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Evolving Paradigms in Sorghum Research: A Bibliometric and Content Analysis of Global Trends and Future Directions

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ABSTRACT

Sorghum has become increasingly popular for diverse applications, including food, feed, and bioenergy. The present study aimed to perform a bibliometric and content analysis on sorghum research in the industrial-agricultural sector to evaluate global research patterns, emerging topics, and future trends. The bibliometric analysis of the Scopus bibliographic metadata was done using Bibliometrix and Vosviewer. The results of this investigation show the descriptive analysis underscored fluctuation in research output and citation impact over the years. The identified four patterns through co-occurrence analysis encompassed central themes of sorghum research, including genetic expression and plant stress cluster, cereal crop and yield cluster, biomass and microbial bioprocessing, and metabolism and antioxidant cluster. The thematic map portrays a comprehensive view of cereal crops and yields, biomass and microbial bioprocessing, metabolism and antioxidant research, environmental remediation and sustainable agriculture practices, and the declining theme of starch. The findings provide valuable insights into the global pattern of sorghum research and emerging trends, thus directing future multidisciplinary research efforts for enhanced knowledge and sustainable practices in the industrial-agricultural sector. The insights from this study can guide future multidisciplinary research efforts towards enhancing knowledge and promoting sustainable practices in the industrial-agricultural sector, particularly in the areas of sorghum genetics, crop yields, biomass processing, and environmental sustainability.

1. INTRODUCTION

Sorghum has become increasingly popular for diverse applications, including food [1-3], feed [4-6], and bioenergy [7-9]. Its widespread cultivation is attributed to its remarkable adaptability and drought tolerance, making it well-suited for changing climates [10, 11]. Additionally, sorghum stands out for its high productivity, minimal nutrient requirements, and cost-effectiveness, making it a competitive crop globally, especially in regions like Africa and Asia [5, 12, 13].

Sorghum, traditionally a staple in the food industry, has now found applications in feed and bioenergy. The sorghum market is more competitive for food than feed and bioenergy [14]. Additionally, sorghum serves as a wheat substitute in various food products [2]. Leveraging fermentation technology allows sorghum to be transformed into functional food. Unlike other grains, sorghum boasts antioxidant, anti-obesity, anti-diabetic, anti-cardiovascular, anti-inflammatory, antibacterial, and anticancer properties [15]. Nevertheless, it is essential to acknowledge sorghum's limitations, including the presence of anti-nutritional substances such as phytates, protein crosslinkers, tannins, and trypsin inhibitors [16-18].

Various factors impact sorghum's role as feed, including corn import restrictions, forage availability, and livestock numbers. Sorghum is recognized for its nutritional value in providing protein and energy when processed with other feed components [6]. With rising corn prices, sorghum's high tannin content hinders efforts to substitute it with sorghum. To address this, new low-tannin sorghum cultivars like Macia have been developed for broiler feed, showing no adverse effects when replacing corn [19]. The Indonesian Cereals Research Institute also released Suri 3 Agritan and Suri 4 Agritan in 2017, low-tannin sorghum varieties with less than 0.1% tannin [5]. This highlights sorghum's potential to replace corn in feed during shortages.

Considering the fluctuating pricing of fossil fuels, the decline of oil reserves, and an increase in greenhouse gas emissions, the crucial role of bioethanol and biodiesel produced from renewable energy sources is growing. Plant biomass offers a sustainable and promising alternative energy source. Sorghum is a raw material for the first generation of biofuels from grains and sugar [9]. Although the feasibility of converting sorghum biomass, specifically cellulose and lignin, into biofuels on a large scale needs to be established, China and India have effectively utilized sweet sorghum to produce bioethanol on a commercial scale [20].

By comprehending the diverse applications of sorghum in food, animal feed, and biofuel contexts, a bibliometric analysis is subsequently conducted to assess global research trends in this field. A comprehensive literature search has been conducted to delineate the scope of sorghum bibliometrics. Table 1 encapsulates the existing studies on sorghum bibliometrics and compares them with the insights generated from the present study. This comparative analysis forms the foundation for the present study, positioning it within the broader context of existing research and highlighting its contribution to the expanding domain of sorghum bibliometrics.

Table 1. A comparison between the present study and previous bibliometric studies on sorghum

Basic of the Comparison	George et al. [14]	Pontieri et al. [21]	Liaqat et al. [22]	Aguiar et al. [23]	Present Study
Period	2000-2020	1995-2021	2000-2022	2012–2022	2019-2023
Keywords	Sorghum	A string of keywords related to sorghum, food innovation, and consumer behavior	sorghum and drought	A string of keywords related to sorghum, food products, and food processing	Sorghum
The focus of the study	Global food security	Healthy food in environmental challenge	Drought	Novel food products	Global trends and future works
Methodology	Bibliometric analysis	Systematic review and bibliometric analysis	Bibliometric analysis	Systematic reviews and Bibliometric analysis	Bibliometrics analysis and content analysis
Tools	VOSviewers	Bibliometrix	VOSviewers	VOSviewer	Vosviewers and Bibiliometrix
Database	Scopus	WOS and scopus	WOS	Scopus	Scopus
Total Document	17,720	198	1,731	231 (processing) and 451 (based food)	7,197

The present study distinguishes itself by offering a contemporary analysis of sorghum research within 2019-2023, surpassing the temporal scope of previous works (Table 1). Employing a comprehensive keyword approach related to sorghum, the study explores diverse facets of sorghum research. Moreover, it focuses on global trends and future work, providing valuable insights into the projected direction in the field. The integration of both bibliometrics analysis and content analysis, along with the use of visualization tools like VOSviewers and Bibiliometrix, enhances the depth and thoroughness of the study, contributing to a more nuanced understanding of sorghum research.

