Bonou *et al. Discover Plants* (2026) 3:34
https://doi.org/10.1007/s44372-026-00489-0

Discover Plants

REVIEW

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Scientometric analysis of global trends and future opportunities for research on Cowpea under water stress

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Abstract

Cowpea (*Vigna unguiculata* (L.) Walp.) is an essential legume for food security in arid and semi-arid regions. Yet, a comprehensive synthesis of research on its responses to water stress is lacking. This study conducted a scientometric analysis using the Web of Science and Scopus databases to map advances and gaps in knowledge about cowpea under water stress. Articles published between May 1948 and August 2024 were considered. The analysis was performed using the Bibliometrix package (RStudio) and VOSviewer. A study was conducted on the distribution of article proportions, the impact of scientific production, the productivity trends of the top 10 authors, researcher collaboration networks, the top 10 most cited articles, three-field graphs, keyword co-occurrence networks, and the cooperation density between countries. The results revealed consistent growth in publications, peaking in 2022, with Hall A. E. identified as the most prolific author. The keyword co-citation analysis highlighted five main research domains: (i) abiotic stresses and growth, (ii) quality and digestibility, (iii) productivity and soil, (iv) pest resistance and genetics, and (v) genomics. The study concludes that future research integrating innovative technologies such as artificial intelligence, remote sensing, and the Internet of Things, along with research on germination, intercropping systems, genetic improvement, and agronomic and nutritional aspects, has the potential to promote more resilient and efficient production systems. The review identifies significant research gaps in drought-tolerant cowpea genomics and calls for stronger collaboration among African and Asian researchers.

Highlights

- Scientometric analysis reveals growth in research on cowpea and water stress.
- RStudio and VOSviewer were used to map global trends and collaborations.
- Abiotic stress, productivity, and genetics are the most recurrent themes.
- Gaps were identified in germination, intercropping, and agronomic practices.
- Technologies such as AI and IoT can optimize cowpea management in the future.

Keywords *Vigna unguiculata* (L.) walp, Water stress, Drought tolerance, Bibliometric analysis, Scientometric mapping.

1 Introduction

Cowpea (*Vigna unguiculata* (L.) Walp.) is a legume of global importance, cultivated in Africa, South America, Asia, and the United States [1–3]. It thrives in low-fertility soils, enriches the soil through nitrogen fixation, and serves multiple purposes as food, feed, and fodder [4, 5]. With high protein content and essential amino acids, cowpea is a key nutritional resource for human and animal diets [6–9]. In Brazil, it plays a fundamental socioeconomic role, particularly for family farmers in the Northeast, due to its resilience, low input requirements, and tolerance to pests and drought [10, 11].

Despite its resilience, cowpea productivity is severely constrained by water stress and recurrent drought, which remain the most critical abiotic factors limiting yield stability in regions where the crop is most needed. Understanding how research has addressed water stress in cowpea is essential to inform strategies for genetic improvement, agronomic management, and climate adaptation. To systematically capture how this knowledge has evolved and identify research gaps, scientometrics provides a robust framework.

Scientometrics is a quantitative field of research that analyzes the dynamics of scientific activity, including research productivity, collaboration patterns, and knowledge dissemination. Bibliometrics, a subset of scientometrics, focuses on the analysis of scholarly publications and citation patterns to evaluate research performance and trends. Scientometric and bibliometric analyses offer powerful tools for mapping the evolution of research, identifying key contributors, and highlighting thematic trends and collaboration networks [12–15].

While bibliometric reviews have been conducted on other aspects of cowpea, such as synthesized information providing stress vigor and biochemical tests in cowpea seeds [16] and the association of rhizobia and arbuscular mycorrhizal fungi in *Vigna unguiculata* L. Walp [17], besides these, other reviews reported exclusively on the drying and physical properties of cowpea grains [18] and on the nutritional use of cowpea (*Vigna unguiculata* L. Walp) for human and animal diets [19], no comprehensive scientometric synthesis has yet examined research on cowpea under water stress. This represents a critical gap, given the central role of drought tolerance and resilience in current and future breeding programs.

Therefore, the objective of this study is to conduct a scientometric analysis of research on cowpea under water stress, using R (Bibliometrix package) and VOSviewer to examine publication dynamics, author productivity, international collaboration, and thematic clusters. By mapping advances and gaps, this study aims to provide insights that can guide future research priorities, breeding strategies, and policies to strengthen cowpea's role in food security under climate change.

2 Materials and methods

2.1 Data sources and search strategy

In the present study, a systematic review was carried out using the Scopus (Elsevier, Amsterdam, The Netherlands) and Web of Science (Clarivate Analytics, Philadelphia, USA) databases as sources, both of which are widely recognized for their extensive coverage of peer-reviewed literature and are frequently employed in bibliometric analyses [20, 21]. The search strategy was based on keywords commonly used in studies addressing cowpea and water stress, as reported in previous research [22–24]. Therefore, the search strategy was structured by grouping the keywords into two main components: crop-related terms and stress-related terms. Crop-related terms included "*Vigna unguiculata*," "Vigna-unguiculata," "Vigna-unguiculata (L.) Walp," and "Cowpea." In contrast, stress-related terms comprised "water stress," "drought stress," "hydric stress," "mitigation," "amelioration," "resilience strategies," and "stress tolerance." The final search formula combined both components using Boolean operators: (Crop terms) AND (Stress terms). This structured approach facilitated comprehensive, reproducible retrieval of relevant studies. For the search, the complete publication period in each database was considered: 1987 for Scopus and May 1948 to August 2024 for WoS. A visual inspection of the files was conducted, and reviews, commentary articles, corrected studies, and articles not within the scope of our study were excluded (Fig. 1).

2.2 Scientometric analysis and scientific mapping

Scientific mapping and descriptive statistical analyses were performed using the Bibliometrix 2.2.1 package [25], implemented in RStudio version 4.4.1 [26] and the VOSviewer software. Only studies indexed in the Web of Science database were considered for the scientometric analyses. This choice was based on three factors: (i) most studies were retrieved in searches performed in both databases; (ii) to avoid possible biases resulting from the heterogeneous attribution of the number of citations between the different databases; and (iii) the number of studies retrieved in the Web of Science was higher than that in Scopus.

