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ARTICLE

A Bibliometric Analysis Unveils Valuable Insights into the Past, Present, and Future Dynamics of Plant Acclimation to Temperature

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ABSTRACT

Plant temperature acclimation is closely related to maintaining a positive carbon gain under future climate change. However, no systematic summary of the field has been conducted. Based on this, we analyzed data on plant temperature acclimation from the Web of Science Core Collection database using bibliometric software R, RStudio and VOSviewer. Our study demonstrated that a stabilized upward trajectory was noted in publications (298 papers) from 1986 to 2011, followed by a swift growth (373 papers) from 2012 to 2022. The most impactful journals were *Plant Cell and Environment*, boasting the greatest count of worldwide citations and articles, the highest H-index and G-index, followed by *Global Change Biology* and *New Phytologist*, and *Frontiers in Plant Science* which had the highest M-index. The USA and China were identified as the most influential countries, while Atkin was the most influential author, and the Chinese Academy of Sciences was the most influential research institution. The most cited articles were published in the *Annual Review of Plant Biology* in 1999. "Cold acclimation" was the most prominent keyword. Future plant temperature acclimation research is expected to focus on thermal acclimation and photosynthesis, which have important significance for future agricultural production, forestry carbon sequestration, and global food security. In general, this study provides a systematic insight of the advancement, trend, and future of plant temperature acclimation research, enhancing the comprehension of how plants will deal with forthcoming climate change.

KEYWORDS

Temperature; acclimation; plant responses; climate change; bibliometric

1 Introduction

Since the mid-19th century, humans have burned a considerable quantity of fossil fuels, which released a substantial amount of greenhouse gases such as CO_2 into the atmosphere, aggravated the greenhouse effect, and contributed to extreme weather (hotter summers or colder winters) [1,2]. For example, seasonal temperature changes expose plants to varying temperatures. As a result, the growth, development, and reproduction of plants will be significantly impacted by temperature variations in a few days of the month [3–5]. The degree to which plants acclimate to temperature is expected to have a significant impact on the future soil-plant-atmosphere carbon cycle. Therefore, it is crucial to explore how plants can adjust their functions to acclimate to future temperature changes.

Plant temperature acclimation describes the response of plants to transient temperatures after experiencing a change in growth temperature for weeks to years [6–9]. The degree of plant acclimation to temperature is usually quantified by photosynthesis and respiration, which are closely related to plant carbon uptake and carbon sink intensity. In general, temperature increased led to higher enzyme activity and faster metabolic reactions, plant photosynthetic rates behaved as a unimodal curve and reached a maximum at 20°C–30°C (T_{opt}), and declined rapidly thereafter [10–13]. While species suffer from temperature acclimation, T_{opt} typically moves slightly upward or downward during a short acclimation period and they fully acclimate after a long period. These changes in T_{opt} are accompanied by an increase in the acclimation temperature [14–16]. Plant respiration rates also showed high sensitivity to temperature which doubled for every 10°C increase (Q_{10}) [7]. However, the Q_{10} value was not a fixed constant and could change depending on the growth temperature [17–19]. Studies showed that species living in warmer climates generally exhibited lower respiration rates compared to those in colder regions [17]. However, there were key uncertainties in the temperature acclimation of photosynthesis and respiration and their responses to the global carbon cycle [8,14,20]. Studying temperature acclimation provided a comprehensive understanding of the carbon gain strategies and feedback from the global carbon cycle. Therefore, it is of great interest to understand the plant acclimation to temperature changes and the strategies developed to mitigate the impact of climate change on agriculture, forestry, and food security.

In recent years, global researchers have carried out extensive investigations regarding plant temperature acclimation, but a small number of papers have summarized knowledge in the field that relies on experiential evidence. However, these papers are restricted by research institutions or individuals and were published in various journals. It is difficult to effectively summarize the information in this field with personal ability. Thus, it is urgent to quantitatively analyze the relevant literature on plant temperature acclimation to summarize the research progress and developmental trends in this field. Bibliometrics is an interdisciplinary science that uses mathematical and statistical methods to quantitatively analyze all knowledge carriers. It is a comprehensive knowledge system focusing on quantification that integrates mathematics, statistics, and philology. Bibliometric analysis can shed new light on the description and characterization of existing knowledge states, as well as forecast research trends on specific topics. This approach has been extensively employed in the domains of library science, information science, environmental science, agriculture, medicine, and others [21–25].

This paper describes the scientific progress of plant temperature acclimation systematically and objectively. It employed bibliometric analysis of research papers published in the Web of Science Core Collection database and visually analyzed the relationships between papers in this field to improve understanding of research trends and prospects. The goals of this investigation were: (1) to categorize the research orientations and emphases to comprehend the progression of plant temperature acclimation research; (2) to assess the contributions of individuals, institutions, and countries to plant temperature acclimation research; (3) to investigate the evolution of research themes over time and predict the future research orientation of plant temperature acclimation.

2 Materials and Methods

2.1 Materials

We collected data from the Web of Science (WOS) Core Collection database in March 2023, using the "Advanced Search" function to retrieve related publications on plant temperature acclimation from the beginning to 2022. In detail, we explored fields and details using Boolean operators, employing the terms TI = (((" acclimation" OR "acclimatization") AND ("temperature")) AND ("plant")) OR AK = (((" acclimation" OR "acclimatization") AND ("temperature"))) OR AB = ((("acclimation" OR "acclimatization") AND ("temperature")) AND ("plant")), after consulting relevant literature, and carried out a literature exploration from January 01, 1900, to December 31, 2022 (including online publishing).

The exploration was conducted for “All Fields” in the WOS Core Collection. We chose the “Exact search” option to improve accuracy and to avoid irrelevant articles in the search results. We selected 671 publications on plant temperature acclimation from 2165 results by reading the title and abstract. A total of 671 publications from a document containing “Full Record and Cited References” were acquired utilizing the “save for other file formats” export feature with a “Plain text file.” The acquired data was then used for further analysis (Fig. 1).