Bibliometric analysis is a compelling method for comprehensively assessing the evolving landscape of research literature. It facilitates the examination of journal influence citation patterns and identifies research themes and emerging issues within a vast body of publications. A quantitative strategy, specifically through bibliometric analysis, has been recognized as a practical approach for this purpose, as highlighted by notable scholars in the field [24-27]. This method allows for a systematic exploration of the dynamics shaping scholarly discourse on sorghum, enabling a nuanced understanding of the trends and patterns prevalent in the existing body of literature.

Despite its significance and relevance, utilizing bibliometric and content analysis in projecting the future direction of sorghum research requires further optimization, necessitating focused attention in this domain. To address this, the authors have formulated three specific research questions (RQs):

RQ1: What distinct research clusters characterize sorghum bibliometrics?

RQ2: What novel research topics are presently emerging in the study of sorghum?

RQ3: What future trends can be projected in sorghum research?

The present study is designed around three key objectives in alignment with the outlined research questions (RQs). Firstly, it seeks to analyze global research patterns in sorghum cultivation and utilization, directly corresponding to exploring distinct research clusters (RQ1). The second objective involves the identification of key research themes and emerging topics in sorghum agriculture and its applications, a direct response to RQ2. Finally, the third objective aims to propose future research directions and potential areas of innovation in sorghum research, aligning directly with the anticipation of future trends (RQ3). This systematic approach not only underscores the authors' commitment to methodological rigor but also strives to offer a comprehensive and forward-thinking contribution to the field of sorghum research, bridging the area of design, nature, and ecodynamics.

The rationale for employing bibliometric analysis and content analysis is their ability to comprehensively evaluate global research patterns, emerging topics, and future trends. Bibliometric analysis quantitatively assesses publication output, citation impact, and collaboration networks, while content analysis qualitatively examines thematic content within publications. These methods are particularly suited to achieve the study's objectives by providing both quantitative metrics and qualitative insights into the landscape of sorghum research, informing future multidisciplinary research efforts and promoting sustainable practices in the industrial-agricultural sector.

2. MATERIALS AND METHODS

2.1 Search methods and data collection

The data retrieval process from the Scopus database (http://www.scopus.com) was meticulously and systematically executed. Scopus, managed by Elsevier, offers a comprehensive and continuously updated repository of over 77.8 million core records, providing researchers with easy access to diverse, high-quality scientific publications and a range of powerful analytical tools for efficient and effective research [28]. The search terms were strategically selected to encompass various dimensions of sorghum, including its agricultural, nutritional, and industrial aspects. This approach was adopted to ensure the inclusiveness of diverse scholarly contributions. The search was conducted across all available fields, including titles, abstracts, and keywords, to maximize the scope of data collection. Utilizing the developed search strategy as outlined, a pool of 32,552 data points was retrieved (Figure 1), representing a comprehensive dataset crucial for the in-depth analysis of the multidimensional aspects of sorghum research.

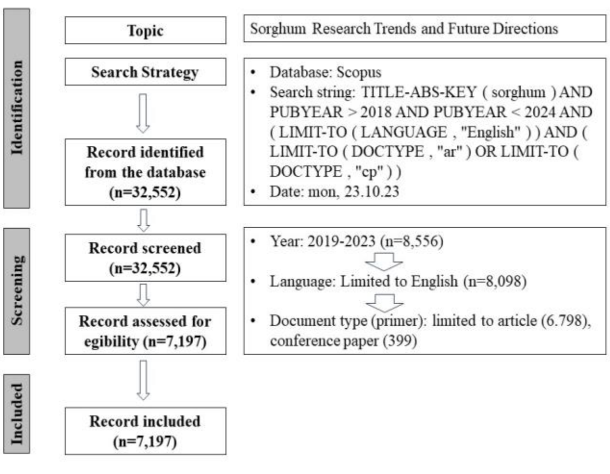

Figure 1. A search procedure modified from the PRISMA flow diagram [29]

Moreover, a temporal restriction was implemented to retrieve publications from the past five years (2019-2023), ensuring the incorporation of the most recent and pertinent literature in the analysis. Upon executing the initial search, the retrieved records underwent a thorough screening process. This process entailed stringent inclusion criteria, emphasizing the English language as the primary requirement and specifically targeting document types, i.e., articles and proceedings. By adhering to these meticulous screening criteria, the study aimed to capture the most recent and innovative research contributions within the sorghum domain, ultimately enhancing the novelty and relevance of the database. The final dataset obtained after this rigorous screening process amounted to 7,197 entries, which formed the foundation for the subsequent bibliometric analysis.

2.2 Bibliometric and content analysis

The bibliometric analysis of the Scopus bibliographic metadata was conducted using VOSviewer version 1.6.19 [30] alongside the Bibliometrix R package version 4.1.1 (R software version 4.2.2) [31, 32]. This comprehensive approach aimed to address key research inquiries concerning sorghum studies. By leveraging the combined power of VOSviewer and Bibliometrix, this study sought to provide an extensive and nuanced understanding of the contemporary and future directions of sorghum research.