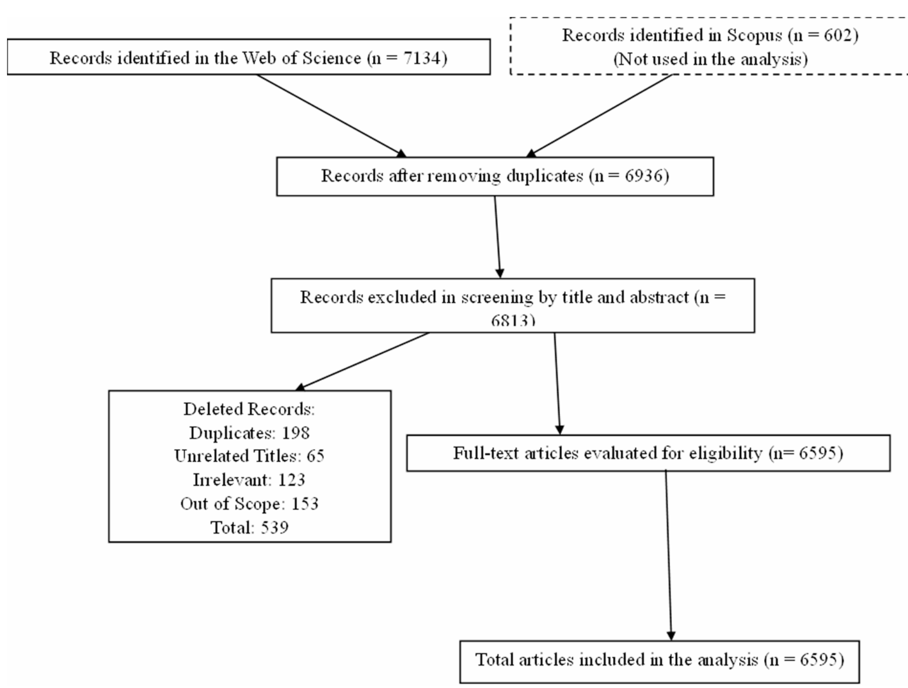

Fig. 1 Flowchart illustrating article inclusion and exclusion criteria

2.3 Metrics analysis

The evolution of publications over the years, the most productive authors, and the production of the principal authors over time are examined. To assess the productivity of each author, the h-index [27] and the number of citations of each article were evaluated. To investigate scientific productivity, Lotka's law was estimated using the authors' publication frequency [28]. The descriptive metrics of the dataset were computed based on the 10 most productive authors. A three-field graph, represented as a Sankey diagram, was generated to visualize the relationships among 10 primary authors, 10 keywords, and 10 journals using Bibliometrix [25]. To analyze the structure of science in studies of cowpea under water stress, a collaborative network analysis among authors, a keyword network based on co-occurrence, and a visualization map of the density of cooperation between countries were generated using VOSviewer version 1.6.20. To ensure a rigorous quantitative assessment of the research field, we followed the methodological guidelines for science mapping and bibliometric performance analysis described by Bota-Avram (2023) [29].

3 Results and discussion

The literature search was consulted before excluding 6595 irrelevant publications on cowpea from 147,397 bibliographic references in the consulted database. The field of cowpea under water stress yielded an average of 86.90 publications per year from May 1948 to August 2024. This literature involved 21,276 authors and generated 24,735 keywords.

3.1 Publication and citation trends

The temporal distribution of publications on cowpea reveals a remarkable growth trajectory since 1948, culminating in a peak of 334 documents in 2022 (Fig. 2). While the overall average annual growth rate is 11.97%, this figure masks a significant shift in research dynamics over time. An early milestone was reached in 1990 when publications first exceeded 100. However, the subsequent period until 2005 was characterized

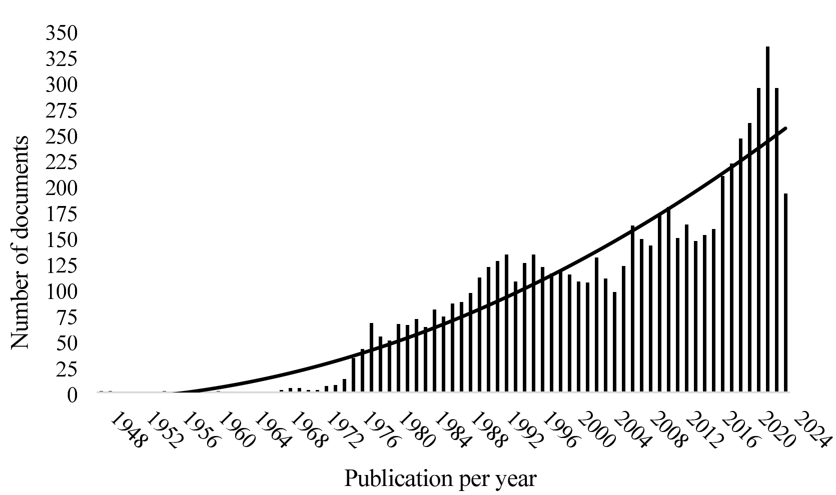

Fig. 2 Annual distribution of the number of publications on cowpea with water stress between May 1948 and August 2024

by fluctuations, reflecting a phase of steady but inconsistent output typical of research reliant on conventional breeding and agronomic methods.

A clear inflection point occurred in 2006, from which the number of publications consistently surpassed 100 and entered a phase of sustained, exponential growth. This modern era of cowpea research is closely linked to key scientific and socio-economic drivers. The acceleration is partially attributed to the advent of next-generation sequencing and other 'omics' technologies, which lowered costs and enabled sophisticated molecular studies [30]. However, this technological boom was reinforced by strategic global initiatives. Programs such as the EMBRAPA/CGIAR's cowpea breeding efforts and the FAO's focus on sustainable agriculture in dryland regions provided the institutional framework and funding to prioritize climate resilience. This combination of technological advancement and international support propelled cowpea research to the forefront. The dramatic increase, representing a nearly 190-fold rise in output since the first publication, signifies the crop's transition from a regional staple to an object of intensive global scientific inquiry.

The most productive authors based on the number of publications were Hall A. E. ($n = 68$; 28.72%), Fery R. L. ($n = 40$; 21.45%), Dakora F. D. ($n = 49$; 20.46%), and Lal R. ($n = 29$; 17.55%) (Fig. 3).

