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Unveiling Research Trends: A Latest Bibliometric Analysis of Heat Stress

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ABSTRACT

Climate change has placed heat stress at the forefront of global concerns, leading to a surge in research activity, particularly in areas like physiological responses and adaptation strategies. This bibliometric analysis, focusing on publications within 2022 to 2024 (until May 2024) retrieved from the established Scopus database, aims to map the intellectual landscape of heat stress research. By examining publication trends, authorship patterns, and frequently cited keywords, the study seeks to unveil the field's underlying structure and identify emerging frontiers, such as the potential impact of heat stress on mental health. This analysis, while acknowledging limitations inherent to bibliometric methods, is expected to provide valuable insights into the evolution of heat stress research, highlighting areas of focus and potential knowledge gaps. These findings will inform researchers, policymakers, and stakeholders about future research directions, potentially guiding efforts towards developing heat mitigation strategies in a warming world

1. Introduction

Heat stress is a growing concern, with potentially detrimental effects on human health and productivity. Several studies have investigated the impact of heat stress on various aspects of human well-being, including physical and mental health, occupational performance, and academic achievement [1]. One such study conducted in New York City public schools utilized administrative data to examine the effects of acute heat stress on high-stakes exam performance. The study found that there was a negative relationship between heat stress and exam performance, suggesting that elevated temperatures can impair cognitive functioning [2–4].

This finding supports the need for interventions and policies to mitigate the impact of heat stress on educational outcomes and highlights the importance of considering climate factors in educational planning and resource allocation. In addition, a cross-sectional study emphasized that stress, including heat stress, can have negative effects on health, productivity, and relationships [2,3,5,6]. It is crucial for researchers and policymakers to stay informed about the latest trends in heat stress

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research in order to develop effective strategies for mitigation and adaptation. By conducting bibliometric analyses of heat stress research, researcher can gain insights into the current research landscape, identify key topics and areas of focus, and track research trends over time.

2. Literature Review

2.1 Physiological Thermoregulation and Heat Stress

Human is a highly regulated system that maintains a constant internal temperature, known as the core body temperature, through a complex physiological process called thermoregulation [7]. Sweating is a crucial thermoregulatory mechanism that facilitates the dissipation of excess heat from the body [7,8]. However, environmental factors such as elevated air temperature, high humidity, and exposure to radiant heat can disrupt this delicate equilibrium. Furthermore, strenuous physical activity generates significant endogenous heat, further challenging the body's thermoregulatory capacity [3].

When the body's ability to dissipate heat is overwhelmed, a condition termed heat stress arises, leading to a potentially hazardous elevation in core temperature and potential adverse health consequences [3]. Understanding the underlying mechanisms and contributing factors to heat stress has been an extensive area of research in the fields of physiology, occupational health, and climate science, with implications spanning a wide range of applications, from athletic performance to workplace safety and environmental adaptation [9–11].

While the general principles of thermoregulation are well-established, the response to heat stress can vary significantly among individuals. Factors such as age, gender, fitness level, and overall health status can influence an individual's heat tolerance and sweating capacity [12–14]. For instance, older adults may experience a diminished sweat response and reduced cutaneous blood flow, rendering them more vulnerable to heat-related illnesses [14]. Similarly, individuals with certain medical conditions, such as cardiovascular or metabolic disorders, may be at an elevated risk of heat-related complications [13,15].

2.2 Consequences of Heat Stress

Heat stress can manifest in a spectrum of health issues, ranging from mild discomfort such as heat rash and muscle cramps to severe and potentially life-threatening conditions like heat exhaustion and heat stroke [4,6,13]. Initially, individuals may experience fatigue, muscle cramping, and dizziness. As the heat stress progresses, more serious outcomes can arise, such as heat exhaustion, and potentially fatal heat stroke [2,5]. Heat exhaustion is characterized by profuse sweating, nausea, weakness, and muscle cramps [13]. If not promptly addressed, it can escalate to heat stroke, which is a medical emergency defined by a core body temperature exceeding 40°C or 104°F, cessation of sweating, and cognitive impairment. This can result in organ damage, coma, or even death due to multi-organ failure [4,16].

Given the potentially grave consequences of heat stress, a comprehensive understanding of the research trends and advancements in this field is crucial for developing effective prevention and management strategies. Researchers have explored various approaches to mitigate the risks associated with heat stress, including the development of innovative cooling technologies, the implementation of targeted interventions, and the investigation of physiological adaptations to extreme thermal environments.

3. Research Questions

Heat stress is an increasingly critical area of research due to its significant impacts on human health, agricultural productivity, and overall environmental sustainability. Understanding the scholarly landscape of heat stress research is essential for identifying key trends, influential authors, prominent research subjects, and patterns of collaboration. This study aims to explore various bibliometric dimensions of heat stress research through the following questions in Table 1 below.

Table 1
Research questions for bibliometric analysis of heat stress

Topics	Research Questions
Trends in Heat Stress Research Over Time	What are the trends in heat stress research over time based on publication year?
Prolific authors	Which authors have published the highest number of articles?
Document Types by Research Subject	What are the types of documents categorized by research subject?
Most Affiliations Contribution	Which authors have the most-cited articles, and what are their institutional affiliations?
Commonly Used Keywords	What are the commonly used keywords associated with heat stress?
International Collaboration Patterns	What patterns of international collaboration exist based on co-authorship?
Co-Citation Network Mapping	How is the network of co-citation mapped in relation to authorship?

4. Methodology

Bibliometrics employs statistical methods to investigate information pertaining to scholarly publications [17,18]. This field serves to evaluate the influence and impact of research by analysing aspects such as citation frequency, authorship patterns, and the interconnectedness between various disciplines [19–22]. The present bibliometric analysis utilized data retrieved from Scopus, a comprehensive abstract and citation database for peer-reviewed scholarly literature [17,18,22,23]. A meticulous search strategy was developed, employing a combination of keywords relevant to the field of heat stress [18,22,24].

The search parameters were restricted to publications within the timeframe of 2022 to 2024 and focused on subject areas encompassing heat stress. The selected period reflects the latest developments in heat stress research, capturing the most recent advancements and trends. This timeframe was chosen deliberately to emphasize the immediate and evolving nature of the topic, specifically in response to growing global challenges such as climate change and its implications for occupational and public health. Furthermore, limiting the scope of duration ensures a manageable dataset for rigorous analysis while providing a snapshot of contemporary research trends that are crucial for future policy-making and technological innovations.

The retrieved data was subsequently exported in an Excel format, encompassing bibliographic information such as titles, authors, affiliations, publication years, citation counts, and additional metadata fields [22,25]. Further refinement of the dataset was achieved through the application of exclusion filters, removing document types and subject areas deemed extraneous to the research focus. The resulting dataset was subjected to a comprehensive bibliometric analysis, leveraging tools and techniques to uncover salient trends, influential researchers, and emerging research trajectories in the field of heat stress.