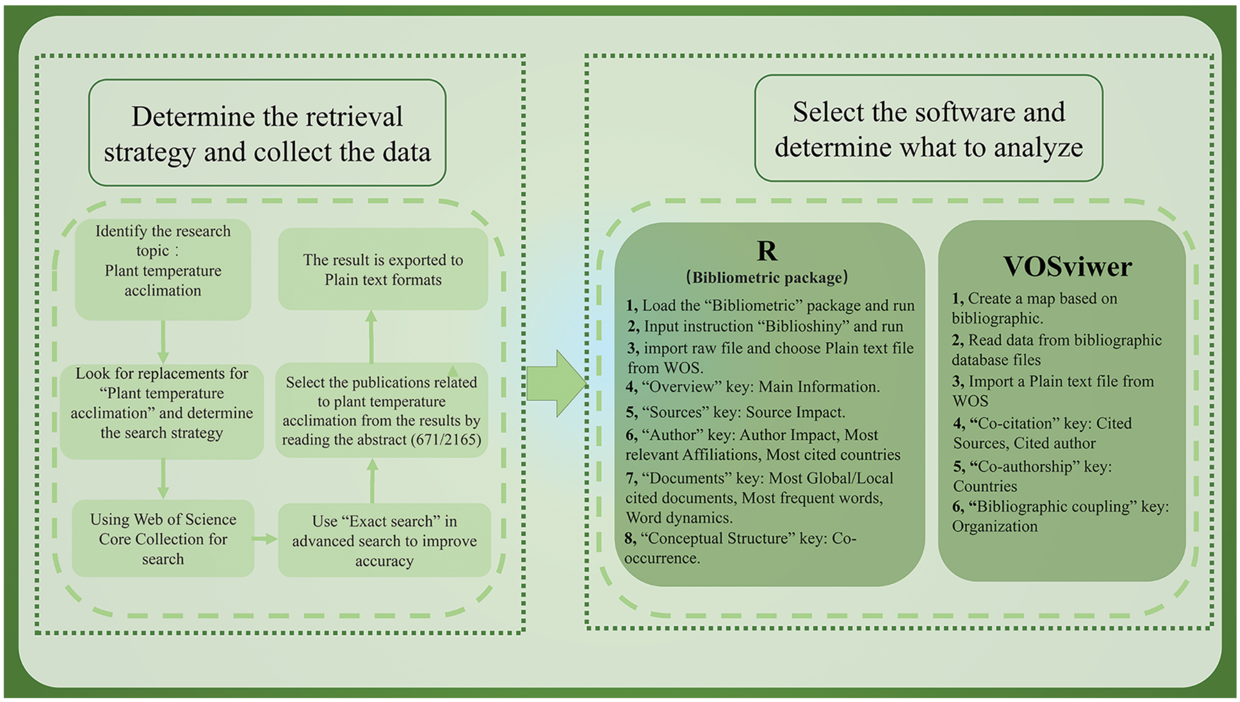

Figure 1: The work procedure

To obtain accurate results, we divided affiliations by the territories of the current country, such as affiliations from England, Scotland, Northern Ireland, Wales, the Cayman Islands, and the Turks and Caicos Islands were reclassified as from the United Kingdom, and affiliations from French Guiana were reclassified as from France. The affiliation of Bonaire and the Netherlands Antilles (Netherlands Antilles) was reclassified as coming from the Netherlands. Greenland’s affiliation was reclassified as coming from Denmark [26,27].

2.2 Materials

VOSviewer (https://www.vosviewer.com/) was developed by The Centre for Science and Technology Studies of Leiden University in the Netherlands [28]. VOSviewer was a Java-based freeware developed in 2009 and updated to version 1.6.18 (published on January 24, 2022), which focused on literature data, model-undirected network analysis, and scientific knowledge visualization. In this study, we mainly used VOSviewer to visualize the results (Fig. 1).

“Bibliometrix” (2023 K-Synth Srl, Academic Spin-Off of the University of Naples Federico II, version 4.0) is an open-source tool developed based on the programming software R (https://www.r-project.org/) and R studio (https://www.rstudio.com/categories/rstudio-ide/) for comprehensive scientific map analysis of scientific literature [29]. “Bibliometrix” fully integrates statistical calculation and data visualization operations, and can import bibliographic data from databases such as “WOS”, “SCOPUS”, and “PubMed” networks for co-citation, coupling, scientific collaboration, and co-keywords analysis. The most significant advantage of “Bibliometrix” is that it provides the most intuitive comprehension of the data after analyzing and screening, and it can supply researchers with tables and export tables, which is highly convenient for researchers. We mainly analyzed the data using the “Bibliometrix” package (Fig. 1).

3 Results

3.1 Main Information

From the “WOS Core Collection database”, we acquired 671 records from 202 sources, including 583 articles, 65 review papers, 11 conference proceedings, 6 book chapters, 4 early access articles, and 2 editorial materials. To some extent, the quantity of publications reflects the popularity of the scientific field. Between 1986 and 2000, only 93 publications on plant temperature acclimation were issued, comprising 13.9% of the overall publications. The quantity of publications surged exponentially from 2001 to 2011 (205 publications, 30.6% of the total), and the mean number of publications rose from 6.2 (1986–2000) to 18.6 (2001–2011) annually. Between 2012 and 2022, there was a consistent rise in the quantity of published works, amounting to a total of 373 releases, constituting roughly 55.6% of the overall publications (Fig. 2b). More publications on this topic have been produced in the last 11 years than in the preceding period, indicating that scientific inquiries in this domain garnered growing interest from both scientists and society have been evident. In relation to the referencing of academic articles, the overall count of worldwide citations in this domain amounted to 336302, averaging 54.1 citations per publication and 1.5 citations per paper annually, and 24313 references were cited.

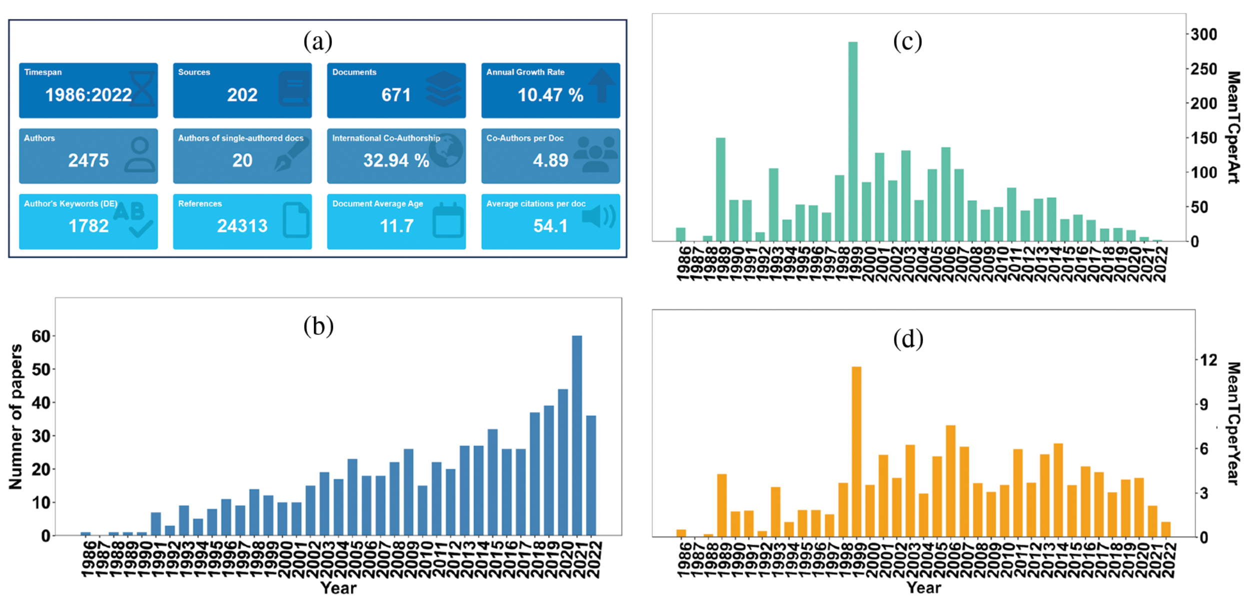

Figure 2: Based on information about research on plant temperature acclimation from 1986 to 2022, including (a) main information [29,30]; (b) the number of publications; (c) represent total cited per publication (MeanTCperPa) and (d) represent total cited per year (MeanTCperYear)

Additionally, interannual fluctuations, like the emergence of severe climatic conditions, might impact the citation count of publications concerning research on plant temperature acclimation. Additionally, we computed the mean overall citations for each article annually. The peak mean overall citation occurred in 1999 (288.50 instances), whereas the minimum mean total citation was merely 2.11 instances in 2022

(Fig. 2c). In terms of the mean total citations per year, 1988 (0.22) had the lowest value, while 1999 (11.54) and 2006 (7.57) had the highest, ranking first and 2nd, respectively (Fig. 2d). Approximately 18.61 publications are published annually on plant temperature acclimation. In addition, a combined total of 2475 authors engaged in the examination of plant temperature acclimation and provided 1782 keywords. As a result, the investigation into plant temperature acclimation is garnering growing interest from publishers, regions, institutions, and researchers.

