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Review

Roots of drought stress: 40 year of research in a Scientometrics analysis

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Received: 18 August 2024 / Accepted: 27 March 2025
Published online: 10 April 2025

Abstract
Drought poses a significant challenge to agriculture and ecosystem sustainability, with critical repercussions on agricultural production. This study addresses gaps in the understanding of plants' genetic and physiological responses to water stress. Our scientometric analysis of research trends over the past 40 years reveals a substantial increase in published studies since the 2000s, indicating an increasing emphasis on innovative strategies to increase plant resilience to drought. The main findings reveal new genetic and physiological markers related to drought tolerance and an increased focus on integrated management practices that combine genetic improvement with efficient water use. This research provides an in-depth view of research trends aimed at mitigating the adverse effects of water stress on crops.

Keywords Agriculture · Bibliometrics · Co-occurrence networks · Food security

1 Introduction

Plants contain approximately 80–95% water in their biomass, which is a vital element for life and is involved in numerous physiological processes that regulate plant growth and development [1]. However, the processes of industrialization, deforestation, and urbanization on a global scale have impacted rainfall patterns and water availability for plants [2–4]. Anthropogenic processes exacerbate climate change, making adverse climatic effects more common and intense.

Climatic events that cause droughts significantly affect agricultural crops, leading to reduced productivity, lower product quality, and decreased yields. Climate change has caused significant variations in global weather conditions, resulting in more frequent and prolonged droughts in many regions. These water scarcity conditions, especially during the growing seasons—when plants are most dependent on soil moisture—induce water stress in plants, negatively affecting their growth and productivity [5].

As climate change intensifies the occurrence and impact of drought stress on agriculture, understanding the breadth and evolution of research in this area becomes increasingly important. To effectively navigate and analyze this growing

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44279-025-00197-5.

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body of literature, bibliometric tools like VOSviewer offer valuable insights. These tools allow researchers to visualize relationships among studies, identify emerging trends, and highlight gaps in the existing knowledge base. Therefore, this study employs a scientometric analysis using VOSviewer to map the current landscape of drought stress research, identify key themes, and guide future research directions. Given the increasing frequency and severity of drought stress due to climate change, it is vital to consolidate and assess the existing research to inform future efforts in the field. Although numerous literature reviews exist, many are limited in scope and do not provide a comprehensive understanding of the vast array of studies on drought stress. A scientometric approach allows for a systematic analysis of publication trends, authorship, and the evolution of research topics over time. This method not only identifies gaps in the current body of knowledge but also facilitates the discovery of emerging trends and patterns that may be overlooked in traditional reviews. Consequently, employing bibliometric tools like VOSviewer in this study enables us to gain a holistic view of drought stress research, guiding future investigations and highlighting priority areas for further exploration.

Numerous studies have sought to understand the impacts of drought and drought stress on plants, particularly those of agricultural interest, owing to their relevance to food security and agricultural sustainability. Understanding the mechanisms of plant response to these stresses is fundamental to developing management strategies and genetic improvements that increase crop tolerance to water scarcity. These studies aimed not only to mitigate the negative effects on plants but also to explore opportunities to enhance the resilience of agricultural crops in the face of adverse climatic conditions [6].

As a result, there have been numerous isolated studies, but there is a need for a broad understanding of research related to drought stress. It is necessary to evaluate the published literature to identify possible patterns in publications as well as trends in studies and scientific fields. In this context, bibliometrics allows quantitative and qualitative analysis of research articles related to a specific theme through mathematical methods [7].

Within this context, the VOSviewer ® software is a tool for constructing and visualizing bibliometric networks based on data exploration. Its analytical power goes beyond academic use, although it is more notable in this field, and it can be used with any type of network data (e.g., social networks) to explore relationships between co-authorship, co-occurrence, citations, and co-citation in one of three possible representations: network visualization, temporal overlay, or density visualization [8]. The main limitation lies in the need to use one database at a time, preventing the integration and exploration of a wider variety of sources [8].

Various studies have demonstrated the potential use of this tool, such as integrative literature studies on the COVID-19 pandemic [9], the use of blockchain, distributed ledger technology aimed at creating an immutable and transparent record of banking and cryptocurrency transactions [10], sustainability in oil and gas production [11], and regulatory policies [12]. A wide range of data can be used to generate bibliometric networks that allow researchers to visualize trends and research themes, helping them better understand the structure and interconnections of their research field.

The primary objective of this study is to conduct a comprehensive scientometric analysis of research on drought stress, focusing specifically on the impact of drought on plants. By utilizing bibliometric tools such as VOSviewer, this research aims to identify existing trends, map the relationships among various topics in the field, and uncover gaps in the literature. Additionally, this study seeks to provide insights that will guide future research efforts and contribute to the development of innovative strategies for enhancing plant resilience to drought. Given the rising frequency and severity of drought stress due to climate change, this study conducts a scientometric analysis of drought stress research to provide insights into current knowledge, identify research priorities, and guide future investigations, addressing the urgent need for innovative solutions.

2 Materials and methods

The period from 1984 to 2024 was selected for the bibliometric analysis with the objective of maximizing the number of articles obtained, respecting the limitation of Elsevier's Scopus® platform, which allows the download of metadata for up to 20,000 articles. The time frame was strategically chosen to maximize data extraction while adhering to the platform's limitations. This ensured a comprehensive and representative analysis of the topic over the past four decades.