4.1 Data Search Strategy

The study employed a sequential screening process to refine search terms for article retrieval. Initially, a broad search using the Scopus database yielded 41,718 articles. Subsequently, the query string was iteratively modified to focus on recent heat stress case studies. This refinement is shown in Table 2, ultimately resulted in a dataset of 7,781 articles suitable for bibliometric analysis. This dataset encompasses all publications within the Scopus database, retrieved in May 2024, that address recent case studies of heat stress. Table 2 showcasing search string for Scopus website while Table 3 illustrates the criterion selection in screening dataset.

Table 2
Search string for Scopus website

Scopus	TITLE-ABS-KEY ("heat stress") AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (PUBSTAGE , "final"))

Table 3
The criterion selection in screening dataset

Criterion	Inclusion	Exclusion
Timeline	2022 – 2024	< 2022
Language	English	Non-English
Document Type	Article, Review	Non-article
Source Type	Journal (Article)	Book, Review
Publication Stage	Final	Article in press

4.2 Data Analysis

VOSviewer is a powerful software tool designed for visualizing and analysing large bibliometric datasets, particularly those extracted from academic databases like Scopus [17,22,26]. It enables researchers to gain valuable insights into their fields of study by identifying key research topics, collaboration patterns, and interrelations [20,22,27]. VOSviewer's strength lies in its ability to convert complex bibliographic data into easily interpretable visual maps and charts, revealing clusters of related research areas, prominent authors, and significant publications [21,28].

The software facilitates the analysis of various bibliometric aspects, including author and country contributions, collaborations, and publication trends over time [20,21,27]. Its advanced visualization tools allow researchers to uncover hidden patterns and trends, fostering a deeper understanding of the scholarly landscape [21]. VOSviewer also excels in generating co-authorship networks and co-citation maps, helping to identify influential collaborations and the intellectual structure of a field [27].

With its interactive features and customizable visualizations, VOSviewer provides researchers with the flexibility to tailor analyses to their specific research goals [21]. By offering a comprehensive overview of the research landscape, VOSviewer has become an indispensable tool for navigating and comprehending the complex interconnections within scholarly literature [17,22,28].

5. Results and Finding

5.1 Trends in Heat Stress from 2022–2024 (May 2024)

An analysis was conducted to elucidate and understand the research trends in heat stress studies over recent years. Fig. 1 shows the trend of publications for the years 2022, 2023, and the first part of 2024 (until May 2024). This data provides valuable insights into the publication patterns over this period. The graph presented in Fig.1 clearly illustrates an upward trajectory depicting the increasing number of publications from 2022 to 2023 that are related to heat stress research. This indicates a growing interest and focus within the scientific community on understanding and addressing the challenges posed by heat stress.

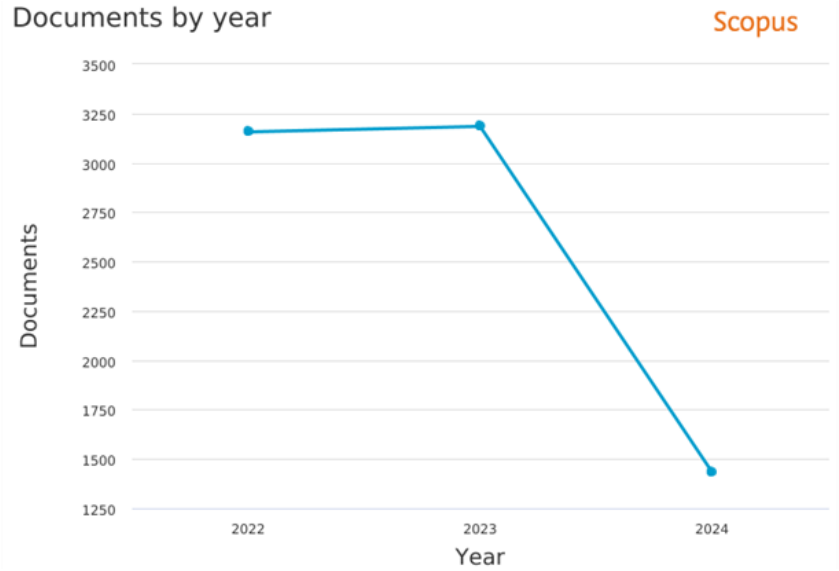

Fig. 1 Trend of publications from 2022 – 2024 (May 2024)

Table 4
Number of publications by year and their corresponding percentages

Year	Number of Publication	Percentages (%)
2022	3159	40.60
2023	3187	40.96
2024	1435	18.44
Total	7781	100

According to Table 4 above, in 2022, there were 3,159 publications, accounting for 40.60% of the total publications within the given time frame. This number experienced a marginal increase in 2023 to 3,187 publications, representing 40.96% of the total. It is noteworthy that the data for 2024 encompasses only a partial year, yet it still accounts for 1,435 publications, which constitutes 18.44% of the total publications. This significant contribution within a partial year suggests a sustained and potentially increasing interest in heat stress research during 2024.

The cumulative number of publications across the three years (including the partial year of 2024) is 7,781, indicating a substantial corpus of research in the field of heat stress. This trend could be attributed to various factors, such as heightened concerns regarding the impact of climate change and global warming on human health and well-being, as well as the need for effective strategies to mitigate and adapt to heat stress in various sectors, including agriculture, industry, and urban planning [29,30]. It is imperative to note that this analysis is predicated solely on the quantitative

aspect of publications and does not provide insights into the specific research areas, methodologies, or findings within the field of heat stress. However, the upward trend in the number of publications suggests a burgeoning interest and ongoing efforts to advance knowledge and develop solutions to address heat stress-related challenges.

5.2 Prolific Authors

In bibliometric analysis, the number of publications is a crucial metric that reflects an author's research productivity and impact within their respective field [31–33]. It provides valuable insights into an author's contribution to the academic community and their influence on scholarly discourse. The author with the highest number of publications is often considered a prolific and influential researcher in their field, as their work has been widely disseminated and potentially cited by other scholars, indicating its significant impact on the research community [23,34]. Fig. 2 showcase the top 10 authors with the most number of articles published from 2022 to May 2024, as derived from data extracted using the Scopus analyser tool from the Scopus database. Whereas Table 5 revealing the total number of articles published by the top 10 authors.