Productivity, however, does not necessarily overlap with long-term scientific influence. When measured by the h-index within this research domain, the four most prominent authors were Hall A. E. (h-index = 32), Close T. J. (h-index = 30), Ehlers J. D. (h-index = 29), and Roberts P. A. (h-index = 29) (Fig. 4).

This distinction indicates that while some authors (Fery R. L.) made pioneering contributions, their work was concentrated in earlier decades, whereas others (Close T. J. and Ehlers J. D.) have had a more sustained and influential impact on shaping the field. Indeed, Fery R. L. and Summerfield R. J. are recognized as pioneers, with Fery R. L. having the most extended timeline of contributions, publishing continuously from 1976 to 2014 (Fig. 4). These findings highlight how early physiological and agronomic research laid the foundation for later advances in molecular breeding and stress physiology,

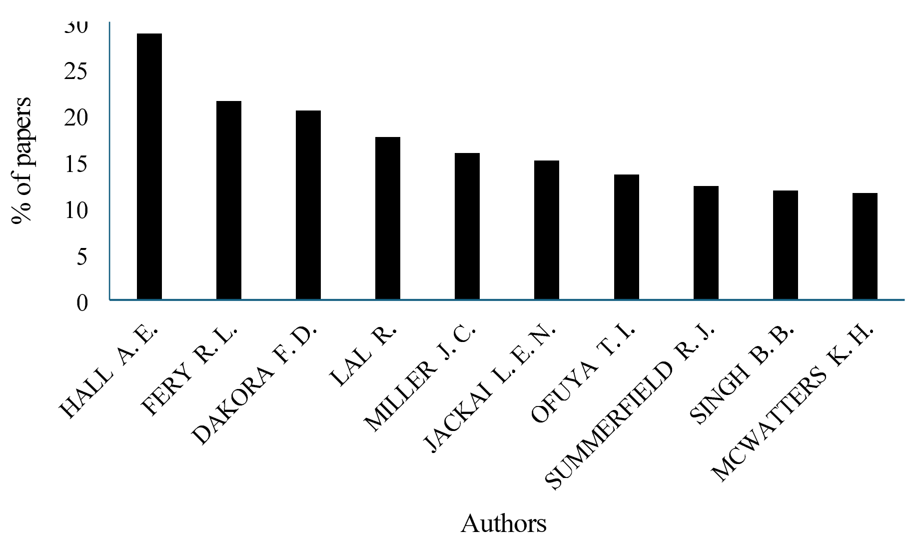

Fig. 3 Authors' overview of scientific knowledge of water-stressed cowpea publications between May 1948 and August 2024, retrieved from the Web of Science database. *The distribution of the proportion of articles is based on the 10 most productive authors

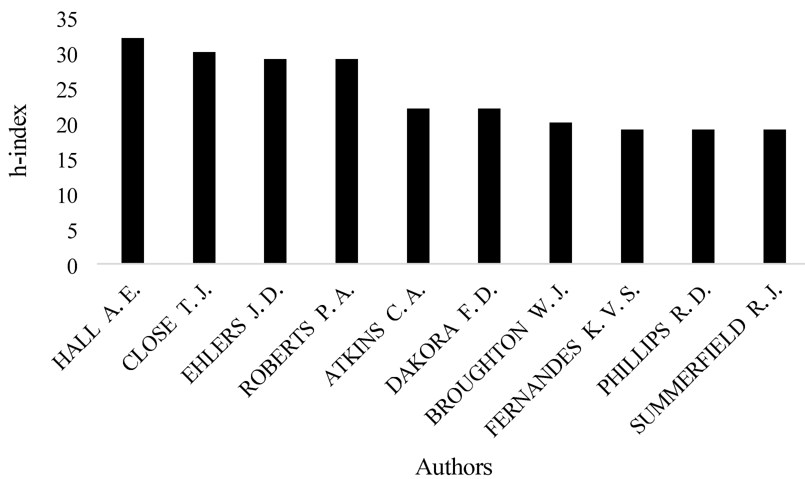

Fig. 4 Impact of scientific production considering the h-index for each of the 10 prominent authors

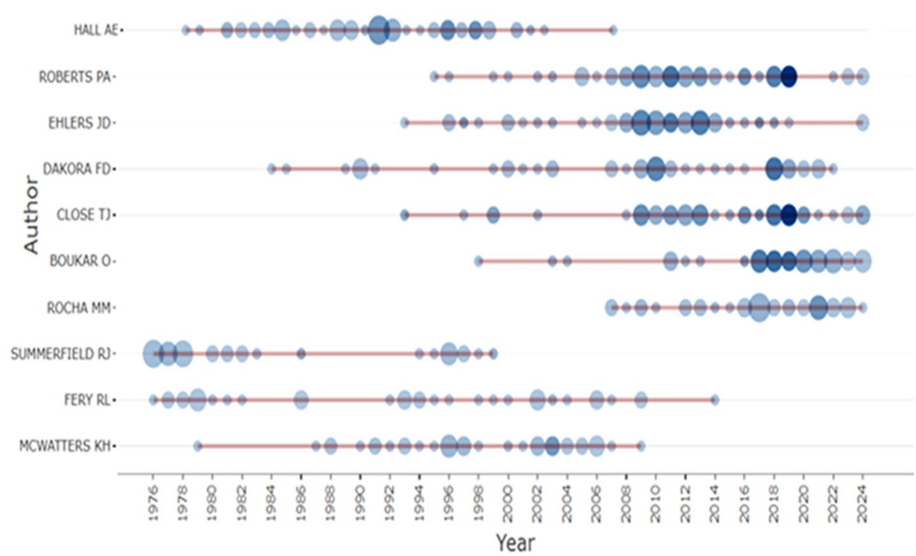

Fig. 5 Productivity of the top 10 authors over time, between May 1948 and August 2024. *Circle size represents the number of publications

thereby explaining why different indicators (publication counts vs. h-index) capture complementary aspects of author influence (Fig. 5).

The collaborative author network enables analysis of the principal authors and collaborations in the field of water stress between May 1948 and August 2024. VOSviewer analyzed the primary authors and their collaborative relationships to generate an author co-occurrence map, as shown in Fig. 6. The collaboration network was grouped into 10 clusters. The colored nodes represent the authors, with node size indicating the number of collaborations (centrality), and the edges indicate joint publications. The colors reflect groups or clusters of collaborative research, which indicate research lines or thematic areas. According to the h-index, the most productive authors showed the highest betweenness centrality values for most clusters. They could be used as a measure of leadership within the detected clusters, e.g., Hall A. E. in the red cluster, Robert Philip A.

