PLANT SCIENCE TODAY
Vol 13(sp5): 01–12
https://doi.org/10.14719/pst.16296

eISSN 2348-1900

REVIEW ARTICLE

Global research trends in sorghum biofortification: A bibliometric analysis of publication patterns, knowledge structures and emerging research priorities

Periyasamy Eniyavan[1,3], Jegadeesan Ramalingam[2], Sundararajan Juliet Hepziba[3], Rengasamy Kannan[4], Bhupathi Nandhini[5], Veeranathan Karunanithi Dhanesh Kumar[6], Ephrem Habyarimana[1*] & Madhavan Arumugam Pillai[3*]

[1]Sorghum Breeding, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Telangana, India

[2]Department of Plant Molecular Biology and Biotechnology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Genetics and Plant Breeding, V.O.C. Agricultural College and Research Institute, Tamil Nadu Agricultural University, Killikulam 628 252, Tamil Nadu, India

[4]Department of Plant Pathology, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[5]Department of Plant Pathology, University of Agricultural Sciences, Dharwad 580 005, Karnataka, India

[6]Department of Agricultural Economics, Agricultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - mapillai1@hotmail.com; Ephrem.Habyarimana@icrisat.org

Received: 23 June 2026; Accepted: 15 August 2026; Available online: Version 1.0: 27 September 2026

Cite this article: Periyasamy E, Jegadeesan R, Sundararajan JH, Rengasamy K, Bhupathi N, Veeranathan KDK, Ephrem H, Madhavan AP. Global research trends in sorghum biofortification: A bibliometric analysis of publication patterns, knowledge structures and emerging research priorities. Plant Science Today. 2026;13(sp5):01–12. https://doi.org/10.14719/pst.16296

Abstract

Biofortification is a process aimed at enhancing the nutrient content of crops to address malnutrition. Sorghum (*Sorghum bicolor* L. Moench) is recognised as a crop with substantial micronutrient content and has gained increasing attention in biofortification research. In this study, a bibliometric analysis was conducted to assess the evolution, structure and gaps in global sorghum biofortification research over the past 25 years (2001–25). A total of 127 documents indexed in the Scopus database were identified based on predefined inclusion and exclusion criteria and analysed using Bibliometrix and VOSviewer. The results indicate a sustained increase in research output, particularly after 2013, with an annual growth rate of 13.75 %, alongside a shift in research focus from processing and nutritional studies toward genetic biofortification approaches. Citation patterns reveal geographic concentration of research productivity, with India recording the highest citation count (851), although such metrics primarily reflect publication volume rather than intrinsic research impact. According to Bradford's law, the Journal of Agricultural and Food Chemistry was identified as the leading source in this research area. Among the institutions involved, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) was the leading contributor. The most frequently occurring author keywords were "sorghum", "iron (Fe)", "zinc (Zn)", "biofortification" and "nutritional value". Knowledge structure analysis revealed major thematic domains related to micronutrient biofortification, plant breeding, nutritional quality and bioavailability. The study also identified major research gaps and limitations. Emerging research priorities include advanced breeding technologies, long-term validation studies, nutritional impact assessment and adoption-oriented research. Overall, the study highlights a technologically advancing but structurally fragmented research landscape and underscores the need for interdisciplinary and translational approaches to enhance the impact of sorghum biofortification on food and nutritional security.

Keywords: bibliometric analysis; biofortification; iron; sorghum; zinc

Introduction

The global human population is projected to increase substantially by 2050, resulting in an estimated 35–56 % rise in global food demand between 2010 and 2050 (1). This rapid increase poses significant challenges in ensuring the availability of safe, nutritious and sufficient food. At the same time, malnutrition, particularly micronutrient deficiencies, remains a major global concern. According to the State of Food Security and Nutrition in the World 2026 report states that, approximately 645 million people faced hunger in 2025, highlighting the continuing global challenge of food and nutritional security (2). Recent evidence further indicates that undernourishment remains prevalent in several regions including Sub-Saharan Africa, Eastern Africa and parts of Asia (Supplementary Table 1) (3). Micronutrients including vitamins A, C, D, E and the B-complex vitamins, alongside minerals such as calcium (Ca), folate (FO), iron (Fe), zinc (Zn) and iodine (I) play critical roles in maintaining human health and supporting metabolic functions (4, 5). Among these, Fe and Zn deficiencies are the most widespread forms of micronutrient malnutrition worldwide (6), emphasising the urgent need for sustainable nutritional interventions (7).

Biofortification is increasingly recognised as an effective and sustainable strategy to improve the nutritional quality of staple crops. It involves enhancing the concentration and bioavailability of essential nutrients in edible plant parts through plant breeding, genetic approaches and agronomic management practices (8). Owing to its cost-effectiveness, sustainability and public acceptance, biofortification is recognised as a promising solution to combat micronutrient deficiencies and improve global health outcomes (9, 10). In recognition of the nutritional and agricultural importance of millets, the United Nations declared 2023 as the "International Year of Millets" (11).

Among millet crops, sorghum (*Sorghum bicolor* L. Moench) is one of the most important cereals cultivated in arid and semi-arid regions. It is a C_4 crop belonging to the Poaceae family and serves as a primary food source for more than 500 million people across 90 countries, particularly in low- and middle-income regions (12). The crop is valued for its adaptability to harsh environmental conditions, including drought and high temperatures, as well as for its high biomass production and relatively short growing cycle. Globally, sorghum is cultivated on more than 45 million hectares with an annual production exceeding 60 million tons (13, 14). In addition to its agronomic advantages, sorghum possesses considerable nutritional potential and is widely consumed either directly or as an ingredient in various food products. Its consumption contributes to increased dietary fibre intake and provides valuable bioactive compounds that support human health (15). In recent years, advances in genomic selection, speed breeding and genome-editing technologies have provided new opportunities to accelerate the development of biofortified crop varieties with improved nutritional quality (16).

Several publications have discussed the nutritional composition, bioactive compounds and functional food properties of sorghum. However, these studies mainly focus on nutritional and food quality aspects, while the evolution and intellectual structure of sorghum biofortification research have received limited attention. Given the nutritional importance of sorghum and the growing interest in its biofortification, a comprehensive understanding of research development and emerging trends in this field is increasingly important. To the best of our knowledge, a bibliometric synthesis of sorghum biofortification has not yet been reported. Therefore, a comprehensive evaluation is needed to identify research gaps and future directions in this domain. Such information would provide valuable insights for plant breeders, nutritionists, policymakers and the scientific community to address malnutrition and improve food and nutritional security. Accordingly, the present study provides a bibliometric overview of global research trends in sorghum biofortification by examining publication volumes, citation patterns, influential publications, leading institutions, prolific authors and thematic keyword networks. Specifically, this study addresses the following research questions:

1. What are the publication trends in sorghum biofortification research?
2. Who are the most prolific and influential authors contributing to this research area?
3. Which journals and sources publish the most influential studies in this field?
4. Which institutions are leading advancements in this field?
5. What emerging themes and future research directions are identified in sorghum biofortification?

Methodology

Database selection and search strategy

The initial phase of a bibliometric study involves selecting an appropriate literature database for document retrieval. Various academic databases are available including Scopus, Web of Science, Google Scholar and PubMed. This study employed the Scopus database, which indexes over 23000 journals across multiple disciplines (17, 18) and offers superior accessibility and data retrieval features (19).

In bibliometric analysis, constructing a valid search strategy is crucial to retrieve as many documents as possible while minimising irrelevant results. In this study, the literature search was conducted in the Scopus database on May 20, 2026, using the Title, Abstract and Keywords (TITLE-ABS-KEY) field. The search query employed was: (sorghum OR "*Sorghum bicolor*") AND (biofortification OR biofortified OR bio-fortification OR bio-fortified OR iron OR zinc). The keywords were combined into a query string, using Boolean operators "OR" and "AND" to encompass the targeted research domain. The query string underwent multiple refinements to ensure it covered relevant areas and contexts for retrieving specific literature.

Inclusion criteria

The search initially yielded 1371 documents using the search string. For this study, the inclusion criteria encompassed 25 years (2001–25). Eligible documents included original research and review articles published in English. Subject areas including Agricultural and Biological Sciences, Biochemistry, Genetics and Molecular Biology were selected.

Exclusion criteria

Documents published before 2001 and after 2025 were excluded from this study. Conference proceedings, book chapters, editorials, letters, notes, short communications, retracted publications, non-English publications and unpublished studies were also excluded.