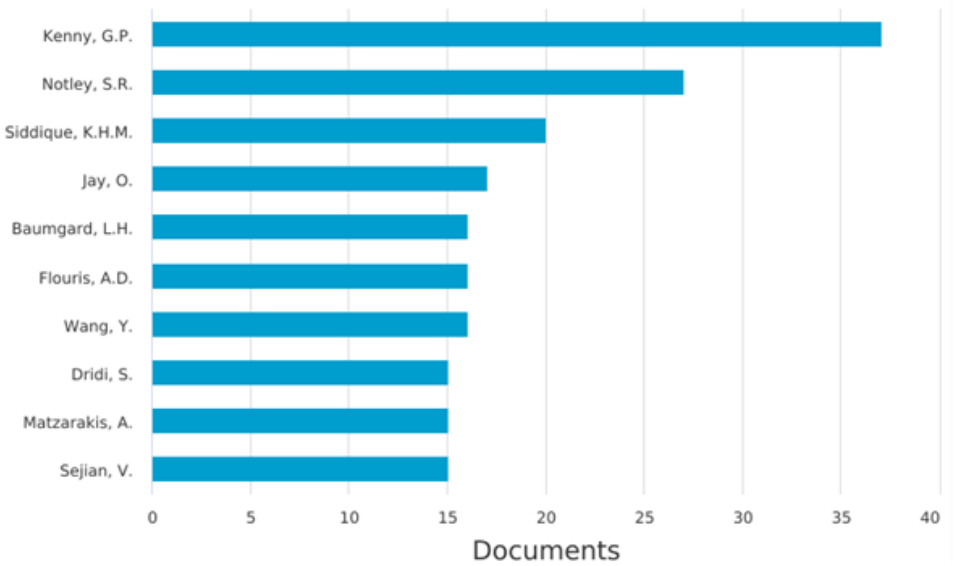

Fig. 2 Top 10 authors with the highest number of published articles

Table 5
Total number of articles published and most cited paper by the top 10 authors from 2022 to May 2024.

Author	Articles	Percentages (%)	Top Articles
Kenny, G.P.	37	0.48	[35–39]
Notley, S.R.	27	0.35	[36–40]
Siddique, K.H.M.	20	0.26	[41–45]
Jay, O.	17	0.22	[46–50]
Baumgard, L.H.	16	0.21	[51–55]
Flouris, A.D.	16	0.21	[35–37,56,57]
Wang, Y.	16	0.21	[58–62]
Dridi, S.	15	0.19	[63–67]
Matzarakis, A.	15	0.19	[68–72]
Sejian, V.	15	0.19	[73–77]

Based on Fig. 2 and Table 5, the author with the most number of articles is Kenny, G. P. with 37 articles, accounting for 0.48% of the total articles analysed. The significant number of publications by Kenny, G. P. suggests a sustained and consistent research output over an extended period of time. This high level of productivity can be attributed to a variety of factors, including but not limited to access to research funding, collaboration with other researchers, and a robust research environment that nurtures academic productivity and innovation [78–80]. It is imperative to note that the analysis also provides insights into the distribution of publications among other authors. The second and third-ranked authors, Notley, S. R. and Siddique, K. H. M., have 27 and 20 articles, respectively.

Their contributions amount to 0.35% and 0.26% of the total heat stress research output, signifying a notable but comparatively lower level of impact compared to Kenny, G. P.'s contribution. Overall, this section serves to elucidate the research productivity of authors within the chosen field or dataset. It provides valuable information for further analysis and evaluation of individual researchers' contributions and impact, thus enhancing the understanding of their overall influence in the academic community [32,34,81].

5.3 Document Types by Research Subject

The pie chart displayed in Fig. 3 elucidates the distribution of research areas related to heat stress. Concurrently, Table 6 exhibits the top 10 prominent research areas in heat stress, along with the corresponding number of publications and percentages, providing a comprehensive overview of the current trends in this field.

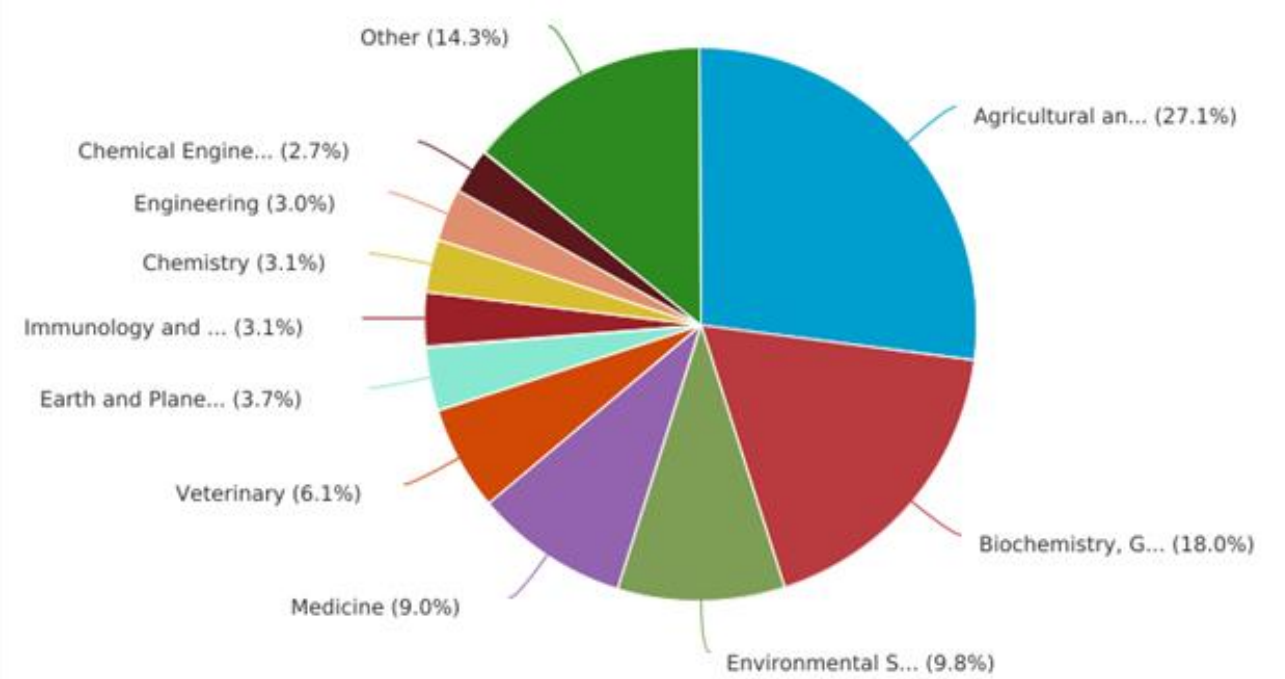

Fig. 3 Distribution of research areas related to heat stress

Table 6
Top 10 prominent research areas in heat stress, along with the corresponding number of publications and percentages