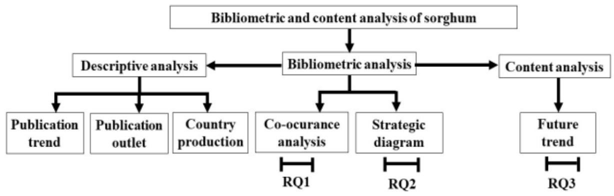

Figure 2. Research structure to answer the research question (RQs) as adopted from study [27]

The selection of relevant papers in the bibliometric and content analysis was guided by Figure 2, which provides descriptive analysis using Bibliometrics and a structured mapping derived from co-occurrence analysis using VOSviewer. The co-occurrence analysis process involves several steps to uncover thematic relationships among keywords within the literature. VOSviewer examined the frequency with which keywords appear together in the literature. Keywords that frequently co-occur were considered to have a closer thematic relationship. The strength of these relationships was visualized through network maps or clusters, providing insights into the underlying themes in the literature. To ensure the reliability of the results, a minimum occurrence threshold was set for keywords. This threshold determines the minimum number of occurrences required for a keyword to be considered significant in the analysis.

In this study, a threshold of 5 was chosen, meaning only keywords appearing at least 5 times were included in the analysis. This threshold helped filter out less relevant or infrequently occurring keywords, ensuring that the analysis focuses on the most significant themes within the literature. Additionally, the selection of keywords was an important aspect of the analysis. Keywords are carefully chosen based on their greatest total link strength. In this case, a selection of 100 keywords was made to capture a broad range of sorghum research trends while ensuring the depth of analysis. In Bibliometrix, descriptive analysis techniques were utilized to provide an overview of the bibliographic data, aiding in identifying key trends and patterns in sorghum research output.

The keyword refinement process included merging singular and plural forms (e.g., “animal” and “animals”) and consolidating synonyms (e.g., “maize” and “zea mays”) (Table 2). Unrelated terms were identified based on system-generated or database-related categories, such as "article," "nonhuman," and "controlled study," which were not directly relevant to the study. Synonyms were merged, and unrelated words were deleted.

Table 2. Refined words

Label	Replace by
article	
nonhuman	
controlled study	
animals	animal
maize	zea mays

This mapping, in turn, facilitates the identification and retrieval of full-text papers from each cluster by overlay visualization (Figure 3). The overlay visualization was generated with nodes exhibiting a minimum strength of 30, and the 500 strongest links among them represented the connections between items. The selected keywords were interconnected, forming a network of yellow or bright green-colored nodes, signifying the latest thematic focus in the analysis. Subsequently, the selected keywords were queried within Bibliometrix to compile a list of papers associated with the selected keyword. Representative newest papers deemed relevant to the selected keyword within each cluster and possessing the highest citations per year are then meticulously chosen. These representative papers provide a foundation for elucidating prospective future research within each identified cluster.

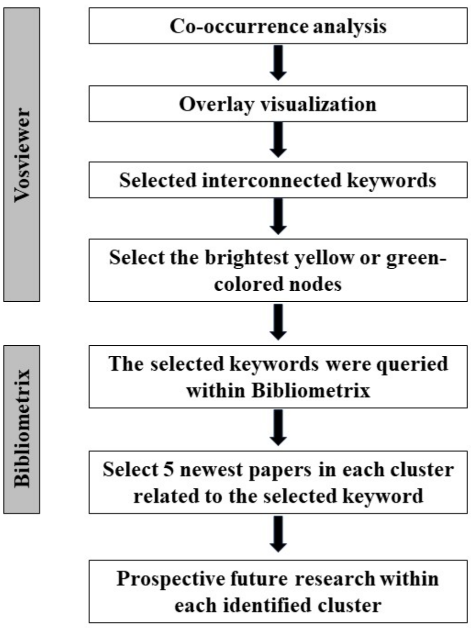

Figure 3. Content analysis procedure developed by the authors

3. RESULT AND DISCUSSION

3.1 Descriptive analysis

3.1.1 Publication trend

Figure 4 provides an overview of the distribution of publications and mean total citations per year within the sorghum research from 2019 to 2023. The trends show a fluctuation in research output and citation impact over the years. In 2019, a substantial number of articles, totalling 1343, were published, with a mean total citation per year reaching 2.91. In the subsequent year (2020), there was a slight increase in the number of articles, totalling 1537, while the mean total citation per year exhibited a slight decline to 2.68. In 2021, the trend continued with 1539 articles, but the mean total citation per year experienced a further decrease to 2.32. Remarkably, in 2022, there were fewer publications (1,519), and the mean total citations per year (1.49) decreased. The most recent data for 2023 reflects a decline in both articles (1259) and mean total citation per year, reaching 0.66. The data declination in 2023 could be attributed to the potential incompleteness of data collection, which was limited to the month of October. This underscores the necessity for prudence in interpreting annual publication trends within the context of this study.