Document screening

The initial search retrieved 1371 documents from the Scopus database, which were subsequently reduced to 1108 documents after applying the publication period criterion (2001–25). This number was further reduced to 1001 documents after restricting the dataset to research and review articles and to 976 documents after applying the English language filter. Following the selection of the relevant subject areas, 667 documents remained. Subsequently, title screening reduced the dataset to 164 documents and abstract screening resulted in a final dataset of 127 documents retained for bibliometric analysis. The study methodology illustration is shown in Fig. 1. Because the search terms included "iron" and "zinc", several publications unrelated to sorghum biofortification were retrieved. Therefore, studies dealing primarily with mineral composition, food chemistry or general nutrient evaluation without focusing on micronutrient enhancement were removed. Duplicate and unrelated publications that did not directly address genetic and agronomic biofortification, nutrient bioavailability or nutritional aspects was also excluded. The search results were exported as a comma-separated (CSV) file, including citation information, abstracts, keywords, references and other essential bibliographic information, for the bibliometric analysis.

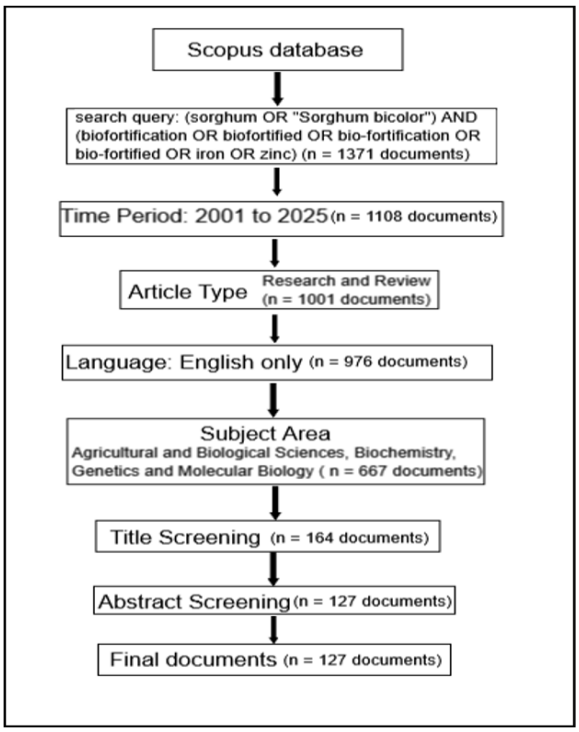


Fig. 1. Methodology flow chart.

Data analysis tools

In this bibliometric study, the authors employed Bibliometrix, an R package designed for bibliometric analysis in RStudio software with Biblioshiny, a web-based interface system developed by Aria and Cuccurullo (20), which provides user- friendly features, various analysis tools and a wide range of visualisations (21). Additionally, VOSviewer was used to produce and explore different bibliometric visualisations, such as bibliographic coupling (22). For both Biblioshiny and VOSviewer tools, the CSV file exported from the Scopus database was used for analysis. For keyword co-occurrence analysis, a minimum occurrence threshold of four was applied.

Results

Descriptive statistics analysis

A total of 127 publications were included in the final bibliometric analysis following the screening procedure described in Fig. 1. The dataset comprised 110 research articles, 16 review articles and one undefined publication (as categorised by the database), distributed across 83 different sources and published between 2001 and 2025. This collection reflects increasing scholarly engagement in sorghum biofortification research, with an annual growth rate of 13.75 %, an average of 30.4 citations per publication and a total of 6529 references. The relatively low average document age of 7.2 years highlights the recent and emerging nature of sorghum biofortification research. On average, each publication involves five co-authors, with international collaborations accounting for 45.67 % of the total publications, reflecting a globally engaged research program across multiple research domains. Table 1 presents the descriptive statistics of the bibliometric dataset.

Trend in research publication volume

Research publication trends in sorghum biofortification from 2001–25 is illustrated in Fig. 2. The initial phase (2001–05) was characterised by very low publication output, reflecting limited research attention to this research area. From 2006–12, publication rates remained relatively stable with some fluctuations. A notable increase in publications was observed after 2013, with a sharp rise observed in 2023 and 2025. Potential drivers of this increase include the growing global attention to micronutrient deficiencies and increased policy interest in climate-resilient crops; however, causal relationships cannot be established from bibliometric data alone. Overall, these research trends indicate an increasing research interest in sorghum biofortification.

Citation analysis

Average citations per year

The average number of citations per year fluctuated throughout the study period. From 2001–08, citations peaked at 10.05 in 2005. Between 2009 and 2016, citation counts varied without a clear trend. After 2017, citations increased steadily, reaching a peak of 9.57 in 2022. The relatively low average citation values observed in 2024 and 2025 can be attributed to citation time-lag effects, as recently published articles have insufficient time to accumulate citations. However, citation counts are inherently influenced by publication age, database expansion and field growth, making direct comparisons across time periods potentially misleading. Therefore, the increase in citation levels observed after 2017 may reflect growing research output and expanded database indexing rather than a proportional increase in research impact or quality (Fig. 3).

Most cited countries

The most cited countries are highlighted in terms of total citation counts and average citations per article among contributing nations, as illustrated in Fig. 4. Country-level citation metrics were derived from the author affiliation information available in the Scopus database and generated through the bibliometric analysis workflow. India recorded the highest total citation count, with 851 citations and an average of 30.4 citations per article. This was followed by the USA, which has 386 total citations with an average of 25.7 citations per article and France, which has 315 total

Table 1. Descriptive statistics

Description	Results
Main information about data	
Timespan	2001 : 2025
Sources (Journals, books, etc)	83
Documents	127
Annual growth rate (%)	13.75
Document average age	7.2
Average citations per doc	30.4
References	6529
Keyword Plus (ID)	797
Author's keywords (DE)	395
Co-authors per doc	5
International co-authorships (%)	45.67
Article	110
Review	16
Undefined*	1

*Undefined documents that are not categorised by Scopus

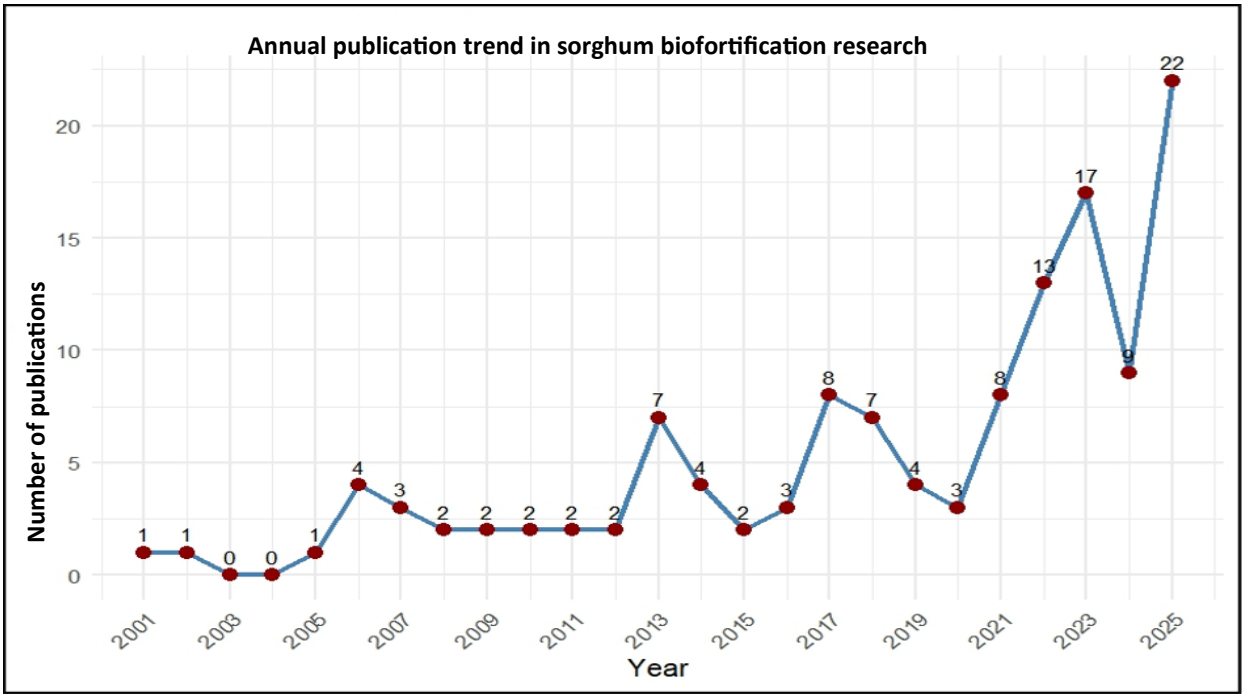


Fig. 2. Trend in research publications on sorghum biofortification.