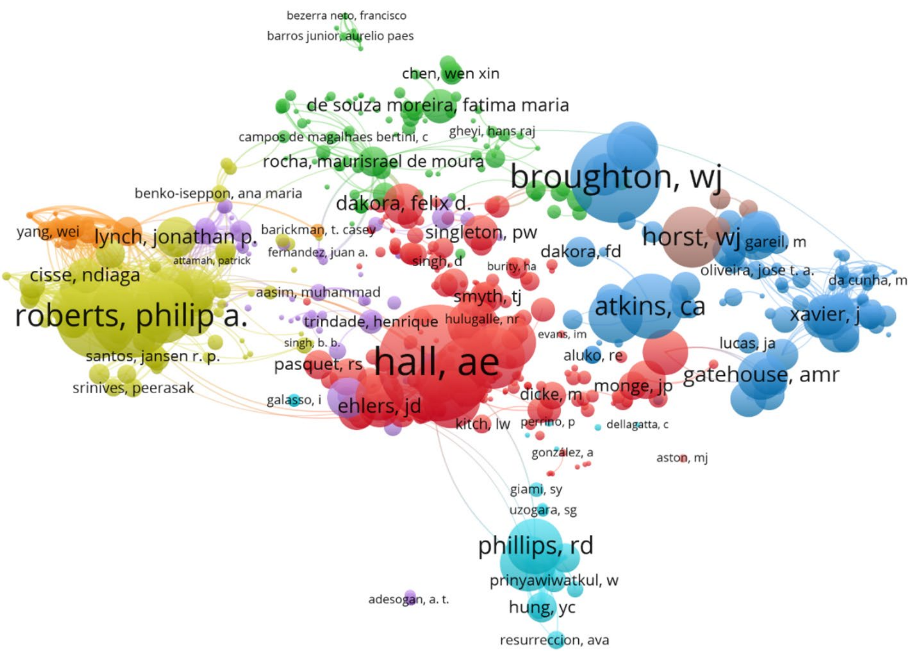

Fig. 6 Co-occurrence map of researchers' collaboration on publications on cowpea with water stress between May 1948 and August 2024

in the yellow cluster, Broughton W. J. in the blue cluster, Phillips R. D. in the light blue cluster, and Rocha Maurisrael de Moura in the green cluster.

Network analysis reveals a highly centralized collaboration structure around Hall A. E., suggesting that this author plays a key role in forming interdisciplinary partnerships. The subgroups represented by the colors brown, orange, and purple indicate significant collaborations in research areas related to plant biochemistry, seed science, and technology. Network analysis suggests opportunities for further cooperation between the groups identified in light blue and green, which are currently disconnected but could benefit from knowledge exchanges.

The results show that the top five authors with the highest number of published articles are Hall A. E. (68), Summerfield R. J. (42), Robert Philip A. (40), Close Timonty J. (39), and Fery R. L. (36). Hall A. E. has the most cited articles with 3091 citations followed by Broughton W. J. (2149), Roberts Philip A. (1948), Close Timothy J. (1866), and Ehlers Jeffrey D. (1273). The top 10 most relevant articles, considering the number of citations, are shown in Table 1. These articles were published between 1997 and 2020, with the total citations ranging from 1341 (Lehmann et al., 2003) to 399 (Stewart et al., 2005). Although ranked ninth on the list, Sharma et al. (2020) presented the highest number of citations per year.

We highlight a mini-review of the top 10-cited papers: Lehmann et al. (2003) investigated nutrient availability and leaching in an archaeological Anthrosol and a typical Ferralsol of the Central Amazon basin through pot and lysimeter experiments under different treatments, including chemical fertilization, manure, and charcoal amendments. The study demonstrated that enriched soils, known as "Terra Preta," were more efficient in retaining nutrients, providing a scientific basis for subsequent research on biochar and sustainable management of tropical soils. However, the experiments were conducted

Table 1 The 10 most cited articles on water-stressed Cowpea from May 1948 to August 2024

Authors	DOI	Journal	YP	TC	TC per Year
Lehmann et al.	https://doi.org/10.1023/A:1022833116184	Plant Soil	2003	1341	61
Snapp et al.	https://doi.org/10.2134/agronj2005.0322a	Agronomy Journal	2005	694	35
Freiberg et al.	https://doi.org/10.1038/387394a0	Nature	1997	566	20
Millaleo et al.	https://doi.org/10.4067/S0718-95162010000200008	Journal of Soil Science and Plant Nutrition	2010	533	35
Lithourgidis et al.	https://doi.org/10.3316/informit.170312269370191	Australian Journal of Crop Science	2011	520	37
Matusova et al.	https://doi.org/10.1104/pp.105.061382	Plant Physiology	2005	471	23
Wheeler et al.	https://doi.org/10.1016/S0167-8809(00)00224-3	Agriculture, Ecosystems and Environment	2000	440	18
Yamato et al.	https://doi.org/10.1111/j.1747-0765.2006.00065.x	Soil Science and Plant Nutrition	2006	425	22
Sharma et al.	https://doi.org/10.1007/s00344-019-10018-x	Journal of Plant Growth Regulation	2020	425	85
Stewart et al.	https://doi.org/10.2134/agronj2005.0001	Agronomy Journal	2005	399	20

TC = Total of Citations YP = Year of Publication

under controlled conditions over a relatively short period, limiting the generalizability of the findings to long-term field scenarios.

Snapp et al. (2005) conducted a comprehensive literature review to evaluate the role of cover crops in cropping system niches, analysing their agronomic and environmental benefits, costs, and performance. The study became a key reference for conservation agriculture policies, highlighting the potential of cover crops to enhance sustainability, soil health, and ecosystem services while also emphasising trade-offs with productivity. A significant limitation, however, lies in its dependence on the quality and scope of existing studies and the inherent heterogeneity of agricultural environments, which restricts the direct applicability of its conclusions across diverse contexts.