Area of Subject	Publication	Percentages
Agricultural and Biological Sciences	3891	27.1
Biochemistry, Genetics and Molecular Biology	2578	18.0
Environmental Science	1406	9.8
Medicine	1289	9.0
Veterinary	882	6.1
Agricultural and Biological Sciences	3891	27.1
Biochemistry, Genetics and Molecular Biology	2578	18.0
Earth and Planetary Sciences	534	3.7
Immunology and Microbiology	451	3.1
Chemistry	450	3.1
Engineering	430	3.0
Chemical Engineering	391	2.7

'Agricultural and Biological Sciences' leads with 27.1% (3,891 publications), reflecting the critical impact of heat stress on agricultural productivity and food security. Research focuses on plant and animal responses to heat stress, developing heat-resistant crops, and sustainable agricultural practices [82,83]. This significant share highlights substantial research efforts in agriculture and related biological disciplines. 'Biochemistry, Genetics and Molecular Biology' follows with 18.0% (2,578 publications), exploring molecular mechanisms of heat stress responses, gene expression changes, and cellular adaptations [84,85]. This field is crucial for developing biotechnological solutions and enhancing organismal resilience to high temperatures.

'Environmental Science' accounts for 9.8% (1,406) articles, addressing ecological implications of heat stress, ecosystem impacts, and adaptive strategies for natural resource management [86,87]. This reflects a growing emphasis on environmental research and sustainable practices. This is followed by 'Medicine' comprises 9.0% (1,289 publications), investigating heat stress effects on human health, morbidity, and public health interventions [49,50]. This indicates increasing concern about heat stress impacts on human well-being. Sequentially, 'Veterinary' represents 6.1% (882 articles), focusing on animal health and livestock productivity under heat stress conditions [88,89]. This field addresses physiological effects on animals and implications for food security.

Smaller contributions come from 'Earth and Planetary Sciences' (3.7%, 534 articles), 'Immunology and Microbiology' (3.1%, 451 articles), 'Chemistry' (3.1%, 450 articles), 'Engineering' (3.0%, 430 articles), and 'Chemical Engineering' (2.7%, 391 articles). These fields provide specialized insights, from studying climate patterns to developing heat mitigation technologies [90-93]. This distribution highlights the multidisciplinary nature of heat stress research. 'Agricultural and Biological Sciences' and 'Biochemistry, Genetics and Molecular Biology' emerge as prominent areas, while 'Environmental Science', 'Medicine', and 'Veterinary' fields contribute significantly. The remaining fields, though smaller in publication share, offer valuable perspectives on various aspects of heat stress, demonstrating the broad scientific interest in this critical issue.

5.4 Frequently Cited Keywords in Heat Stress Research

Fig. 4 below illustrates the network mapping visualization of co-occurrence for authors' keywords. Meanwhile, the Table 7 below presents the total occurrences and total link strength, providing a comprehensive overview of the data. Fig. 4 and Table 7 provide insights into the research landscape pertaining to heat stress and its multifaceted impacts, derived from an analysis of keywords, their

frequencies of occurrence, and cumulative link strengths. In this visualization, keywords are represented as nodes (circles), while the links (lines) between nodes indicate co-occurrence relationships among the keywords [20,21].

The node size and link thickness correspond to the relative significance or strength of the keywords and their inter-relationships, respectively. The occurrences metric quantifies the frequency or prevalence of each keyword within the analysed dataset, with higher occurrences suggesting that a particular keyword is more widely discussed or researched within the domain [20,21,24,27]. Furthermore, the total link strength metric quantifies the degree of interconnectedness or co-occurrence of a keyword with other keywords in the dataset. A higher total link strength implies a stronger association or more frequent co-occurrence of a keyword with other keywords, indicating a higher level of interdisciplinary relevance or interconnectedness within the research landscape [17,19,94].

The purpose of the network mapping visualization in Fig. 4 is to illustrate the intellectual structure and thematic relationships within the field of heat stress research. By representing keywords as nodes and their co-occurrence relationships as links, the visualization highlights key research themes, trends, and areas of focus. This mapping enables researchers to identify dominant topics, emerging fields, and potential gaps in the literature, thereby facilitating a deeper understanding of the research landscape. Furthermore, the visualization aids in uncovering interdisciplinary connections and collaborative opportunities within the domain of heat stress.