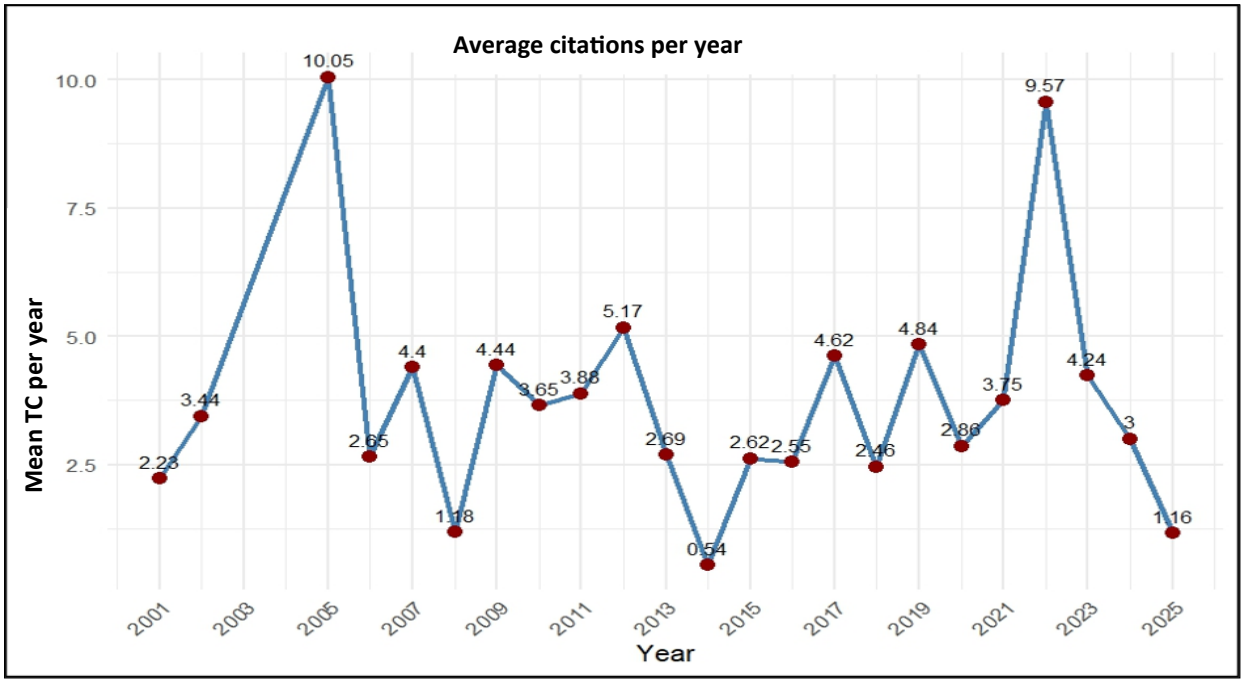


Fig. 3. Average citations per year by publication year (2001–25).

The y-axis (mean TC per year) shows the mean number of citations accumulated annually by publications from each year, calculated as total citations (TC) divided by the number of years since publication.

citations with an average of 157.5 citations per article. However, this average is derived from only two publications and may not be representative of overall citation performance. Total citation counts are largely influenced by publication volume and collaboration networks, rather than reflecting intrinsic research quality. For instance, India's dominance in total citations aligns with its high publication output in sorghum-related research. In contrast, high average citation rate observed for France likely reflects a small number of highly cited publications rather than consistently high citation performance across all outputs. Therefore, national citation rankings should be considered indicators of research visibility within indexed literature rather than definitive measures of scientific or developmental impact. Overall, Fig. 4 illustrates variations among countries in terms of total citation volume and citation intensity per article.

Most globally cited documents

In this bibliometric analysis, the objective was to identify highly cited publications that have significantly influenced research in the field of biofortification. These papers serve as a resource for acquiring deeper knowledge in this area. The Scopus database was utilised for the period from 2001–25. We highlight the top 10 documents, detailing their journals, authors and Digital Object Identifier (DOI) (Table 2). Furthermore, highly cited research publications offer valuable insights into biofortification research and can assist in identifying and addressing research gaps through future research directions in this field.

The research article entitled "Effects of soaking whole cereal and legume seeds on iron, zinc and phytate contents" (23) has the highest number of citations (221) and was published in *Food Chemistry*. This work highlights the effects of soaking on phytate reduction and mineral bioavailability in sorghum and other cereals, providing an important foundation for research on biofortification and nutritional quality improvement. The second most cited article is "Zinc and iron contents and their bioaccessibility in cereals and pulses consumed in India" also received 221 citations (24). This study highlighted sorghum as a significant source of Zn and Fe content and emphasised the influence of phytate on mineral availability. It is highly cited, particularly for its contribution to understanding nutritional quality research programs. Notably, the third and fourth positions are held with 170 and 146 citations, respectively (25, 26). These highly cited studies, published in leading journals, underscore the importance of biofortification research and its multidisciplinary relevance.

Key contributors

Bradford's law

Bradford's law illustrates that research on sorghum biofortification is concentrated within a limited number of core journals, as shown in Fig. 5. This indicates that a substantial proportion of the literature in this field is published in a small set of journals. Among the leading journals, the *Journal of Agricultural and Food Chemistry* and *Journal of Cereal Science* each recorded seven publications, followed by *Food Chemistry*, *Frontiers in Nutrition* and *Journal of Food Composition and Analysis*, each with five publications. Other contributing journals include *Foods*, *Indian Journal of Genetics and Plant Breeding*, *Plant Science Today*, *African Journal of Food, Agriculture, Nutrition and Development* and *Annals of the New York Academy of Sciences*. This distribution reflects the multidisciplinary nature of sorghum biofortification research, spanning nutrition, food science, crop improvement and agricultural sciences. The identified core sources conform to Bradford's law, in which a small number of journals account for a share of publications, while many additional journals contribute fewer studies.

Table 2. The top 10 most cited documents, including their respective journals, digital object identifier (DOI) and total citation counts (2001–25)

Sl. No.	Article title	Authors and year	Journal name	DOI	TC	References
1	Effects of soaking whole cereal and legume seeds on iron, zinc and phytate contents	Lestienne et al. 2005	*Food Chemistry*	http://doi.org/10.1016/j.foodchem.2004.03.040	221	(23)
2	Zinc and iron contents and their bioaccessibility in cereals and pulses consumed in India	Hemalatha et al. 2007	*Food Chemistry*	http://doi.org/10.1016/j.foodchem.2006.07.015	221	(24)
3	Nanoparticle and ionic Zn promote nutrient loading of sorghum grain under low NPK fertilisation	Dimkpa et al. 2017	*Journal of Agricultural and Food Chemistry*	http://doi.org/10.1021/acs.jafc.7b02961	170	(25)
4	Biofortification of crops for reducing malnutrition	Khush GS et al. 2012	*Plant Biotechnology Reports*	http://doi.org/10.1007/s11816-012-0216-5	146	(26)
5	Fermentation and enzyme treatment of tannin sorghum gruels: effects on phenolic compounds, phytate and in vitro accessible iron	Towo et al. 2006	*Food Chemistry*	http://doi.org/10.1016/j.foodchem.2004.11.027	135	(27)
6	Iron and zinc biofortification strategies in dicot plants by intercropping with gramineous species. A review	Zuo and Zhang, 2009	*Agronomy for Sustainable Development*	http://doi.org/10.1051/agro:2008055	130	(28)
7	Sorghum (*Sorghum bicolor* L.) as a potential source of bioactive substances and their biological properties	Espitia-Hernández P et al. 2022	*Critical Reviews in Food Science and Nutrition*	http://doi.org/10.1080/10408398.2020.1852389	124	(29)
8	Nutritional, phytochemical and functional potential of sorghum: A review	Tanwar et al. 2023	*Food Chemistry*	http://doi.org/10.1016/j.focha.2023.100501	123	(30)
9	Bioaccessibility of carotenoids from transgenic provitamin A biofortified sorghum	Lipkie et al. 2013	*Journal of Agricultural and Food Chemistry*	http://doi.org/10.1021/jf305361s	110	(31)
10	CRISPR-based genome editing for nutrient enrichment in crops: A promising approach toward global food security	Kumar et al. 2022	*Frontiers in Genetics*	http://doi.org/10.3389/fgene.2022.932859	106	(32)

DOI: digital object identifier; TC: total citations; Zn: zinc; N: nitrogen; P: phosphorus; K: potassium; CRISPR: clustered regularly interspaced short palindromic repeats.

