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A bibliometric analysis review of the *Pennisetum* (1970–2023)

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Pennisetum, a herbaceous plant belonging to the Poaceae family, is prevalent in tropical and subtropical regions and encompasses ~140 species. Its versatility is evidenced by its applications in forage, paper weaving, soil erosion control, and energy production. Current research on *Pennisetum* spans diverse fields including hay production, molecular breeding, and heavy metal absorption. However, this body of research is marked by redundancy, with a lack of clear focus. This article employs bibliometric methods to analyze the key research areas topics from 1970 to 2023. It also further discusses the future research direction of *Pennisetum*. Over the past five decades, research on *Pennisetum* has seen a significant increase, primarily concentrating on cultivation and breeding, ecological restoration, and industrial applications. These domains have become pivotal in advancing *Pennisetum*-related research. The paper also forecasts future innovations in *Pennisetum* research, focusing on molecular breeding, agricultural management, and novel material development. As a seminal contribution, this study offers a comprehensive graphical overview of *Pennisetum* research, establishing a foundational resource for ongoing scientific discourse.

KEYWORDS

***Pennisetum*, bibliometrics, cultivation and breeding, ecological restoration, industrial applications, novel materials**

1 Introduction

Pennisetum Americanum and *Pennisetum purpureum Schumach* are prominent pasture grass hybrids within the genus *Pennisetum*. This genus is characterized by its triploid C4 herbaceous plants, typically annual or perennial, and part of the Gramineae family (Tan F. et al., 2021). Commonly known as *Pennisetum alopecuroides*, *Pennisetum purpureum*, Chinese *Pennisetum*, King grass, Giant elephant Grass, and Napier grass. The genus encompasses a diverse array of over 140 species (Brunken, 1977), exhibiting varying chromosome numbers (5, 7, 8, or 9) and life cycles (annual, biennial, or perennial). Ploidy levels range from diploid to octoploid, encompassing both sexual and apomictic reproduction methods (Martel, 1997; Dos Reis et al., 2014; Donadío et al., 2018). *Pennisetum* is notable for its highly developed root system, capable of rapidly forming a fibrous network (Li et al., 2022). Plants undergo certain changes in their physiological structure during adaptation to the environment in which they are currently located. Roots undergo morphological changes to enhance their ability to absorb water and nutrients during periods of water scarcity (Gupta et al., 2020), and the well-developed root fibers of *Pennisetum* are able to increase the contact area of water and nutrients, promote water and nutrient uptake, and enhance the utilization efficiency of both. This characteristic confers increased resilience to drought and tolerance to acidic and alkaline soils, enabling its adaptation to diverse environments (Ma et al., 2012; Tan H. et al., 2021). Additionally, the biological traits of high yield and rapid growth have led to its widespread cultivation in countries like India, Vietnam, the United States, the Philippines, and Japan. Globally, *American Pennisetum* covers ∼31 million hectares,[1] with China alone accounting for around 100 million acres. In certain southern regions of China, the cultivation of *Pennisetum* exceeds 100,000 acres.

The exceptional environmental adaptability and distinctive physiological traits of *Pennisetum* render it highly versatile across various sectors. Firstly, its leaves are tender, juicy, and rich in protein, making it a vital food source for ruminants (Lowe et al., 2003; Antony and Thomas, 2014). The rapid growth of *Pennisetum* aligns well with the high demand in pasture forage. Consequently, research in this area primarily focuses on enhancing the quality of *Pennisetum* as silage feed. Studies have assessed metrics like yield and nutritional value, revealing that when combined with other species (such as ryegrass and tall fescue), elephant grass is adaptable to both organic and conventional production systems. However, it has been observed that planting elephant grass independently yields favorable results in terms of both production and grazing efficiency (Simonetti et al., 2019). Additional research has explored the integration of peanut cultivation within elephant grass forage systems, evaluating the impact of varying grazing intensities on forage yield, feed intake, and grazing efficiency (Vieira et al., 2019). These studies reveal that the benefits of elephant grass are related to its cropping pattern. Secondly, to maximize the production capacity of this genus and explore its genetic advantages, significant focus has been placed on cultivation and breeding. In the realm of genetic improvement, the genome sequencing of pearl millet [*Pennisetum* glaucum (L.) R.Br.] has been undertaken to enhance breeding efficiency and expedite the realization of its drought resistance traits (Serba and Yadav, 2016). Studies in this domain have investigated the effects of different cultivation strategies on *Pennisetum* yield in saline-alkaline soils (Wang et al., 2014). Scholars have found through relevant research that the genus *Pennisetum* has the best overwintering characteristics, which is beneficial for the development of related industries in subtropical regions (Zhu et al., 2022).

In addition to its significant roles in forage production and genetic research, *Pennisetum* also plays a crucial role in the field of ecological restoration. As a plant with high environmental tolerance, it thrives in various barren landscapes, contributing to environmental conservation. One of its remarkable capabilities is the absorption of heavy metals from contaminated soil, a cost-effective and eco-friendly approach to phytoremediation. Research indicates that it can extract between 0.94 and 1.31 kg ha^{-1} of Cd, producing 28 to 79 t ha^{-1} of dry biomass annually in soils containing 8–100 mg Cd kg^{-1}(Zhang et al., 2014; Hu et al., 2018). Guo et al. (2021) found better enrichment of As in pig farm waste streams with green and purple *Pennisetum*. Therefore, *Pennisetum* is increasingly planted in areas with heavy metal-contaminated soil as a phytoremediation strategy. This method effectively absorbs pollutants without harming the environment. Beyond heavy metal absorption, *Pennisetum* is also effective in preventing soil erosion. Comparative studies between *Pennisetum aloccuride* and Arundinella hart regarding land runoff and soil erosion demonstrated that *Pennisetum aloccuride* effectively controls soil erosion (Huang et al., 2010; Jiang et al., 2020). Moreover, narrow grass belts composed of *Pennisetum* purpureum are gaining popularity in many sub-Saharan African countries as a method for soil erosion control (Owino et al., 2006). These diverse applications underscore the genus *Pennisetum*'s multifaceted contributions to ecological restoration and environmental protection.

In recent years, with the rapid economic and technological development, the pursuit of clean energy and energy crops has become a central focus in industrial production. Within this context, *Pennisetum*, as an energy plant, has garnered attention for its utility in industrial applications. Research has demonstrated that the chemical composition, biomass yield, and specific methane yield of *Pennisetum* hybrid species are significantly influenced by factors such as harvest timing and cutting frequency (Li et al., 2016a). This suggests that strategic cultivation practices can optimize *Pennisetum*'s efficiency as an energy source. Camelo and Alessandra conducted a study on a new hybrid of pearl millet (*Pennisetum glaucum*) and Napier grass, exploring its potential as an alternative energy resource. The findings indicated that this hybrid can produce bio-oil and biochar, presenting promising applications in the plastics industry (Camelo et al., 2018). Furthermore, energy crops are increasingly recognized for their importance in the production of second-generation bioethanol, owing to their physiological characteristics. Hybrid *Pennisetum*, as a novel energy crop, exhibits substantial potential in bioethanol production. This potential is bolstered by its high biomass yield and efficient conversion capabilities (Zhang et al., 2016). Overall, in industrial manufacturing, the genus *Pennisetum* is becoming more and more prominent, particularly in the clean energy sector.

The versatility of *Pennisetum* extends beyond its current applications, positioning it as a vital ingredient across various fields. Despite its diverse usage, current research on *Pennisetum* is often repetitive and lacks focus. This trend hinders the full realization of its potential and the comprehensive utilization of resources. To address this issue, understanding the current key research areas and identifying future research trends of *Pennisetum* is essential. Bibliometrics, a widely adopted statistical method, offers a solution. It facilitates the summarization of current key research areas and the prediction of future research hotspots (Tan H. et al., 2021; Chen et al., 2022). Bibliometrics can conduct qualitative and quantitative analyses of the contributions and collaborations of authors, institutions, countries, and journals. Additionally, it evaluates the development and emerging trends in scientific research (Devos and Ménard, 2020; Ghisi et al., 2020; Mulet-Forteza et al., 2021).

