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Knowledge Graph Analysis in Climate Action Research

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Abstract: Climate change is a global challenge for humanity, and climate action is essential to address its impacts. With the purpose of building a clear theoretical framework for the research field of climate action and to gain a deeper understanding, this paper conducts a bibliometric analysis of 28,457 articles, which were selected from WoS data sources. These articles were analyzed through VOSviewer and CiteSpace, with the aims of exploring publication growth trends and categories, co-authorship analysis, national and regional collaboration, organization cooperation, co-citation journals, citations, keywords, and funding information. Subsequently, a knowledge graph for climate action was constructed, emerging trends were analyzed, and a clear theoretical framework was established. The research outcome offers effective, substantive, and forward-looking suggestions for the sustainable development of climate action.

Keywords: climate action; knowledge graph; bibliometric analysis

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1. Introduction

In recent years, global climate change has been recognized as one of the most severe challenges facing humanity, affecting various corners of the world with its environmental, economic, and social impacts [1,2]. It has been scientifically proven that the climate is changing mainly due to CO_2 emissions from burning fossil fuels, followed by the rise in global temperature, which causes numerous dangerous phenomena, such as changes in weather and climate, hot spells, floods, droughts, hurricanes, the acidification of oceans, sea level rises, the melting of icecaps, the reappearance of old diseases, landslides, etc. [3,4]. These disasters have not only inflicted irreversible harm on ecosystems but also pose a serious threat to food production, water resources, public health, and energy security [5,6]. As extreme weather events become increasingly common, nations across the globe are recognizing the urgent need to implement effective strategies to tackle these challenges. To respond to climate change, the international community has been actively advancing climate action over the past few decades [7]. Governments, businesses, and civil society have made considerable efforts in reducing greenhouse gas emissions, enhancing climate resilience, and promoting the development of a green economy. Despite the initial establishment of a global framework and targets for climate action, significant discrepancies remain in terms of implementation and effectiveness [8,9]. The gap between policy and practice is still particularly pronounced.

Global climate change represents a challenge that all nations must confront. The 21st Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) marked a turning point for the climate regime [10,11]. Following the Copenhagen summit of 2009, the regime has been shifting from a "regulatory" model of binding, negotiated emissions targets to a "catalytic and facilitative" model that seeks to create conditions under which actors progressively reduce their emissions through coordinated policy shifts [12,13]. Although the Paris Agreement outlines global objectives for emissions reduction, there are considerable variations in how countries execute and assess the success of their efforts. Developed countries have made strides in transitioning to renewable energy, whereas developing nations encounter obstacles related to funding and technology [14,15], resulting in uneven advancements in global climate action [16,17]. Current research on climate action mainly focuses on assessing the impacts of climate change on the environment and society, as well as mitigation and adaptation strategies at the national level [18,19]. While these studies have established a robust foundation for comprehending climate change, numerous questions remain unanswered, particularly concerning global cooperation networks, the efficacy of climate policies, public engagement, and regional disparities [20,21]. For instance, the dynamics of collaboration and coordination among nations in climate action have not been thoroughly investigated, and the disconnect between policy and practice presents challenges to the long-term effectiveness of climate initiatives [22].

Climate action requires differentiated mitigation and adaptation strategies tailored to the national circumstances of countries worldwide. The first global stocktake (GST) and the nationally determined contributions (NDCs) submitted by parties to the Paris Agreement (PA) have clarified the pathways for global climate action [23]. The first global stocktake (GST) and nationally determined contributions (NDCs) of parties to the Paris Agreement (PA) suggest that building the capacity of developing countries under Article 11 of the PA is the first step towards collective progress in achieving the PA goal. The NDCs propose an inverse-order framework for climate action in developing countries, starting with capacity-building support that leads to technical knowledge, climate finance, technology transfers, and greenhouse gas (GHG) emissions reduction. This suggests that the approach to carbon reduction in developing countries differs from that in developed countries. Developed countries need to implement immediate mitigation actions while supporting developing countries in avoiding a carbon-intensive development path as they advance their less-developed sectors [24]. The current order of global climate action prioritizes mitigation efforts, followed by adaptation and means of implementation and support for the developing world [25].