3.2 Publisher's Citations and Sources

Regarding research into plant temperature acclimation, the leading 5 journals that issued the highest number of papers were *Plant Cell and Environment* (36 papers), *Global Change Biology* (28 papers), *New Phytologist* (27 papers), *Frontiers in Plant Science* (25 papers), *Physiologia Plantarum* (21 papers), and *Journal of Experimental Botany* (21 papers). The top 5 journals that garnered the most extensive worldwide citations in the past were *Plant Cell and Environment* (3441), *Global Change Biology* (2140), *Physiologia Plantarum* (1825), *New Phytologist* (1673), and *Journal of Experimental Botany* (1414) (Table 1). The H-index, signifying that H publications have garnered a minimum of H citations, is frequently employed to assess the academic influence of a journal or an individual. Thus, the H-index could signify the scholarly accomplishments of a publication or an individual. Among all the publications pertaining to plant temperature acclimation investigation, the leading 5 H-indexed journals were *Plant Cell and Environment* (26), *Global Change Biology* (22), *New Phytologist* (21), *Journal of Experimental Botany* (16), and *Physiologia Plantarum* (15) (Table 1). For the majority of Local Cited Sources (from Reference Lists) in all papers, the leading 5 journals were *Plant Physiology* (3600), *Plant Cell and Environment* (2043), *Physiologia Plantarum* (1168), *Journal of Experimental Botany* (1156), and *New Phytologist* (1145) (Fig. 3). In general, *Plant Cell and Environment* secured the leading position concerning the quantity of articles, H-index, and G-index, along with the highest total worldwide citations, whereas *Frontiers in Plant Science* occupied the foremost spot in the M-index (Table 1).

Table 1: The most pertinent source data between 1986 and 2022 in papers associated with plant temperature acclimatization

Rank	Source	H-index	G-index	M-index	TC	NP	IF (2023)	Subject category (position)
1	*Plant Cell and Environment*	26	36	0.788	3441	36	7.3	Plant Science (Q1/13/487) & Plant Physiology (Q1/13/182)
2	*Global Change Biology*	22	28	0.880	2140	28	11.6	General Environment Science (Q1/4/227) & Ecology (Q1/6/437) & Global and Planetary Change (Q1/3/113) & Environmental Chemistry (Q6/139)
3	*New Phytologist*	21	27	0.677	1673	27	9.4	Plant Science (Q1/8/487) & Physiology (Q1/9/182)
4	*Journal of Experimental Botany*	16	21	0.485	1414	21	6.9	Plant Science (Q1/16/487) & Physiology (Q1/17/182)
5	*Physiologia Plantarum*	15	21	0.484	1825	21	5.9	Plant Science (Q1/33/487) & Physiology (Q1/27/182) & Genetics (Q1/55/328) & Cell Biology (Q2/74/274)
6	*Frontiers in Plant Science*	14	24	1.273	571	25	5.6	Plant Science (Q1/56/487)
7	*Annals of Botany*	12	13	0.414	724	13	4.2	Plant Science (Q1/64/830)

(Continued)

Table 1 (continued)

Rank	Source	H-index	G-index	M-index	TC	NP	IF (2023)	Subject category (position)
8	*Environmental And Experimental Botany*	12	20	0.375	482	20	5.7	Plant Science (Q1/26/487) & Agronomy and Crop Science (Q1/23/376) & Ecology, Evolution, Behavior and Systematics (Q1/35/687)
9	*Journal of Plant Physiology*	12	16	0.429	552	16	4.3	Plant Science (Q1/61/487) & Agronomy and Crop Science (Q1/46/376) & Physiology (Q1/46/182)
10	*Plant Physiology*	12	12	0.364	1346	12	7.4	Plant Science (Q1/15/487) & Genetics (Q1/23/328) & Physiology (Q1/16/182)

Note: TC represents the overall worldwide citations, NP denotes the paper count, and IF stands for the Journal impact factor (2023).

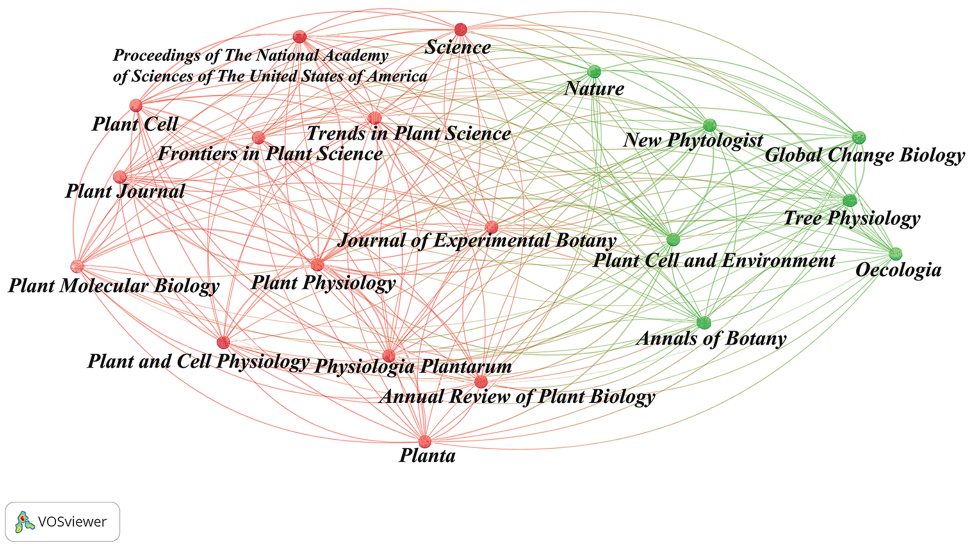

Figure 3: Co-citation network for the top 20 journals utilizing the VOS clustering algorithm. Various shaded areas denoted distinct clustering outcomes. The connecting lines in red, green, and blue signify journal co-citations. Additionally, the magnitude of each node reflects the co-citations of journals referenced in the paper

Generally, Journals exhibited various fields or individual disciplines from an interdisciplinary standpoint. This inquiry provided an understanding of the numerous disciplines with high interest in this theme. Table 1 also displayed that the leading 10 journals encompassed various 10 distinct subject domains, and Plant Science appeared most frequently among them. Among the leading 10 journals, 80% of them encompassed multiple subject areas, and only the *journal of Annals of Botany* and the journal of *Frontiers in Plant Science* had one subject area. "Plant Science" emerged as the predominant field among the diverse journals, exemplified by 9 out of the 10 highest-ranking journals. Plant Science, Physiology, Agronomy and Crop Science, and Genetics were the top 4 subject areas. We also analyzed the co-citation relationship of the top 20 journals, and the results showed that they fell into two categories represented by *Science* and *Nature* (Fig. 3). The red cluster had a total of 13 journals, which were the most active group in the co-citation relationship. It suggested that these 13 journals exhibited a substantial number of reciprocal citations in the examination of plant temperature acclimation, thus indicating a close association (Fig. 3).

3.3 Author's Country

3.3.1 The Top 10 Countries for Papers Published and Cited in Different Periods

The number of published papers and global citations in a country's research can reflect the level and emphasis of scientific research. Between 1986 and 2022, 66 countries were highlighted in the 671 publications on plant temperature acclimation, more than 26.4% of all research publications published in the USA (177 documents, with each document was cited 80 times) or in partnership with the USA. In comparison, China ranked the 2nd (16.7%, 112 documents, with each document was cited 30.12 times) and Canada ranked the 3rd (10.1%, 68 papers, each paper was cited 80.6 times). From 1986 to 2000, the majority of countries had a low number of articles and citations, while the USA (25 papers and 3854 citations) retained the top position in terms of both the number of papers and citations, and Canada (13 papers and 1601 citations) ranked 2nd. From 2001 to 2011, The quantity of papers issued in the USA (53 papers) consistently ascended, and the USA possessed the highest overall number of citations (3761 times) among all pertinent nations. It cannot be ignored that the quantity of publications and citations in the UK (24 papers, 2726 citations) and Japan (20 papers, 1664 citations) increased rapidly, ranking 2nd and 3rd, respectively. Between 2012 and 2022, the number of publications and citations increased significantly in all countries. Especially, the USA (99 publications and 1675 citations) secured the top position, while China (92 publications and 1942 citations) claimed the second spot (Table 2). In conclusion, the USA and Canada made substantial contributions to plant temperature acclimation research from 1986 to 2022, while China has made great contributions in the last 10 years. However, among nations with more than 1000 citations, Sweden (27 papers) achieved the topmost mean number of citations (130.1 instances), whereas the UK (49 papers, with each paper receiving 93.8 citations) and the USA (177 papers, with each paper obtaining 80 citations) secured the 2nd and 3rd positions, respectively, indicating their production of high-quality papers in the domain of plant temperature acclimation. In general, the USA made greater contributions to plant temperature acclimation research, sustaining a high level of total papers issued, research influence, excellence, and overall citations throughout the three intervals.