In this context, this paper adopts a bibliometric approach and employs bibliometric mapping to conduct a general and comprehensive review of literature related to *Pennisetum* from 1970 to 2023. The specific objectives of this study are to: (1) illustrate the temporal trends in publications over the past five decades; (2) identify the primary topics currently targeted in *Pennisetum* research; (3) analyze future research hotspots in the field, with the results serving as a means to identify potential knowledge

1 Data sources: https://zhuanlan.zhihu.com/p/611036848.

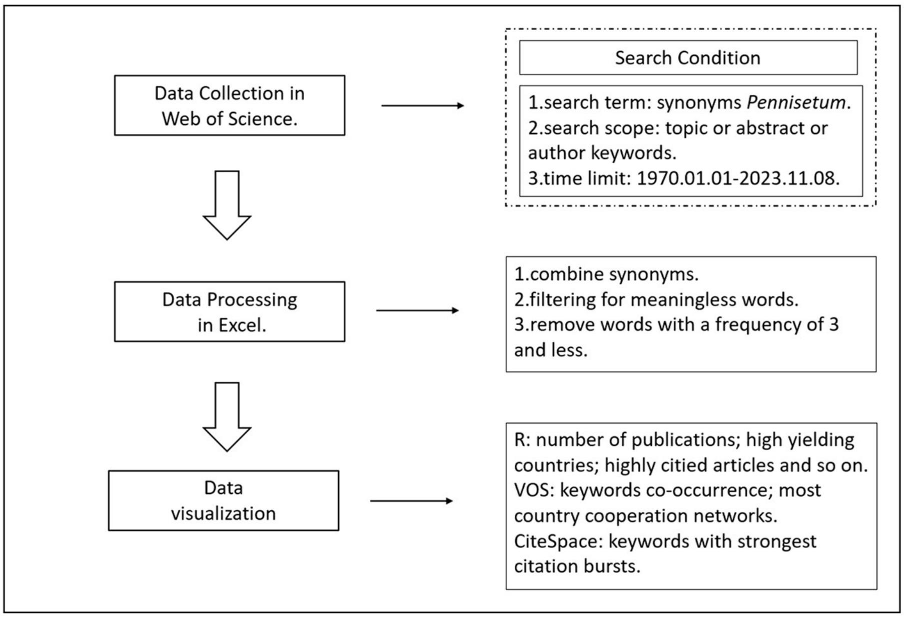

FIGURE 1
The data technology roadmap of this article.

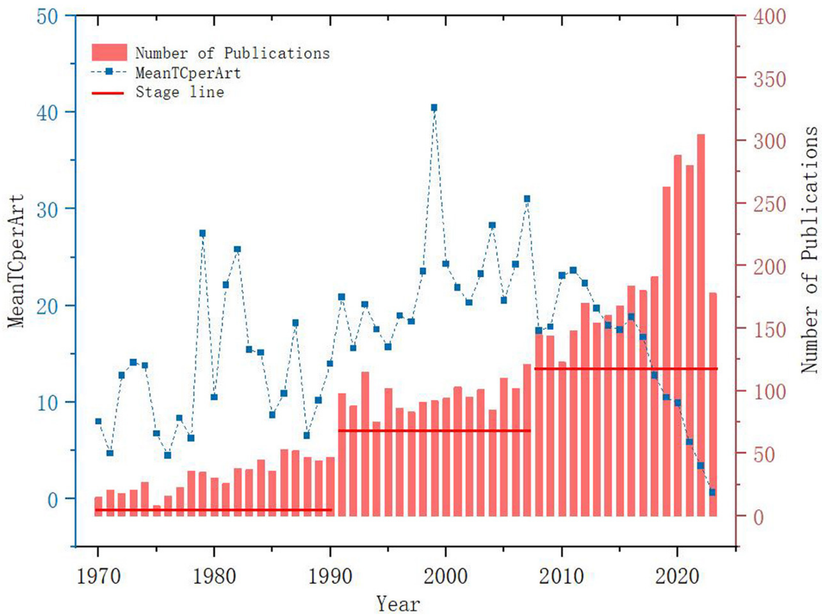

FIGURE 2
Total changes in the number of publications from 1970 to 2023.

gaps in this crop. The paper is structured as follows: Initially, it provides a brief overview of the current status and significance of *Pennisetum* research. Subsequently, the methodology employed for bibliometric analysis and mapping is detailed. The results section comprises performance and citation analysis, followed by scientific mapping. The third section offers a discussion on the main findings. Finally, the conclusion encapsulates the key discoveries of the study.

2 Data source and study method

2.1 Data collection

The data utilized in this study was sourced from the Web of Science Core Collection, a renowned database for scientific research. The search strategy employed the following terms: "*Pennisetum alopecuroides* OR *Pennisetum alopecuroides* (L.)

Spreng. OR *Pennisetum* OR *Pennisetum purpureum* OR P. purpureum OR Chinese *Pennisetum* OR *Pennisetum* hydridum." On November 8, 2023, a comprehensive collection of data was gathered, focusing on instances where *Pennisetum* was mentioned in the topics, abstracts, or author keywords. The timeframe for publication dates was set from January 1, 1970, to November 8, 2023. This process culminated in the accumulation of 5,397 academic publications, which formed the primary dataset for this research. The dataset facilitates critical analyses such as co-authorship networks among nations, journal participation, co-citation analysis, and keyword frequency evaluation.

2.2 Data processing

The data processing in this study primarily utilized the "Bibliometrix" package within the R programming language, supplemented by tools such as VOSviewer, Excel, and CiteSpace. The initial step involved a meticulous manual filtering of the data in Excel. Following this, the refined dataset was imported into R, VOSviewer, and CiteSpace for advanced data visualization. The resultant visualizations encompassed a range of aspects, including trends in publication counts over time, identification of leading nations, and journals, analysis of highly cited publications, detection of keywords with the Strongest Citation Bursts, construction of keyword co-occurrence networks, and the formation of national co-occurrence networks. These graphical representations provided a robust foundation for the subsequent analytical phases of the study. The data processing timeline and methodology for this research are illustrated in Figure 1.

3 Results and analyses

3.1 *Pennisetum* research publication output trends

The analysis of *Pennisetum* research publications from the Web of Science Core Data Collection between 1970 and 2023 reveals a total of 5,397 publications. Among these, research papers constitute 91%, while the remaining 9% comprises conference papers, conference abstracts, reviews, book chapters, and other types of publications. A discernible trend is the overall increase in *Pennisetum*-related literature over this period, with a notable tripling in the number of articles from 1990 to 2021, as depicted in Figure 2. The evolution of *Pennisetum* research can be segmented into three distinct phases based on annual publication counts. First Phase (1970–1990): This initial stage is characterized by a relatively low and stable publication rate, with fewer than 50 publications per year and minimal fluctuations; Second Phase (1991–2007): Marked by a significant surge in 1991, this phase witnesses a steady yet less variable growth in the volume of publications; Third Phase (2008–2023): The most recent stage exhibits a general increase in publication numbers, reaching the highest counts in this period. However, an interesting observation is that despite the continuous growth in the volume of literature, the average citation per article does not follow a consistent upward trajectory; rather, it fluctuates. Notably, the average annual citation rate of articles published before 2007 was significantly higher than those published after 2007. The year 1999 stands out as having the highest average annual citation rate among articles. This trend suggests that while the quantity of *Pennisetum*-related research has increased, the impact or citation influence of individual articles has varied over time.

TABLE 1 Top 15 countries with the most research publications on *Pennisetum* based on the Web of Science database (1970–2023).

Region	No. of publications	TC	Average article citations
BRAZIL	2,070	7,186	10.00
INDIA	2,032	11,958	10.90
USA	1,319	18,108	30.80
China	1,221	7,916	16.30
France	340	3,072	24.80
Australia	339	3,657	25.00
Mexico	336	863	7.60
UK	288	4,922	43.90
Japan	235	1,997	20.00
Nigeria	235	842	9.00
Pakistan	204	822	11.30
Germany	203	2,967	27.00
South Africa	202	1,367	16.90
Kenya	185	1,777	26.10
Thailand	163	529	9.40

TC, total citation.

3.2 Participation of various countries in research on the *Pennisetum*

The involvement of different countries in *Pennisetum* research reveals interesting patterns. Based on the number of publications, the top five contributing countries are Brazil, India, the United States, China, and France (as shown in Table 1). Notably, the top four countries each have published over 1,000 papers on the subject. When considering overall citations, the United States leads, followed by India and China. This highlights the significant role and influence of the United States in *Pennisetum* research, both in terms of publication volume and impact, underscoring the relative importance of this plant in the country.