European member states have high emissions reduction potential. They send a strong signal to the rest of the world with their action or inaction on climate change [26]. Schwerdtle integrated insights from multiple research fields to explore the relationship between climate impacts, public attitudes, and policy. National level climate policies (NLCPs), climate change impacts, and public attitudes in 27 European countries were analyzed through three databases. Anova tests evaluated differences before and after the Paris Agreement, while linear models assessed trends and geographic variations. The results indicate that after the Paris Agreement, the NLCP in the eastern macro region has not improved but rather deteriorated. On the contrary, public awareness of climate change is escalating, with higher levels of concern in countries in the north compared to those in the south [27,28]. Despite worsening climate impacts, public attitudes are increasingly supportive of climate action; however, overall policy responses remain insufficient, demonstrating macro regional differences. The December 2015 Paris Agreement and related decisions confirm this evolution. Skodienė and Liobikienė revealed that personal responsibility within the 27 European countries has augmented since the signing of the

Paris Agreement, increasing 1.7 times between 2015 and 2019. Nevertheless, the study shows that concerns about climate change vary across Europe, with countries such as Portugal, Spain, and Germany showing higher levels of concern than Ireland or Eastern European countries [29]. Chan et al. constructed a database of 52 climate actions initiated at the 2014 UN Climate Summit in New York to evaluate the extent to which climate actions are implemented in both developed and developing countries. They discovered that climate actions are beginning to yield results, and the output performance after one year is higher than what might have been anticipated based on previous experiences with similar actions [30]. Moreover, imbalances between developing and developed countries persist. While numerous actions are targeted at low-income and lower–middle-income economies, the implementation gap in these countries remains significant. Sattar proposed a unified and specific reporting framework based on differentiated learning experiences to help all parties better communicate and implement their intended nationally determined contributions (NDCs) and global climate goals (GST) [31]. The inconsistencies in the reporting and communication support needs of developed and developing countries in research on climate action within a "common but differentiated" framework is not only a reporting issue but also a strategic one. Developed countries may fail to communicate support to developing countries in GST reports because developing countries fail to communicate their NDC support needs up front. International collaboration is crucial for advancing climate policy; however, disparities among nations regarding their collective responsibilities impede the effective execution of these policies.

The networks formed for international collaboration in climate action are undeniably intricate and frequently lack effectiveness, which greatly complicate the alignment and coordination of national policies designed to combat climate change [32,33]. And there is a persistent and concerning gap between the commitments outlined in policy frameworks and the actual execution of these policies. Numerous countries face significant economic and political challenges that impede their capacity to meet the emission reduction targets they have established [34,35]. The existing literature primarily concentrates on the role of renewable energy, carbon capture technologies, and other strategies in mitigating climate change, as well as enhancing nations' capacities to adapt to climate impacts, particularly in sectors like agriculture and urban planning [36,37]. Additionally, public awareness and engagement are critical to the success of climate action, yet significant disparities persist across countries in promoting public participation [38]. The potential of emerging technologies such as artificial intelligence and big data in supporting climate action remains underexplored, and important issues like climate justice and future trends require further investigation [39]. This paper seeks to gather a wide range of articles from relevant academic journals, research datasets, conferences, and global information sources. It will systematically summarize the findings related to climate action through bibliometric analysis and methodological approaches to offer a clearer insight into the current landscape of this essential area of research.

2. Materials and Methods

2.1. Data Source

This study used "climate action" as the main keyword. Records related to climate action are retrieved through the Web of Science Core Collection's advanced search platform [40,41,42,43,44]. The timeframe was set from 2000 to 2024, using topic fields (that is, the record's title, abstract, author keywords, and a combination of keywords and fields). The data were collected on 18 December 2024 via the library of Chengdu University of technology [45].

A total of 30,115 records were identified through the above search strategy. Before downloading the literature data, we excluded papers that did not meet the criteria for a standard research paper and were considered to be of low relevance to the topic, focusing on the Science Citation Index Expanded (SCI-Expanded) and the Social Sciences Citation Index (SSCI). After refining the selection by limiting the language of publication to English and the type of the literature to articles and reviews, 28,457 records were left for further analysis (Sections 3.2–3.7) [45].