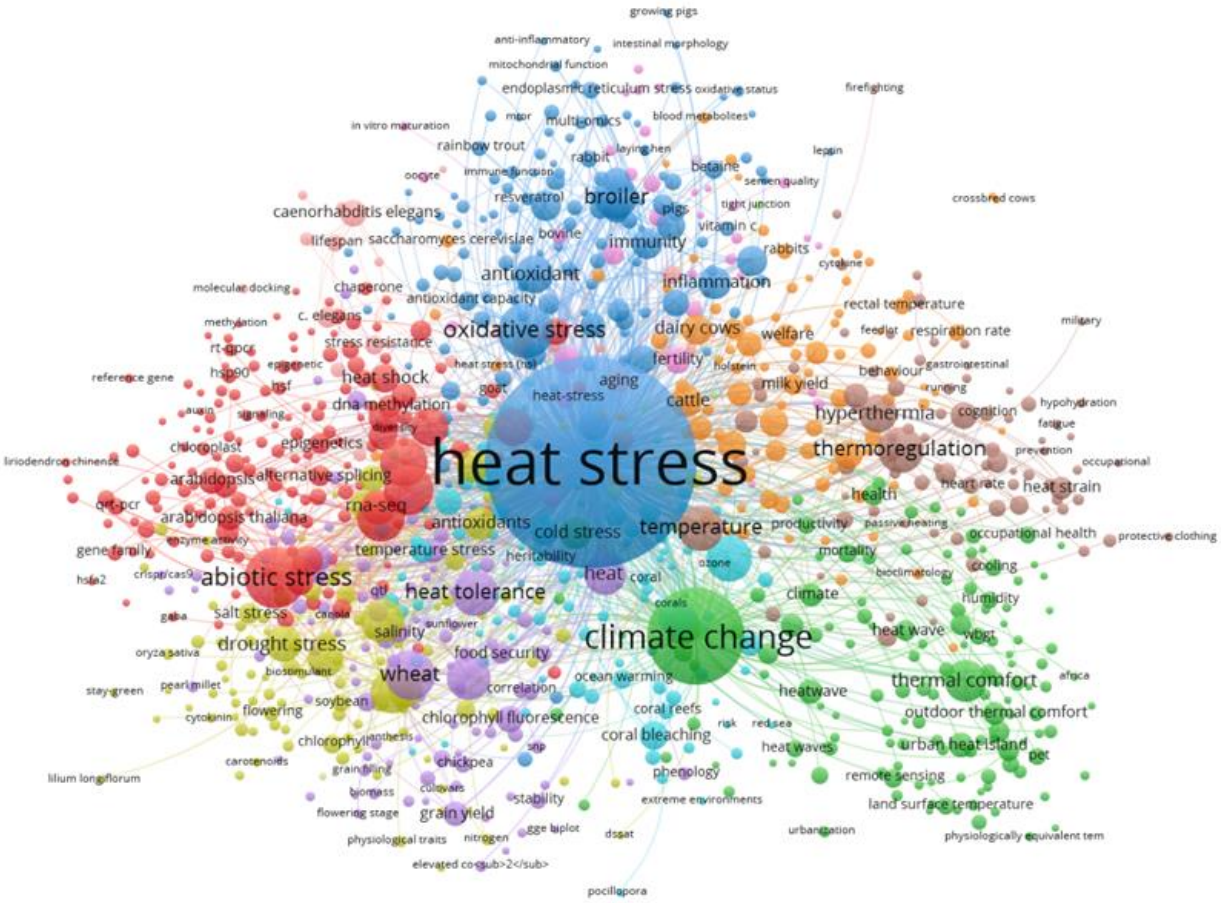

Fig. 4 Network mapping visualization of co-occurrence for authors' keywords

Table 7
Total occurrences and link strength for the top 10 most popular keywords related to heat stress

Keywords	Occurrences	Total Link Strength
Heat stress	2723	5849
Climate change	573	1381
Abiotic stress	236	571
Oxidative stress	194	496
Gene expression	157	397
Wheat	148	421
Thermotolerance	144	358
Transcriptome	140	371
Temperature	136	382
Thermoregulation	133	311

The centrality and dominance of the keyword 'heat stress' within the domain are evident from its substantial node size, indicating the highest frequency of occurrence at 2,723 mentions. This high frequency underscores the significant emphasis placed on this topic by the research community. Furthermore, the total link strength of 5,849 for 'heat stress' highlights its extensive interconnectedness with other keywords, suggesting its pivotal role and intersection with numerous research areas. The prominence of this keyword likely reflects global concerns over rising temperatures and their impact on biological systems, particularly in the fields of agriculture and ecology [84,85].

The keyword 'climate change' emerges as the second most frequently occurring term, with 573 occurrences and a total link strength of 1,381. This prevalence indicates a broad recognition of climate change as a critical factor influencing various stressors and biological responses [49,95]. However, the relatively lower link strength compared to 'heat stress' suggests that while 'climate change' is a major theme, its direct interactions with other specific research topics may be more specialized or less integrated. The keyword 'abiotic stress', with 236 occurrences and a total link strength of 571, reflects the significant interest in non-biological factors that adversely affect organisms. The moderate occurrence and link strength highlight its importance in the study of environmental stressors, albeit less central than 'heat stress' and 'climate change'. This keyword often encompasses various stresses, including temperature extremes, salinity, and drought, which are critical for understanding resilience and adaptation in plants and other organisms [84,92].

Other highly occurring keywords, such as 'oxidative stress' (194 occurrences, link strength 496), 'gene expression' (157 occurrences, link strength 397), and 'wheat' (148 occurrences, link strength 421), suggest extensive exploration of these topics in the research field related to heat stress. 'Oxidative stress' is a well-recognized phenomenon associated with cellular damage and defense mechanisms, closely connected to 'heat stress' and 'abiotic stress', highlighting its role in stress physiology and molecular responses [92,96]. The prevalence of 'gene expression' underscores the focus on understanding the molecular underpinnings of stress responses, crucial for elucidating genetic regulation and stress management [96,97].

Conversely, the prominence of 'wheat' reflects its importance as a major crop and model organism in stress research, emphasizing its significance in agricultural studies aimed at improving stress tolerance and crop resilience. The visual representation in Fig. 4 reveals that larger nodes and thicker links correspond to well-established or dominant research areas, while smaller nodes or clusters indicate emerging or niche topics within the domain. For instance, keywords like 'epigenetics', 'dna methylation', 'metabolomics', 'proteomics', and 'machine learning' appear as smaller nodes, suggesting potential emerging or interdisciplinary research areas.

Furthermore, Fig. 4 depicts clusters or groups of closely related keywords, illustrated by their spatial proximity and colour coding. These clusters provide insights into specific sub-domains or research areas within the broader research domain. For example, the blue cluster centered around keywords such as 'heat stress', 'oxidative stress', 'antioxidant', 'cortisol', 'broiler', 'vitamin C', 'betaine', and 'rabbits' appears focused on the physiological and metabolic responses to heat stress, particularly in livestock and animal models. The presence of keywords like 'antioxidant', 'vitamin C', and 'betaine' suggests research on potential mitigating strategies and mechanisms for combating oxidative stress induced by heat stress.

Another cluster, the red cluster, contains keywords like 'mortality', 'dehydration', 'occupational', 'covid-19', 'heat strain', 'protective clothing', 'wbgt' (wet-bulb globe temperature), and 'thermal environment'. This cluster appears to be focused on the impacts of heat stress on human health, occupational safety, and the development of protective measures and guidelines for mitigating heat-related risks, particularly in the context of occupational settings and extreme heat events. Additionally, the green cluster appears centered around keywords like 'heat tolerance', 'thermotolerance', 'thermoregulation', 'broiler', 'heat', and 'heat shock proteins', potentially indicating a research area related to animal physiology and heat stress responses.

By analysing the links between different clusters, researchers can identify potential interdisciplinary connections or overlapping research areas. The interconnections between these clusters indicate the interdisciplinary nature of heat stress research, involving various aspects such as molecular biology, plant physiology, animal science, human health, climate change, and urban planning. The co-occurrence of keywords from different domains suggests potential collaborations and knowledge integration across diverse fields.

5.5 International Collaboration Patterns Based on Co-Authorship

Citations are a critical indicator of the impact and relevance of research within the scientific community, playing a pivotal role in showcasing the extent to which a piece of work has been referenced by others [98,99]. Fig. 5 presents a detailed list of the top 10 countries engaged in co-authorship collaboration in the field of heat stress research, highlighting their significant contributions to this domain. This analysis aims to provide a comprehensive overview of the contributions from these leading nations, focusing on their document output, citation count, and total link strength. Fig. 5 reveals that China and the United States stand out as the most prominent players in terms of publication output and citation impact. These two countries, through their outstanding research outputs, have accumulated the highest number of citations, reflecting significant influence and recognition within the field. Notably, the United States leads with the highest total link strength, indicating robust collaborative ties and co-authorship networks with other nations [84,85].