In Brazil, India, China, and France, *Pennisetum* is predominantly utilized as ruminant feed, and these countries have substantial production levels. This high production volume fuels further research in the field, reflecting a strong connection between practical application and scientific investigation. Among the countries that published research on *Pennisetum* between

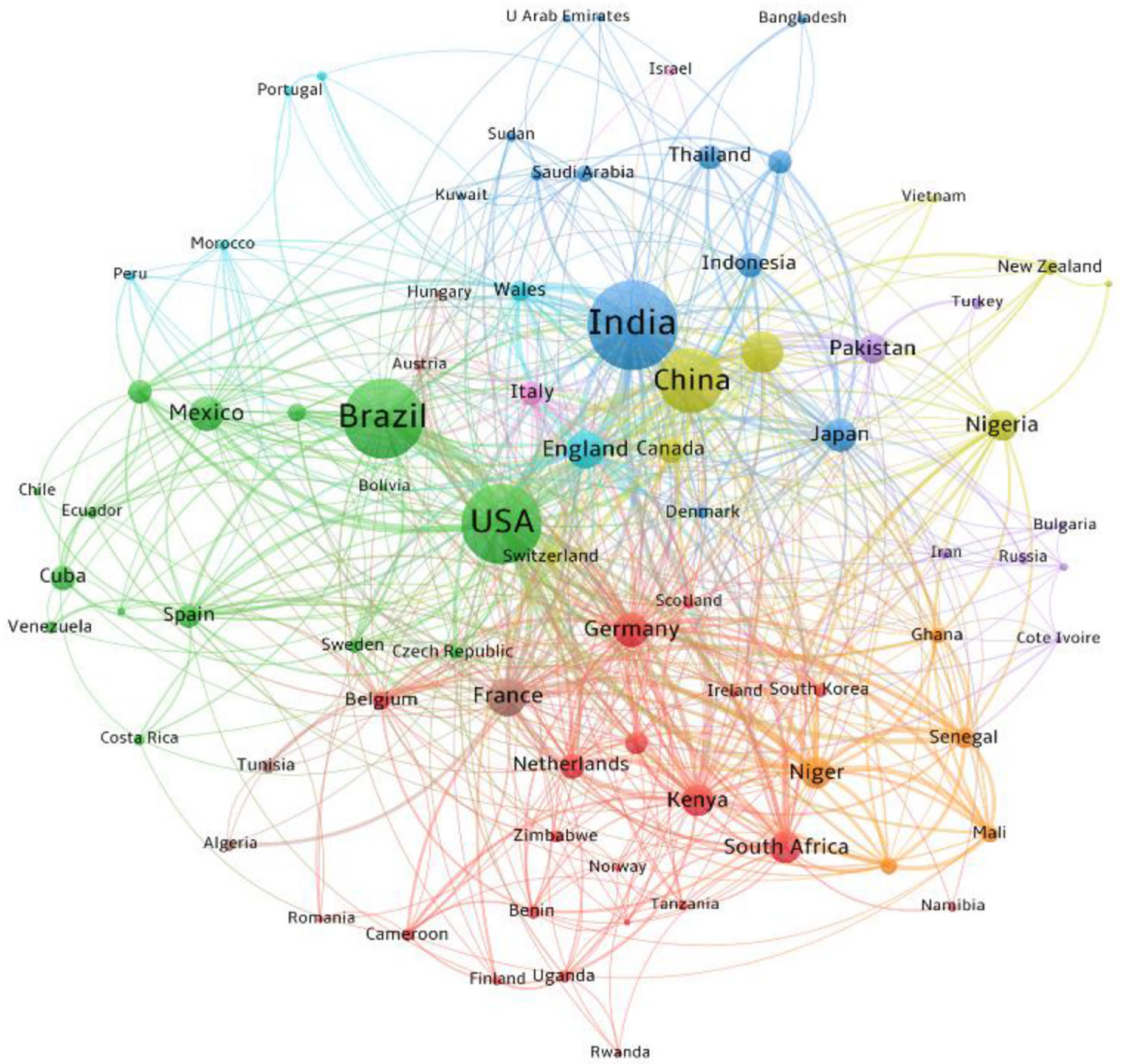

FIGURE 3
Network visualization of co-authorship of countries with a minimum of five publications.

1970 and 2023, only 13 nations had a total exceeding 200 publications, this suggests that global attention to the genus *Pennisetum* is relatively concentrated within a small group of countries.

To gain insight into the collaborative patterns among countries most actively researching *Pennisetum*, this study analyzed the national co-occurrence networks. The focus was on countries with five or more publications linked by co-authorship. The analysis resulted in the formation of nine clusters (depicted in Figure 3). This clustering indicates that *Pennisetum* research has evolved into a global network rather than being confined to isolated regional studies. Such international collaboration is highly beneficial for the advancement of *Pennisetum* research. It promotes resource sharing and maximizes the utilization of available resources, thereby enhancing the overall efficiency and scope of research efforts in this field.

3.3 Most published journals on *Pennisetum*

The analysis of the most productive affiliations in *Pennisetum* research during the period under review is presented in Table 2. The findings highlight the top five journals with the highest total publication volume on *Pennisetum* research. These journals are: *Indian Journal of Agriculture Sciences, Revista Brasileira de Zootecnia-Brazilian Journal of Animal Science*, *Indian Journal of Agronomy*, *Crop Science*, *Cuban Journal of Agricultural Science*. When it comes to citations, the scenario shifts slightly. The top five most cited journals in *Pennisetum* research are: *Theoretical and Applied Genetics*, *Agronomy Journal*, *Crop Science*, *Journal of Experimental Botany* and *Bioresource Technology*. It is noteworthy that the journal with the highest h-index in this field is *Theoretical and Applied Genetics*, followed by *Bioresource Technology* and *Field Crops Research*.

TABLE 2 The 20 most productive journals in the *Pennisetum* research fields.

Journal	NP	TC	h_index	g_index	IF
Indian Journal of Agricultural Sciences	163	570	11	16	0.4
Revista Brasileira de Zootecnia-Brazilian Journal of Animal Science	120	1,195	18	24	1
Indian Journal of Agronomy	103	183	5	7	-
Crop Science	101	2,264	24	44	2.3
Cuban Journal of Agricultural Science	84	140	6	7	0.1
Pesquisa Agropecuaria Brasileira	80	1,272	20	32	0.8
Theoretical and Applied Genetics	77	2,604	29	49	5.4
Agronomy Journal	70	2,434	22	48	2.1
Euphytica	57	782	15	25	1.9
Field Crops Research	50	1,696	25	40	5.8
Journal of Experimental Botany	48	2,104	25	45	6.9
Bioresource Technology	47	2,012	27	44	11.4
Frontiers in Plant Science	45	569	14	22	5.6
Semina-Ciencias Agrarias	42	177	7	10	0.5
Plant and Soil	40	1,211	20	34	4.9
Current Science	37	106	6	8	1
Animal Feed Science and Technology	36	676	17	24	3.2
Tropical Animal Health and Production	36	328	12	16	1.7
Asian-Australasian Journal of Animal Sciences	33	409	12	18	2.7
Environmental Science and Pollution Research	33	380	12	18	5.8

NP, number of publications; h-index, a scientist or affiliation has index *h* if h of his/her/its Np papers have at least h citations each, and the other (Np-h) papers have no more than h citations each (Hirsch, 2010); g-index, given a set of articles ranked in decreasing order of the number of citations that they received, the g-index is the unique largest number such that the top g articles received together at least g^2 citations (Egghe, 2006). IF, impact factor.

These findings elucidate an important aspect of academic publishing: the number of publications a journal has does not always correlate with its citation and impact indices. A journal may have a high volume of publications, but this doesn't automatically translate to a high impact or citation rate. Conversely, journals with fewer publications can sometimes have articles of higher quality, as indicated by their citation rates and h-index. This underscores the importance of considering both quantity and quality when evaluating the influence and significance of journals in a specific research area.

3.4 Citation analysis

To gain a more nuanced understanding of the current research domains within the field of *Pennisetum*, a detailed analysis was conducted on 30 highly cited articles selected from the 5,397 literature pieces (as detailed in Table 3). This analysis, centered on the titles of these articles, reveals that their research themes are primarily clustered into several distinct areas.

3.4.1 Cultivation and breeding

This is a prominent field, with the top four most cited articles among the top 30 focusing on cultivation and breeding practices (Tien et al., 1979; Garciahuidobro et al., 1982; Luo, 2011; Varshney et al., 2017). This highlights the significant emphasis on developing and improving *Pennisetum* varieties through breeding techniques and cultivation methods.