Freiberg et al. (1997) provided important insights into the molecular and biochemical mechanisms underlying Rhizobium–legume symbiosis, particularly the genes and proteins involved in establishing and maintaining this interaction. Their findings significantly advanced the understanding of biological nitrogen fixation, which is of great relevance for legumes such as cowpea, since symbiotic N supply becomes especially critical under water deficit when nutrient uptake is restricted. This work laid the foundation for genetic improvement and the development of more efficient inoculants; however, because it was primarily based on laboratory studies, the inherent complexity of field conditions and plant-microbe interactions may still limit its direct application in agricultural systems.

Millaleo et al. (2010) synthesized knowledge on manganese as both an essential micronutrient and a potential toxic element in plants, discussing its uptake, transport, and detoxification mechanisms. For cowpea grown in acidic, drought-prone soils, Mn management is particularly relevant, as imbalances may exacerbate stress responses. Yet, the work was purely a literature review without new experimental evidence, and its conclusions depend on the variability of previously published studies.

Lithourgidis et al. (2011) discussed the ecological and agronomic benefits of annual intercropping systems, including increased resource use efficiency, enhanced soil fertility, and pest suppression. These principles are directly applicable to cowpea, which is often grown as an intercrop in semi-arid regions to optimize land and water use under drought. However, as the study was a literature review, results are context-dependent and strongly influenced by crop choice, climate, and management practices.

Matusova et al. (2005) identified strigolactones as the root-derived germination stimulants for parasitic weeds such as Striga and Orobanche. These findings are essential for cowpea cultivation in drought-prone regions, as water stress often increases host susceptibility to parasitism, further reducing yields. Still, because the experiments targeted a limited set of species under controlled conditions, broader applicability to cowpea in field environments requires caution.

Wheeler et al. (2000) examined the impact of temperature variability on crop yields using long-term datasets and field experiments. Their findings emphasized that not only mean temperatures but also fluctuations strongly influence productivity, a factor critical for cowpea production in regions where heat and water stress interact. Nevertheless, the review faced challenges in separating the effects of mean versus variable temperatures, and conclusions may not fully capture the resilience strategies of specific crops.

Yamato et al. (2006) tested the application of *Acacia mangium* bark charcoal combined with fertilizers in the tropical soils of South Sumatra. Their results showed improved yields and soil properties, indicating that charcoal amendments may buffer soil fertility under conditions of degradation and water stress, which are relevant to cowpea production in marginal environments. However, the study was short-term and small-scale, and the benefits were less evident in fertile soils, limiting its generalizability.

Sharma et al. (2019) reviewed plant photosynthetic responses to different abiotic stresses, including drought, salinity, and high temperature. The synthesis demonstrated how stress impairs pigment stability, photosystem efficiency, gas exchange, and membrane integrity, while also outlining tolerance mechanisms. This knowledge is particularly applicable to cowpea, a crop sensitive to water limitation, as it provides a physiological framework for breeding and management strategies. Nonetheless, the review relied on heterogeneous literature and lacked large-scale, original experimental validation.

Stewart et al. (2005) evaluated the global contribution of commercial fertilizers to food production through long-term trials and nutrient balance analyses. They concluded that mineral fertilizers account for 40–60% of yield gains, underscoring their role in meeting food demands. For cowpea under water-limited conditions, this highlights the need to balance fertilizer use with biological nitrogen fixation to avoid inefficiencies under stress. Still, the analysis largely ignored environmental side effects and was limited by the representativeness of the datasets.

The three-field chart is a Sankey chart (Fig. 7), which visualizes flows and connections between three major categories: SO (Sources): The sources of journals where the articles were published and located on the left, AU (Authors): The studies' authors are in the center, and DE (Descriptors): Descriptors or keywords associated with the articles are on the right. The colored blocks (rectangles) on the left represent the journals where the articles related to cowpea were published. The block size correlates with the number of articles published in the respective journal. Journals such as Plant Physiology, HortScience, Euphytica, and Crop Science publish the most publications by the authors represented.

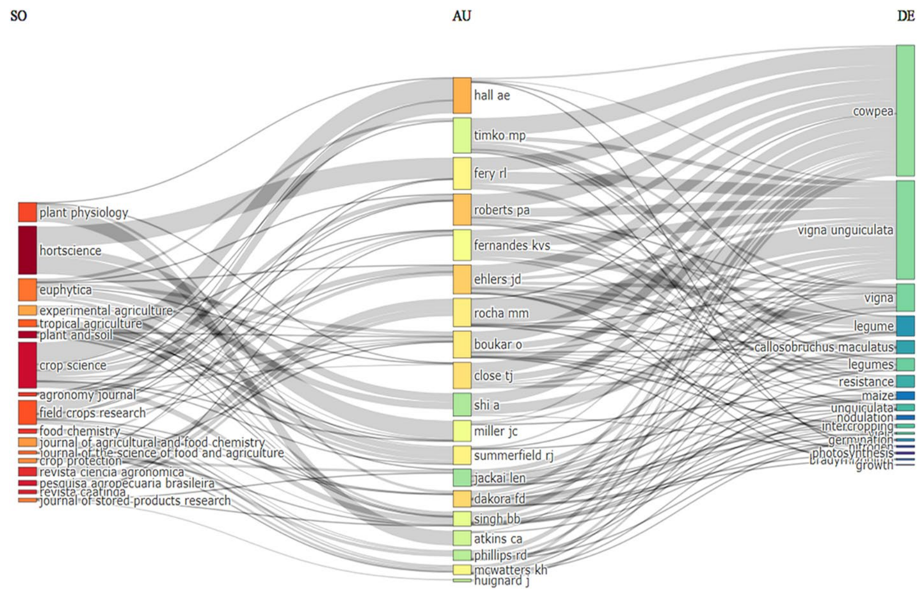

Fig. 7 Three-field graph depicting the production of scientific knowledge about cowpea and water stress. *The three-field plot connects journals (SO, left blocks), authors (AU, middle blocks), and keywords (DE, right blocks). Each rectangle's size is proportional to the number of publications, while the width of the connecting lines indicates the strength of association between fields. Larger blocks represent journals with higher output, authors with greater productivity, and the most frequent keywords

This suggests a strong association between these journals and topics of plant physiology and crop genetics. It is also noted that authors such as Hall, A. E., and Fery, R. L., predominantly publish in these journals. Authors such as Hall A. E. and Roberts P. A. appear central, with publications in several journals on respective topics. This indicates that these authors have a significant multidisciplinary involvement in research on cowpea and other related plants.