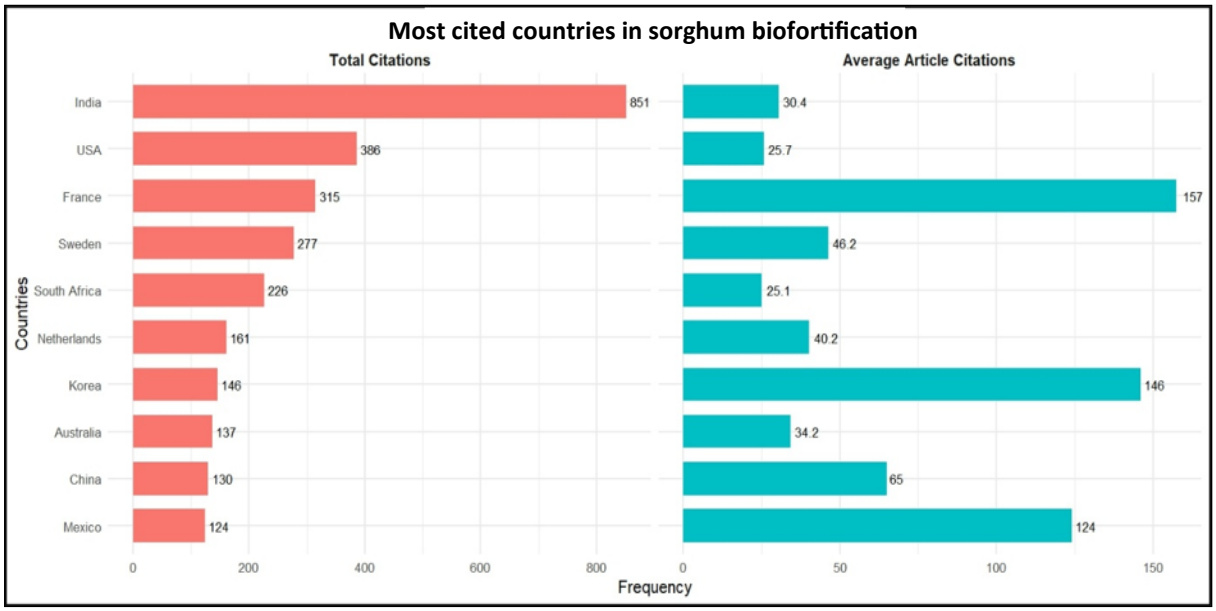


Fig. 4. Top 10 most cited countries (total citations and average article citations).

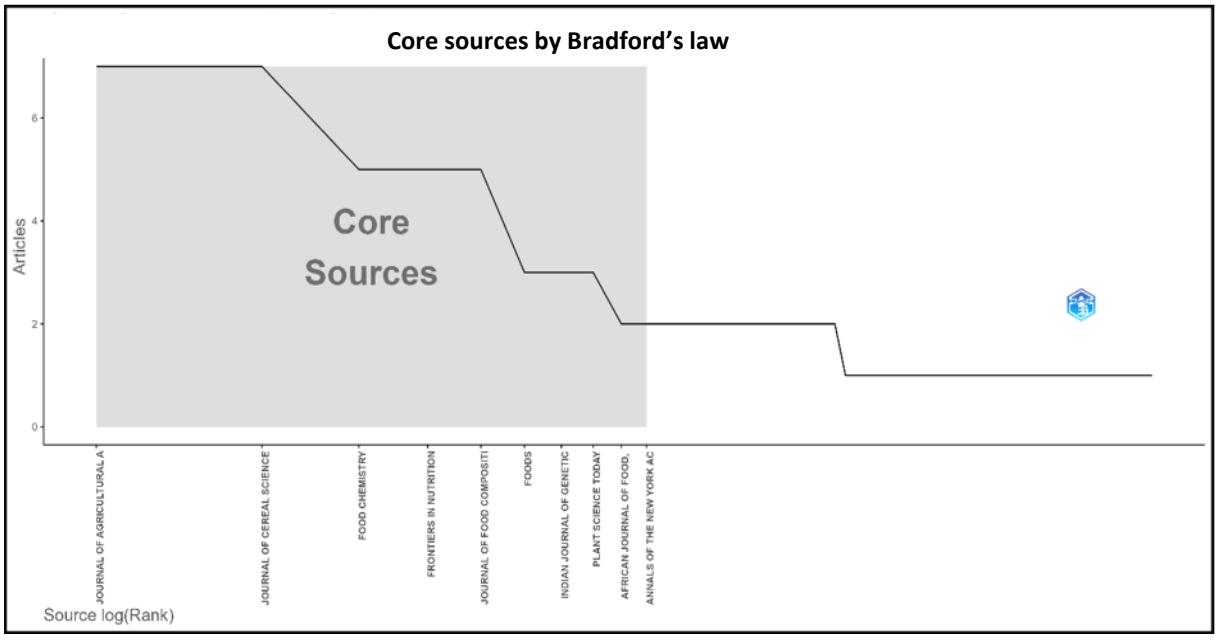


Fig. 5. Core journals identified by Bradford's law in sorghum biofortification research. The shaded regions mark the journals producing the highest share of publications in the dataset; sources are ranked by descending productivity (x-axis, log scale) against number of articles (y-axis).

Local impact of sources

Local impact analysis evaluates the influence of journals within the sorghum biofortification dataset rather than across the broader scientific literature. The H-index and total citations (TC) of sources within the analysed dataset are presented in Fig. 6. *Journal of Agricultural and Food Chemistry* was the most influential journal, with the highest h-index and a TC of 515, indicating its strong influence within sorghum biofortification research. Although *Food Chemistry* recorded a higher TC (547) than the *Journal of Cereal Science* (212), but *Journal of Cereal Science* exhibited a stronger h-index. This suggests a more consistent citation performance, as a larger proportion of its publications received substantial citations within the dataset. Unlike global citation metrics, which reflect citations received across the entire Scopus database, the local citation indicators presented here reflect the contribution and influence of journals within the publications included in this bibliometric analysis. Other influential journals based on h-index and TC include *Foods*, *Frontiers in Nutrition* and *Indian Journal of Genetics and Plant Breeding*, *Journal of Food Composition and Analysis*, *Annals of the New York Academy of Sciences*, *Asian Journal of Dairy and Food Research*, *BMC Genomics*.

Most relevant affiliations

Various research institutions and universities have actively contributed to biofortification research, as shown in Fig. 7. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) made the most significant contribution, with 32 occurrences. This was followed by the Federal University of Lavras with 24 occurrences, Kansas State University with 22 occurrences and Tamil Nadu Agricultural University with 14 occurrences, University of São Paulo and Swedish University of Agricultural Sciences each have 12 occurrences, while Wageningen University and University of the Free State each have 11 occurrences, Université D'Abomey-Calavi and University of Pretoria each have 10 occurrences. These affiliation patterns reflect the geographic distribution and research priorities of biofortification research, rather than merely showing publication counts. The prominence

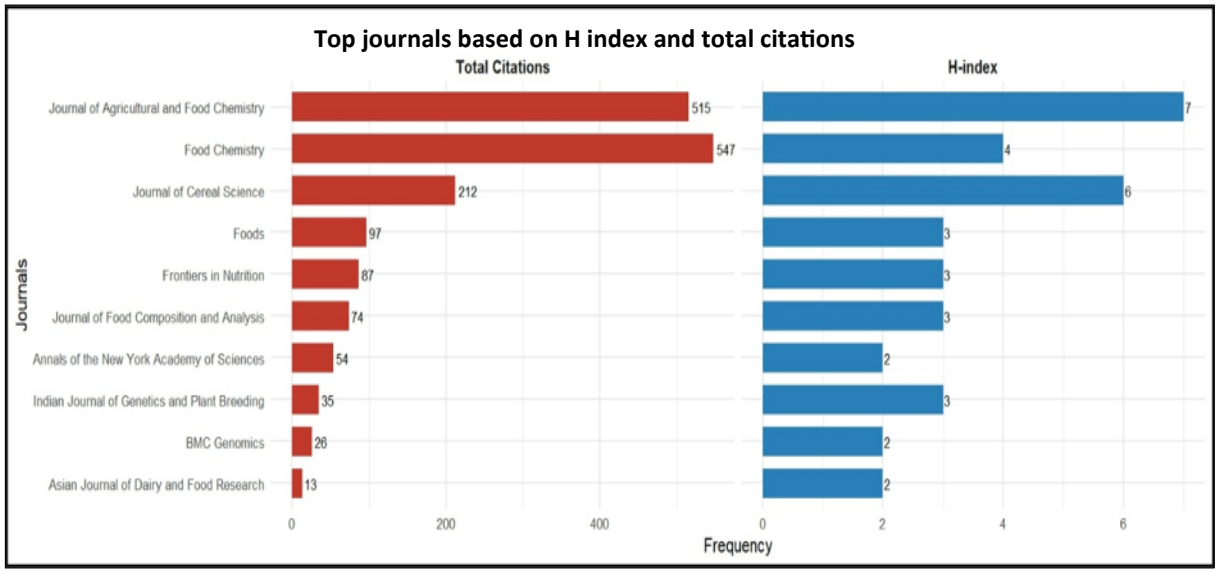


Fig. 6. Local impact of sources based on h-index and total citations (TC).