3.4.2 Ecological restoration

This category encompasses articles that delve into two main sub-areas: heavy metal uptake (Zhang et al., 2010; Yin et al., 2020) and erosion control (Mant et al., 2006; Cui et al., 2016). *Pennisetum*'s capacity to absorb heavy metals like cadmium from contaminated soils is a major focus, underscoring its role in environmental remediation. Additionally, the plant's rapidly developing root system positions it as an effective tool for soil erosion control.

3.4.3 Industrial applications

The third major research area pertains to industrial applications, with a specific emphasis on energy production (Strezov et al., 2008; Li et al., 2012; Kang et al., 2018) and the development of industrial materials (Woodard and Prine, 1993; Eliana et al., 2014; Ridzuan et al., 2016). Energy production,

TABLE 3 The top 30 highly-cited papers related to *Pennisetum* research (1970–2023).

Rank	TC	Title	DOI
1	663	Plant-growth substances produced by Azospirillum-Brasilense and their effect on the growth of pearl-millet (*Pennisetum-Americanum* L) (Tien et al., 1979)	10.1128/AEM.37.5.1016-1024.1979
2	372	Time, temperature and germination of pearl-millet (*Pennisetum*-Typhoides S-And-H). 1. Constant temperature (Garciahuidobro et al., 1982)	10.1093/jxb/33.2.288
3	245	Temperature thresholds and crop production: a review (Luo, 2011)	10.1007/s10584-011-0028-6
4	208	Pearl millet genome sequence provides a resource to improve agronomic traits in arid environments (Varshney et al., 2017)	10.1038/nbt.3943
5	192	Ecophysiology of introduced *Pennisetum-Setaceum* on Hawaii - the role of phenotypic plasticity (Williams et al., 1995)	10.2307/1938158
6	177	Capacity and mechanisms of ammonium and cadmium sorption on different wetland-plant derived biochars (Cui et al., 2016)	10.1016/j.scitotenv.2015.09.022
7	164	Tight clustering and hemizygosity of apomixis-linked molecular markers in *Pennisetum Squamulatum* genetic control of apospory by a divergent locus that may have no allelic form in sexual genotypes (Ozias-Akins et al., 1998)	10.1073/pnas.95.9.5127
8	162	Isolation and culture of cereal protoplasts.2. Embryogenesis and plantlet formation from protoplasts of *Pennisetum-Americanum* (Vasil and Vasil, 1980)	10.1007/BF00265079
9	161	Potential of four forage grasses in remediation of Cd and Zn contaminated soils (Zhang et al., 2010)	10.1016/j.biortech.2009.11.065
10	161	Terminal drought-tolerant pearl millet [*Pennisetum* Glaucum (L.) R.Br.] have high leaf Aba and limit transpiration at high vapor pressure deficit (Kholová et al., 2010b)	10.1093/jxb/erq013
11	159	Novel Fe-Mn binary oxide-biochar as an adsorbent for removing Cd (Ii) from aqueous solutions (Yin et al., 2020)	10.1016/j.cej.2020.124465
12	154	Constitutive water-conserving mechanisms are correlated with the terminal drought tolerance of pearl millet [*Pennisetum Glaucum* (L.) R. Br.] (Kholová et al., 2010a)	10.1093/jxb/erp314
13	146	Thermal conversion of elephant grass (*Pennisetum Purpureum Schum*) to bio-gas, bio-oil and charcoal (Strezov et al., 2008)	10.1016/j.biortech.2008.02.039
14	138	Biogas production potential and kinetics of microwave and conventional thermal pretreatment of grass (Li et al., 2012)	10.1007/s12010-011-9503-9
15	136	Somatic embryogenesis and plant-regeneration from tissue-cultures of *Pennisetum Americanum*, and *P-Americanumxp-Purpureum* hybrid (Vasil and Vasil, 1981)	10.2307/2443193
16	125	Characterization of natural cellulosic fiber from *Pennisetum Purpureum* stem as potential reinforcement of polymer composites (Ridzuan et al., 2016)	10.1016/j.matdes.2015.10.052
17	123	A Parthenogenesis gene of apomict origin elicits embryo formation from unfertilized eggs in a sexual plant (Conner et al., 2015)	10.1073/pnas.1505856112
18	118	Characterization of plant-growth-promoting traits of *Acinetobacter* species isolated from rhizosphere of *Pennisetum Glaucum* (Rokhbakhsh-Zamin et al., 2011)	10.4014/jmb.1012.12006
19	105	Effects of the pretreatment method on enzymatic hydrolysis and ethanol fermentability of the cellulosic fraction from elephant grass (Eliana et al., 2014)	10.1016/j.fuel.2013.10.055
20	99	Biochemical and molecular analysis of plants derived from embryogenic tissue cultures of napier grass (*Pennisetum Purpureum* K. *Schum*) (Shenoy and Vasil, 1992)	10.1007/BF00232955
21	99	Phytoremediation of chromium by model constructed wetland (Mant et al., 2006)	10.1016/j.biortech.2005.09.010
22	98	Structural changes and enzymatic response of Napier grass (*Pennisetum Purpureum*) stem induced by alkaline pretreatment (Phitsuwan et al., 2016)	10.1016/j.biortech.2016.06.089
23	98	Development and mapping of simple sequence repeat markers for pearl millet from data mining of expressed sequence tags (Senthilvel et al., 2008)	10.1186/1471-2229-8-119
24	95	An Integrated genetic map and a new set of simple sequence repeat markers for pearl millet, *Pennisetum Glaucum* (Qi et al., 2004)	10.1007/s00122-004-1765-y
25	93	Dry-matter accumulation of elephantgrass, energycane, and elephantmillet in a subtropical climate (Woodard and Prine, 1993)	10.2135/cropsci1993.0011183X003300040038x
26	92	Characterization of an embryogenic cell-suspension culture derived from cultured inflorescences of *Pennisetum-Americanum* (Pearl Millet, Gramineae) (Vasil and Vasil, 1982)	10.2307/2443105

(Continued)

TABLE 3 (Continued)

Rank	TC	Title	DOI
27	90	Improving methane production from anaerobic digestion of *Pennisetum* hybrid by alkaline pretreatment (Kang et al., 2018)	10.1016/j.biortech.2017.12.001
28	88	Genome size variation and basic chromosome number in pearl millet and fourteen related *Pennisetum* species (Martel et al., 1997)	10.1093/oxfordjournals.jhered.a023072
29	88	Lewis acid-facilitated deep eutectic solvent (des) pretreatment for producing high-purity and antioxidative lignin (Wang et al., 2020)	10.1021/acssuschemeng.9b05846
30	87	Systematic study of *Pennisetum*-Sect - *Pennisetum* (Gramineae) (Brunken, 1977)	10.2307/2442104

in particular, stands out as a key area of interest, reflecting the growing global focus on sustainable and renewable energy sources.

The citation frequency and relevance of these articles provide valuable insights into the current research foci within the *Pennisetum* field. Thus, it can be inferred that cultivation and breeding, ecological restoration, and industrial applications are the primary areas of interest and development in *Pennisetum* research. This analysis not only helps in understanding the current trends but also aids in identifying potential areas for future research and development.

3.5 Co-occurrence of keywords plus

The co-occurrence analysis of keywords in *Pennisetum* research offers valuable insights into the primary focus areas in recent years, guiding scientists interested in this field. From the pool of 5,397 documents on *Pennisetum*, a total of 7,564 keywords were identified as co-occurring. Using VOSviewer, a threshold was set for a keyword occurrence frequency of 15, resulting in 308 keywords meeting this criterion. These keywords were then categorized into six distinct clusters (as illustrated in Figure 4).

3.5.1 Green cluster

Dominated by the keyword "*Pennisetum*", this cluster includes terms like "identification," "apomixes," and "genetic diversity." The presence of these keywords suggests a recent research emphasis on breeding and cultivation within the *Pennisetum* genus.

3.5.2 Purple cluster

This cluster features keywords such as "phytoextraction," "toxicity," and "extract." The focus on "accumulation," "zinc," and "heavy-metal" indicates that the field of heavy-metal remediation through plant absorption has garnered significant attention.

3.5.3 Red cluster

Keywords like "yield," "soil," "management," and "nitrogen" are prevalent here. Related terms such as "water-use," "sandy soil," and "conservation" point toward research in soil erosion control.

3.5.4 Blue cluster

Focused on "digestibility", with associated terms like "quality," "fermentation," and "cattle." This cluster is primarily concerned with the use of *Pennisetum* as pasture or silage, as indicated by keywords like "pasture," "feed-intake," "cows," "diet," "rumen," etc.