The descriptors (DE) represent the keywords and terms associated with the articles, such as cowpea *(Vigna unguiculata)*, resistance, germination, and nodulation, as well as other related terms identified in the graph. These keywords reveal the study topics related to the articles, such as pest resistance (e.g., *Callosobruchus maculatus*), germination, and nodulation. A strong correlation is observed between publications in Plant Physiology and the descriptors related to photosynthesis and nodulation. This suggests that this journal is a vital publication vehicle for research results on physiological processes in leguminous plants. This points to increased interest in optimizing the physiological performance of legumes under adverse conditions. The Sankey plot structure suggests significant overlap between studies on physiology and resistance in cowpea. However, topics such as intercropping and germination appear with fewer connections, suggesting that these areas may benefit from greater attention in future collaborative research.

Understanding the role of legumes in agricultural systems has evolved significantly over the past few decades. Seminal studies in the early 1980s, such as those by Neves et al. [31] and Atkins et al. [32], were instrumental in elucidating the basic physiological mechanisms of carbon metabolism and nitrogen assimilation in these crops. Building on this fundamental knowledge, research has advanced to understand how abiotic environmental factors influence plant development, with Covell et al. [33]'s study on the effect of temperature on germination serving as a landmark. More recently, this perspective has expanded from the physiological to the ecosystem level, with influential research such as that by Sanginga et al. [34], which demonstrated the importance of integrating legumes for the sustainability of agricultural production systems. Currently, the frontier of knowledge is advancing toward quantifying the environmental impacts of these practices, as evidenced by the work of Pimentel et al. [35], which investigates greenhouse gas emissions associated with the use of legumes as cover crops.

The temporal evolution of keywords (Fig. 8) shows that cowpea research under water stress has shifted from predominantly agronomic to more molecular and technology-oriented approaches. In the earlier decades (1990s to early 2000s), the most recurrent terms were strongly linked to agronomic management and production constraints, such as crop rotation, soil fertility, plant population, intercropping, root knot nematode, and *Callosobruchus maculatus*. These reflect a focus on pest control, soil plant interactions, and traditional crop husbandry, which aligned with the urgent food security priorities in smallholder production systems.

From the mid-2000s onwards, the thematic focus gradually shifted to include stress physiology and nutritional quality, with keywords such as abiotic stress, antioxidant activity, digestibility, photosynthesis, and genetic diversity. This signals a transition from descriptive agronomic research toward a more mechanistic understanding of cowpea resilience under drought.

In the most recent decade (2015–2023), the graph shows an apparent emergence of molecular and genomic terms, including plant breeding, genomics, and functional diversity, alongside sustainability-related concepts such as biocontrol and soil health. This indicates a growing emphasis on genetic improvement, breeding for drought tolerance, and molecular characterization. However, the expected integration of remote sensing, artificial intelligence, and IoT is notably absent, confirming that while the field has advanced from agronomy to molecular genetics, it has not yet embraced the full spectrum of digital agriculture technologies.

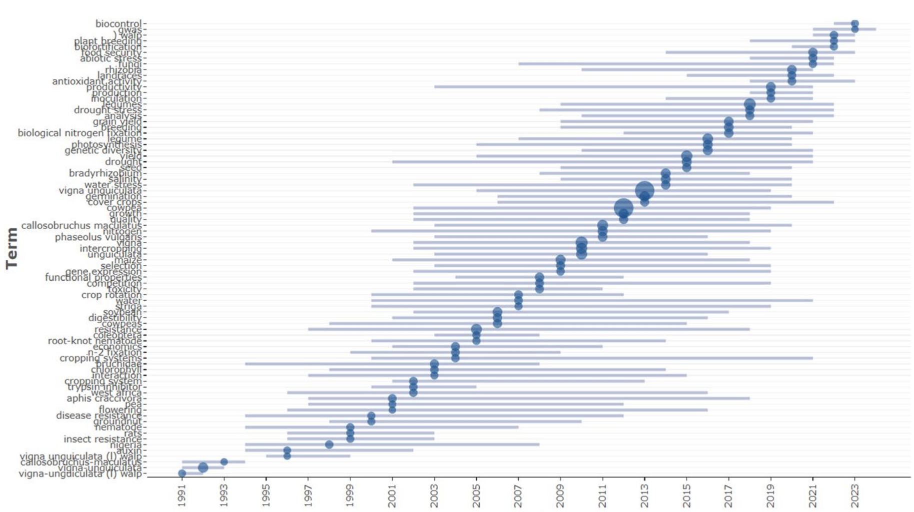

Fig. 8 Temporal evolution of research keywords on cowpea with water stress publications between May 1948 and August 2024. *The figure illustrates the chronological development of the most frequent terms (keywords) associated with cowpea research. Each horizontal bar represents the period in which a specific keyword was actively used in publications. At the same time, the blue nodes correspond to the first appearance and intensity of use of the term. The larger the node, the greater the frequency of occurrence of that keyword in a given year

3.2 Research themes and hotspots

Through software analysis, 24,735 keywords were detected in 6,595 publications from May 1948 to August 2024. A total of seven clusters were generated by co-occurrence analysis. Based on the relationship between the weight of link attributes in different keywords and the strength of total links, the clusters are shown in Fig. 9.

Red Cluster (Abiotic stress and growth): This cluster is associated with tolerance, abiotic stress, development, genetic diversity, photosynthesis, and salt stress. These terms suggest that a significant portion of the research on cowpea focuses on tolerance to stress conditions, such as salinity, and on the plant's genetic and physiological responses to these stresses [24, 36, 37].

Blue Cluster (Nutritional quality and digestibility): This group concerns quality, digestibility, food, antinutritional factors, cooking, and seeds. This cluster is linked to research on cowpea's nutritional quality and digestibility, as well as the impact of antinutritional factors [38, 39].

Green Cluster (Productivity and soil): Topics such as soil, productivity, organic matter, maize, and cover crops indicate studies focused on cowpea productivity and its relationship with soil management, crop rotation (especially with corn), and cultivation practices that improve soil health [40–42].

Yellow Cluster (Pest resistance and seeds): Keywords such as resistance, seeds, varieties, *Callosobruchus maculatus (a common pest of cowpea), and selection indicate that an essential field of research is* pest resistance, seed quality, and the development of resilient varieties [43–47].