Any issues (irrelevant studies, non-peer-reviewed articles, incompleteness, duplicate publications) identified were excluded from the database [13]. Furthermore, the analysis was not restricted to a specific country, nor did we exclude journals during the filtering process. This approach allowed us to maintain a relevant and focused dataset that meaningfully contributes to the discussion of drought stress and its implications for agricultural sustainability.

For the purpose for graphical visualization of the word cloud, VOSviewer® [14] software was used. The term "drought AND stress" was selected, and these data were exported csv format. After this step, the data were refined to avoid inconsistencies and duplicate entries, which could interfere with the analysis. To enhance the integrity and reliability of the dataset used for our bibliometric analysis, a systematic refinement process was implemented, which included the following steps: (1) Initial Data Extraction: Metadata for all relevant articles was extracted from the Scopus® database, focusing on publications related to drought stress from 1984 to 2024. (2) Duplicate Identification: The initial dataset was imported into software, which is equipped to detect duplicate records through its analysis capabilities. VOSviewer® evaluates entries based on multiple indicators, including the combination of titles, authors, publication years, and DOI numbers. Duplicate articles identified during this step were systematically removed to ensure only unique entries remained. (3) Inconsistency Review: After duplicates were addressed, a secondary manual review was conducted to assess data consistency. This involved cross-referencing author names and publication details against the original sources to identify and correct any inconsistencies, such as variations in spelling or formatting, inaccuracies.

Thus, using VOSviewer® software, a word cloud (A visual representation of the frequency of terms in a textual dataset, where most frequent words) was created through text mining (A technique that uses algorithms to extract patterns, trends, and relevant information from large volumes of text), with the comparison of titles and abstracts using the Full Counting method, with a minimum of at least 10 similar term occurrences (Fig. 1).

3 Results and discussion

The choice of the "Full Counting" method for the generation of the word cloud was motivated by the need for an accurate and comprehensive representation of the frequency of terms related to water stress in the reviewed literature [8], thus providing a comprehensive view of the topic addressed by this analysis. The data obtained allowed for the filtering of 18,858 articles published between 1984 and 2024 addressing the topic of interest (Fig. 2).

The scientometric analysis of articles published in the Scopus® database on the topic of drought stress can be visualized through the co-occurrence networks generated by VOSviewer® software (Fig. 3).

The "Full Counting" method considers each occurrence of a specific term in a dataset, ensuring that all instances are considered, regardless of their position or context in the texts. Although this method has its limitations, such as the

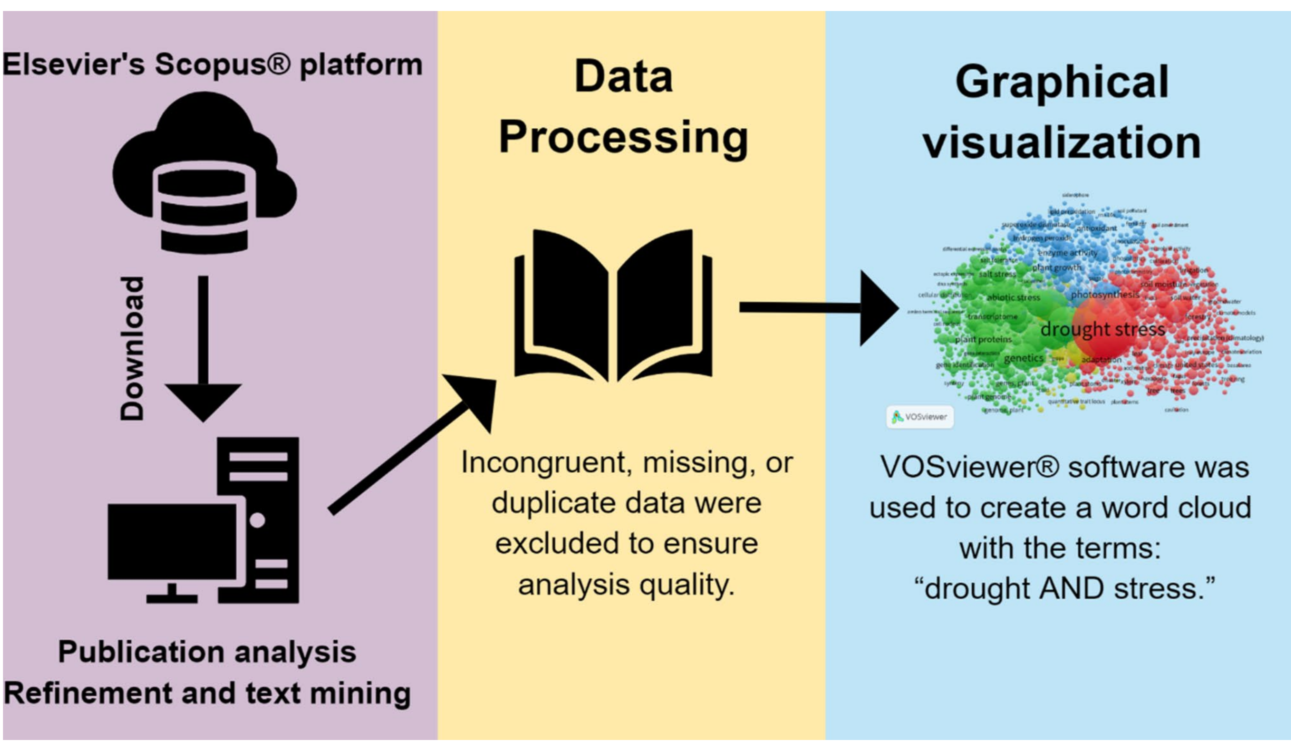

Fig. 1 Protocol for data collection, analysis, and visualization were performed using VOSviewer® software