3.5.5 Cyan cluster

The most frequently occurring terms here are "biomass" and "pretreatment". This cluster also encompasses keywords related to industrial application such as "bioethanol production," "methane production," and "biogas production."

3.5.6 Yellow cluster

The keyword "plant" is prominent here, followed by "growth". This cluster also aligns with cultivation and breeding, evidenced by terms like "mechanism," "gene," "expression," and "tissue culture."

The keyword clustering analysis reveals that each cluster encapsulates a distinct theme. The green and yellow clusters are focused on breeding and cultivation; the red and purple clusters pertain to ecological restoration; the blue cluster centralizes on pasture or silage usage; and the cyan cluster is dedicated to industrial applications. This segmentation of themes provides a comprehensive understanding of the current research landscape in *Pennisetum*, highlighting diverse areas of interest and potential avenues for future research.

3.6 Keywords time trend

The analysis of keyword trends over time provides a dynamic perspective on the evolving research interests in the field of *Pennisetum*. Two key graphical representations, the Keyword Time Trend graph (Figure 5) and the Keywords with the Strongest Citation Bursts graph (Figure 6), offer valuable insights into these trends.

3.6.1 Keyword time trend analysis

The Keyword Time Trend graph (Figure 5) visualizes the frequency and timeline of high-frequency keywords. The color intensity of the timeline indicates the recency of a keyword's prominence. From this graph: Keywords like "*Pennisetum*," "growth," "plant," and "forage" were predominantly featured in the period 2010–2014; post-2016, terms such as "diversity," "quality," and "residue" gained prominence; In the last 5 years, the focus shifted to terms like "heavy metals," "lignocellulosic biomass," and "biogas production."

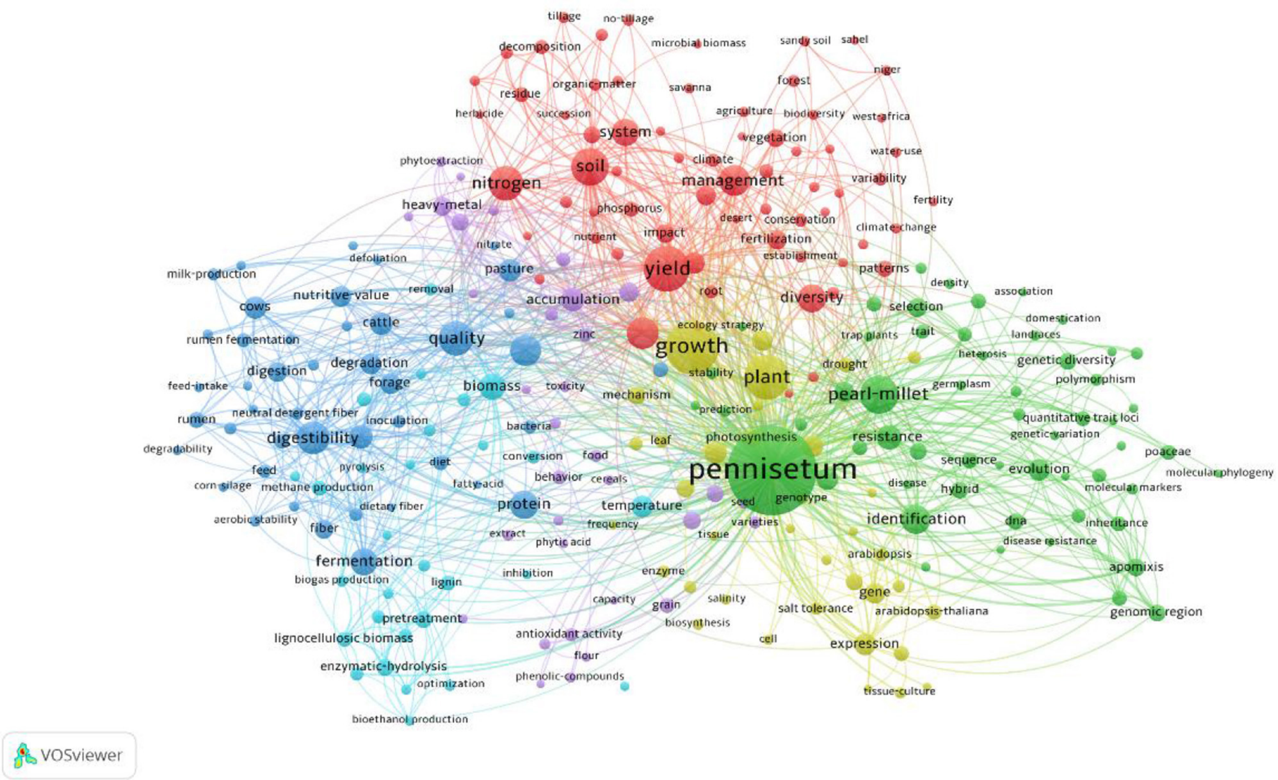

FIGURE 4
Network visualization of co-occurrence of keywords plus in *Pennisetum* related research based on Web of Science database (1970–2023).

3.6.2 Keywords with the strongest citation bursts analysis

Complementing the Time Trend graph, the Keywords with the Strongest Citation Bursts graph (Figure 6), created using CiteSpace, offers a more detailed understanding of the timing and intensity of keyword usage. Key elements of this graph include:

Year: The time when a keyword first appeared; Strength: The intensity of the keyword's usage; Begin: The central appearance or outbreak time point of the keyword; End: The time when the keyword's popularity started to decline.

In this graph, the red area on the time axis indicates the burst period (Begin-End), the gray area shows periods of lesser attention, and the blue area signifies ongoing use but with reduced intensity. Notable observations from this analysis include: Keywords like "dna," "apomixes," and "cattle" had the longest duration of bursts, implying that relevant research continues to receive attention. Although "accumulation" and "fiber" were used earlier, they have gained more prominence recently. The most recent focus, especially in the past 5 years, has been on terms like "heavy metals" and "lignocellulosic biomass".

These analyses collectively reveal a dynamic shift in research focus within the *Pennisetum* field, moving from basic plant characteristics and forage aspects to more specific areas like ecological restoration, genetic studies, and biomass utilization. This evolution reflects broader trends in agricultural and environmental research, indicating areas of growing interest and potential future research directions.

4 Discussion

The primary focus of this study entails employing bibliometric methodologies to scrutinize articles pertaining to *Pennisetum* published over the last five decades. This analysis encompasses an examination of themes, abstracts, and keywords utilizing VOSviewer, the R programming language, and CiteSpace. The overarching objective is to discern shifts in research interests and forecast future trends within the field of *Pennisetum*. Firstly, it is noteworthy that contemporary research on *Pennisetum* has experienced a progressive surge in attention, characterized by substantial enhancements in both the quantity and caliber of related studies, in comparison to its nascent stages of development. Moreover, there is evidence of an emerging trend toward global collaborative research endeavors. Secondly, our investigation has revealed that the current focal points of *Pennisetum* research tend to coalesce around three primary areas. Lastly, through a review of recent literature and a comprehensive analysis of our earlier findings, we have further subdivided these key research domains and identified three burgeoning areas of interest for future investigation. It is worth noting that research pertaining to the forage applications of *Pennisetum* is poised to remain a consistent and enduring theme.