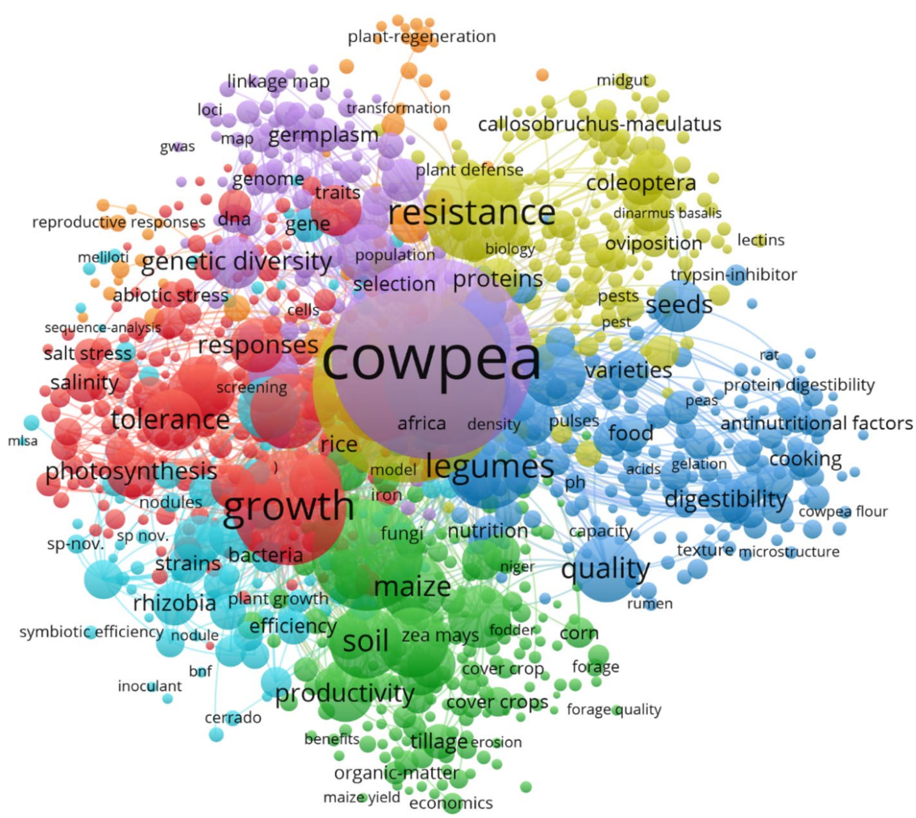

Fig. 9 Keyword network based on the co-occurrence method in cowpea with water stress publications between May 1948 and August 2024

Purple Cluster (Genomics and genetics): Topics such as genome, germplasm, linkage map, transformation, and traits indicate significant research on cowpea genetics and genomics, with a focus on breeding and genetic transformation [5, 48–50]. Keywords with larger font in Fig. 9, such as cowpea, growth, resistance, tolerance, and quality, indicate that these are the most discussed topics in the cowpea literature [51–53].

Synthesizing these bibliometric clusters reveals clear thematic research priorities. The Green Cluster aligns with Agronomy and Cropping Systems, prioritizing soil health and sustainable management. The Red Cluster highlights Stress Physiology, focusing on the biological mechanisms of survival under abiotic pressure. The Yellow and Purple Clusters collectively represent Breeding and Genetics, illustrating a transition from conventional selection for pest resistance to modern molecular genomics. Finally, the Blue Cluster emphasizes Food Quality and Nutrition, linking agricultural output directly to food security goals. These thematic areas do not operate in isolation; instead, they reflect a multidisciplinary research priority to develop varieties that are not only resilient to climate change but also nutritious and high-yielding.

For example, in West Africa, the International Institute of Tropical Agriculture (IITA) developed and disseminated drought-tolerant varieties, such as IT97K-499-35, which significantly improved productivity under water-scarce conditions [54]. In India, breeding programs led by ICRISAT introduced cowpea lines adapted to semi-arid environments and more resilient to drought. Similarly, in Brazil, Embrapa advanced cowpea breeding efforts, developing cultivars adapted to the semi-arid Northeast region that combine drought tolerance with high grain quality [11]. These examples illustrate how scientific advances captured in scientometric clusters translate into tangible agricultural outcomes, reinforcing the relevance of cowpea research in addressing water-stress challenges.

The keyword graph highlights not only the main focus areas, such as growth and resistance, but also suggests emerging opportunities, including the integration of studies on adaptation to water stress and the nutritional quality of cowpea [55, 56], and on water stress and stress attenuators [57–59]. The lines between the nodes indicate the co-occurrence of keywords in the same articles. The thicker the lines, the more frequent this co-occurrence. This means that topics represented by nodes with many connections are often studied together, such as resistance and growth or tolerance and genetic diversity.

Based on the analysis of the surveyed publications, research on cowpea under water stress primarily focuses on Vigna unguiculata's resistance to pests, diseases, and environmental conditions [60–63]. Furthermore, growth and stress tolerance, as reflected in cowpea's physiological responses to abiotic stresses such as salinity and drought [64–66], as well as nutrition and quality, indicate an emphasis on the nutritional properties and quality of cowpea-derived products [67–70]. The soil and efficiency related to agricultural practices that optimize cowpea productivity and its integration with other crops, such as corn [71–73], and genetic improvement, which indicates that there is also a focus on the development of new cowpea varieties that are more tolerant to abiotic and biotic stresses [74–76].