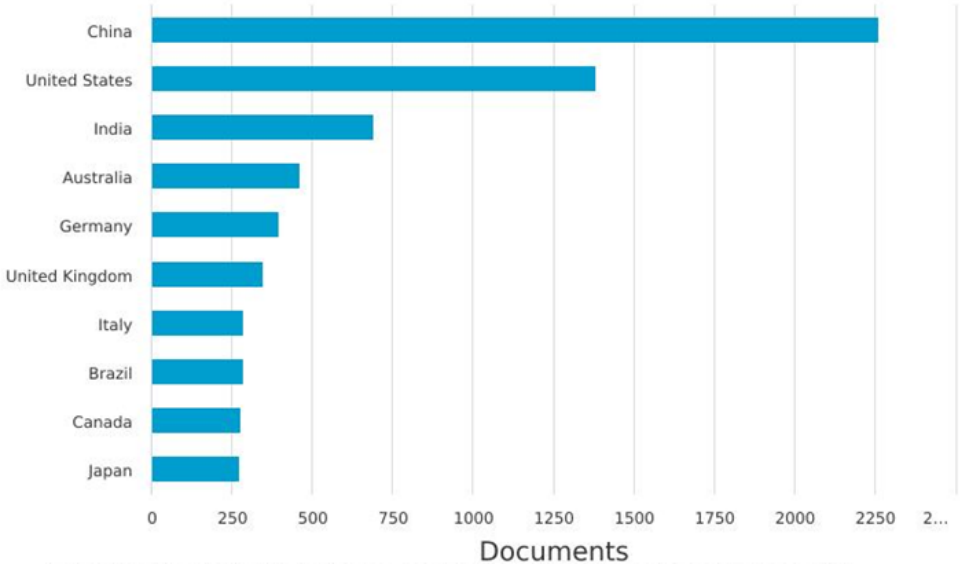

Fig. 5 Top 10 countries engaged in co-authorship collaboration in the field of heat stress research

Based on Fig. 5 and Table 8, China leads the field with 2,332 documents and 13,385 citations, underscoring its dominant role in heat stress research. The high document output and substantial citation count reflect China's emphasis on addressing agricultural challenges and climate adaptation through research endeavours. This substantial output underscores China's prominent role in advancing scholarly research and its commitment to maintaining a robust presence in the academic community [49,95]. Additionally, a total link strength of 956 indicates strong collaborative networks both domestically and internationally. Following closely, the United States ranks second with 1,428 documents and 9,603 citations, exhibiting a higher total link strength (1,326) compared to China. This suggests extensive international collaboration and influence, with American research in heat stress spanning diverse fields, including agriculture, environmental science, and public health, thereby contributing to its significant citation impact [84,85].

Australia, with 469 documents and 3,672 citations, demonstrates robust research activity relative to its size. A total link strength of 657 underscores its strong collaborative efforts, particularly within the Asia-Pacific region. Australian research often focuses on the effects of heat stress on ecosystems and agriculture, reflecting its unique environmental challenges [49,95]. Subsequently, India has produced 698 documents and received 3,602 citations. Despite having a lower total link strength of 409 compared to other leading countries, India's collaborative efforts remain notable. Indian research frequently addresses heat stress in the context of agriculture and human health, driven by the country's exposure to high temperatures and climate variability [86,100]. Germany's 405 documents and 3,154 citations reflect its strong research presence in Europe, with a total link strength of 630 indicating active collaboration within Europe and globally. German research in heat stress often integrates advanced technologies and interdisciplinary approaches, contributing to its high citation impact [49,95].

Table 8
Total documents, citations and link strength for the top 10 countries related to heat stress research

Country	Documents	Citations	Total Link Strength
China	2332	13385	956
United states	1428	9603	1326
Australia	469	3672	657
India	698	3602	409
Germany	405	3154	630
United Kingdom	358	2656	691
Italy	291	2128	429
Pakistan	244	1941	343
Spain	236	1591	322
Egypt	266	1579	323

The United Kingdom (UK), with 358 documents and 2,656 citations, shows significant research impact relative to its output. A total link strength of 691 highlights its collaborative research networks, particularly with European and Commonwealth countries. UK research often focuses on the physiological and ecological aspects of heat stress [49,95]. Meanwhile, Italy has contributed 291 documents and received 2,128 citations. Its total link strength of 429 suggests moderate collaborative activities, with Italian research in heat stress typically emphasizing agricultural productivity and environmental impacts, reflecting the country's Mediterranean climate and agricultural heritage [49,101].

Pakistan, with 244 documents and 1,941 citations, is an emerging player in heat stress research. A total link strength of 343 indicates growing collaborative efforts, as Pakistani research often addresses the impacts of heat stress on agriculture and food security, driven by the country's vulnerability to climate change [44,102]. Spain has produced 236 documents and garnered 1,591 citations, with a total link strength of 322 highlighting its involvement in European and international research networks. Spanish research on heat stress frequently focuses on agricultural and ecological impacts, aligned with its diverse climates and agricultural sectors [49,103].

Lastly, Egypt, with 266 documents and 1,579 citations, shows a significant research contribution from Africa. A total link strength of 323 indicates active international collaboration, with Egyptian research often focusing on the impacts of heat stress on agriculture and water resources, critical for the country's arid climate and reliance on the Nile River. These countries from other regions exhibit notable performance, suggesting a global distribution of research activities [102,104].