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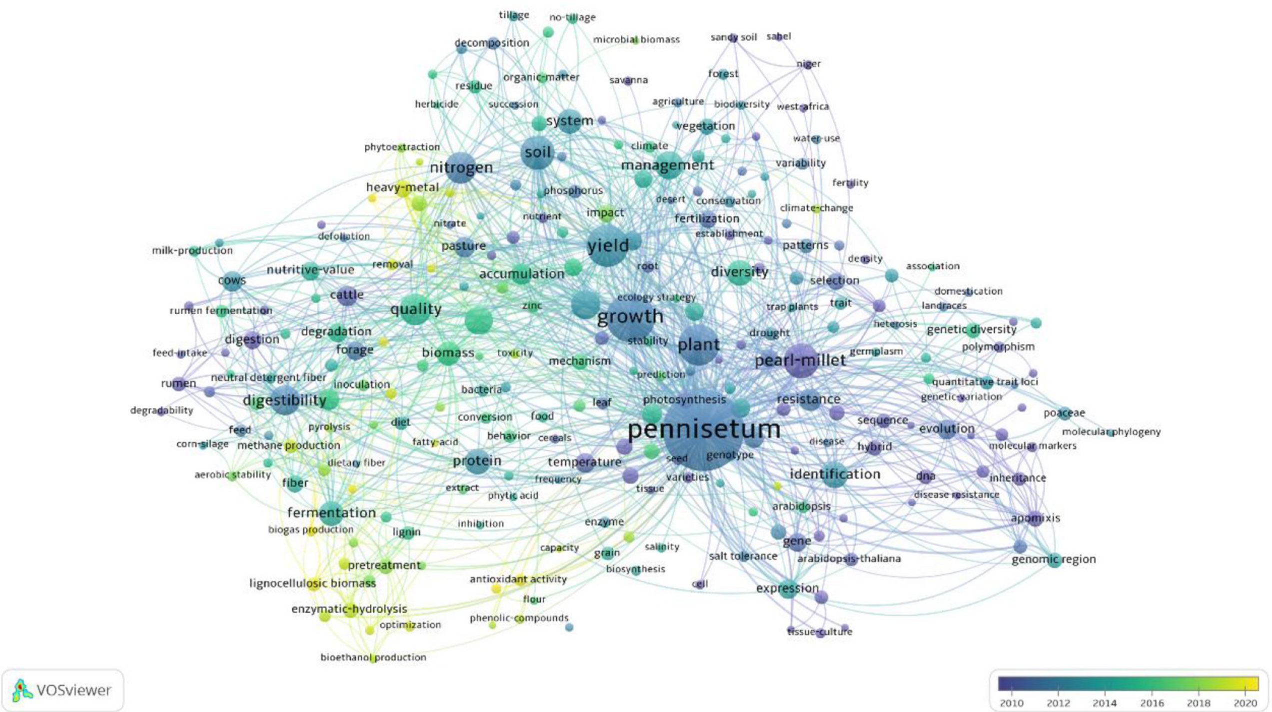
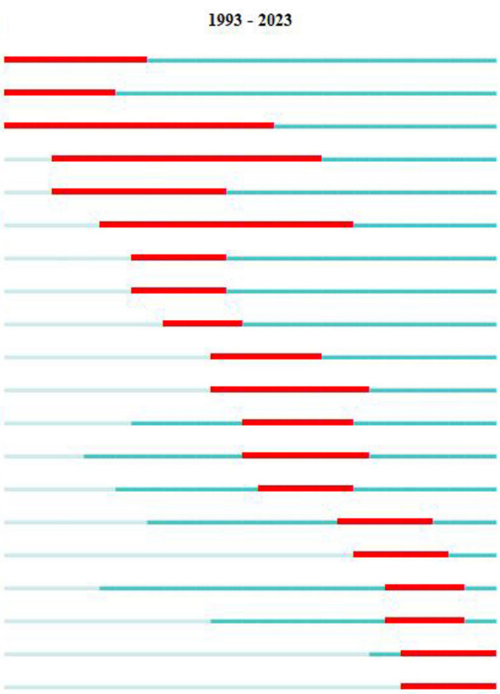


FIGURE 5
Keyword time trend graph.



Keywords	Year	Strength	Begin	End	1993 - 2023
somatic embryogenesis	1993	15.3	**1993**	2001	
plant regeneration	1993	11.41	**1993**	1999	
dna	1993	7.07	**1993**	2009	
apomixis	1996	6.95	**1996**	2012	
forage	1996	6.69	**1996**	2006	
cattle	1999	10.83	**1999**	2014	
downy mildew	2001	6.48	**2001**	2006	
marker	2001	6.48	**2001**	2006	
inheritance	2003	6.57	**2003**	2007	
genomic region	2006	7.77	**2006**	2012	
dry matter	2006	6.8	**2006**	2015	
management	2001	12.31	**2008**	2014	
system	1998	8.15	**2008**	2015	
evolution	2000	8.69	**2009**	2014	
fermentation	2002	12.27	**2014**	2019	
enzymatic hydrolysis	2015	15.02	**2015**	2020	
fiber	1999	8.02	**2017**	2021	
accumulation	2006	6.68	**2017**	2021	
heavy metals	2016	15.35	**2018**	2023	
lignocellulosic biomass	2018	11.95	**2018**	2023	

FIGURE 6
Top 20 keywords with the strongest citation bursts.

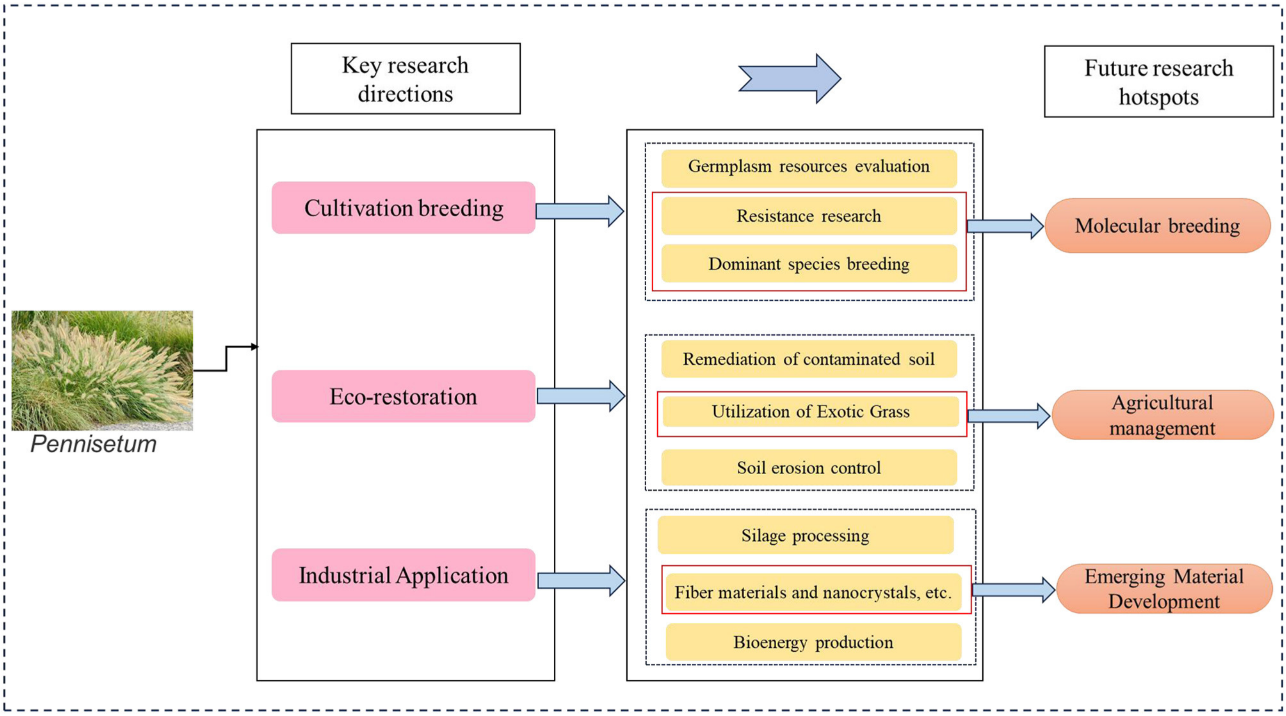


FIGURE 7
Key research areas and future research hotspots of the *Pennisetum*.

4.1 Research attention and emerging global cooperation

From the perspective of annual publication trends in the field of *Pennisetum*, the number of articles published each year has shown a consistent increase since 1970. This upward trajectory reflects a growing interest and research focus on *Pennisetum*. Based on this trend, we can divide the research timeline into three distinct periods: the embryonic stage (1970–1990), the developmental stage (1991–2007), and the mature stage (2008–2023). Initially, research on *Pennisetum* was primarily centered around its application in forage feed (Hsu et al., 1990; Wu et al., 2020). However, as economic development and scientific and technological advancements have occurred, the research scope of *Pennisetum* has gradually broadened, extending beyond forage research. Presently, research directions encompass a diverse range of fields, including stress resistance, cultivation, breeding, and environmental restoration.

When considering the volume of national publications, it's noteworthy that Brazil and the United States occupy the first and third positions, respectively, with India in second place. The United States and Brazil have developed robust animal husbandry industries, characterized by high-quality pasture and ample grassland, owing to their unique geographical and environmental features. *Pennisetum*, with its tender, protein-rich leaves and high crude fiber content, plays a pivotal role in improving the quality of cattle meat products and enhancing animal digestion. Consequently, its use as a primary source of nutrition for ruminants not only fulfills their forage requirements but also elevates the quality of livestock and dairy products (Schneider et al., 2016; Dourado et al., 2019).