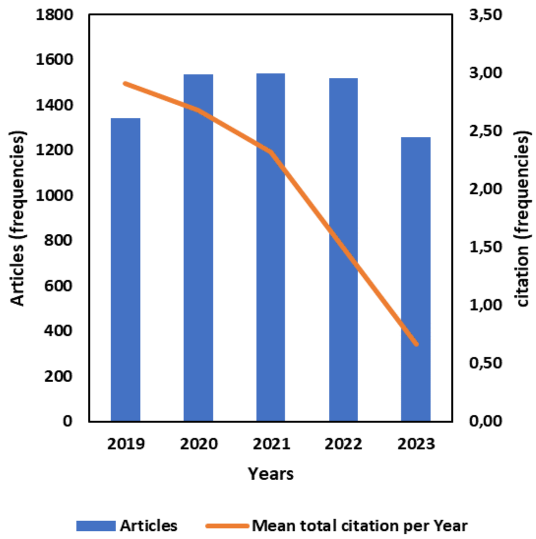

Figure 4. Publication trend

The observed fluctuations in sorghum research output and its corresponding citation impact underscore the dynamic nature of the field. This dynamism may be attributed to various factors, including shifts in research focus and emerging trends, external influences such as global events and funding dynamics, advancements in research methodologies, changes in collaboration networks among researchers, variations in publication outlets, and evolving modes of scientific communication. A previous study has revealed a decrease in the number of research articles solely published by researchers within the industry, signifying a change in focus towards the utilization and commercialization of internal research findings [33].

3.1.2 Publication outlet

The IOP Conference Series: Earth and Environmental Science, Frontiers in Plant Science, and Agronomy have emerged as leading platforms for disseminating cutting-edge research on sorghum (Figure 5). Research on sorghum is predominantly published in the IOP Conference Series Earth and Environmental Science, accounting for 179 publications. These journals have collectively contributed 413 articles, fostering a comprehensive understanding of the crop's environmental impact, genetic diversity, and agronomic practices.

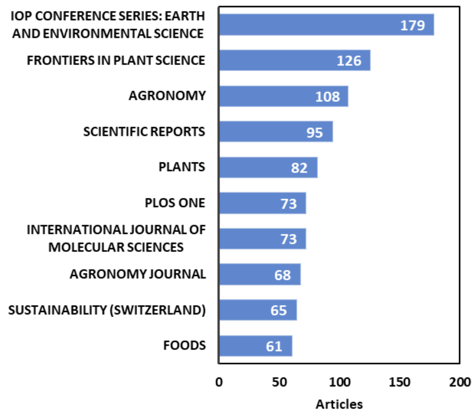

Figure 5. Top 10 journals or conference proceedings that are outlets for publication

Additionally, the Scientific Reports and Plants journals have each published a substantial number of articles highlighting the multidimensional significance of sorghum in the agricultural and environmental sciences (Figure 5). The International Journal of Molecular Sciences and PLOS One have also played pivotal roles in unravelling the molecular intricacies underlying sorghum's diverse traits, with 73 articles dedicated to shedding light on its genetic and molecular mechanisms. Furthermore, the Agronomy Journal, Sustainability (Switzerland), and Foods have offered a holistic perspective on sorghum's sustainable cultivation, nutritional value, and economic viability, collectively publishing 203 articles. This abundance of study highlights the global effort to improve the knowledge and sustainable management of sorghum, which will ultimately support the crop's critical role in maintaining food security and agricultural sustainability on a global scale.

3.1.3 Country production

Examining the data provided, the examination of the occurrence rate of publications on sorghum research in various geographical areas provides insights into the worldwide scope of studies on sorghum (Figure 6). The United States of America and China are the leading contributors, with 7,488 and 7,449 research publications, respectively. This relates to the top sorghum-producing countries in the world: the United States of America, Nigeria, Mexico, India, and Sudan [34]. This substantial research output from these two major global players underscores the significant emphasis on sorghum research within these regions. The prevalence of extensive research activities in these countries suggests a strong commitment to advancing knowledge in the field, indicating the pivotal role that the United States and China play in shaping the discourse and advancements in sorghum-related research on a global scale.

Moreover, the prominent contributions from Brazil, India, and Indonesia, with 4,190, 4,018, and 1,489 research publications, respectively, highlight the growing significance of sorghum research in these regions (Figure 6). These findings reflect the increasing attention and efforts dedicated to exploring sorghum's potential, particularly in agricultural sustainability, food security, and bioenergy production. The research output from these countries signifies a concerted focus on leveraging sorghum's diverse applications and its role in addressing critical challenges such as climate change and sustainable agriculture, making them key players in the global pursuit of innovative sorghum-based solutions. Furthermore, the presence of Australia, Pakistan, Mexico, Italy, and Nigeria in the analysis, with 1206, 1034, 985, 767, and 732 research publications, respectively, underscores the widespread interest and diverse engagement in sorghum research across different geographical regions.

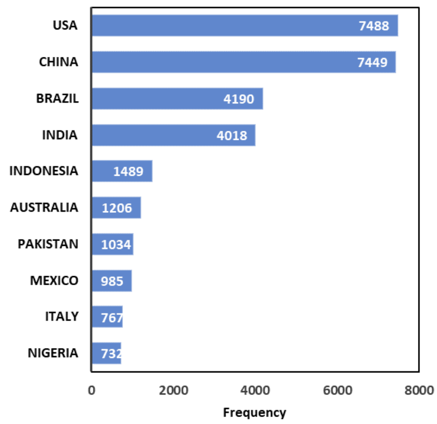

Figure 6. Top 10 countries scientific production

3.2 Global research pattern

The visualization facilitated by VOSviewer addresses RQ1 by offering insights into the current landscape of sorghum research. The co-occurrence analysis graphic illustrates the interrelationships among study subjects, their respective levels of popularity, and the formation of distinct clusters of topics. As illustrated in Figure 7, the network visualization resulting from the co-occurrence analysis reveals the existence of four separate thematic clusters. Each cluster, identified by distinct colors (red, yellow, green, and blue), corresponds to clusters 1, 2, 3, and 4, respectively.