TC: total citations; h-index: highest number of publications.

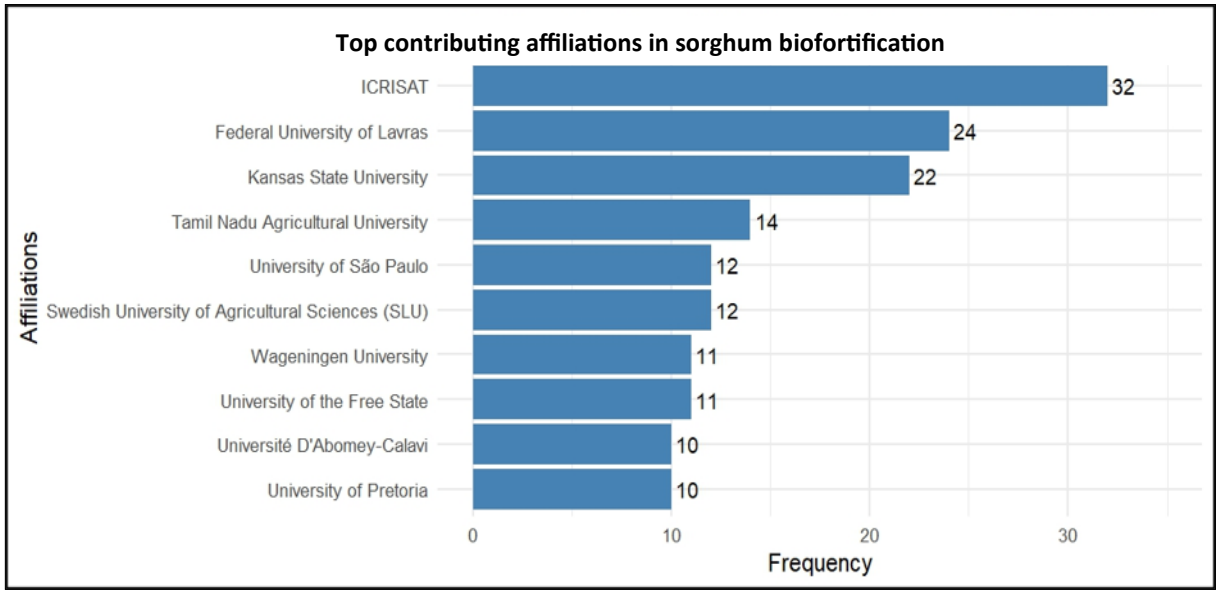


Fig. 7. Top ten affiliations based on occurrences in documents.

of ICRISAT and agricultural universities suggests a strong emphasis on crop improvement and nutritional research in regions where sorghum is an important staple crop. Most of the leading affiliations identified in this analysis are public research institutions or universities, whereas industry and policy-oriented organisations are less represented among the most productive institutions. This pattern may indicate greater research activity within the public research sector, although further analysis would be required to assess institutional participation across the broader innovation and adoption pathway.

Dominant keywords

Keyword frequency in sorghum biofortification research is presented in Fig. 8. The term sorghum occurred most frequently (68 occurrences), followed by zinc (43), iron (39), biofortification (26), nutritional value (18), plant breeding (17), fermentation (14), chemistry (13), phytic acid (12) and digestion (11). This keyword distribution not only reflects topic prevalence but also highlights a strong research focus on Fe and Zn biofortification, indicating limited diversification toward other micronutrients. This focus aligns with global nutritional priorities; however, it also suggests an imbalance in research scope. The co-occurrence of "plant breeding" and "biofortification" reflects a dominant focus on genetic approaches, whereas terms such as "fermentation" and "phytic acid" indicate a secondary emphasis on processing and bioaccessibility. The absence of adoption- and value chain-related terms suggests limited downstream integration, revealing a gap between technological development and nutritional impact.

Trend topics

The different research phases in sorghum biofortification, with circles representing keyword occurrence frequency; large circles indicate higher frequency whereas small circles indicate lower frequency (Fig. 9). The early phase (2005–12) includes terms such as phytic acid and *in vitro* study, reflecting a strong focus on processing-based and biochemical research, particularly the reduction of antinutritional factors and laboratory-based nutritional evaluation. This focus coincided with efforts to improve mineral bioavailability and understand nutritional constraints associated with sorghum consumption. The intermediate phase (2013–20) indicates a transition toward

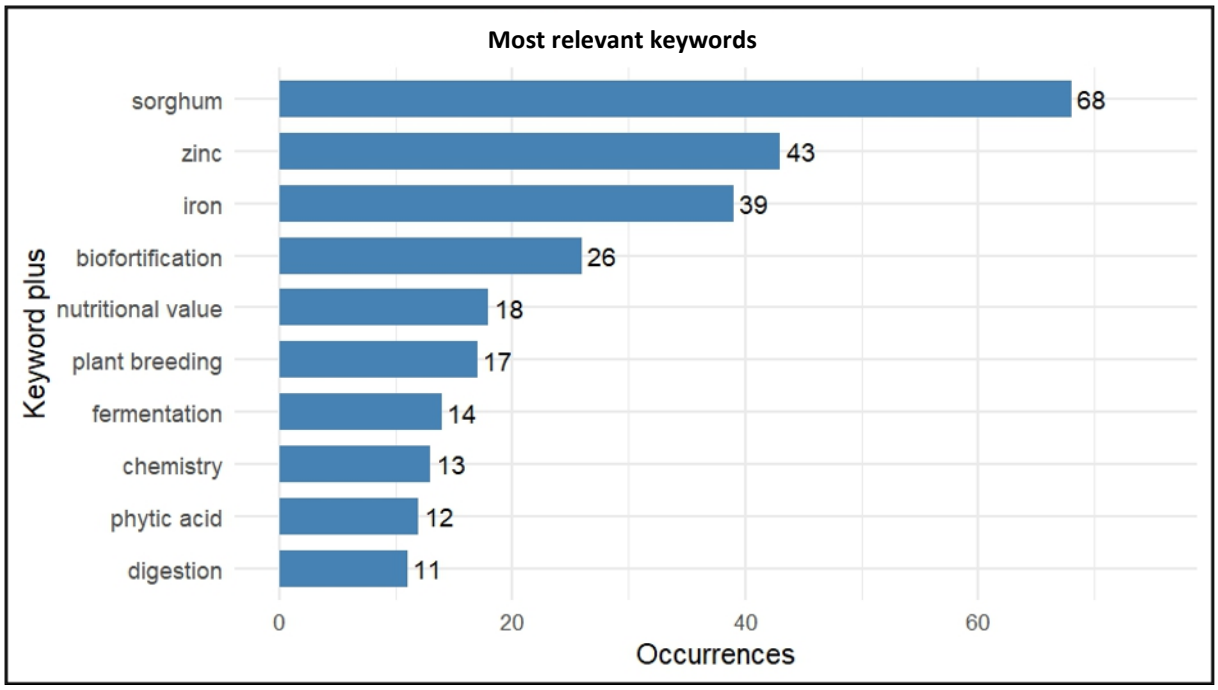


Fig. 8. Top 10 most used keywords.

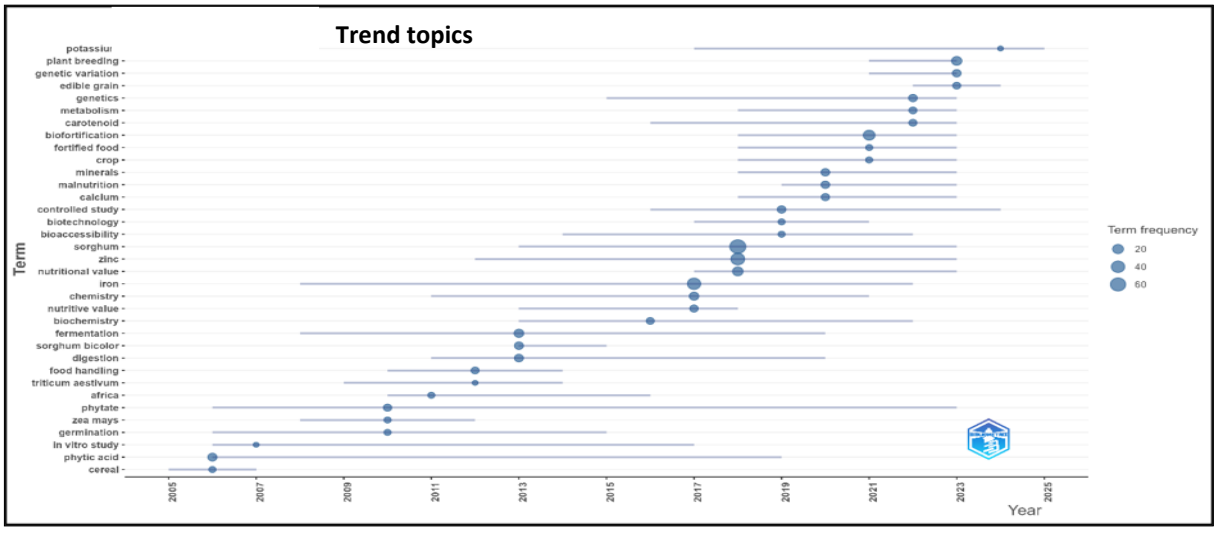


Fig. 9. Trend topics identified in sorghum biofortification.