2.2. Tools

The scientific knowledge graph is a relatively new research method in scientometrics and information metrology [46]. It can not only reveal the source of knowledge and its development law [47,48,49] but also graphically express the relationship and evolution law of knowledge structures in related fields [50,51]. VOSviewer 1.6.20 and CiteSpace 6.3.1 are two visual analysis tools widely used in the field of bibliometrics to assist researchers in discovering patterns and structures within the scientific literature through network construction and visualization. The efficacy of these tools is significantly influenced by parameter selection. Additionally, methodological deviations present challenges that researchers must address during their application [52,53].

VOSviewer offers a range of parameter settings that impact the layout and clustering outcomes of the network. For instance, parameters such as Attraction and Repulsion in the layout function optimize the map's configuration. Parameters like Resolution (clustering resolution) and Min.cluster size (minimum cluster member size) in the clustering function directly influence clustering effectiveness [53]. These parameters should be adjusted according to the study objectives and data characteristics. A high resolution may lead to an excessive number of small clusters, while a low resolution might merge clusters that should remain distinct. Advanced clustering parameters, including Random starts (number of runs for the VOS layout optimization algorithm) and Max. iterations (maximum number of iterations), also critically affect computational accuracy [53,54]. Balancing computational resources with analytical precision is essential when adjusting these parameters. VOSviewer's analysis can be susceptible to various biases. First, biases can arise from data source selection and pre-processing steps. For example, a dataset containing substantial duplicate or non-scientific content can skew results. Second, VOSviewer's clustering algorithm, based on similarity measures, may overlook certain small clusters or misclassify edge nodes into the main cluster. Moreover, visual perception can influence the interpretation of VOSviewer's visualization results, where different colors and shapes may alter researchers' interpretations. Researchers should be aware of these potential biases and take appropriate measures to mitigate their effects [53,54].

Parameter selection in CiteSpace is equally critical. Its settings directly influence the construction and visualization of knowledge graphs. Key parameters include Time Slicing, Node Type, Threshold, and Similarity Measures [55] The Time Slicing parameter enables users to segment the literature into multiple datasets based on time spans, which is crucial for handling extensive literature collections. Node Type parameters involve selecting entities for analysis, such as keywords, authors, institutions, etc., revealing different research perspectives. The Threshold parameter controls the network size by limiting the number of nodes, preventing overly complex or sparse networks. Similarity Measures determine the strength of connections between nodes, commonly using methods like cosine similarity and the Jaccard index, which significantly impact clustering results [55,56]. Potential biases in CiteSpace analysis include data selection bias, threshold setting bias, and time-dependent bias. Data selection bias concerns the representativeness and comprehensiveness of input data, where improper selection can distort results. Threshold setting bias relates to the accuracy of clustering results affected by too high or too low thresholds. Time-dependent bias refers to the risk of misinterpreting research trends due to time slice settings, particularly in rapidly evolving fields [55,56].

2.3. Research Process

Bibliometric analysis reveals the research trends of a large number of studies. Using mathematical and statistical measurement methods, the relevant factors affecting the publication of the literature were analyzed. By analyzing the number of published and cited studies, this paper reflects the development of the research and the influence value and reference significance of the articles on subsequent research. Bibliometric analysis measures the output of individuals, research teams, research institutions, and countries across multiple disciplines and technical fields by building interconnected network maps. This study adopts the bibliometric analysis method and uses tools such as CiteSpace and VOSviewer to systematically investigate and summarize the current status and trends of climate action research. It not only highlights the current research hotspots and knowledge structure but also provides a solid theoretical framework for future climate action research, especially in terms of identifying gaps and guiding new directions.

Based on specific challenges facing climate action, such as policy inconsistencies, inadequate funding, and conflicts between economic growth and environmental protection, this paper aims to address the following research questions:

1. What are the trends in publication and citations of articles related to climate action?
2. How do keywords such as carbon neutrality, climate change, and global climate governance emerge and relate to each other in climate action?
3. What is the relationship between the year of publication of the climate action literature and the year of policy reform (e.g., the 2015 Paris Agreement)?
4. The emergence and relevance of keywords such as carbon neutrality, climate change, global climate governance, public donations, and UN climate action.
5. How can countries and researchers promote and influence each other on climate action?