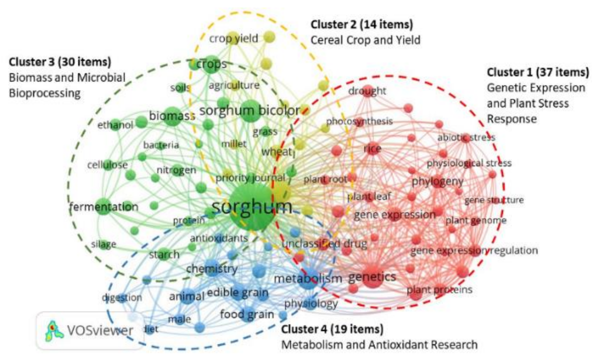

Figure 7. Network visualization from co-occurrence analysis

The red cluster investigates the genetic expression and plant stress response, whereas the yellow cluster is committed to advancing sorghum research within the domain of cereal crops and yield. The green cluster is involved in research related to sorghum's utilization for biomass and microbial bioprocessing, and simultaneously, the blue cluster specializes in exploring metabolism and antioxidant research (Figure 7).

Cluster 1, the red cluster, is related to a genetic program utilizing genomic research to find suitable sorghum varieties specific for food, feed, and bioenergy based on the qualities defined by the academic community and industrial needs (Figure 7). Genetic research on sorghum focuses on studies related to the genetic traits of sorghum that confer drought tolerance, supported by research on sorghum genotype characteristics, gene expression in drought-tolerant sorghum plants, and genetics.

Additionally, research on the plant protein content in sorghum is an interesting theme. Cultivated sorghum is distinctive in that it may be used as food, feed, forage, fuel, beverage, and a broom. Four primary forms of sorghum are grown globally: grain, sweet, forage, and broom. These diverse sorghum varieties vary significantly from place to place [35]. Therefore, the breeding program cannot be separated from the development of sorghum as food, feed, or energy.

Next, cluster 2, in yellow, concerns research on climate change, sustainable agricultural methods, and food security in sorghum production (Figure 7). Sorghum is a promising cereal crop for food production and addressing global food security challenges [22]. Sorghum, a staple food in many regions, faces growing pressures from climate change and resource constraints. An analysis is undertaken to explore critical research areas to unlock the full potential of sorghum as a resilient crop for sustainable food production [36]. Emphasis is placed on advancing climate-resilient sorghum varieties, optimizing sustainable agricultural practices, and preserving soil health through effective organic matter management [37].

Furthermore, cluster 3, the green cluster, is related to the words sorghum, *Sorghum bicolor*, biomass, crops, and fermentation (Figure 7). These keywords highlight the growing significance of sustainable and eco-friendly energy development from biomass, particularly sorghum, as an essential response to the increasing global demand for petroleum-based fuels and the associated environmental challenges, including greenhouse gas emissions, global warming, and climate change [38].

Finally, cluster 4, denoted by blue, is dedicated to the research topic associated with metabolism, chemistry, food grain, edible grain, animal, and human (Figure 7). Sorghum is a multifunctional cereal grain that is highly significant in metabolism and nutrient consumption. Its chemical composition gives it an important role in the agricultural production of cereal crops. As an edible grain, sorghum provides the nutritional needs of both humans and animals and contributes to the growth, development, and aging processes, impacting both males and females. Recent studies have shown that sorghum-based diets can be as effective as corn-based diets in promoting growth and weight gain in animals, especially with the development of low-tannin sorghum varieties [39]. Sorghum also has a lower risk of mycotoxin contamination compared to corn [40].

3.3 Emerging topics

To address the research question concerning emerging trends in sorghum research (RQ2), the thematic map generated by Bibliometrix offers a valuable tool for analysis. Cobo et al. first introduced this thematic map [41]. Using a strategic diagram approach with four quadrants. Each quadrant indicates a group of themes, namely motor theme, basic theme, niche theme, and emerging/declining theme, in quadrants 1, 2, 3, and 4, respectively. A thematic diagram in Figure 8 presents research topics related to sorghum research.

The light green node represents cereal crop and yield keywords that fall between the basic and motor themes (Figure 8). It signifies a research topic with characteristics of fundamental knowledge (basic theme) and a highly prominent, widely recognized area of study (motor theme). This positioning suggests that the topic is both a core concept that forms the fundamental building block of the field and an area of active and significant research interest.