bioaccessibility and nutritional validation, with increased focus on Fe and Zn availability, suggesting a shift from compositional analysis to functional nutritional relevance. This transition aligns with the growing emphasis on addressing micronutrient deficiencies through crop-based nutritional interventions. The recent phase (2021–25) was dominated by terms such as biofortification, plant breeding and genetics, highlighting intensified interest in breeding and molecular approaches. The emergence of these keywords reflects the growing integration of modern crop improvement strategies aimed at developing nutrient-enriched sorghum varieties. However, this progression shows a mostly linear and fragmented development, with limited integration across the domains. The absence of adoption -related themes further highlights a significant gap in translating research advances into real-world impact.

Network visualisation of co-occurrence of author keywords

This co-occurrence network visualisation of author keywords identifies and illustrates the major themes and connections among the collected publications (33). In this study, VOSviewer was used to visualise the co-occurrence of author keywords and identify the knowledge structure of the research field. Four distinct clusters based on the author keywords are illustrated in Fig. 10. A minimum occurrence threshold of 4 was applied, resulting in 79 keywords meeting the inclusion criterion. This threshold was selected to balance network comprehensiveness and interpretability by excluding infrequently occurring keywords while retaining a sufficient number of relevant terms to capture the major research themes within the dataset. This approach reduced noise in the network and facilitated clearer identification and interpretation of the thematic clusters, thereby enhancing the robustness of the bibliometric analysis (34).

Red cluster (biofortification and nutritional security)

The red cluster has biofortification as a central keyword, with related terms including zinc, micronutrients, food security, genetic variation, transgenic plant, breeding, Africa, fortified food, biotechnology, cultivar and trace element. This cluster highlights the role of micronutrient enhancement in improving food security. The terms plant breeding and biotechnology indicate the combination of traditional breeding approaches and advanced molecular technologies to develop nutritionally enriched

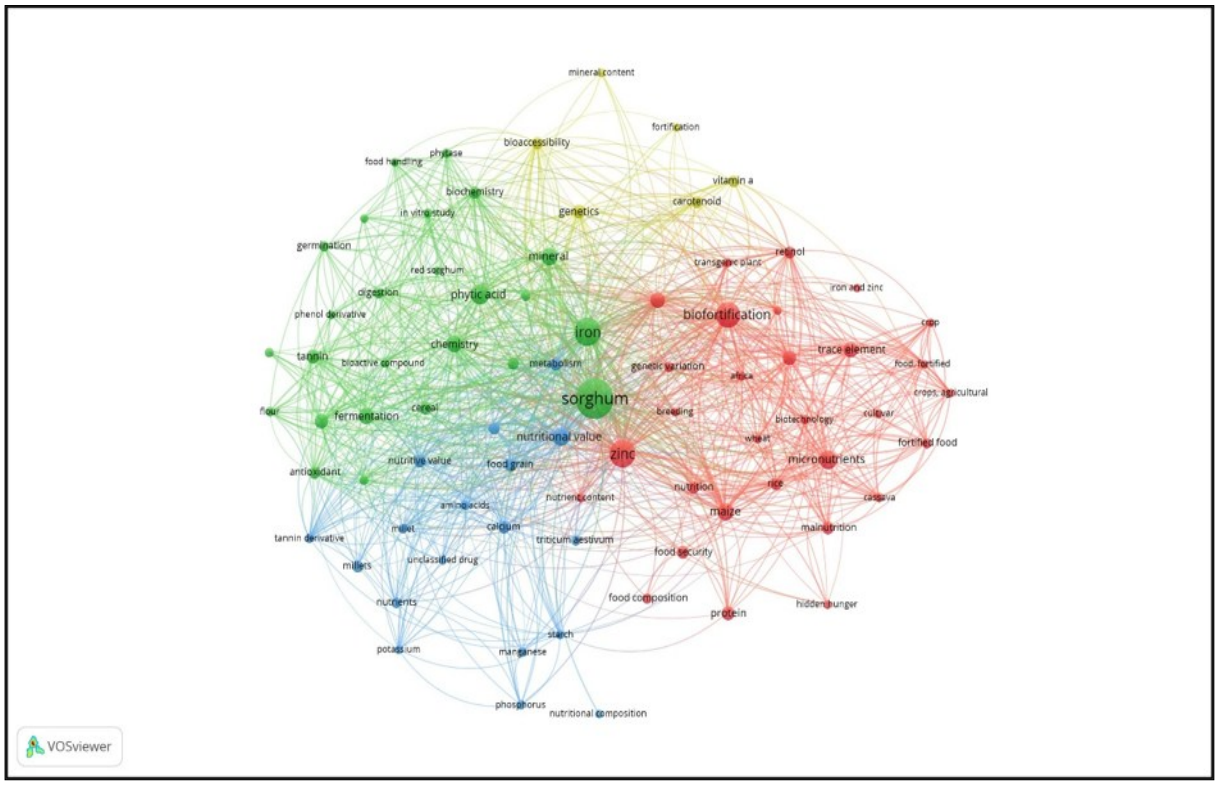


Fig. 10. Co-occurrence network visualisation of author keywords.

biofortified varieties. The keyword Africa indicates that sorghum is a staple crop and a major growing area, providing a livelihood for its people.

Green cluster (food chemistry and bioavailability)

The green cluster with "Sorghum" as a central keyword, shows connections between different terms such as iron, red sorghum, mineral, antioxidant, biochemistry, cereal, antioxidant, bioactive compound and tannin. This cluster highlights the nutritional availability and functional compounds of red sorghum, which contains various bioactive compounds and exhibits potent antioxidant activity. It is also a good source of Fe, which can help reduce anemia. Following the International Year of Millets in 2023, people are shifting towards health-based diet, including millet in their lifestyle due to the functional food properties of sorghum, its high micronutrient content and good antioxidant properties.

Blue cluster (nutritional composition and grain quality)

The blue cluster focus on nutritional value, food grain, amino acids, millets, manganese (Mn), starch, calcium (Ca), tannin derivatives. This cluster highlights mineral profiling and nutrient evaluation. The association of amino acids, Ca and nutritional value reflects growing interest in improving the overall quality and dietary significance of the sorghum crop. The mineral content, such as manganese and Ca, indicates that ongoing research on micronutrient enhancement in sorghum crop. The term millets also indicate that it is a climate-resilient food crop thriving under drought conditions. This suggests that with increased awareness of health-based lifestyle, people are moving towards millets, which contain higher nutritional compounds compared to other cereal crops.

Yellow cluster (genetics and bioaccessibility)

The yellow cluster focuses on genetics, carotenoid, mineral content and vitamin A. This cluster highlights advances in genetics, nutrient bioaccessibility and mineral content. The presence of keywords like vitamin A and carotenoid, beyond research on Fe and Zn levels, indicates progress in enhancing other micronutrients in sorghum. Research is advancing towards improving multiple micronutrients globally in sorghum and other cereals.

Overall, the network visualisation of the author keyword co-occurrence illustrates the interrelationship among sorghum biofortification and multidisciplinary fields such as breeding, micronutrient enhancement, nutrition, genetics, biochemistry and public health.

Factorial map

The conceptual structure map generated using multiple correspondence analysis (MCA) identified the thematic relationships and conceptual clusters within sorghum biofortification research. The red cluster represents the interconnected themes of biofortification, food security, malnutrition, plant breeding and sorghum (Fig. 11). Terms such as plant breeding, transgenic plants and genetic variation which underscore the combination of conventional and advanced breeding technologies to develop the nutritionally enriched sorghum varieties. The occurrence of keywords including iron, zinc, manganese and nutrition-related keywords indicates the major focus on micronutrient enhancement to combat the hidden hunger and malnutrition. In addition, terms such as tannin, flavonoids, phytic acid and bioavailability indicate a growing research interest in bioactive compounds, antinutritional factors and nutrient utilisation. Keywords such as malnutrition and food security highlight the global public health priorities driving research on sorghum biofortification. Overall, the conceptual structure map reveals the multidisciplinary nature of sorghum biofortification research, through the integration of crop improvement, nutritional quality, food science and human health aspects within the interconnected thematic domains.