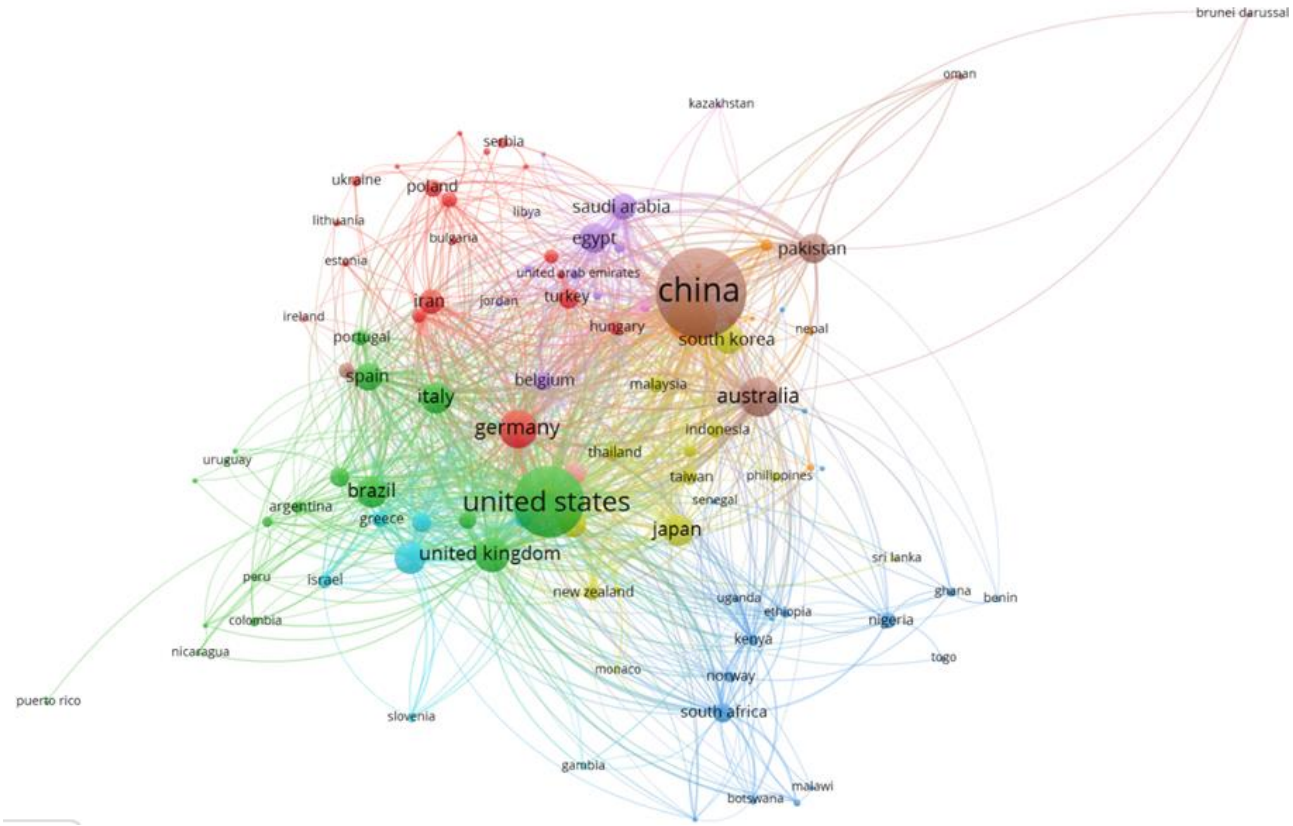

Fig. 6 Network mapping visualization of co-authorship collaboration between countries

To complement the data in Table 8, Fig. 6 illustrates the network mapping visualization of co-authorship collaboration between countries, offering a visual representation of the interconnections and collaborations within the heat stress research domain. The visualization of country-based co-authorship networks offers valuable insights into the global structure of scientific collaboration [17,19,21]. The United States emerges as the most prominent node, indicating its central role in global research collaborations. Its extensive connections with numerous countries across different clusters underscore its influence and capacity to foster international research partnerships.

China is another significant hub, with a substantial number of publications and diverse international collaborations. The prominence of China in the network illustrates its growing impact on global scientific research. Germany and the United Kingdom also show strong presence and connectivity, reflecting their established research infrastructure and collaborative efforts with various international partners. In North America and Europe, countries like the United States, United Kingdom, and Germany form a dense cluster, indicating robust intra-regional collaborations. These nations also maintain strong links with other regions, reflecting their pivotal role in global research networks. In the Asia-Pacific region, China, along with Japan, South Korea, and Australia, forms another significant cluster.

These countries show high levels of intra-regional collaboration while also engaging extensively with North America and Europe. In the Middle East and Africa, countries such as Saudi Arabia, Egypt, and South Africa form smaller clusters, with connections mainly to major hubs like the United States and China. This pattern reflects the growing research contributions from these regions and their reliance on partnerships with established research powerhouses. In Latin America, Brazil and Argentina exhibit notable co-authorship activities, primarily within the region and with European and North American countries. This observation indicates an emerging and dynamic research landscape characterized by a growing number of international collaborations [82,105,106].

In Africa, Nigeria and South Africa stand out, showcasing their growing involvement in global research networks. Their connections with both regional and international partners highlight the expanding range of research activities on the continent, encompassing diverse collaborations and initiatives [107–109]. Certain countries, such as Brunei Darussalam, appear on the periphery of the network, with limited co-authorship connections. This could be indicative of either emerging research capabilities or geographical, political, and economic constraints affecting their collaborative potential. The analysis of the top 10 countries in heat stress research demonstrates the global nature of this field, with dominant players like China and the United States leading the way, while other nations are gradually increasing their participation and integration into the international research community.

5.6 Network Mapping of Co-Citation in Relation to Authorship

In the realm of bibliometrics, co-citation and cited-author analyses are essential tools in uncovering the key contributors and intellectual structure within a particular research domain [28,81]. These methods provide valuable insights into the interconnectedness of scholarly work and aid in identifying influential authors and their impact on the field [24,32,33]. This analysis thoroughly examines the top 10 authors in heat stress research using data obtained from the Scopus Analyzer, delving into their citation counts, total link strength, and their influence on the field. The network mapping visualization presented in Fig. 7 showcases the co-citation network based on co-citation and cited-author analyses for the top 10 authors in heat stress research. Meanwhile, Table 9 below presents total citations and link strength for the top 10 authors related to heat stress research.