3. Results

3.1. Growth Trend and Category Analysis of Publications

Climate action was essential for understanding individual impacts on climate and indirect impacts on society and the biosphere. In 2021, M. de Gouveia and R. InglesiLotz performed a bibliometric [57] analysis of the Web of Science Core Collection (1956–2019) to assess the rising significance of climate change research. Results revealed a substantial exponential growth in climate change publications and their proportion of total outputs. The study examined causal relationships among CO_2 emissions, research output, and R&D expenditure (GERD), factoring in GDP for the top 50 climate change research-producing nations, differentiating between developed and developing countries by income. Panel data techniques, following Emirmahmutoglu and Kose [58], were applied for the 1996–2019 period. Granger causality analysis demonstrated causality from research output to CO_2, CO_2 to GERD, and GDP to GERD across the sample [57]. Liu [59] reassessed a prior bibliometric analysis of climate change research dynamics in *Scientometrics*, investigating the correlation between research output and CO_2 emissions. The study advocates for enhancements in data sources, search domains, and queries while clarifying anomalous spikes in research output during certain years within the Web of Science Core Collection. Notably, the increase in COVID-19-related publications in 2020 correlates with the pandemic [60]. When encountering unexplained surges in research outputs, it is crucial to evaluate data sources. The insufficiency of abstract/author keywords/keywords plus information in the Web of Science Core Collection significantly contributes to the abnormal output increases around 1990 [60]. Furthermore, the introduction of a new sub-database and the unusual rise in source titles within it may also explain these spikes in specific years. Therefore, an analysis of the number of publications provided insights into rediscovery trends in climate action on a particular topic. Citation frequency is an important index to measure the quality of academic works. Figure 1 shows the number of articles published and cited in the climate action field over time.

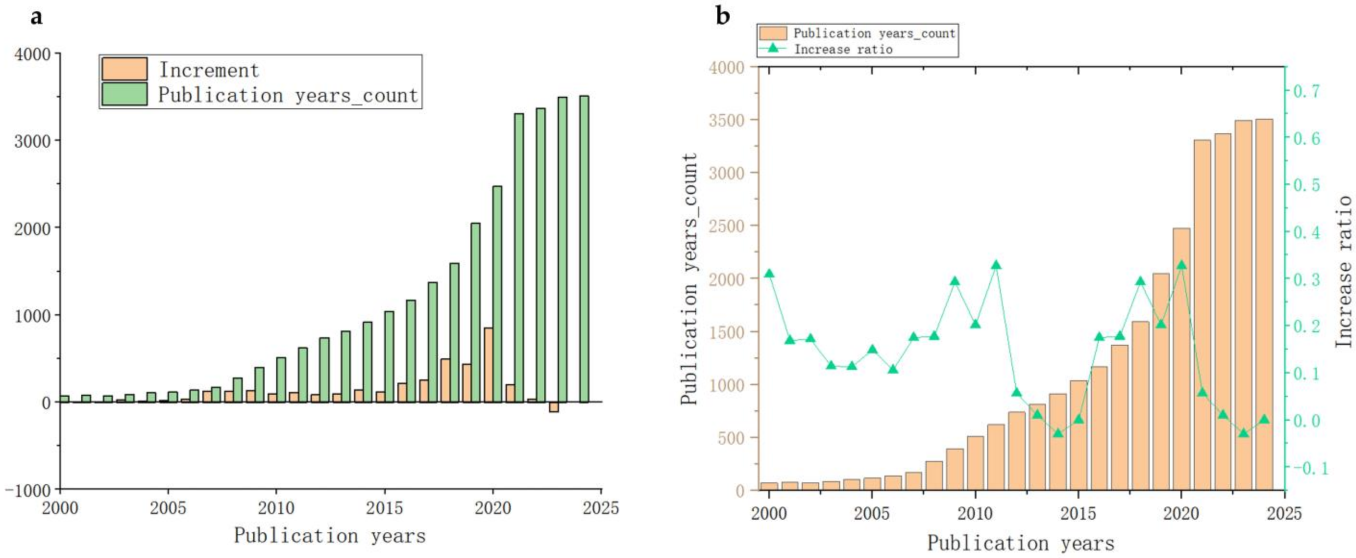

Figure 1. The number of annual publications on research on climate action from 2000 to 2024. (**a**) Number of publications per year from 2000 to 2024 and its annual growth rate. (**b**) Number of publications per year from 2000 to 2024 and its annual growth rate.