India, primarily focusing on agriculture development due to economic and natural constraints, has become a major agricultural nation with a substantial agricultural product export industry. However, agricultural development in India is highly contingent on natural conditions, necessitating the selection of crop species suited to local climate and terrain. India predominantly raises cows, with a tradition of dairy farming, but faces challenges related to the poor quality of dairy cows and products. Additionally, the limited availability of land for fodder crops and pasture hampers agricultural development. Therefore, there is a growing need for a crop that can both enhance the quality of dairy products and exhibit high productivity, making *Pennisetum* the ideal choice due to its inherent advantages (Toderich et al., 2018; Singh et al., 2020).

China, the first Asian country to feature prominently on the list of high-yield countries, holds the fourth position overall. *Pennisetum* thrives in a hot and humid climate, with optimal growth temperatures ranging between 25 and 30°C. As a result, *Pennisetum* is cultivated in various regions of China for multiple purposes (Deng et al., 2019; Zi et al., 2021). In the northwest, it is primarily grown for soil and water conservation, windbreak, and sand fixation. In saline or soil-polluted areas, *Pennisetum* is employed to enhance soil quality. Additionally, the southwestern region extensively utilizes *Pennisetum* for its forage function (Xu et al., 2015; Hei et al., 2016).

The last five countries in the high-yield country ranking for *Pennisetum* research are Pakistan, Germany, South Africa, Kenya, and Thailand. It is noteworthy that Germany and Thailand, despite engaging in research across various fields related to the genus *Pennisetum*, have produced relatively limited literature in this domain. This scarcity can be attributed to the lack of researchers in *Pennisetum* in both countries as well as the low level of interest in the field.

Kenya, South Africa, and Pakistan, on the other hand, share the common characteristic of being situated in arid or semi-arid regions characterized by harsh climates. In such environments, crops that can withstand drought conditions and meet essential food needs are paramount. *Pennisetum* glaucum (L.) R. Br. has demonstrated adaptability to these challenging conditions and has consequently emerged as a vital food and fodder crop in India and Africa (Yadav et al., 2021). This particular crop not only exhibits drought tolerance but also demonstrates soil-fixing capabilities and high productivity, rendering it suitable for large-scale cultivation. This characteristic may elucidate the substantial volume of related studies conducted in these regions (Mula et al., 1999; Mwendia et al., 2017).

In conclusion, interest in *Pennisetum* has been steadily increasing, evident in both the annual publication trends and the involvement of high-producing countries in research. Furthermore, research on *Pennisetum* transcends regional boundaries and has become a global endeavor. Each country conducts research in accordance with its specific needs and interests, fostering diverse collaborations and connections based on *Pennisetum* research. These collaborative efforts aim to enhance the availability of this crop and forage while realizing its comprehensive utilization.

4.2 Significant research areas concentrate on three main directions: cultivation and breeding, ecological restoration, and industrial application

In our citation analysis, we have organized the top 30 highly cited articles into three primary categories based on their titles: cultivation and breeding, ecological restoration, and industrial application. Similarly, during the keyword cluster analysis, each cluster was attributed to a major thematic area, aligning consistently with the categories derived from the citation analysis.

Within the domain of cultivation and breeding of *Pennisetum*, research encompasses a wide array of directions. In the context of cultivation and breeding, researchers place particular emphasis on assessing the state of *Pennisetum* resources. This entails the exploration of genetic resources and gene sequences within the *Pennisetum* (Martel et al., 1996; Li et al., 2015). Such investigations have yielded valuable insights into genes that significantly contribute to its growth and development, thereby establishing a robust foundation for the selection and cultivation of advantageous genes or species. Apart from germplasm resource research, many scholars are intrigued by the remarkable environmental adaptability demonstrated by *Pennisetum*, prompting extensive inquiries into its tolerance to stressors such as salt, alkali, and drought (Misra et al., 1995; Vanoosterom et al., 1995; Li et al., 2016b). In regions characterized by challenging environmental conditions, research into stress resistance plays a pivotal role in identifying *Pennisetum* varieties that can thrive under conditions of drought or saline-alkali. The overarching objective is to enhance our understanding of the physiological and biochemical properties of these plants and to cultivate more advantageous *Pennisetum* species through these comprehensive investigations.

In order to fulfill the objective of sustainable development, ecological restoration seeks to minimize ecological costs while causing no harm to the existing ecosystem. When employed for ecological restoration purposes, *Pennisetum* contributes to the enhancement of soil productivity while simultaneously improving the local biological environment. The root adsorption capacity of *Pennisetum* positions it as a valuable asset for remediating polluted soil. Some scholars investigating the capacity of three different tropical grasses to uptake heavy metals identified *Pennisetum* as a potential phytostabilizer for cadmium (Cd), zinc (Zn), and copper (Cu) in phytoremediation efforts (Ng et al., 2016). According to research by Jiang et al. (2019), *Pennisetum* grown near municipal waste not only enhanced the plant's ability to produce fiber paper but also removed heavy metal contaminants from the sludge. Furthermore, when these plants are placed in areas susceptible to soil erosion, they can reduce water evaporation, enhance soil water retention, and accelerate plant recovery rates (Yang et al., 2016; Vadivel et al., 2019). The role of *Pennisetum* in ecological restoration extends beyond these aspects and also includes its effectiveness in remediating saline soil and purifying artificial wetland water bodies (Udom et al., 2018; Ujang et al., 2021).

Industry traditionally underpins a country's development, and the availability of energy resources reflects a nation's comprehensive strength. However, many countries worldwide are currently grappling with energy shortages. Simultaneously, in the context of global climate change, the development of clean energy has become a focal point for nations globally. *Pennisetum* has emerged as an energy crop for industrial production in recent years. *Pennisetum* boasts a high lignocellulose content, making it a promising candidate for energy utilization. Its applications in industrial production encompass biogas production (Huang et al., 2011) and bioethanol production (Yasuda et al., 2014; Blessie et al., 2021). Additionally, *Pennisetum* stems and leaves can be directly burned to generate heat for electricity production. Elephant grass-based power stations have been established in the UK (Zhang, 2014), and *Pennisetum* serves as the primary fuel for a 90 MW biomass power plant in Thailand (Zhang et al., 2017). In the course of examining its agronomic and biomass quality attributes, it has also been discovered that elephant grass contains the capacity to directly burn biomass and make second generation ethanol (Rocha et al., 2017). *Pennisetum* is favored in industrial production due to its cost-effectiveness, high efficiency, and the environmentally friendly nature of its derivative products, which align with current energy demands.

In summary, research on *Pennisetum* spans a diverse array of directions, with a notable focus on cultivation and breeding. However, attention toward ecological restoration and industrial production has surged in recent years. *Pennisetum* is mostly used in phytoremediation in ecological restoration, while in industrial production, it predominantly serves as a source of energy production.

4.3 Future research hotspots in *Pennisetum* research

The timing of high-frequency keyword occurrences can serve as a reflection of the areas of focus within related research over different periods. Additionally, the keyword burst chart provides insights into the initiation, culmination, and intensity of a keyword's usage. Therefore, the amalgamation of both graphs is instrumental in comprehending the dynamics of the research field and projecting future research hotspots based on the temporal trends in keyword appearance.

Upon combining Figures 5, 6, it becomes evident that several terms related to molecular breeding, such as "identification," "marker," and "genomic region," are recurrent in both Figures. This phenomenon arises from the application of genetic engineering techniques to enhance crop varieties, offering viable solutions to conventional breeding challenges. Moreover, it holds the potential to generate novel species or traits, surmounting obstacles associated with interspecific hybridization. Consequently, molecular breeding is poised to be a focal point of future research across various domains.

Molecular breeding of *Pennisetum* represents a method of genetic enhancement employing modern biotechnology to cultivate new varieties endowed with superior traits. Recent years have witnessed significant advancements in the realm of *Pennisetum* molecular breeding, propelled by ongoing technological progress. First and foremost, multiple *Pennisetum* varieties have undergone genome sequencing and genetic variation analysis, resulting in the discovery of numerous pivotal genes associated with yield, stress resistance, disease resistance, and more. This genetic knowledge serves as fundamental data for advancing molecular breeding endeavors (Negawo et al., 2017; Zhao et al., 2019; Jin et al., 2023). Furthermore, novel technological tools have emerged within the molecular breeding arsenal for the *Pennisetum* genus, encompassing gene cloning, gene editing, gene transformation, and others. These innovative methodologies enable effective modification of *Pennisetum* traits, leading to shortened breeding cycles and heightened breeding efficiency (Roy et al., 2022). Additionally, substantial accomplishments have been achieved through the application of molecular breeding in *Pennisetum*. For instance, genetic engineering has been harnessed to cultivate new *Pennisetum* varieties endowed with exceptional attributes like insect resistance, disease resistance, and drought resistance. These efforts have yielded promising results in practical applications (de Souza et al., 2019; Srivastava et al., 2020, 2022). To sum up, the molecular breeding of *Pennisetum* has made remarkable strides, offering vital technical support for genetic enhancement and the cultivation of exceptional *Pennisetum* varieties. Nonetheless, it is important to acknowledge that molecular breeding still grapples with certain limitations, necessitating comprehensive consideration in alignment with practical application requirements and technological constraints.