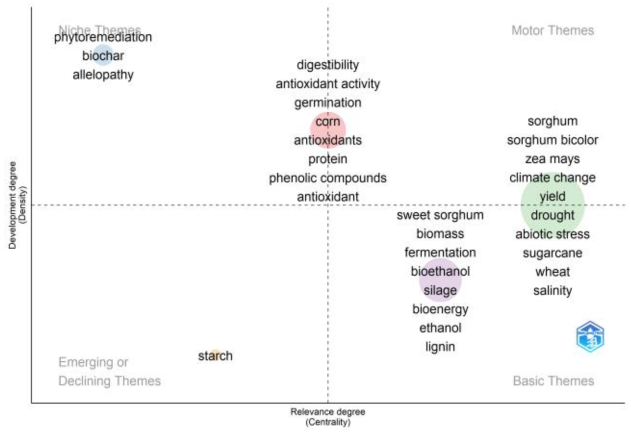

Figure 8. Thematic map

Keywords located in this overlapping region often represent topics that have a crucial and enduring impact on the field, serving as the backbone of research while remaining at the forefront of current scholarly activity. Researchers studying such topics benefit from their foundational knowledge, enabling them to contribute to the ongoing development of the fundamental principles and the advancements at the forefront of the field. This positioning underscores the critical importance of the topic to the overall understanding of the field and its potential for continued relevance and impact in shaping the direction of future research. It suggests that the topic is an essential aspect of foundational knowledge and a driving force behind the current advancements and developments within the broader research domain.

Additionally, the significance of biomass and microbial bioprocessing in the thematic map is underscored by the presence of the purple node within the basic themes (Figure 8). This node encapsulates keywords related to the conversion of sorghum into bioethanol, indicating a well-established body of knowledge in this domain. The clustering of terms such as sweet sorghum, biomass, fermentation, bioethanol, and lignin within this thematic entity highlights the comprehensive understanding and research focus on leveraging sorghum for bioenergy production. The co-location of these keywords emphasizes the interconnectedness of concepts associated with sorghum-derived bioethanol, suggesting a consolidated body of literature exploring the various facets of biomass processing, microbial fermentation, and bioenergy extraction from sweet sorghum. This observation signifies the maturity of research in this area and serves as a valuable reference point for researchers and practitioners engaged in exploring sustainable bioenergy alternatives.

The intersection of the light red node denotes metabolism and antioxidant research between motor and niche themes (Figure 8). It highlights this topic's pivotal position, signifying its widespread recognition and distinctive relevance within the field. The convergence highlights significant research attention, underscoring its central role in the domain's exploration, positioned within the motor theme. Simultaneously, its inclusion in the niche theme emphasizes the intricate and specialized facets that distinguish it from more generalized research subjects. This indicates a dynamic and multi-faceted approach to exploring the genetic aspect, combining comprehensive understanding and specialized expertise to unravel the complexities inherent to this crucial aspect of sorghum research.

Researchers are encouraged to investigate specialized topics contained within the light blue node to promote the progress of research in environmental remediation and sustainable agriculture practices. This specific cluster, characterized by its connection to terms associated with the restoration of the environment and the implementation of sustainable agricultural techniques, acts as a valuable source for potential scientific studies. By exploring this specific field of study, researchers have the potential to uncover pioneering approaches and resolutions that aid in the advancement of environmentally sustainable farming methods and the restoration of ecological balance.

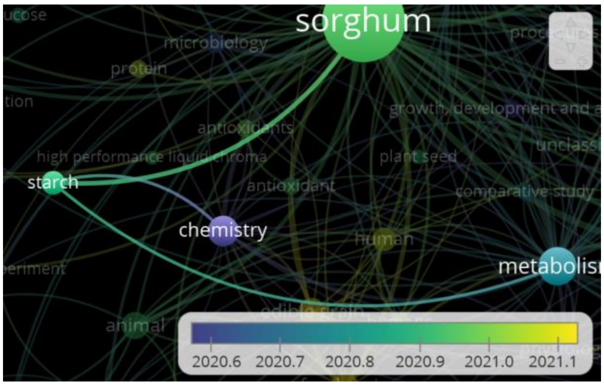

Figure 9. Overlay visualization of starch

Figure 8 shows the position of the light orange node, which represents the keyword of starch, as the primary focus for analyzing its present state, whether it is emerging or declining. A method of overlay visualization is utilized to determine the current state of the starch theme, as illustrated in Figure 9. The results of this examination expose an observable decrease in the frequency and importance of the concept of starch.

Previous literature has highlighted one reason for the limited exploration of starch characteristics and applications was the underutilization of sorghum germplasm resources as a starch source [42]. Sorghum starch remains underutilized in industry due to the need for further processing to enhance its versatility for food applications [43]. This insight points out possible directions for further investigation into methods for enhancing the use of sorghum starch in diverse industrial applications.

3.4 Future works and directions

To address RQ3, a mapping of future research and projects was carried out in this study. Two analyses were performed to address this RQ3: a co-occurrence analysis with an overlay visualization and a content analysis (Figure 10). The overlay visualization provides an overview of which research topics are developing and significantly influence sorghum research. Meanwhile, content analysis is used to explore potential future work.

In the genetic expression and plant stress cluster (Figure 10(a)), future research should focus on expanding spectral libraries for VIS-NIR-SWIR leaf spectra analysis. This approach aims to enable rapid and cost-effective analysis of physiological and biochemical traits, with a dynamic expansion strategy ensuring robust model deployment across diverse applications [44].