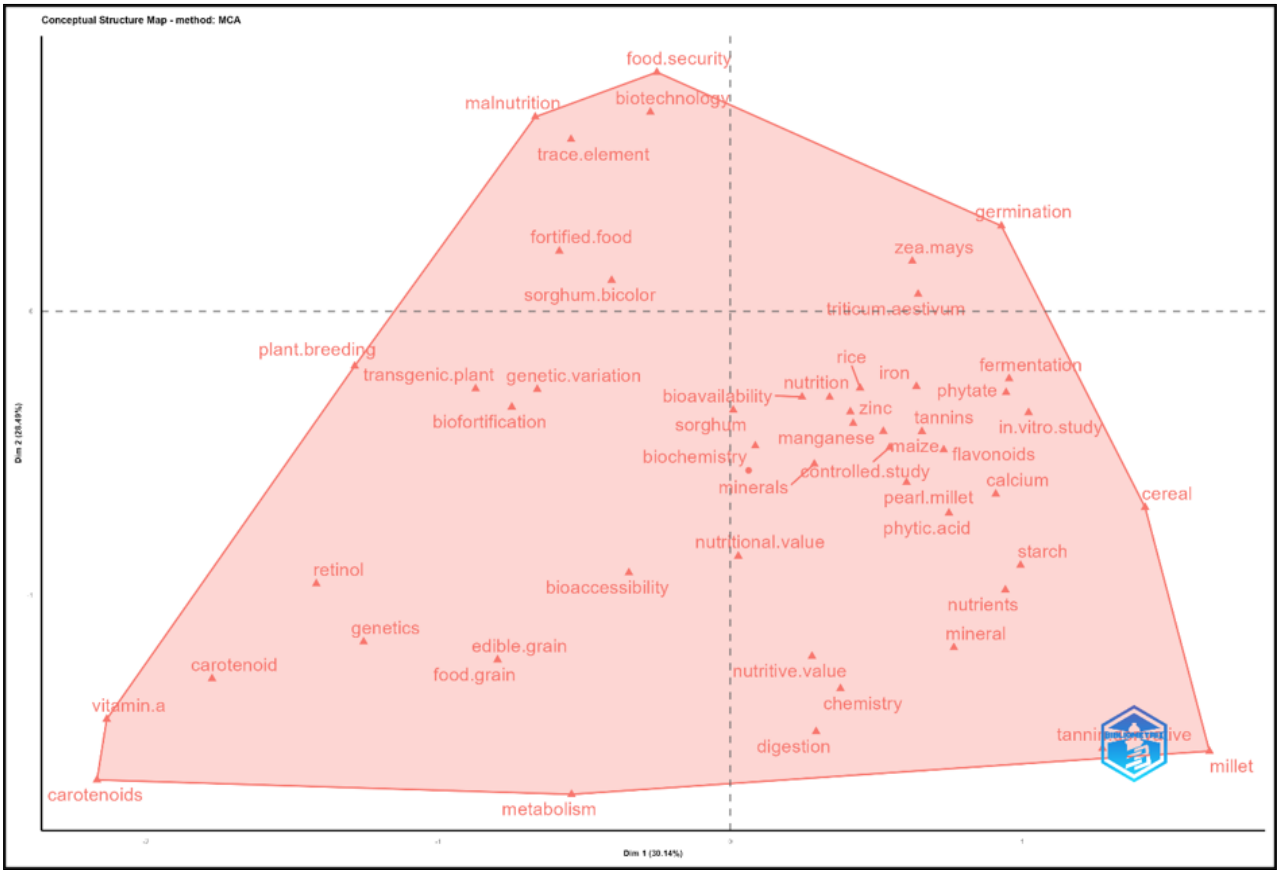


Fig. 11. Thematic map and conceptual structure map of sorghum biofortification based on keyword.

Knowledge gaps revealed by bibliometric analysis

1. The current research landscape predominantly focuses on Fe and Zn biofortification, indicating limited diversification toward other crucial micronutrients such as vitamin A, Ca, folate and selenium (Se), which are important for addressing complex nutritional deficiencies.
2. The relatively low representation of advanced breeding approaches (e.g., genomic selection) suggests a lag in the adoption of high-resolution tools, potentially constraining genetic improvement efficiency.
3. Emerging technologies such as genomic selection, speed breeding, gene editing and CRISPR/Cas-based approaches remain underrepresented in the current literature, despite their potential to accelerate the development of nutrient-enriched sorghum varieties and enhance biofortification efficiency.
4. More critically, research is disproportionately concentrated in upstream domains, while socio-economic evaluation, consumer acceptance and policy frameworks remain underdeveloped, limiting translational relevance.
5. The scarcity of long-term field validation and adoption studies restricts understanding of varietal stability and real-world performance.
6. Similarly, limited research on product development and health outcomes highlights a weak linkage between crop improvement and dietary impact.
7. Overall, the absence of studies linking biofortification with public health metrics and SDG indicators underscores a critical gap in evaluating societal impact. Collectively, these gaps may reflect research priorities focused on Fe and Zn enhancement, technological and resource constraints, limited interdisciplinary integration and the challenges associated with evaluating long-term adoption, nutritional outcomes and societal impacts.

Limitations of the study

This bibliometric study has certain limitations that must be acknowledged should be considered when interpreting the findings and to maintain methodological transparency.

1. First, the search was limited to a single database, relying exclusively on Scopus as the primary source of bibliographic information. While Scopus is a reputable and widely used index, it does not fully cover locally published studies. Future research should consider combining multiple databases (WOSCC, PubMed, Google Scholar) to achieve broader coverage and a more comprehensive literature collection.
2. Second, only English language publications were included, which may introduce language bias by excluding relevant studies published in other languages.
3. Third, the selected study period (2001–25) excludes studies published after 2025, resulting in an incomplete dataset. This limitation should be considered when interpreting the results.
4. Fourth, the software tools used for analysis and visualisation employ algorithmic clustering methods to map intellectual structures and thematic relationships. While these tools facilitate convenient and efficient analysis, the results may be sensitive to parameter settings and could affect the interpretation of complex relationships.
5. Fifth, citation-based indicators may be influenced by factors such as journal reputation, publication age, self-citations and disciplinary citation practices. Therefore, citation metrics should be interpreted as indicators of research visibility rather than definitive measures of scientific quality.

Conclusion

This review presents a bibliometric synthesis of the current research landscape, providing a structured analysis of research dynamics, thematic domains and knowledge gaps in sorghum biofortification. The application of bibliometric tools (Bibliometrix and VOSviewer) enabled a systematic mapping of publication patterns and thematic evolution, although these approaches primarily capture research activity rather than impact or quality. A total of 127 documents published between 2001 and 2025 were analysed, revealing increasing research attention, particularly after 2013, with strong methodological and thematic concentration. Citation patterns suggest geographic concentration of research output, with India and other key contributors playing prominent roles; however, these patterns reflect publication and collaboration dynamics rather than intrinsic research impact. The dominance of keywords such as sorghum, iron (Fe), zinc (Zn), biofortification, underscores a narrow focus on mineral biofortification and genetic approaches, with limited diversification into other multi-nutrient strategies. Future research should focus on integrating genetic improvement and nutritional evaluation frameworks, alongside long-term efficacy studies and assessments of public health outcomes. Greater emphasis on adoption pathways, consumer acceptance and policy support is essential to bridge the gap between technological development and real-world impact. Future research should also prioritise evaluating micronutrient bioavailability under field conditions and assessing the contribution of sorghum biofortification to public health outcomes and Sustainable Development Goals (SDGs). In addition, systematic reviews, meta-analyses and qualitative studies could complement bibliometric analyses by providing deeper insights into research effectiveness and real-world impact. While sorghum biofortification remains a promising strategy for improving micronutrient availability, its effectiveness cannot be fully assessed through bibliometric evidence alone. Advancing this field will require interdisciplinary and translational research approaches to support evidence-based decision-making and achieve meaningful contributions to food and nutritional security.

Acknowledgements

The authors acknowledges the financial support received from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, for research funding. The authors gratefully acknowledge the support provided by the Tamil Nadu Agricultural University (TNAU) e-library for facilitating access to the Scopus database. During the preparation of this manuscript, the authors used RStudio and VOSviewer for data analysis, Mind the Graph for flowchart preparation and EndNote for reference management. The first author also expresses their gratitude to Ms. Prathibha H R for her valuable assistance in proofreading the manuscript.