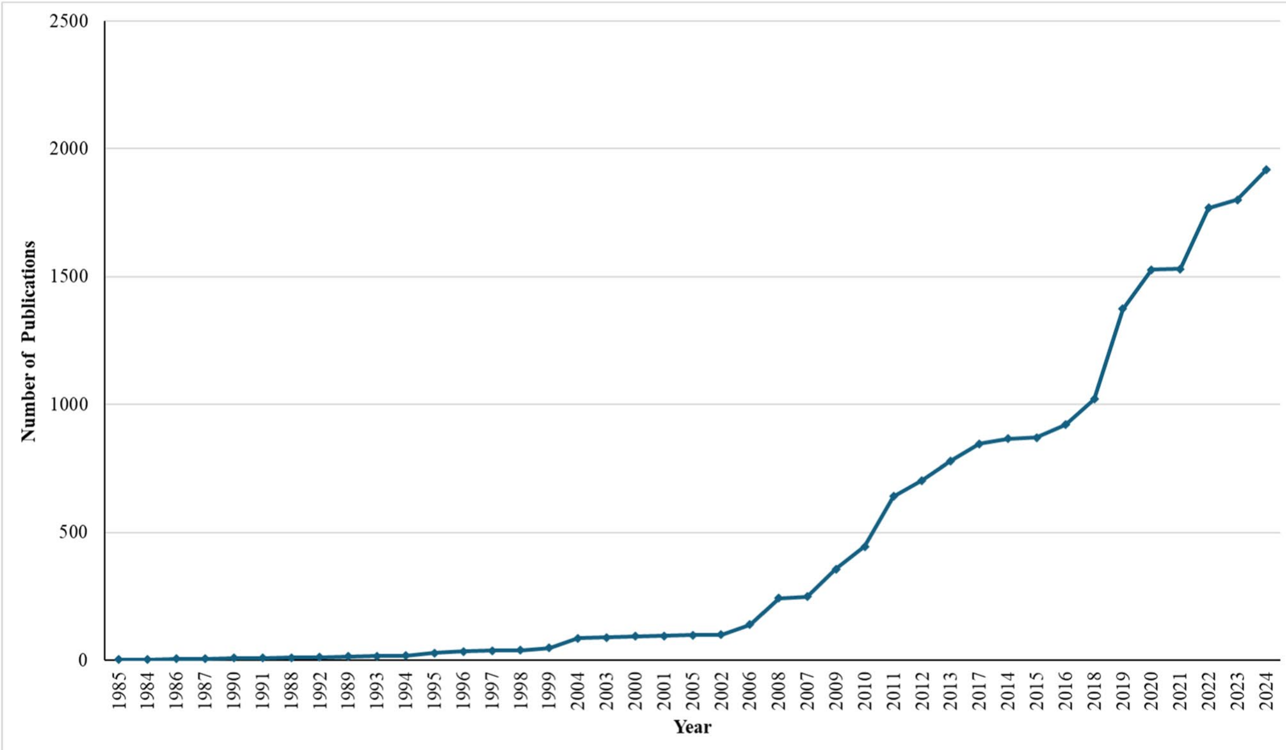

Fig. 2 Number of studies over the period evaluated in this research (1984–2024)