Table 2: Fluctuations in the overall count of documents and references for the leading 10 nations in the investigation of plant temperature acclimation were observed during the periods 1986–2000, 2001–2011, and 2012–2022

Rank	Periods								
	1986–2000			2001–2011			2012–2022		
	Nation	TP	TC	Nation	TP	TC	Nation	TP	TC
1	USA	26	3854	USA	54	3761	USA	97	1675
2	Canada	13	1601	UK	24	2726	China	92	1942
3	Poland	9	206	Japan	20	1664	Australia	43	555
4	Russia	7	46	Canada	17	1736	Canada	38	805
5	Sweden	6	134	Australia	17	1133	Germany	37	491
6	Germany	4	16	Germany	13	1063	Japan	24	1142
7	UK	4	862	Spain	13	1412	UK	21	383
8	Australia	4	36	China	15	633	Spain	20	492
9	Netherlands	4	22	Sweden	11	727	France	17	511
10	Bulgaria	3	72	Poland	9	492	Poland	16	270

Note: TP represents the overall count of papers, while TC denotes the total number of worldwide citations.

3.3.2 The Top 10 Countries for Papers Published and Cited in Different Periods

A total of 66 nations have published articles on plant temperature acclimation, with 20 countries meeting the threshold of having at least 10 publications and being interconnected in the network diagram. Fig. 4 displays a co-authorship chart illustrating the extent of communication and cooperation among authors from different countries regarding plant temperature acclimation. The size of the nodes represents the strength of the links, with larger nodes indicating greater cooperation and collaboration with plant temperature acclimation researchers from other countries. The co-authorship analysis reveals that the United States (USA) and China played a prominent role in this research topic, with the most nodes and the densest links in the co-authorship map. The USA had the highest link strength among all countries, with 17 links and a total link strength of 135, followed by Germany (16 links, 52 overall connection potency), Australia (14 links, 94 overall connection potency), China (15 links, 69 overall connection potency), France (13 links, 29 overall connection potency), Canada (12 links, 55 overall connection potency), the UK (12 links, 56 overall connection potency), Sweden (10 links, 44 overall connection potency), Japan (9 links, 29 overall connection potency), Spain (8 links, 21 overall connection potency), Poland (9 links, 13 overall connection potency), Brazil (7 links, 11 overall connection potency), and the Netherlands (7 links, 11 overall connection potency). On the other hand, Finland, Denmark, Italy, Russia, the Czech Republic, Iran, and India had a relatively small node size, fewer links, and lower total link strength, despite producing a certain number of articles on plant temperature acclimation. The analysis suggests that Australia and Sweden were extensively engaged in constructing a collaborative network with researchers from diverse nations, as evidenced by having fewer files with more total link strength. In contrast, China and Japan should strengthen cooperation with other countries, as they had more files with less total link strength. In summary, the co-authorship analysis revealed the key players in the field of plant temperature acclimation research, as well as the level of collaboration among different countries. The findings suggest the need for strengthening cooperation and collaboration among researchers from different countries to advance the field further.

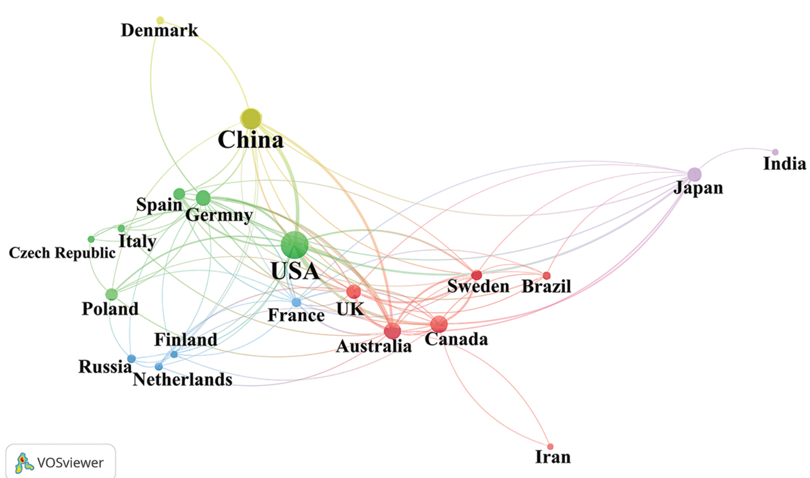

Figure 4: Co-authorship network of the foremost 20 nations using the VOS clustering algorithm. Various hued areas depict distinct clustering outcomes. The crimson, verdant, yellow, lilac and azure connecting lines signify co-authorship amid nations. The magnitude of each vertex denoted the frequency of nations that had an appearance in the article

3.4 Most Influential Contributors and Institutions

3.4.1 Most Influential Institutions

As scientific research developed, increasing studies were completed through reciprocal cooperation among different countries and institutions, which could lead to greater influence and scientific research value. In this study, a sum of 751 academic institutions engaged in research on plant temperature acclimation. Among the foremost 10 institutes, 2 came from Canada, 2 from Australia, and 1 from each of China, the UK, the USA, Poland, Sweden, and Spain (Table 3). As expected, Canada and Australia had a total of 4 institutes that made up 40% of the list, and all the most efficient establishments were owned by the top ten nations with the greatest influence and productivity, which corresponded to the most productive countries. Chinese Academy of Sciences attained the top position concerning the overall quantity of publications (27 publications, 4.0%), followed by the University of Western Ontario (23 publications, 3.4%), and the Western Sydney University (22 publications, 3.3%). The University of York had the greatest total cited papers (TC = 3057). The University of Western Ontario (TC = 2956) and Umeå University (TC = 2553) ranked 2nd and 3rd among the most cited institutes. The sum of citations for these institutions ranged from 3057 to 497. We additionally conducted clustering of all research establishments utilizing the VOS clustering algorithm and subsequently chose the foremost 20 establishments that issued articles to investigate collaborative connections among them (Fig. 5). The collaborative network was primarily clustered into 5 classifications symbolized by the Chinese Academy of Sciences (5 items), the University of Western Ontario (4 items), the University of York (4 items), the University of Minnesota (4 items), and the Polish Academy of Sciences (3 items). The 5 clusters worked closely together and made remarkable achievements in the acclimation of plant temperature.

Table 3: The organization that garnered the most citations in research on plant temperature acclimation from 1986 to 2022, relying on two statistical metrics (TC) and the quantity of published papers (NP)

Rank	Institute	Country	Total publication	Total citation articles (TC)	Contribution (%)
1	Chinese Academy of Sciences	China	27	982	4.0%
2	University of Western Ontario	Canada	23	2956	3.4%
3	Western Sydney University	Australia	22	879	3.3%
4	University of Minnesota	USA	21	1446	3.1%
5	University of York	UK	18	3057	2.7%
6	Australian National University	Australia	18	1110	2.7%
7	Polish Academy of Sciences	Poland	18	973	2.7%
8	The Spanish National Research Council (CSIC)	Spain	16	1051	2.4%
9	University of Saskatchewan	Canada	15	497	2.2%
10	Umeå University	Sweden	14	2553	2.0%

Note: TP represents the overall count of papers, while TC denotes the total number of worldwide citations.