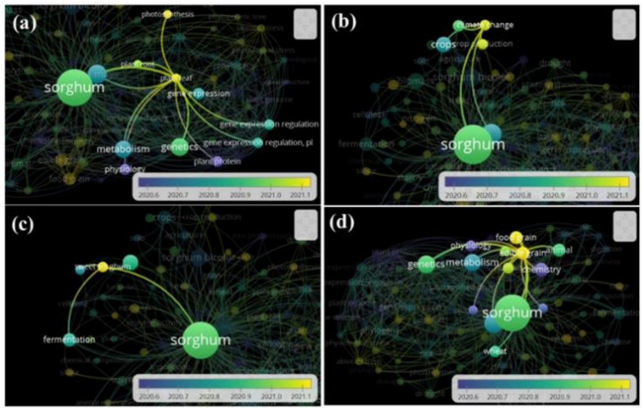

Figure 10. Overlay visualization of potential future research (a) Genetic expression and plant stress cluster, (b) Cereal crop and yield cluster, (c) Biomass and microbial bioprocessing, (d) Metabolism and antioxidant cluster

A thorough investigation of sorghum's reaction to salt stress is recommended, including understanding specific genes, validating transcriptomic results through qRT-PCR, and investigating the role of anatomical changes. Insights into ion accumulation, peroxidases, and chitinase may pave the way for genetic improvements in salt stress tolerance [45].

Particular initiatives were emphasized to improve the leaf base strategy for genome editing and transformation of maize and sorghum. This involves refining protocols, understanding molecular mechanisms, and evaluating real-world applicability through field trials. The method's adaptability for introducing additional traits in crop improvement efforts is also emphasized [46].

Investigating the genetic and molecular mechanisms impacting correlations between distant cells in sorghum leaves is recommended. This pertains to factors impacting stomatal conductance and intrinsic water-use efficiency, with implications for biomechanical trade-offs and strategies to mitigate water-related costs for wider leaves under stress conditions [47].

In plant image recognition, an improved methodology is suggested for skeleton structure extraction in monocot plant images. Future research directions involve extending predictive capabilities to diverse monocot species, focusing on sorghum and maize plant images. Continuous evaluation and improvement, including datasets with both separated and occluded leaves, will enhance the model's generalizability and effectiveness across various plant species and datasets [48].

Next, in the context of cereal crops and yield cluster and their susceptibility to climate change (Figure 10(b)), this study offers valuable insights, leading to practical recommendations for extension workers and future research projects. Adjusting sowing dates is an effective strategy for mitigating abiotic stresses, ultimately fostering resilience in crop production. Propagating short-cycle varieties that exhibit resistance to drought and floods aligns seamlessly with sustainable agriculture principles, particularly in fluctuating climate patterns. Strengthening weather-informed advisories through rain gauges empowers farmers to make informed decisions, which is crucial for adapting to changing climatic conditions. It is recommended that future research use sophisticated statistical models, like the R^2 adjusted, to achieve a more comprehensive knowledge of the factors affecting agricultural yield dynamics [49].

In future research, it is recommended that the exploration of agricultural yield models and economic frameworks be broadened to better understand the uncertainty associated with net economic effects. Additionally, analyzing the economic model under the Representative Concentration Pathway (RCP) 4.5 scenario provides a basis for comparing results with more severe climate change scenarios [50]. This approach enhances understanding of the economic impacts of climate change on agricultural yields and informs adaptive strategies.

Wheat blending with sorghum emerges as a promising strategy for the future, offering increased biodiversity and improved nutrition. This practice is a valuable tool to mitigate the effects of ongoing climate change. Blending sorghum and various wheat cultivars increases genetic variety and improves the final product's nutritional value. This proactive strategy addresses agricultural and nutritional challenges in evolving climate conditions, contributing to more sustainable and resilient food systems [51].

The study on *Sorghum halepense* future global habitats highlights the need for ongoing research. Utilizing eight models, the authors identified a singular model meeting rigorous evaluation criteria for predictive accuracy. This underscores the complex interplay between *S. halepense*, climate change, and land-use change. Further research is crucial to enhance global early warning and preventive strategies, addressing invasive species management's dynamic implications [52].

Future research on sorghum in Burkina Faso should expand beyond the five major crops studied, focusing on specific impacts of climate change. Additionally, exploring broader agricultural effects, assessing the efficacy of climate-smart practices, and examining economic implications for food security and livelihoods are recommended. Investigating the relationship between extreme climate indices and sorghum yields across different climatic zones will provide valuable insights into enhancing sorghum resilience in climate change [53].

Furthermore, the Biomass and Microbial Bioprocessing cluster research focused on sweet sorghum (Figure 10(c)) and offers directions for future research to improve agricultural products with added value. Investigating the incorporation of locally available, cost-effective protein and bioactive sources, like sorghum, can improve functional and nutritional values at a low cost. Further research on cookies based on sorghum, orange-flesh sweet potato, and mushroom protein isolates can validate anti-inflammatory and anti-hyperglycemia potentials in human subjects. Assessing consumer acceptability on a larger scale and exploring the health benefits of protein derivatives from various sources, including mushrooms and sweet potatoes, offer opportunities for advancing knowledge in both the food and human health industries [54].

A comprehensive strategy is proposed to treat soil cadmium (Cd) contamination, emphasizing employing biomass containing Cd to develop phytoremediation. The research emphasizes biorefinery applications for Cd-polluted biomass to reduce environmental pollution and enable bioethanol production. It is suggested to further optimize the utilization of carbohydrates and bioethanol production from sweet sorghum fields polluted by Cd [55].

More studies are required to understand the functional significance of ZmSWEETs in stress tolerance completely, and a thorough analysis of ZmSWEETs in maize is also recommended. The research also recommends a focus on unraveling regulatory mechanisms, including identifying miRNAs and transcription factors influencing ZmSWEET expression. Further investigation is recommended to better understand the structural and functional properties of SWEET transporters in additional cereal species and their function in stress tolerance to expand knowledge [56].