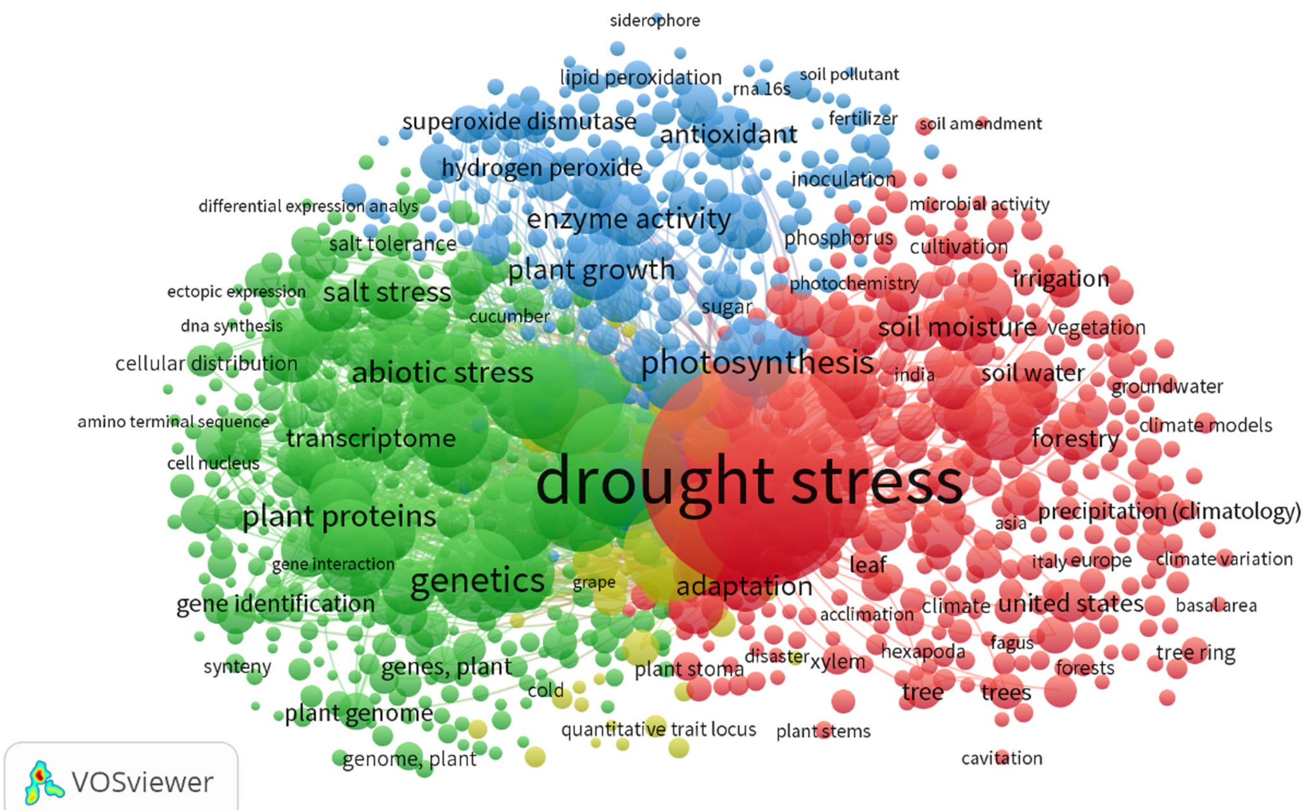

Fig. 3 Visualization of term co-occurrence networks in scientific articles from the past 40 years on drought stress using VOSviewer® software. Caption: Different colors indicate groupings based on their similarities. Green cluster: Genetic Factors; Blue Cluster: Physiology and Biochemistry; Red Cluster: Soil and Water Management; Yellow Cluster: Water stress-mitigation strategies

inclusion of common words (e.g. "and", "the", "but") that do not add significance to the research, it offers a clear and representative visualization of the frequencies of terms in the context of water stress, making it a valuable choice for initial exploratory analyses such as this research.

The data visualization thus reveals a complex network of interactions between various research topics, highlighting the main areas of study and their connections. This makes it easier to identify trends and gaps in current research. Three main clusters are easily distinguishable (blue, green and red), which show different aspects of studies on water stress in plants. The central red cluster, which highlights the term "water stress", is the focus of the analysis and is interconnected with a variety of sub-themes.

The results of the co-occurrence network analysis identified different thematic clusters, categorized by color. The red cluster is focused on soil and water management strategies, highlighting terms such as "irrigation" and "soil moisture". These findings emphasize the essential role of efficient resource management in mitigating the effects of water stress. The blue cluster is related to soil biodiversity and agricultural sustainability, with central terms such as "microbiome" and "agroecological practices", indicating a growing interest in integrating soil microbiology and sustainable production. The green cluster explores climate modeling and environmental impacts, with an emphasis on "climate change" and "predictive modeling", underlining the importance of scenario forecasting for agricultural adaptation.

For a better understanding of each of these clusters, a small grouping called Physiology and Biochemistry of Water Stress has been highlighted in the blue cluster. In our analysis, we identified several key parameters that reflect plant responses to water stress in this cluster. The main parameters considered include the rate of photosynthesis. This is one of the most critical parameters, as the rate of photosynthesis is significantly affected by water stress conditions. The impact of drought on photosynthetic efficiency is an important area of focus, given its crucial role in biomass production and plant health [15].

Chlorophyll content is a key indicator of plant health and its ability to carry out photosynthesis. The degradation of chlorophyll under water stress was considered to assess the impact of stress on photosynthetic function. In addition, the analysis of the activities of different enzymes, such as those involved in photosynthesis and the response to oxidative stress, was fundamental. For example, the activity of superoxide dismutase (SOD) and catalase is important in the defense against reactive oxygen species (ROS) [16]. The accumulation of compatible osmolytes, such as proline and sugars, was also considered, as these molecules help plants to maintain cell turgor and protect biomolecules during periods of stress. The measurement of ROS levels and the plants' antioxidant defense mechanisms was also evaluated, since water stress can lead to an increase in the production of these harmful molecules [16]. These terms indicate that this group of studies is largely focused on the physiological and biochemical effects of water stress on plants.

In fact, photosynthesis is a critical process for plant growth [6, 15] and is strongly affected by a lack of water, resulting in studies exploring the biochemical pathways and enzymatic responses that mediate this adaptation [16–19]. Water stress can significantly affect plant photosynthesis. As a fundamental process for the production of energy and biomass, photosynthesis depends crucially on the availability of water [6, 20]. Plants exposed to periods of water stress may show a reduction in the rate of photosynthesis due to a decrease in the opening of stomata, which is responsible for the gas exchange necessary for photosynthesis [21]. The main reasons for these reductions include reduced rates of net photosynthesis due to metabolic limitations, oxidative damage to chloroplasts, stomatal closure and abandonment of grain filling and development [17, 22].

Water stress is characterized by a decrease in water content, leaf water potential, turgor pressure, stomatal activity and cell expansion and proliferation. In addition, it inhibits photosynthesis, respiration, translocation, ion absorption, carbohydrate and nutrient metabolism, along with stunted development, all of which contribute to reduced plant growth [22, 23].