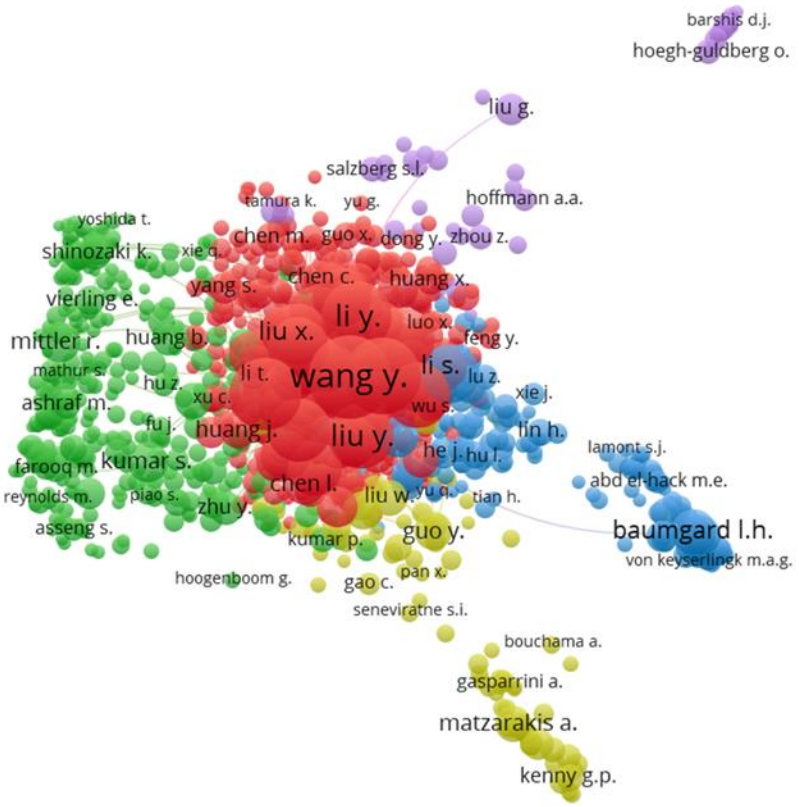

Fig. 7 Network mapping visualization of co-citation in heat stress research

The analysis on Fig. 7 sheds light on the structure and dynamics of this network, elucidating the influential figures and their collaborative relationships within the field. The network reveals several distinct clusters, each representing a group of authors who are frequently co-cited together. The primary clusters can be identified by their distinct colours. The largest and most prominent cluster, represented in red, appears to be the central hub of the network. The red cluster is dominated by Wang Y., Li Y., Liu Y., and Wang X., who are central figures in heat stress research and were identified as the top-cited authors, as indicated by the large size of their nodes and the dense connections between them [61,62].

The size and centrality of this cluster indicate that these authors are highly influential and widely cited within the field, suggesting that they are likely to be the leaders or pioneers in their respective research areas. Their work forms the core of the field, with numerous co-citation links suggesting extensive collaboration and cross-referencing. Surrounding the central red cluster are several smaller clusters, represented in different colours, including green, blue, and yellow. These peripheral clusters represent more specialized or niche research areas within the broader field. For instance, the green cluster includes authors like Mittler R., Vierling E., and Shinozaki K., who are known for their work in plant stress biology and molecular chaperones. This group is also highly interconnected, reflecting a collaborative sub-community within the broader research landscape.

The presence of these authors highlights their significant contributions to understanding the biological and physiological responses to heat stress. This cluster's proximity to the central cluster suggests a strong connection or collaboration between these researchers and the core group. Similarly, the purple cluster, featuring notable authors such as Hoegh-Guldberg O. and Barshis D.J., represents a crucial area of heat stress research, likely focusing on ecological and environmental aspects, despite being smaller.

The blue cluster is characterized by the presence of Baumgard L.H. and Von Keyserlingk M.A.G., who are prominent in studies related to animal physiology and agricultural impacts of heat stress [51,53]. Their connections with other clusters indicate interdisciplinary collaborations. Meanwhile, the yellow cluster, containing authors such as Matzarakis A. and Kenny G.P., focuses on human health and urban heat stress issues [35,36]. The interconnections with other clusters underscore the interdisciplinary nature of heat stress research, integrating environmental science, public health, and urban planning.

The analysis confirms that Wang Y. is the most influential author in the heat stress research network. The prominence of his node, coupled with extensive co-citation links, underscores his significant contributions and central role in the field. Similarly, Li Y., Liu Y., and Wang X. are pivotal figures whose research is frequently referenced and co-cited, indicating their foundational impact on heat stress studies. Interestingly, there are areas where clusters overlap or intersect, indicating potential interdisciplinary connections or collaborations between different research communities.

For example, the overlap between the red and green clusters suggests collaborative efforts between researchers in the core field and those specializing in plant stress biology or molecular chaperones. While most authors are clustered within distinct groups, there are a few notable exceptions, such as Hoegh-Guldberg O., Barshis D.J., and Kenny G.P., who appear as outliers or isolated nodes in the network. These authors represent researchers with unique or interdisciplinary perspectives, or they may be working in emerging or underrepresented areas within the field.

Table 9
Total citations and link strength for the top 10 authors related to heat stress research

Author	Citations	Total Link Strength
Wang y.	5088	623824
Zhang y.	4404	537864
Wang x.	3781	464232
Li y.	3535	430931
Wang j.	3215	381595
Li j.	3212	397680
Liu y.	3067	361305
Zhang x.	3041	387227
Li x.	2829	364218
Zhang j.	2663	323835

Based on Table 9 above, the analysis reveals that Wang Y. is the most prominent author in the field of heat stress research, with the highest number of citations (5,088) and the strongest co-citation link strength (623,824). This suggests that Wang Y.'s work is highly influential and frequently referenced in conjunction with other leading researchers in the field [61,62]. Following closely is Zhang Y., with 4,404 citations and a total link strength of 537,864. Zhang Y. also plays a pivotal role in the research community, as evidenced by the high citation count and substantial co-citation links, indicating frequent collaboration and cross-referencing with other top researchers.

Wang X. and Li Y. also exhibit significant impact with 3,781 and 3,535 citations, respectively. Their total link strengths, 464,232 for Wang X. and 430,931 for Li Y., underscore their considerable contributions and the interconnected nature of their research with others in the field. Interestingly, the analysis highlights a recurring pattern in the names of the top authors, with ‘Wang’, ‘Zhang’, and ‘Li’ appearing multiple times. This could be indicative of common surnames in the regions where heat stress research is heavily conducted or a reflection of collaborative research groups with these names.

Wang J. and Li J. have nearly identical citation counts, 3,215 and 3,212, respectively, but Li J. has a higher total link strength (397,680) compared to Wang J. (381,595). This suggests that while their individual impacts are similar, Li J. exhibits a broader network of collaboration or more frequent co-citation occurrences. Liu Y., Zhang X., Li X., and Zhang J. also make substantial contributions, with citation counts ranging from 2,663 to 3,067 and total link strengths between 323,835 and 387,227. These findings illustrate that these authors are integral parts of the research community, contributing valuable insights and often being cited alongside other key researchers.

6. Conclusions

The bibliometric analysis presented in this study provides a comprehensive overview of the current research landscape from 2022 – 2024 (May 2024) in the field of heat stress. The findings reveal a range of significant trends and insights that contribute to a deeper understanding of the scientific community's efforts in addressing the challenges posed by heat stress. The analysis of publication output, subject areas, top affiliations, co-authorship networks, and influential authors highlights the multidisciplinary nature of heat stress research.

The dominance of Chinese institutions, the leading role of the United States, and the emerging contributions from other regions, such as Latin America and Africa, underscore the global collaborative efforts in this domain. The identification of research hotspots and the mapping of co-

citation networks among influential authors offer valuable insights into the intellectual structure and interconnectedness of heat stress research.

This analysis serves as a valuable resource for researchers, policymakers, and stakeholders to better comprehend the current state of the art, recognize the key players, and identify potential avenues for future collaboration and knowledge exchange. As the scientific community continues to grapple with the complexities of heat stress, this study provides a solid foundation for informing future research directions, fostering interdisciplinary collaborations, and driving progress in addressing the critical challenges posed by heat-related stressors.

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