3.4.2 Most Influential Authors

From 1986 to 2022, a total of 2475 authors participated in plant temperature acclimation research. Surprisingly, only 31 authors from the group released over 5 research articles throughout the research duration, and 20 articles were single-authored. The focus was on the top 10 most published authors (Table 4), all of them released over 9 papers to ascertain the fundamental capability of plant temperature acclimation. Most of the authors were from Australia, the USA, and Germany, corresponding to the most productive countries. It was surprising that China, which had the 2nd most published articles, had no author among the top 10. Atkin, Owen K from Australia, surfaced as the most productive researcher with 24 publications (3.6% of the total). Reich, Peter B. published 18 articles (2.7%) and thereby appeared as the 2nd, followed by Tjoelker, Mark G (16 publications, 2.4%), Hincha, Dirk K (15 publications, 2.2%), and Salinas, Julio (15 publications, 2.2%). The top 5 total citation authors were Atkin, Owen K (TC = 3160) from Australia, Huner, Npa (TC = 24408) from UK and Canada, Tjoelker, Mark G (TC = 22359) from Australia, Reich, Peter B (TC = 1494), and Salinas, Julio (TC = 1209), while other authors had a total citation of less than 1000. The co-citation relationship of the top 20 authors was analyzed, and the results showed that they fell into 3 categories represented by Huner, Npa, Way, Danielle A, and Atkin, Owen K (Fig. 3). The different color clusters were the most active group in the co-citation relationship. It indicated that these authors had a high number of reference relationships in the study of plant temperature acclimation, so they were closely related (Fig. 6).

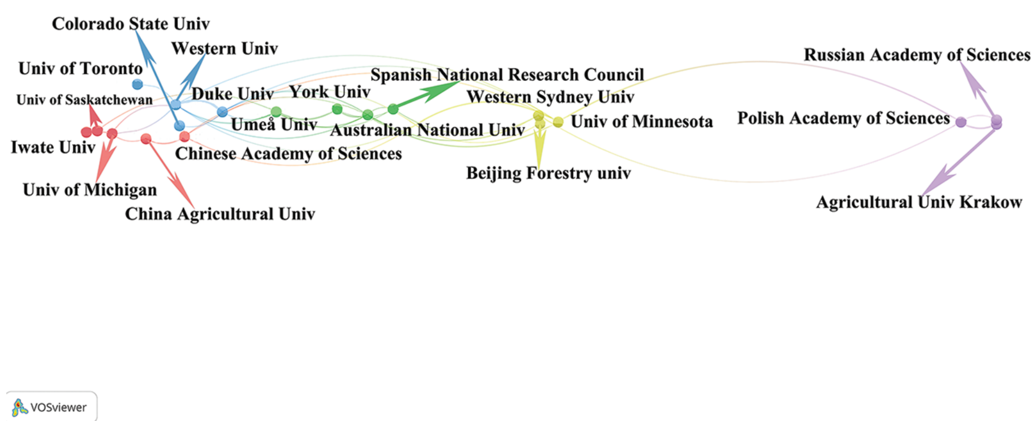

Figure 5: Collaborative network analysis of the foremost 20 production institutions or universities using the VOS clustering algorithm was conducted. Nodes denote diverse institutions or universities. Varied hues signify distinct clustering outcomes. Color-coded connecting lines depict the collaborations among institutions or universities

Table 4: The authors most frequently referenced in research on plant temperature acclimation from 1986 to 2022, utilized two statistical metrics (TC) and the quantity of published papers (NP)

Rank	Scholar	Affiliation	Region	NP	TC
1	Atkin, Owen K	Australian National University	Australia	24	3160
2	Reich, Peter B	Friedrich Schiller University of Jena, University of Michigan, University of Minnesota,	Germany, USA, Australia	18	1494
3	Tjoelker, Mark G	Western Sydney University	Australia	16	2359
4	Huner, Norman P.A	Western University	Canada	15	2408
5	Salinas, Julio	The Spanish National Research Council (CSIC)	Spain	15	1206

(Continued)

Table 4 (continued)

Rank	Scholar	Affiliation	Region	NP	TC
6	Hincha, Dirk K	Max Planck Institute Molecular Plant Physiology	Germany	12	708
7	Way, Danielle A	Australian National University, Western University, Duke University, University of Toronto	Australia, Canada, USA	11	1086
8	Rapacz, Marcin	Agricultural University Krakow	Poland	10	379
9	Hurry, Vaughan	Umea University, Swedish University of Agricultural Sciences	Sweden	9	694
10	Smith, Nicholas G	Texas Tech University	USA	9	633

Note: TP represents the overall count of papers, while TC denotes the total number of worldwide citations.

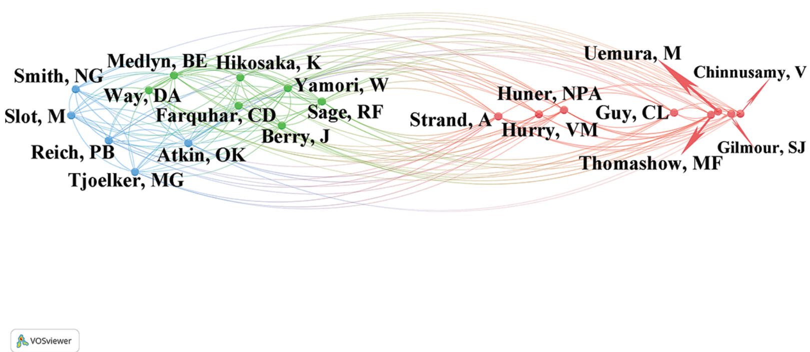

Figure 6: The co-citation framework of the Top 20 authors using the VOS clustering algorithm was established. Distinctive hues denote diverse clustering outcomes. The connecting lines in red and green signify co-citations between authors. Additionally, the magnitude of each node mirrors the co-citations of authors referenced in the publication

3.5 Most Cited Documents

In general, the number of citations of publications is used directly as an indicator to measure their influence and quality via commonly cited pieces. In temperature acclimation research, a total of 671 output publications were produced, and 631 articles were cited at least once, with a total of 88 articles receiving 100 citations. Surprisingly, 8 of the 10 most-cited publications were published between 2001 and 2011, indicating the significance of those eleven years in expanding the body of knowledge. Additionally, most of these research articles were published by the most influential countries and journals. The top 10 cited papers on plant temperature acclimation from 1986 to 2022 were compiled and are presented in Table 5.