Another cluster observed was green, which can be associated with Genetic Factors and their relationship with abiotic stresses. In this cluster, we found items such as "genetics", "plant proteins" and "abiotic stress". This cluster suggests a significant focus on identifying genes and proteins that confer tolerance to water stress. Genomic and proteomic studies are essential to understanding the molecular basis of stress resistance, allowing the development of more resistant cultivars.

The investigation of plant genetic factors associated with drought stress highlights the significant efforts made to understand the genetic mechanisms that contribute to plant resilience against water scarcity. Various genes and loci involved in these responses, such as those regulating stomatal closure and the synthesis of protective proteins, have been identified in recent studies [6, 24]. Additionally, genomic analyses have facilitated the discovery of genetic markers linked to drought tolerance, enhancing the ability to select robust genotypes through genetic enhancement programs [21]. Genetic engineering is also being utilized to develop transgenic plants that can better withstand drought by introducing specific genes that promote drought resistance [25]. Understanding these genetic components is crucial for breeding more resilient cultivars that can thrive in water-limited environments [26].

Moreover, the red cluster discusses the critical role of soil and water resource management in mitigating drought stress. It emphasizes the significance of practices like improving soil structure, conserving organic matter, and employing efficient irrigation techniques to optimize water availability for crops in drought-prone areas. Proper management is essential to maintain adequate soil moisture, which significantly influences plant growth and photosynthetic activity adversely impacted by drought conditions [27].

The synthesis of knowledge across physiological, genetic, and management strategies underscores the need for a multidisciplinary approach to effectively address drought stress. By identifying and filling research gaps, future studies can advance our understanding of the complex interactions involved, promoting comprehensive strategies that enhance agricultural productivity under increasing water scarcity.

Another possible analysis with VOSviewer® is the verification of the cloud of related words over time, which brings new possibilities for analysis (Fig. 4).

Temporal scale evaluation indicated that the earliest research on this subject was conducted in the red cluster (Fig. 3), focusing on irrigation and soil management aspects, and later shifted to physiological, enzymatic, and genetic studies. This aligns with the recent advent of various technologies that have popularized and facilitated access to genetic, physiological, biochemical, and other technologies.

In the word cloud, there is still a density of terms such as "Abiotic Stress," "Plant Proteins," "Photosynthesis," and "Transcriptome," indicating numerous publications with these terms (Fig. 5).

The high frequency of publications on these topics suggests a multidisciplinary approach to understanding and mitigating the effects of drought stress on plants, because they are broad and comprehensive terms. These studies are essential for developing management strategies and genetic improvements that can enhance plant resistance to stress and contribute to the sustainability of agriculture in the face of climate change.

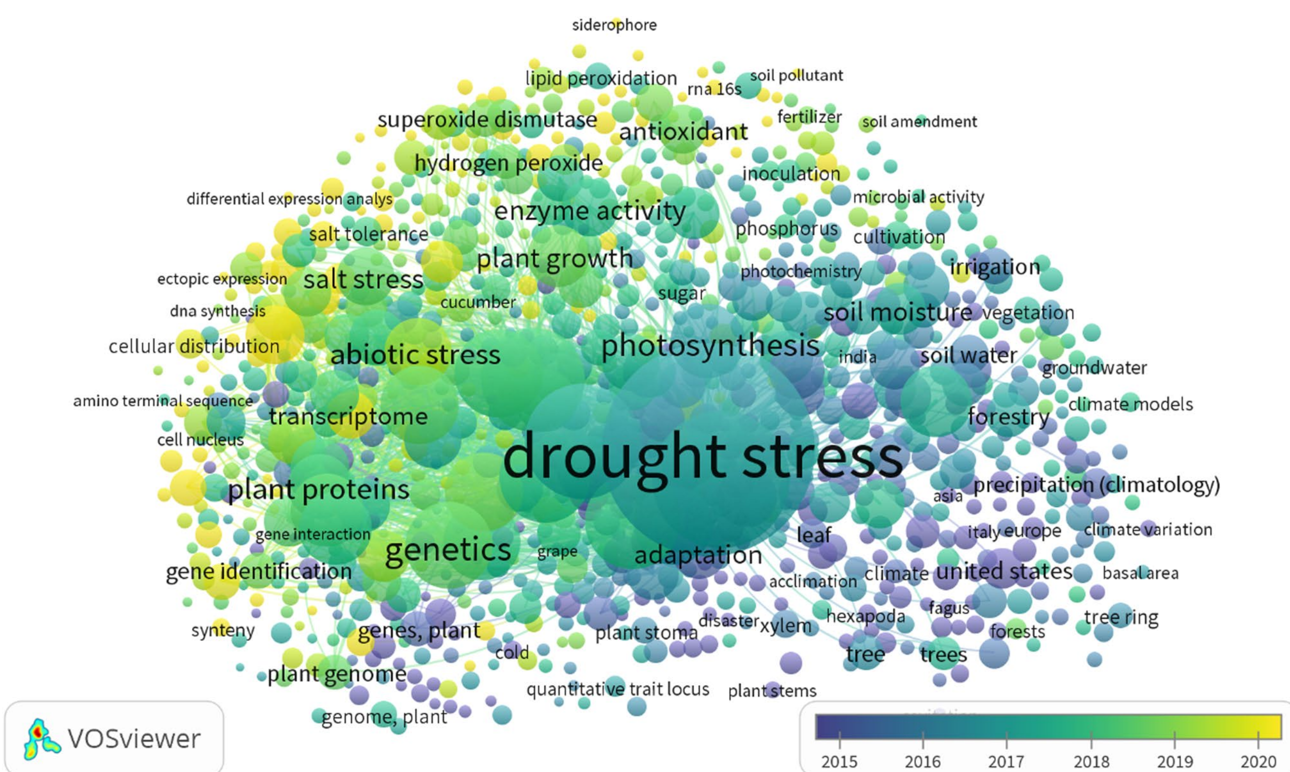

Fig. 4 Visualization of the term co-occurrence map in scientific articles from the past 40 years on drought stress using VOSviewer® software on a temporal scale