The research highlights the potential of BRS 506 sorghum as a promising crop for exploration in the Brazilian semiarid region. It suggests more research in crop development programs, particularly emphasizing ionic redistribution as a strategy to improve stress tolerance without sacrificing the synthesis of osmoregulatory chemicals. The emphasis on BRS 506 sorghum and the exploration of innovative stress-tolerance mechanisms contribute valuable insights for sustainable agricultural practices in the challenging climatic conditions of the Brazilian semiarid region [57].

Further studies on how the *S. bicolor* variety grows in salinized soil to remove hydrocarbons are recommended. Exploring these mechanisms holds promise for enhancing understanding of phytoremediation processes in contaminated environments. The research recommends further fieldwork to validate and elaborate on the study's findings. Conducting further field studies will provide valuable empirical evidence and contribute to the robustness and applicability of the proposed hydrocarbon removal strategies, fostering advancements in sustainable soil remediation practices [58].

Finally, within the metabolism and antioxidant research cluster with the keyword food grain (Figure 10(d)), future research should explore the techno-functional potential of germinated sorghum flours and investigate the susceptibility of kafirin, whether in isolate form or as part of protein bodies (PBs), to in vitro degradation by digestive enzymes. The identification of proteases can be utilized as biomarkers for selecting sorghum genotypes with enhanced kafirin digestibility post-germination. Further studies are needed to uncover the molecular and cellular processes during sorghum grain germination, particularly focusing on kafirin biochemistry. Label-free proteomics with LC-HDMS is recommended for advanced cereal grain protein profiling in sorghum germination studies. Finally, research should address the impact of temperature on seed germination time, biochemical changes, and in vitro protein digestibility of sorghum proteins [59].

Miniaturized NIR instrument development strategies have been outlined, emphasizing performance optimization. It suggests evaluating the interplay between data pre-processing techniques and calibration, exploring the feasibility of using handheld NIR devices for in-field sorghum phenotyping, and continuously improving protein calibration models for enhanced accuracy. The research proposes validation with a smaller set of subsamples, incorporating those with higher prediction errors. Further investigations include direct scanning of sorghum grains on plants, developing extended-range moisture calibrations, and assessing the efficacy of handheld NIR devices for quality trait evaluation compared to standard benchtop spectrometers [60].

This study outlines future research directions to optimize the enzymatic hydrolysis of sorghum grain pericarp. Key areas include fine-tuning enzyme proportions, evaluating their impact on nutritional profiles, and exploring applications for improved sorghum digestibility in diverse food formulations. Additionally, research is needed to assess the enzyme cocktail's effectiveness in reducing grain breakage during milling and developing innovative pre-treatments to minimize nutrient loss during sorghum decortication [61].

Future research focuses on an in-depth comprehension of the microbial dynamics involved in grain fermentation using sorghum. Utilizing high-throughput sequencing, investigations will explore the impact of different fermentation periods on microbial diversity. Key focuses include unraveling bacterial succession and LAB metabolite accumulation, studying the effects of LAB-produced lactic acid on pH and community structure, and analyzing core microbiota and dominant taxa. The research examines ethyl lactate and ethyl acetate formation by LAB and their contribution to liquor flavor. Overall, the goal is to scrutinize compounds and their dynamic changes in flavor during different fermentation stages [62].

The proposed future research aims to enhance the utilization of flours from popped grains across diverse food applications. Experiments will assess their behavior in different food matrices, evaluate their role as additives, and examine their impact on techno-functional properties and shelf-life. Investigating their potential as binding agents for improved stability in various food products and exploring their capacity as carriers for vitamins, aromas, and flavors are key focuses. Additionally, optimizing popping conditions to achieve desired functional attributes and understanding the physicochemical impact of popping on different grains will be crucial for advancing their application in the food industry [63].

4. CONCLUSIONS

In conclusion, this study employed bibliometric and content analysis to explore research patterns, emerging topics, and future trends in sorghum research. The analysis revealed fluctuations in research output and citation impact, with significant contributions from the United States and China shaping the global discourse. Furthermore, key journals such as the IOP Conference Series (Earth and Environmental Science), Frontiers in Plant Science, and Agronomy emerged as influential platforms for disseminating cutting-edge sorghum research. This study identified central themes in sorghum research through co-occurrence analysis, including genetic expression and plant stress, cereal crop and yield, biomass and microbial bioprocessing, and metabolism and antioxidants.

The thematic map portrays a comprehensive overview of current research priorities, with cereal crops and yields as a dominant focus. While biomass and microbial bioprocessing serve as foundational themes, metabolism and antioxidant research bridge the gap between basic and motor themes. Notably, niche topics focusing on environmental remediation and sustainable agriculture practices provide specialized insights. Interestingly, a decline in the theme of starch research suggests a potential shift in focus.

These findings suggest diverse sorghum research directions, including genetic expression, plant stress responses, plant image recognition, climate change adaptation, biomass and microbial bioprocessing, soil remediation, and food grain applications. These insights offer valuable guidance for advancing knowledge and fostering sustainable practices across multidisciplinary domains. In terms of impact, this study contributes valuable insights into the global pattern of sorghum research and emerging trends. This study may stimulate further multidisciplinary research efforts and promote sustainable practices in the industrial-agricultural sector by positioning these findings within the broader context of sorghum research.

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