Among these papers, there were a total of 7 review papers and 3 research papers. The document boasting the maximum worldwide overall citations and local total citations was released in the journal of *Annual Review of Plant Biology* [31]. Reference [31] reviewed the progress in research before 1999 in determining the nature and function of antifreeze genes, as well as the regulation and signal transduction mechanisms of low-temperature genes. One conclusion from these studies was that cold acclimation, or the expression of certain cold-inducing genes, could stabilize cell membranes against freezing-induced damage. We also summarized the other papers in the top 10 cited papers according to the number of citations from high to low. Reference [7] reviewed the extent to which short- and long-term temperature sensitivity of respiration varied in plants and the potential mechanisms responsible for such changes. They confirmed that the respiratory acclimation mechanisms based on the adjustment of Q_{10} (Type I) (i.e., respiration doubling per 10°C rise in temperature) and the respiratory acclimation mechanism based on the change of enzyme capacity of the respiratory system (Type II) were confirmed. Reference [32] explained how plants acclimate to cold and light from the perspective of energy balance (photosynthesis). Reference [33] reviewed the pre-2007 understanding of the temperature response of photosynthesis in land plants within a temperature range that did not damage the photosynthetic apparatus. Reference [34] reviewed some recent studies on reactive oxygen species and temperature stress in plants and proposed a model of reactive oxygen species involved in temperature stress perception and defense. Reference [35] reported on the role of the ZAT12 gene in cold acclimation and demonstrated that this gene is involved in a variety of other abiotic stress responses. Reference [36] used a model of photosynthesis to parameterize 19 gas exchange studies on plants. The obtained parameter values described the shape and amplitude of the temperature response for the maximum rates of Rubisco activity (V_{cmax}) and electron transport (J_{max}). Reference [37] evaluated photosynthetic temperature acclimation in higher plants by analyzing published data and discussed potential physiological and biochemical mechanisms of temperature acclimation in C_3, C_4, and *CAM* plants. Reference [38] found that CBF genes were involved in a cold-response pathway in plants and increased freezing tolerance, and CBF proteins from different plants conserved amino acid sequences. Reference [39] found that thermal stress induced the accumulation of phenolic substances in plants by activating the biosynthesis of phenolic substances and inhibiting the oxidation of phenolic substances, which is an acclimatized mechanism of plants for thermal stress.

Table 5: The highest-ranked 10 referenced documents derived from research on plant temperature acclimation between 1986 and 2022, primarily relying on two statistical measures (TC and LTC)

Rank	Author	Journal	DOI	LC	GC	LC/GC ratio (%)	Normalized local citations	Normalized global citations
1	(Thomashow, 1999) [31]	*Annual Review of Plant Biology*	https://doi.org/10.1146/annurev.arplant.50.1.571	129	2462	5.24	5.84	8.53
2	(Atkin et al., 2003) [7]	*Trends in Plant Science*	https://doi.org/10.1016/S1360-1385(03)00136-5	87	868	10.02	9.55	6.61
3	(Huner et al., 1998) [32]	*Trends in Plant Science*	https://doi.org/10.1016/S1360-1385(98)01248-5	44	757	5.81	7.70	7.90
4	(Sage et al., 2007) [33]	*Plant Cell and Environment*	https://doi.org/10.1111/j.1365-3040.2007.01682.x	47	705	6.67	4.98	6.75
5	(Suzuki et al., 2006) [34]	*Physiologia Plantarum*	https://doi.org/10.1111/j.0031-9317.2005.00582.x	15	681	2.20	1.57	5.00
6	(Vogel et al., 2005) [35]	*The Plant Journal*	https://doi.org/10.1111/j.1365-313X.2004.02288.x	27	574	4.70	3.57	5.50
7	(Medlyn et al., 2002) [36]	*Plant Cell and Environment*	https://doi.org/10.1046/j.1365-3040.2002.00891.x	36	558	6.45	4.91	6.32
8	(Yamori et al., 2014) [37]	*Photosynthesis Research*	https://doi.org/10.1007/s11120-013-9874-6	39	556	7.01	8.29	8.79
9	(Jaglo et al., 2001) [38]	*Plant physiology*	https://doi.org/10.1104/pp.010548	20	476	4.20	4.65	3.71
10	(Rivero et al., 2001) [39]	*Plant Science*	https://doi.org/10.1016/S0168-9452(00)00395-2	1	440	0.23	0.23	3.43

Note: DOI was the digital object unique identifier; GC represented the overall global count of citations; LC denoted the overall local count of citations.

3.6 The Dynamic and Co-Occurrence of Keywords

In scientific papers, keywords are useful for identifying research gaps as well as research patterns and directions of concern. Keywords with high frequencies indicate trends in hotspots of recent research. This investigation filtered the foremost 20 common keywords for the examination of plant temperature acclimatization from 1986 to 2022 (Fig. 7). All keywords relatively had a lower frequency during 1986–2000, and the keywords “acclimation,” “cold acclimation,” “photosynthesis,” “temperature,” and “low temperature” were the top 5 commonly occurring words (Table 6). For these 17 years, most keywords appeared no more than 15 times during the period, indicating that plant temperature acclimation research was still in its infancy (Fig. 7). Researchers paid more attention to plant cold acclimation and mostly focused on the study of photosynthesis and chlorophyll fluorescence after plants experienced cold acclimation. Between 2001 and 2011, The occurrence of every keyword had noticeably risen, suggesting that investigations into plant temperature acclimatization had progressively but consistently grown over this timeframe (Fig. 7) (Table 6). The top 5 keywords in this stage were “cold acclimation,” “acclimation,” “temperature,” “photosynthesis,” and “freezing tolerance.” Cold acclimation and photosynthesis remained hotspots for research, and “respiration” grew rapidly and became one of the hotspots over this period. It is worth noting that “climate change” and “thermal acclimation” suddenly appeared and grew rapidly in this period (Fig. 7) (Table 6). This could be related to the IPCC, Fourth Assessment Report in 2007, which declared an increased frequency of extreme weather caused by rising temperatures. This attracted international attention on climate change and prompted research into the effects of temperature rise on plants (*e.g.,* crops, grasses, trees) [40]. During the period 2012–2022, all keywords grew significantly, particularly “cold acclimation,” “climate change,” and “*Arabidopsis thaliana*,” with plant temperature acclimation research developing rapidly and researchers paying increasing attention to future climate change.

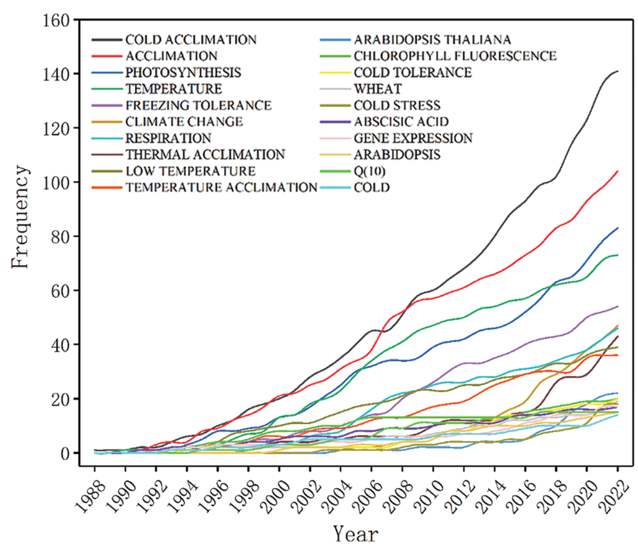

Figure 7: The tendency in the occurrence frequency of the leading 20 keywords in scholarly articles on plant temperature acclimatization from 1986 to 2022. It appears that the quantity of lines in the diagram is beneath what the figure legends suggest

The VOS algorithm was employed to cluster the leading 43 keywords associated with plant temperature acclimation research that occurred more than 8 times (Fig. 8). The most prevalent recurring keyword was “cold acclimation” (frequency of 141 occurrences). Researchers studied plant temperature acclimation beginning with low temperatures because they are more challenging for living organisms to tolerate and acclimate to, and therefore have significant impacts on plant survival and growth. Furthermore, low temperatures are associated with many important biological processes, such as cold acclimation and cryopreservation. All key terms were grouped into four categories in the co-occurrence network (Fig. 8). The red cluster was the largest, with a total of 21 keywords, the majority of which were cold acclimation, freezing tolerance, low temperature, *Arabidopsis thaliana*, and so on. Therefore, low temperature was the primary environmental factor of research in this clustering. The researchers used wheat and *Arabidopsis thaliana* as research objects to investigate the acclimation phenomenon of plants under low temperatures. The researchers aimed to reduce photoinhibition and increase plant yield, solving the problem of food security. The green clusters, with a total of 15 keywords, mainly included temperature, photosynthesis, respiration, thermal acclimation, climate change, etc. In contrast to the red cluster, the main research directions of the green clustering were thermal acclimation, photosynthesis, and respiration. In the context of global warming, plant photosynthesis and respiration changed significantly under high temperatures, so plant thermal acclimation became a hot spot. The blue cluster had 5 keywords, which mainly included acclimation, chlorophyll fluorescence, heat stress, thermotolerance, and stomatal conductance. The blue cluster showed how chlorophyll fluorescence parameters and stomatal conductance changed after temperature acclimation, which were the most commonly used parameters in experimental studies. Finally, the yellow cluster had only 2 keywords, mainly including photoperiod and growth. In this cluster, researchers paid more attention to the effect of photoperiod on plant growth. For plants in nature, temperature depends to a certain extent on the intensity of light. When the intensity of light is very low, the photoperiod becomes shorter, and plants experience lower temperatures, which slows down their growth. Therefore, the yellow cluster focuses primarily on the effects of changes in photoperiod on plant growth.