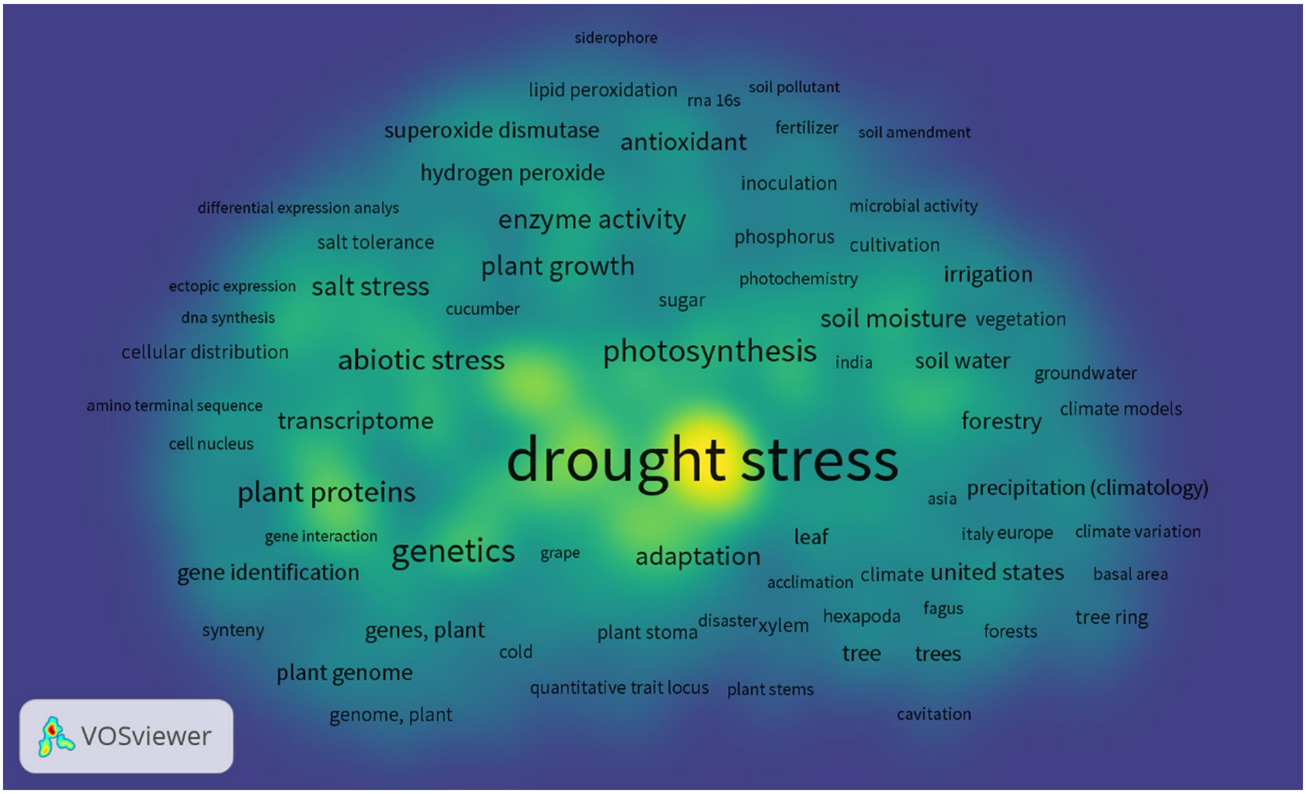

Fig. 5 Visualization of publication density in the word cloud of correlation with the drought stress theme. Caption: The intensity of yellow indicates the presence of a higher density of publications

3.1 Exploring knowledge gaps

Research has revealed a complex relationship between drought stress and physiological responses in plants. Plants use various biochemical pathways and gene regulatory networks to mitigate drought stress. For instance, studies on soybeans have emphasized that a thorough understanding of transcriptomic responses to drought is crucial for breeding drought-tolerant cultivars [27]. Similarly, wheat displays a variety of morpho-physiological traits that can be used to improve drought resilience [28]. However, the specific molecular pathways and their interactions remain poorly defined, highlighting the need for further exploration of the genetic factors influencing drought tolerance in different crops [29, 30].

The interplay between drought and biotic stresses, such as pathogen infections, complicates our understanding of plant responses. Drought can increase plant vulnerability to pathogens; studies on chickpeas have shown higher infection rates under drought conditions [31]. This underscores the need for integrated crop management strategies that address both abiotic and biotic stress factors. Additionally, ROS have been identified as key players in mediating plant defense responses during drought, suggesting their potential role as signaling agents in stress adaptation [32, 33]. Experimental approaches that can be employed to elucidate the mechanisms by which ROS act as signaling molecules in plant adaptation to stress. Some promising approaches include the use of genetic and transgenic mutants, controlled stress analysis, application of inhibitors and antioxidants, immunolocalization techniques, RNA sequencing (RNA-Seq), and advanced microscopy imaging. These methodologies allow not only to quantify ROS levels during stress, but also to investigate signaling pathways and subsequent effects on gene expression and cellular responses. Using a combination of these techniques, it will be possible to better understand how ROS act as crucial signalers in the adaptation of plants to adverse conditions.