In addition to molecular breeding, agricultural management of *Pennisetum* emerges as another crucial research area for future investigation. Agricultural development serves as the foundation of industrial progress, and the natural environment stands as a prerequisite for agricultural advancement. Adding cover crops to crop rotation systems is the most popular agricultural management strategy used to improve crop productivity (Wang et al., 2023). Apart from its application as a cover crop (Boer et al., 2007; Ruis et al., 2019), *Pennisetum* have two roles in the advancement of agriculture. On one hand, it can serve as a valuable resource for ecological remediation, addressing issues like the remediation of heavy metal-contaminated soil, windbreak, and sand fixation. On the other hand, being an exotic grass species with robust adaptability, it has the capacity to rapidly colonize nearby agricultural soil, potentially impacting other crops and ecosystems. Thus, it becomes imperative to effectively manage this plant to maximize its benefits within the realm of agriculture.

Plant invasions can seriously affect a region's environment and even upset the ecosystem's overall balance. Shrub invasion was found to affect changes in soil systems, primarily by altering soil organic and inorganic carbon stocks (Ding et al., 2020a). Shrub invasion can also invade ecoregional microorganisms, albeit the impact on soil fungi and bacteria will vary (Ding et al., 2020b). *Pennisetum* exhibits a formidable invasive potential, and biofuels derived from it may extend beyond their intended planting areas, encroaching upon neighboring agricultural and natural regions, thereby posing challenges to local ecosystems (Brooks et al., 2010). For instance, on the island of Hawaii, African bunchgrass (*Pennisetum setaceum*) has invaded the understory of the remaining fragments of native dry forest, contributing to the degradation of what was once a diverse ecosystem (Cordell and Sandquist, 2008). Consequently, the active management of invasive species has emerged as a pressing concern. Furthermore, despite its invasive nature, *Pennisetum* can also supplant and control other invasive species. In China, the natural environment and crop survival face significant threats from invasive species such as plane grass and ragweed. Planting *Pennisetum* × sinese in invaded areas creates a dynamic of mutual competition among plants. Ultimately, the plant barrier formed by *Pennisetum* × sinese effectively inhibits the growth and reproduction of foreign species. Whether *Pennisetum* is treated as an invasive species or an alternative species, judicious management of this plant can prove beneficial for agricultural development, offering solutions that outweigh potential drawbacks.

Molecular breeding seeks to genetically enhance the advantageous traits of *Pennisetum*, while agricultural management aims to harness the plant's strengths within the realm of agriculture. However, as an energy crop, *Pennisetum*'s utility extends far beyond agriculture. Its high fiber content and substantial lignin biomass position it as a valuable resource not only for energy production but also for the development of new materials.

In the keyword emergence and keyword burst maps (Figures 5, 6), recent years have seen the emergence of terms like "optimization," "lignocellulosic biomass," "lignin," "fiber," and "enzymatic hydrolysis." These terms reflect the increasing attention some scholars have started to devote to the role of *Pennisetum* in the field of emerging materials research and development, albeit with a relatively low degree of focus. Research and development in emerging materials hold promise for industrial progress, and the wide accessibility of *Pennisetum*, coupled with its cost-effectiveness and high utilization rate, aligns perfectly with the current emphasis on ecological conservation. Therefore, dedicating more attention to this field in the future is likely to yield valuable outcomes for public benefit.

Pretreatment technology plays a pivotal role in enhancing the industrial utilization of *Pennisetum*, optimizing its comprehensive utilization, and facilitating the production of related products. For instance, Wang et al. conducted research on the effects of ammonia pretreatment on the structural and hydrolytic properties of *Pennisetum* and hybrid *Pennisetum*. Their findings indicated that ammonia pretreatment improved cellulose crystallinity and hydrolysis capacity of *Pennisetum* (Wang et al., 2016). Elephant grass that has been steam-blasted has been shown to be a useful substrate for the production of enzymes necessary for the hydrolysis of lignocellulosic biomass (Scholl et al., 2015). Similarly, medium-temperature and [EMIM]AC pretreatment achieved high hydrolysis rates of fermentable sugars from *Pennisetum* (Xin et al., 2016).

The substantial fiber content of *Pennisetum* has paved the way for its application in the production of chemical materials. Typically, only *Pennisetum* leaves are utilized, while the straw is often discarded or burned, resulting in resource wastage. Some scholars have taken an innovative approach by extracting cellulose from *Pennisetum* straw to create magnetic cellulose adsorbents for the removal of antibiotics like tetracycline (TC) from water. This research has shown promising results, warranting further investigation (Sun et al., 2021). Other scholars have prepared cellulose nanocrystals using *Pennisetum* as a raw material through ammonium sulfate oxidation (Aryasena et al., 2022), Synthesis of a new silver nanoparticle (Ag-NPs) from the husk of pearl millet (Musere et al., 2021). In researching potential raw material resources for lightweight composites, scholars have found that behaviors derived from *Pennisetum* glaucum have high water-absorbent properties and can be used as coatings for wet wipes in cleaning applications (Vinod et al., 2023). Furthermore, *Pennisetum* fibers have been utilized as reinforcing materials for polymer-based materials (Cabrera-García et al., 2023).

In conclusion, *Pennisetum*'s potential transcends agriculture and energy production, encompassing the development of new materials. Focusing more attention on this aspect of *Pennisetum* research holds great promise for future industrial applications and ecological conservation.

From the discussion above, it is evident that future research hotspots related to the genus *Pennisetum* will predominantly revolve around molecular breeding, agricultural management of *Pennisetum*, and the advancement of emerging materials. However, it's important to recognize that research hotspots are not static, and new directions may emerge in the course of future research endeavors.

Nonetheless, it is crucial to acknowledge the limitations of this article. Firstly, it relies solely on articles published in the Web of Science core dataset, potentially overlooking valuable *Pennisetum* literature from other sources. Secondly, the analysis primarily focuses on high-yield countries, journals, and highly cited articles, while omitting an examination of high-yield authors and institutions. Consequently, this article does not identify the authors and institutions that have made the most significant contributions to the field of *Pennisetum* research. These limitations notwithstanding, the article provides valuable insights and serves as a reference for current and prospective *Pennisetum* research to a certain extent.

5 Conclusions

This bibliometric evaluation of scientific literature concerning *Pennisetum* provides an insightful analysis of both historical and contemporary research trends associated with this crop (Figure 7). Through a detailed performance analysis encompassing countries, journals, and highly cited articles, several key conclusions have been reached. Over the last five decades, *Pennisetum* research has garnered considerable attention, fostering a global network of cooperation among various countries. This international collaboration has been instrumental in tackling complex challenges and in the efficient use of resources. Notably, *Pennisetum* serves as an essential feed source for ruminants, significantly impacting the quality of livestock products. Consequently, enhancing the yield and quality of *Pennisetum* silage continues to be a primary research objective within this genus. Furthermore, current research on *Pennisetum* is centered around three pivotal themes: cultivation and breeding, ecological restoration, and industrial application. These themes represent the main areas of focus, propelling forward progress and innovation in *Pennisetum*-related studies. Looking ahead, this paper identifies potential future research directions, such as molecular breeding, agricultural management practices, and the creation of novel materials. These areas are poised to become significant subjects in *Pennisetum* research.

Author contributions

YZ: Data curation, Methodology, Writing – original draft, Writing – review & editing. JL: Investigation, Software, Writing – review & editing. XW: Software, Supervision, Writing – review & editing. YY: Formal analysis, Writing – review & editing. ZZ: Formal analysis, Writing – review & editing. XD: Formal analysis, Writing – review & editing. YG: Formal analysis, Software, Writing – review & editing. PW: Funding acquisition, Methodology, Writing – review & editing.

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Conflict of interest

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

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