Table 6: Fluctuations in the leading 10 keywords in research on plant temperature acclimatization between 1986–2000, 2001–2011, and 2012–2022

Period	1986–2000		2001–2011		2012–2022	
Rank	Words	Occurrences	Words	Occurrences	Words	Occurrences
1	Acclimation	21	Cold acclimation	44	Cold acclimation	85
2	Cold acclimation	20	Acclimation	39	Acclimation	50
3	Temperature	13	Temperature	36	Photosynthesis	48
4	Photosynthesis	12	Photosynthesis	28	Climate change	41
5	Low temperature	10	Freezing tolerance	25	Thermal acclimation	29
6	ChlorophyII fluorescence	8	Respiration	23	Freezing tolerance	29
7	Photoinhibition	8	Low temperature	14	Temperature	24
8	Temperature acclimation	6	Temperature acclimation	12	*Arabidopsis thaliana*	21
9	Abscisic acid	5	Climate change	8	Low temperature	19
10	Freezing tolerance	5	Thermal acclimation	8	Respiration	18

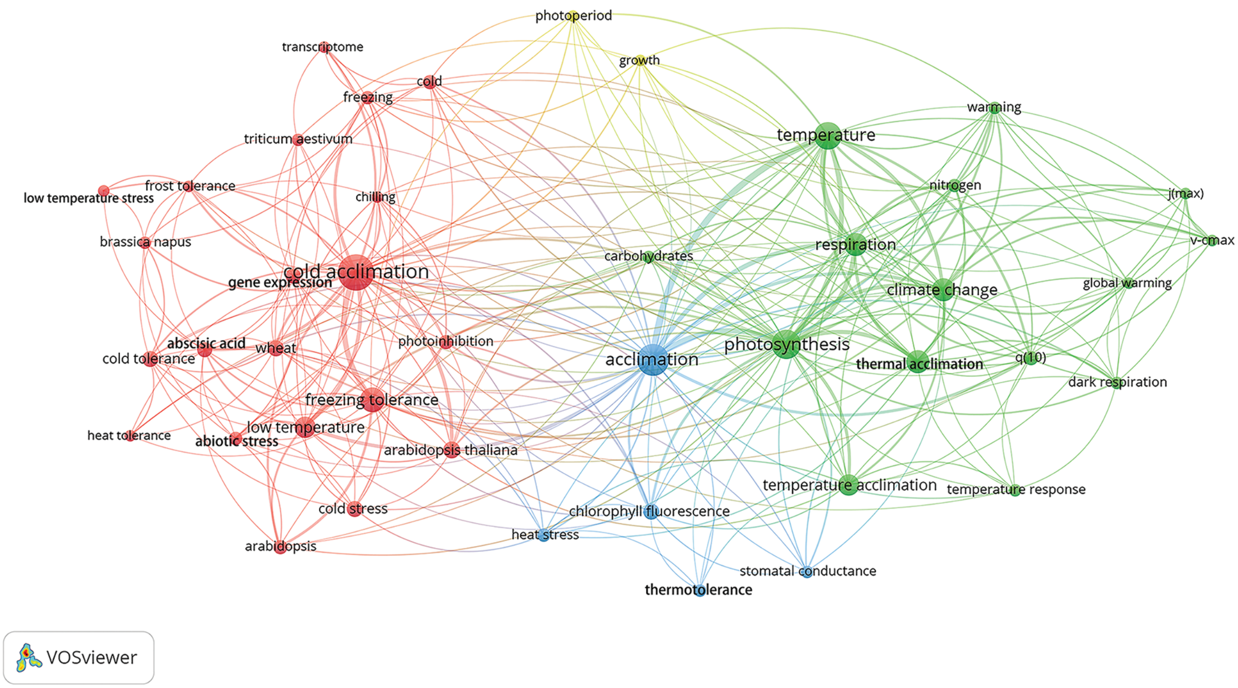

Figure 8: Co-occurrence network analysis o of the foremost 43 keywords utilizing the VOS clustering algorithm was performed. Distinctive hue zones signify varied clustering outcomes. The crimson, verdant, lavender and azure linked lines signify the co-occurrence of keywords. The magnitude of each vertex reflects the frequency of keywords that transpired in the investigation

4 Discussion

Global temperatures are expected to rise by 2°C–4°C by the end of the 21st century, and global warming is still ongoing [41]. There is an urgent need to know how plants acclimate to temperature to cope with more frequent extreme weather. It is widely recognized that plants frequently exhibit trade-offs between stress tolerance and optimal yield. However, plants often face threats beyond the optimal temperature in their life history. When the plant's optimal temperature is exceeded, its yield declines and more energy is allocated to survival [42]. Thus, studying plants acclimatized to temperature is one of the solutions to future plant survival and food security problems, and become a research hotspot in recent years. Since 2001, the research of plant temperature acclimation has piqued the interest of researchers from an increasing number of countries (Fig. 2a). According to an analysis of journal papers, the four most influential journals in the research of plant temperature acclimation were *Plant Cell and Environment* (with the greatest number of total global citations and publications, the highest H-index and G-index), followed by *Global Change Biology* and *New Phytologist*. *Frontiers in Plant Science* achieved the maximum M-index, and "plant science" was the most commonly occurring subject category. In the co-citation analysis of journals, we found that the average impact factor of the 13 journals in the red cluster was below 15, while the average impact factor of the journals in the green cluster was above 15. As the three most influential journals in this study were also in the green cluster, they also referred to each other more often. Meanwhile, they also referred to *Nature*, *Tree Physiology*, and other journals more frequently. It is suggested that high-quality papers in the field of plant temperature acclimation can be published with more citations from papers in journals in the green cluster.

Globally, the USA and China were the two most influential countries in the study of plant temperature acclimation. Unsurprisingly, only China is a developing country among the top 10 most productive countries, with the remaining nine developed countries [43]. Temperature control and monitoring of plant growth environments were necessary for the study of plant temperature acclimation. Developed countries (with higher GDP) tend to have better experimental conditions compared to developing countries. In particular, the USA is the most developed country in the world, and has the best economic conditions for plant temperature acclimation research, so the number of publications and citations ranks first in all stages. China as a unique developing country started relatively late but made progress rapidly. China has become the second-highest producer of articles in this field in just 11 years. The top-3 most influential institutions were the Chinese Academy of Sciences, the University of Western Ontario, and the Western Sydney University. The University of York had the highest number of total global citations. Although the Chinese Academy of Sciences was the most productive institution, its article citation rate was not satisfactory, which may be related to China starting relatively late in this field. The University of York and the University of Western Ontario produced a lot of high-quality articles with a high citation rate. As for the most prolific authors, Atkin, Owen K was the author with the most published papers and citations. His main research interests include (1) the response and acclimation of plant respiration and photosynthesis to temperature [6,7,44,45,46]; (2) The relationship between plant nutrients and plant traits [47,48]; (3) Effects of drought and elevated CO_2 on plant leaf respiration [49–51]. Atkin, Owen K has made enormous contributions to the study of plant temperature acclimation.