Genetic diversity is crucial for enhancing drought tolerance. Crop landraces, which exhibit greater genetic variation than modern cultivars, show promising traits for drought resistance [30]. This variability could be used to develop new cultivars with improved resilience. Genome-wide association studies in wheat have identified important genetic markers linked to seedling drought stress tolerance, emphasizing the importance of genetic research in breeding programs [29]. Furthermore, plant growth-promoting rhizobacteria (PGPR) has been shown to enhance drought tolerance by modulating phytohormone levels and improving physiological responses to stress [34, 35].

Although significant advancements have been made in understanding plant responses to drought stress, considerable knowledge gaps persist. These include the need for deeper insights into the molecular mechanisms of drought tolerance, interactions between abiotic and biotic stresses, and potential genetic diversity in breeding programs. Addressing these gaps is vital for developing effective strategies to mitigate the impact of drought on agricultural productivity.

3.2 Challenges of drought stress in plants

The study of water stress in plants presents great difficulties, largely due to the complexity of responses of plants subjected to water stress. Thus, one of the main challenges is the very biological nature of this object of study by environmentalists, pedologists, geneticists and physiologists. Plants have a multifaceted nature of responses to water stress, which involve physiological, biochemical and molecular mechanisms. As noted by Anjum et al., water stress significantly affects growth and productivity, requiring a deeper understanding of the underlying mechanisms that confer drought tolerance [36], adaptation, or death to drought in plants [14]. This complexity is compounded by the fact that different plant species exhibit varying responses to drought, influenced by genetic, environmental, and their stage of growth and development factors [14]. In addition, the dynamic changes that occur in plants during water stress complicate the study of these responses. Plants adapt to drought by undergoing various morphological, physiological, and biochemical changes, complicating the identification of specific adaptive mechanisms [37]. This dynamic nature of plant responses requires comprehensive studies that can capture the temporal and spatial variations in stress responses, which are often overlooked in traditional experimental designs.

The biochemical and physiological processes involved in drought tolerance also present challenges. Khan and Hamayun highlight that photosynthesis is particularly sensitive to water stress, affecting chloroplast function and stomatal regulation [38]. The intricate interplay between various biochemical pathways, such as the accumulation of osmolytes and the reprogramming of phytohormone production, adds another layer of complexity to the understanding of drought responses. For example, the role of salicylic acid in enhancing antioxidant defense systems during water stress is well documented, but the precise mechanisms by which it operates have yet to be fully elucidated [39].

In addition, the role of PGPR in increasing drought tolerance adds another layer of complexity. PGPR can modulate levels of stress-responsive phytohormones and genes, thereby improving drought tolerance [35]. However, the variability in the efficacy of PGPR in different plant species and environmental conditions presents a challenge for its application in the amplitude and need on an industrial scale, to maintain agricultural practices.

The challenge of water stress research is also reflected in the need for interdisciplinary approaches, such as those proposed in this work, which integrate molecular biology, ecology and agronomy. The multifaceted nature of drought responses requires collaboration between researchers from various fields to develop comprehensive strategies to mitigate drought impacts on crops. For example, the integration of modern analyses such as Omic's technologies (transcriptomics, proteomics and metabolomics), can pave the way for new, even more integrative knowledge involved in drought responses [40]. However, the implementation of such integrative approaches requires significant resources and expertise, which are not always available.

3.3 Future research

This study can help to identify gaps in research and highlight issues that are underexplored in the field of drought-related research. By analyzing trends and patterns in the existing literature, this study can reveal areas that require further investigation and suggest priorities for future research efforts. This integrated approach can guide researchers toward less-explored topics, ultimately contributing to a more comprehensive understanding of water stress and its impacts on agriculture and the environment. Despite the significant increase in water stress research in recent decades, there are still gaps in understanding the genetic and physiological mechanisms that allow plants to adapt to drought.

Many investigations have focused on mitigation strategies, but there is an urgent need to deepen our knowledge of how different plant species respond to water stress at molecular and cellular levels. This lack of understanding may limit the development of drought-resistant rice cultivars. This study aimed to identify research gaps and highlight underexplored issues in drought-related research. By analyzing existing literature trends, we will pinpoint areas that need further investigation and suggest priorities for future research. This approach can guide researchers toward less studied topics, enhancing our understanding of water stress and its impacts on agriculture and the environment.

Despite a significant increase in water stress research, gaps remain in our understanding of the genetic and physiological mechanisms that enable plant adaptation to drought. Although many studies have focused on mitigation strategies, there is an urgent need to explore how various plant species respond to water stress at molecular and cellular levels. This knowledge deficiency may hinder the development of drought-resistant cultivars.

In addition, this article highlights the scarcity of studies that integrate soil and water management practices with technological innovations to address water stress. While there is research on the importance of water resource management, few studies have explored how the combination of soil conservation techniques, efficient irrigation, and emerging technologies such as hydrogels can be applied synergistically to improve crop resilience. The interconnection between management and technology represents a promising area that needs to be explored. Finally, this article highlights the need for a more robust multidisciplinary approach in water stress research. While there is a growing interest in new technologies and sustainable practices, most studies still operate in silos, without considering the interactions between biological, environmental, and social factors. The lack of an integrated view can result in management strategies that do not adequately address the complexity of water stress and underestimate the impacts of climate change on agriculture. This gap suggests that future research should focus on interdisciplinary collaboration to develop more effective and sustainable solutions.

