moisture, low pH soil, low fertile soil, and marginal land, thereby contributing to the broader goal of food–nutritional and livelihood security for vulnerable farming communities.

Limitations of this study

The authors made concerted efforts to comprehensively search for all relevant material within the Scopus database. However, it is important to acknowledge several limitations inherent in this research:

1. **Temporal scope:** The search for relevant studies is confined to the period from 2000 to 2023. This temporal restriction may exclude earlier valuable contributions or recent developments that fall outside this timeframe.
2. **Database limitation:** The exclusive reliance on the Scopus database for sourcing relevant studies poses a limitation. Unindexed journals and publications from sources not covered by Scopus might have been overlooked, potentially leading to an incomplete representation of the available literature.
3. **Language bias:** The study considers only papers published in the English language. This linguistic criterion may introduce bias towards English-speaking countries and exclude valuable research published in other languages, limiting the study's global inclusivity.

Despite these limitations, the authors believe that the findings and insights drawn from the available data within the specified parameters provide a valuable contribution to the understanding of the research landscape in the field of pearl millet-based cropping systems and soil health.

Conclusions

This study reveals pearl millet as a strategically important crop for sustainable agriculture in arid and semi-arid regions, demonstrating exceptional salinity tolerance (>12 dS m^{-1}) and adaptability to marginal conditions. Integration with conservation practices—subsurface drainage, residue mulching, and deficit irrigation—enhances yields by over 25% under saline conditions while improving soil health and water use efficiency. The bibliometric analysis identified steady research growth but highlighted critical knowledge gaps requiring attention: comparative assessments of pearl millet systems versus alternative cropping systems, quantification of carbon sequestration potential, and development of location-specific production strategies for diverse agroecological contexts.

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