3.3 Geographical and institutional contributions

A total of 134 countries are involved in research on water-stressed cowpea. The density of cooperation among countries is visualized in Fig. 10. The analysis of countries in

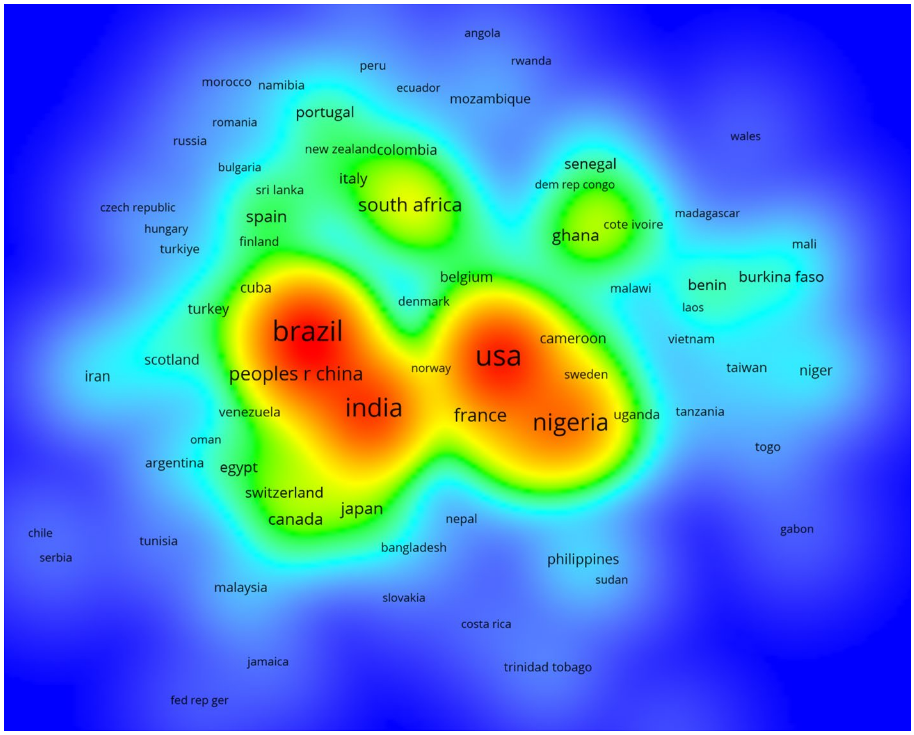

Fig. 10 Visualization of the cooperation density between countries in scientific articles on cowpea with water stress published between May 1948 and August 2024

cowpea research shows that the five countries with the highest number of publications are: the United States (1143), Brazil (1078), India (792), Nigeria (575), and South Africa (246). In addition to the number of publications, centrality is one of the criteria to measure the strength of a country's research in this area of knowledge. Based on the data, the top five countries by centrality are Brazil, India, the United States, Nigeria, and China. Despite being among the top five in terms of publication numbers, South Africa is not among the top five in terms of centrality ranking.

It is essential to recognize that the results presented in this study may be subject to biases inherent in the databases used. The predominance of English-language articles, often prioritized by international indexers, may limit the representation of relevant contributions in other languages, especially in regions where cowpea is widely cultivated, such as Africa and Latin America. Furthermore, the lack of gray literature (technical reports, theses, and institutional documents) restricts the analysis to formal publications, potentially underestimating local innovations or successful agricultural practices that do not reach indexed journals. These limitations should be considered when interpreting the results, as they influence both the identification of global trends and the visibility of regional collaborations and technological advances.

3.4 Future perspectives

Genomic selection for water-stress tolerance traits in cowpea is still in its infancy, offering a promising opportunity to accelerate marker-assisted breeding and expand the available genetic base [77]. Despite advances in functional genomics, there is a scarcity of transcriptomic datasets generated under field conditions, which limits understanding of response mechanisms in real-world water-deficit scenarios [78]. In this context, integrating high-throughput phenotyping with artificial intelligence and Internet of Things (IoT) tools has been identified as an innovative approach to monitor large-scale physiological responses and accelerate the identification of resilient genotypes. Furthermore, systematic analysis of genotype × environment interactions remains incipient, especially in semi-arid environments, where cowpea is a strategic crop for food security and climate change adaptation [79].

Overall, the clusters suggest that cowpea research is concentrated on stress tolerance, nutritional improvement, soil productivity, pest resistance, and genetic enhancement. However, some emerging, underexplored areas are evident, such as integrating water stress with nutritional quality, the role of stress attenuators (biostimulants, microbial associations), and the use of modern digital/remote-sensing phenotyping to complement physiological studies. These gaps highlight opportunities for future investigations that link crop performance under abiotic stress with food quality, resilience, and sustainable production systems. In addition, more studies are needed in underrepresented regions and production systems to ensure global applicability of findings and to address the socioeconomic role of cowpea in smallholder agriculture.

4 Conclusion

This scientometric analysis demonstrates a significant growth in cowpea research under water stress from 1948 to 2024, with the United States, Brazil, India, and Nigeria leading scientific contributions. Prominent researchers such as Hall, A. E., and Fery, R. L., laid the foundations for this field. In contrast, recurrent keywords such as resistance, growth, tolerance, and genetic diversity highlight the central research focus areas. The analysis also revealed primary thematic directions, including pest resistance, physiological responses to abiotic stress, nutritional quality, soil management, and genetic improvement.

Nevertheless, essential knowledge gaps persist. Limited attention has been given to integrating water stress tolerance with nutritional traits, to the role of stress mitigators such as biostimulants and symbiotic microorganisms, and to the application of digital phenotyping and remote sensing in cowpea research. Furthermore, research remains unevenly distributed, with an underrepresentation of specific regions where cowpea plays a crucial socioeconomic role.

To advance the field, future efforts must prioritize multidisciplinary strategies. Specifically, we recommend integrating omics approaches to decipher complex stress-response networks, applying machine learning for high-throughput phenotyping, and using climate modelling to predict crop performance under future environmental scenarios. For breeders, this implies investing in genomic-assisted selection for stress tolerance. For agronomists, emphasis should be placed on innovative cultivation systems to enhance productivity under variable climates. Finally, for policymakers, supporting collaborative research networks and funding digital agriculture are critical to ensuring that scientific progress translates into resilient and sustainable cowpea production systems.

Acknowledgements
The authors would like to extend sincere appreciation to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Grant Number 001) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for awarding grants to researchers.

Author contributions
SIB: Writing—review & editing. GFD: Writing—review & editing. RSA: Writing—review & editing. PMOV: Writing—review & editing. AMFO: Writing—review & editing. IEC: Writing—review & editing. RLFS: Writing——review & editing-

supervision. JDN: Writing—review & editing. VLAL: Writing—review & editing. CA VA: Writing—review—editing & visualization. ASM: Writing—review- editing & supervision.

Funding
There was no funding.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethical approval
Not applicable.

Consent to participate
Not applicable.

Consent to publish
Not applicable.

Competing interests
Alberto Soares de Melo declares that he is a member of the Editorial Board of Discover Plants and confirms that he was not involved in the processing or decision-making regarding his own submission.

Received: 10 May 2025 / Accepted: 23 January 2026

Published online: 11 February 2026

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