Authors' contributions

PE, MAP, EPH contributed to the study conception and design. PE, MAP, EH were responsible for the material preparation, methodology, data collection and data analysis. PE and BN prepared the first draft of the manuscript. MAP, EPH, JR, SJH, RK, BN and VKDK contributed to manuscript review and editing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Paperpal to improve language clarity and structure. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Van Dijk M, Morley T, Rau ML, Saghai Y. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nat Food. 2021;2(7):494–501. http://doi.org/10.1038/s43016-021-00322-9
2. FAO, IFAD, UNICEF, WFP, WHO. The State of Food Security and Nutrition in the World 2026 – Understanding and addressing the high cost of a healthy diet. Rome: FAO; 2026.
3. Food and Agriculture Organization of the United Nations. FAOSTAT: Suite of Food Security Indicators. Rome: FAO; 2026. http://www.fao.org/faostat/en/#data/FS
4. Younes S. The role of micronutrients on the treatment of diabetes. Hum Nutr Metab. 2024;35:200238. http://doi.org/10.1016/j.hnm.2023.200238
5. Kiani AK, Dhuli K, Donato K, Aquilanti B, Velluti V, Matera G, et al. Main nutritional deficiencies. J Prev Med Hyg. 2022;63(2 Suppl 3). http://doi.org/10.15167/2421-4248/jpmh2022.63.2S3.2752
6. Raza Q, Saher H, Shahzadi F, Riaz A, Bibi T, Sabar M. Genetic diversity in traditional genotypes for grain iron, zinc and β-carotene contents reveal potential for breeding micronutrient dense rice. J Exp Biol Agric Sci. 2019;7(2):194–203. http://doi.org/10.18006/2019.7(2).194.203
7. Jangir CK, Kumar S, Lakhran H, Meena RS. Towards mitigating malnutrition in pulses through biofortification. Trends Biosci. 2017;10(17):2999–3002.
8. Patil R, Diwan JR, Nidagundi JM, Lokesha R, Ravi MV, Boranayak MB, et al. Genetic diversity of brown rice for iron and zinc content. Electron J Plant Breed. 2015;6(1):196–203.
9. Kondaiah P, Yaduvanshi PS, Sharp PA, Pullakhandam R. Iron and zinc homeostasis and interactions: does enteric zinc excretion cross-talk with intestinal iron absorption? Nutrients. 2019;11(8):1885. http://doi.org/10.3390/nu11081885
10. Maqbool MA, Beshir A. Zinc biofortification of maize (*Zea mays* L.): status and challenges. Plant Breed. 2019;138(1):1–28. http://doi.org/10.1111/pbr.12658
11. Nesari TM. Celebrating international year of millets: way towards holistic well-being. J Ayurveda Case Rep. 2023;6(1):1–4. http://doi.org/10.4103/jacr.jacr_14_23
12. Abdelhalim TS, Abdelhalim NS, Kamal NM, Mohamed EE, Hassan AB. Exploiting the potential of Sudanese sorghum landraces in biofortification: physicochemical quality of the grain of sorghum (*Sorghum bicolor* L. Moench) landraces. Food Chem. 2021;337:127604. http://doi.org/10.1016/j.foodchem.2020.127604
13. Hossain MS, Islam MN, Rahman MM, Mostofa MG, Khan MAR. Sorghum: a prospective crop for climatic vulnerability, food and nutritional security. J Agric Food Res. 2022;8:100300. http://doi.org/10.1016/j.jafr.2022.100300
14. Sarshad A, Talei D, Torabi M, Rafiei F, Nejatkhah P. Morphological and biochemical responses of *Sorghum bicolor* (L.) Moench under drought stress. SN Appl Sci. 2021;3(1):81. http://doi.org/10.1007/s42452-020-03977-4

15. Aguiar EV, Santos FG, Queiroz VAV, Capriles VD. A decade of evidence of sorghum potential in the development of novel food products: insights from a bibliometric analysis. Foods. 2023;12(20):3790. http://doi.org/10.3390/foods12203790

16. Zulfiqar U, Khokhar A, Maqsood MF, Shahbaz M, Naz N, Sara M, et al. Genetic biofortification: advancing crop nutrition to tackle hidden hunger. Funct Integr Genomics. 2024;24(2):34. http://doi.org/10.1007/s10142-024-01308-z

17. Falagas ME, Pitsouni EI, Malietzis GA, Pappas G. Comparison of PubMed, Scopus, Web of Science and Google Scholar: strengths and weaknesses. FASEB J. 2008;22(2):338–42. http://doi.org/10.1096/fj.07-9492lsf

18. Singh VK, Singh P, Karmakar M, Leta J, Mayr P. The journal coverage of Web of Science, Scopus and Dimensions: a comparative analysis. Scientometrics. 2021;126(6):5113–42. http://doi.org/10.1007/s11192-021-03948-5

19. Pranckutė R. Web of Science (WoS) and Scopus: the titans of bibliographic information in today's academic world. Publications. 2021;9(1):12. http://doi.org/10.3390/publications9010012

20. Aria M, Cuccurullo C. bibliometrix: an R-tool for comprehensive science mapping analysis. J Informetr. 2017;11(4):959–75.

21. Moral-Muñoz JA, Herrera-Viedma E, Santisteban-Espejo A, Cobo MJ. Software tools for conducting bibliometric analysis in science: an up-to-date review. El Prof Inf. 2020;29(1). http://doi.org/10.3145/epi.2020.ene.03

22. Arruda H, Silva ER, Lessa M, Proenca Jr D, Bartholo R. Resource review. J Med Libr Assoc. 2022;110(3):392–95.

23. Lestienne I, Icard-Vernière C, Mouquet C, Picq C, Trèche S. Effects of soaking whole cereal and legume seeds on iron, zinc and phytate contents. Food Chem. 2005;89(3):421–25. http://doi.org/10.1016/j.foodchem.2004.03.040

24. Hemalatha S, Platel K, Srinivasan K. Zinc and iron contents and their bioaccessibility in cereals and pulses consumed in India. Food Chem. 2007;102(4):1328–36. http://doi.org/10.1016/j.foodchem.2006.07.015

25. Dimkpa CO, White JC, Elmer WH, Gardea-Torresdey J. Nanoparticle and ionic Zn promote nutrient loading of sorghum grain under low NPK fertilization. J Agric Food Chem. 2017;65(39):8552–59. http://doi.org/10.1021/acs.jafc.7b02961

26. Khush GS, Lee S, Cho J-I, Jeon J-S. Biofortification of crops for reducing malnutrition. Plant Biotechnol Rep. 2012;6(3):195–202. http://doi.org/10.1007/s11816-012-0216-5

27. Towo E, Matuschek E, Svanberg U. Fermentation and enzyme treatment of tannin sorghum gruels: effects on phenolic compounds, phytate and in vitro accessible iron. Food Chem. 2006;94(3):369–76. http://doi.org/10.1016/j.foodchem.2004.11.027

28. Zuo Y, Zhang F. Iron and zinc biofortification strategies in dicot plants by intercropping with gramineous species: a review. Agron Sustain Dev. 2009;29(1):63–71. http://doi.org/10.1051/agro:2008055

29. Espitia-Hernández P, Chavez Gonzalez ML, Ascacio-Valdés JA, Dávila-Medina D, Flores-Naveda A, Silva T, et al. Sorghum (*Sorghum bicolor* L.) as a potential source of bioactive substances and their biological properties. Crit Rev Food Sci Nutr. 2022;62(8):2269–80. http://doi.org/10.1080/10408398.2020.1852389

30. Tanwar R, Panghal A, Chaudhary G, Kumari A, Chhikara N. Nutritional, phytochemical and functional potential of sorghum: a review. Food Chem Adv. 2023;3:100501. http://doi.org/10.1016/j.focha.2023.100501

31. Lipkie TE, De Moura FF, Zhao Z-Y, Albertsen MC, Che P, Glassman K, et al. Bioaccessibility of carotenoids from transgenic provitamin A biofortified sorghum. J Agric Food Chem. 2013;61(24):5764–67. http://doi.org/10.1021/jf305361s

32. Kumar D, Yadav A, Ahmad R, Dwivedi UN, Yadav K. CRISPR-based genome editing for nutrient enrichment in crops: a promising approach toward global food security. Front Genet. 2022;13:932859. http://doi.org/10.3389/fgene.2022.932859

33. Gusenbauer M. Search where you will find most: comparing the disciplinary coverage of 56 bibliographic databases. Scientometrics. 2022;127(5):2683–745. http://doi.org/10.1007/s11192-022-04289-7

34. Hassan W, Duarte AE. Bibliometric analysis: a few suggestions. Curr Probl Cardiol. 2024;49(8):102640. http://doi.org/10.1016/j.cpcardiol.2024.102640

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (https://creativecommons.org/licenses/by/4.0/)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.