From the top 10 most cited papers (Table 5), a total of 4 articles were discussed in plant photosynthesis. These articles have studied photosynthetic adjustment during changes in growth temperature [32]; Photosynthetic temperature response and acclimation of C3 and C4 plants [33]; Photosynthetic model based on biochemistry [36]; The temperature responses and acclimation of C3, C4, and CAM plant photosynthesis, and interspecific differences in photosynthetic temperature acclimation among different plant groups [37]. Three papers investigated plant cold acclimation, reviewing the properties and functions of antifreeze genes, mechanisms of hypothermia gene regulation and signal transduction [31]; The role of CBF transcription activators in cryogenic transcriptome configuration, and other transcription factors involved in this process [35]; and Components of the *Arabidopsis* C-Repeat/Dehydration Responsive Element Binding Factor Cold-Response Pathway [38]. One paper studies plant thermal acclimation, which concluded that thermal stress induces the accumulation of phenolic substances in plants by activating phenolic substance biosynthesis and inhibiting phenolic substance oxidation [39]. The other two papers investigated plant respiration and reactive oxygen species during temperature acclimation, respectively [7,34]. We concluded top-10 citation papers and predicted as follows: (1) Plant photosynthesis will continue to be a research hotspot, and will be more combined with respiration, this is key to quantifying the carbon cycle in plants. (2) Plant cold acclimation has been carried out more at the molecular biology level and has achieved great success. (3) Thermal acclimation will become a research hotspot with future climate warming, it also can be proved by the evolution of keywords. Additionally, there are few basic research papers in the top 10 papers (only 3, and most of them are on *Arabidopsis*). Therefore, future research deserves more work in the basic research of plant temperature acclimation. This includes conducting longer-term temperature treatments, experiments on plants at different latitudes or climate gradients, different plant functional types (e.g., trees, crops or grasses; angiosperms or gymnosperms; evergreen or deciduous), and different ecosystems, especially thermal acclimation.

The evolution of keywords over time can be used to predict research topics. From 1986 to 2000, the frequency of all keywords was lower, and plant temperature acclimation was in its initial phase. Researchers have studied plant photosynthesis during temperature acclimation [52,53]. Reference [54] found low phosphate could lead to increased expression of Rubisco, which played an important role in triggering cold acclimation of leaves. Reference [55] studied the cold acclimation of guard cellular chloroplasts in *Saxifraga cernua* L. Reference [56] studied the photosynthetic acclimation of wheat under high temperatures. Reference [57] studied the functional activity of the photosynthetic apparatus of pea plants (*Pisum sativum* L.) under high temperatures. From 2001 to 2011, the frequency of all keywords increased steadily compared to the previous 15 years. "Cold acclimation" and "temperature" became the two keywords that have shown the most progress. As temperature is now recognized as a major factor that restricts plant yield, researchers have started to focus on the net photosynthetic rate of plants under temperature acclimation to improve grain yield. Some researchers have studied the cold acclimation of wheat [58–63]. Reference [64] examined the changes in invertase activity and the content of sugars in the course of acclimation of potato plants to hypothermia. In addition, thermal acclimation has also attracted the attention of some scholars on climate change [65–67]. The period from 2012 to 2022 was the golden era for the development of plant temperature acclimation. All relevant keywords, especially "cold acclimation", "climate change", and "thermal acclimation", witnessed significant growth. Photosynthesis has been considered the most direct indicator to evaluate plant temperature acclimation during this period. Reference [68] studied the cold acclimation of *Populus balsamifera* photosynthesis. Reference [69] proposed a modeling method for thermal acclimation to photosynthesis and respiration in plants. Reference [70] studied the thermal acclimation of *Pinus taiwanensis* carbon metabolism. Since the IPCC report of 2007, attention to climate change has rapidly increased in this decade. Researchers' interest in studying climate change has also multiplied [40,71]. Therefore, "cold acclimation" and "thermal acclimation" have become the fastest-growing keywords during this period. Taking climate change as a guiding principle, exploring plant temperature acclimation is of great significance for the future growth and development of plants, and for solving food security problems.

After grasping the historical and current objectives of research on plant temperature acclimation, it was imperative to explore forthcoming trends in research. In the cluster analysis of the foremost 43 keywords, the crimson cluster primarily concentrated on the examination of gene expression, photoinhibition, and cold tolerance of *Arabidopsis thaliana*, wheat, and *Brassica napus* under low-temperature acclimation [52,69,72–75]. The green cluster mainly focused on photosynthesis and respiration acclimation of plants under different growth temperatures (especially high temperatures) associated with climate change [69,70,76–81]. The yellow cluster mainly focused on the relationship between photoperiod and plant growth under temperature acclimation [82–85]. All three clusters have been the main research directions from 1986 to 2022. However, blue and green clusters have rapidly increased in the last 11 years, enabling us to forecast the future research direction of plant temperature acclimation. Firstly, climate change will continue to attract more attention in the future, and all research will revolve around it [8,70,86,87]. Secondly, the gradual rise in global temperature will attract more researchers' attention to plant thermal acclimation [70,79,81,86]. Finally, photosynthesis can continue to be a hot spot. The photosynthesis of plants determines their growth and development and further affects plant yield [88–91]. However, plant respiration strengthens will accelerate metabolism then leads to restricted growth [92,93]. Consequently, future research needs to include plant respiration acclimation combined with photosynthetic acclimation, included in the Terrestrial Biosphere Models (TBMs) to study the carbon balance of plants and the capacity of plants to acclimate to new environments, ensuring that plants adjust their strategies to facilitate growth, development, and reproduction. To validate our predictions, we performed a separate bibliometric analysis using the results from January to November 2023. The results showed that of the 21 articles published in 2023, a total of 13 papers are related to the "cold acclimation" of plants, 12 are related to "photosynthesis" or "respiration", and 7 are related to "thermal acclimation". Therefore, cold acclimation, photosynthesis, and respiration will still be the research hotspots at this stage, but people's interest in thermal acclimation is increasing.

5 Conclusion

In conclusion, plant cold acclimation is still the current research hotspot. *Plant Cell and Environment*, *Global Change Biology*, and *New Phytologist* were the top-3 most influential journals. The most influential countries were the USA, China, and Canada. The most influential author was Atkin, Owen K. The most influential research institutions are the Chinese Academy of Sciences and York University, and the most cited articles are published in the *Annual Review of Plant Biology*. This paper aims to draw the attention of scholars to plant temperature acclimation through this empirical review. We suggest that researchers should conduct more basic experiments about temperature acclimation of plants of the future; Predicting that people will pay more attention to climate change in the future, thermal acclimation and photosynthesis will become hot topics in plant temperature acclimation. However, this paper has some limitations. We extracted data from the WOS core database, while some papers were published in SCOPUS, PUBMED, and even in databases exclusive to certain countries. Therefore, we suggest that researchers collect databases from all over the world for future bibliometric analysis. In general, this investigation methodically unveiled the development, patterns, and forthcoming aspects of plant temperature acclimatization, aiding researchers in enhancing their comprehension of how plants would acclimate to alterations in growth temperature. The insights from this analysis hold considerable significance for future agricultural production, forestry carbon sequestration, and global food security. By improving our understanding of how plants will acclimate to temperature, researchers can develop strategies to mitigate the detrimental effects of climate change on crop yields, forest health, and food availability.

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Availability of Data and Materials: The information corroborating the results of this investigation can be obtained from the corresponding author upon a reasonable inquiry.

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