The proposed directions emphasize the exploration of innovative technologies and multidisciplinary approaches, which are increasingly recognized as crucial for enhancing crop resilience to drought stress. Recent studies have indicated a significant shift toward integrating genetic, physiological, and environmental factors in understanding plant responses to water scarcity [37]. This holistic perspective is vital for developing effective management strategies and improving genetic traits associated with drought tolerance.

Moreover, the investigation of the interactions between abiotic and biotic stresses resonates with current research priorities that aim to create comprehensive frameworks for addressing the complexities of drought impacts on agriculture [2]. By focusing on these interconnected areas, future research can build on the existing findings and fill critical gaps, ultimately contributing to a more sustainable agricultural system in the face of climate change. Therefore, while the initial recommendations may appear underdeveloped, they are aligned with broader goals in drought research, emphasizing the need for integrated approaches that leverage advancements in technology and genetic understanding. This article highlights a lack of studies integrating soil and water management with technological innovations to tackle water stress. Although research emphasizes the importance of water resource management, few studies have examined how combining soil conservation, efficient irrigation, and technologies, such as hydrogels, can enhance crop resilience. This promising intersection warrants further research.

Additionally, the article stresses the need for a robust multidisciplinary approach to water stress research. While interest in new technologies and sustainable practices is growing, many studies remain isolated, failing to consider the interactions between biological, environmental, and social factors. This narrow perspective can lead to ineffective management strategies that overlook the complexities of water stress and the impact of climate change on agriculture.

Future research should prioritize interdisciplinary collaboration to develop more effective and sustainable solutions and rely increasingly on the identification of molecular markers associated with drought tolerance and the use of gene editing technologies, such as CRISPR, can accelerate the development of more resistant cultivars. Additionally, implementing water management practices, such as using smart irrigation technologies and training farmers in conservation techniques, are crucial. Conducting field trials with cultivars developed under real conditions and for prolonged periods would help validate their effectiveness. Incorporating modeling and simulation will also allow you to predict the results of different management and cultivation strategies. Finally, collaboration between different disciplines and the direct involvement of farmers are key to creating practical solutions that are adapted to local conditions. The proposed directions underscore the importance of innovative technologies and multidisciplinary approaches to bolster crop resilience to droughts. Recent studies have shown a significant shift toward integrating genetic, physiological, and environmental factors in understanding plant responses to water scarcity. This holistic view is essential for developing effective management strategies and enhancing drought-tolerance traits.

Moreover, investigating the interactions between abiotic and biotic stresses aligns with current research priorities aimed at creating comprehensive frameworks for addressing drought effects on agriculture. By focusing research on these interconnected areas, future studies can expand current knowledge, fill important gaps and contribute to a more sustainable agricultural system in a climate change scenario. Although initial recommendations may seem underdeveloped, they align with broader objectives in drought research, highlighting the necessity for integrated approaches that utilize advancements in technology, genetic and physiologic understanding.

4 Conclusion

Drought continues to be a significant challenge for agriculture and the environment, negatively impacting agricultural production and the sustainability of ecosystems. Our data indicates that between 2000 and 2020, there was a 40% increase in publications addressing integrated strategies to combat these effects, highlighting the urgent need for innovation in this field.

Looking at 40 years of studies on drought stress, we can see that the studies are widely connected, with a sharp increase in interest and research production on drought stress from the 2000s onwards, with the application of more sophisticated techniques such as genetics and "omics" technologies (genomics, proteomics, and metabolomics). While each of the omics technologies has its own set of benefits and applications, the combination of these can provide a more complete and integrated understanding of plant responses to water stress. This multidimensional approach allows researchers to reveal not only which genes and proteins are important, but also how their functions are intertwined in response to stress.

The growing emphasis on new approaches, such as the use of advanced technologies and sustainable practices, has highlighted the evolution of research to address drought stress. This scientometric study not only reveals key advancements (integrative studies) over the last four decades but also offers new insights into plant responses to drought stress, with significant implications for agricultural sustainability and food security. These findings underscore the importance of integrated multidisciplinary strategies to mitigate the impacts of drought stress and ensure the resilience of agricultural systems in a changing climate.

Acknowledgements We would like to thank Mind the Graph for providing the tool used to generate the scheme for Fig. 1. We also acknowledge the financial support provided by UNESP for the execution of this project.

Authors' contributions Conceptual ACRC, PGP; Methodology ACRC, PGP, DLR; Research, ACRC, PGP, HLM; Writing—Original Draft, PGP, ACRC; Writing—Review and Editing, ACRC, PGP, HLM, DLR; Resources, PGP, DLR; Software: PGP, DLR; Supervision, ACRC, HLM, DLR.

Funding This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability The datasets generated and/or analyzed during the present study are available in the corresponding author's email upon reasonable request. During the preparation of this work, the author(s) used ChatGPT® to translate fragments of text. After using this tool/service, the author(s) reviewed and edited the content as needed and took (s) full responsibility for the content of the publication

Declarations

Ethics approval and Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest All authors read and approved the final manuscript. The authors declare that they have no conflicts of interest. The authors are solely responsible for the content and writing of this manuscript.

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