The recent growth of the Web of Science Core Collection (WoSCC) has impacted research output in bibliometric studies. However, the expansion trends of different citation indexes vary, benefiting some fields while disadvantaging others [61]. Liu et al. [61] analyzed WoSCC's coverage across the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts and Humanities Citation Index (A&HCI) from 2001 to 2020. Results showed that unlike SCIE/SSCI, the A&HCI database has seen stagnant or minimal increases in annual publication volumes across all document types. Despite an increase in A&HCI journals, the average publication volume per journal has declined or remained stable for citable items. Furthermore, since 2018, the A&HCI database has ceased systematically indexing selected items from SCIE/SSCI journals. The study concludes by exploring the potential causes and implications of the uneven growth among WoSCC's citation indexes [61].

Figure 1 illustrates the number of publications and citations on the topic of "climate action" from 2000 to the present, as well as the difference between the two adjacent years and the trend in the number of publications as a percentage of the total from year to year. There were 28,457 in total. In terms of annual productivity, there was an average of 112 articles per year between 2000 and 2006 compared to 169 articles in 2007. There were 276 articles in 2008, 396 in 2009, 512 in 2010, 621 in 2011, 739 in 2012, 814 in 2013, and 914 in 2014. Since 2015, the number of publications has exceeded 1000 per year. It was 1037 in 2015, 1166 in 2016, 1371 in 2017, 1594 in 2018, 2049 in 2019, 2475 in 2020, 3306 in 2021, 3,366 in 2022, 3493 in 2023 and 3488 in 2024 (till 18 December 2024). The figures indicated a growing interest in "climate action" research.

Before 2000, there were very few studies on climate action, and by 2003, with no more than 100 studies per year. It began to grow steadily and rapidly after 2007 and began to soar after 2018. The number of papers and citations related to climate action steadily rose every year. One of the reasons may be that the country is waking up to the huge impact of climate change on humanity and realizing the importance of protecting the environment.

The 28,457 articles were divided into 200 categories. The top 10 categories are shown in Table 1.

Table 1. The top 10 categories.

Rank	WoS Categories	Number *	Proportions (%)
1	Environmental Sciences	8919	31.34
2	Environmental Studies	5768	20.26
3	Green Sustainable Science Technology	2725	9.57
4	Ecology	2629	9.24
5	Meteorology Atmospheric Sciences	2538	8.92
6	Geosciences Multidisciplinary	1559	5.48
7	Water Resources	1474	5.18
8	Biodiversity Conservation	1384	4.86
9	Energy Fuels	1322	4.64
10	Economics	1110	3.90

* The total number is over 28,457 because some articles have more than one classification and are therefore double counted.

With "Environmental Sciences" as the primary category, a total of 8919 studies were published, accounting for 31.34% of the total publications. The second category with the most relevant papers was "Environmental Studies", which included 5768 papers, followed by "Green Sustainable Science Technology" with 2725 papers. The first two categories account for almost half of the contributions, and it can be inferred that climate action is strongly correlated with environmental development.

It is important to note that a paper may fall into multiple categories, which may influence some or all of the statistics. Interdisciplinary studies have gained significant traction over the past two decades. Collaborative efforts have become a prevalent trend in scientific research, with researchers from various fields working together to advance research and development on climate action.

3.2. Co-Authorship Analysis

International cooperation has attracted increasing attention in the field of scientific research, and many researchers utilize bibliometrics to explore and analyze international collaboration [62]. VOSviewer examined partnerships among states, institutions, and authors [53]. Co-authorship served as a significant indicator of collaboration [63]. VOSviewer employs the co-authorship feature to identify partnerships between authors, organizations, and countries. A total of 95,902 authors have contributed to 28,457 publications related to climate action. Figure 2 illustrates the collaboration among authors in the domain of climate action research. If individual authors utilize different names in their publications, they should be merged only if the ORCID remains unchanged [64].

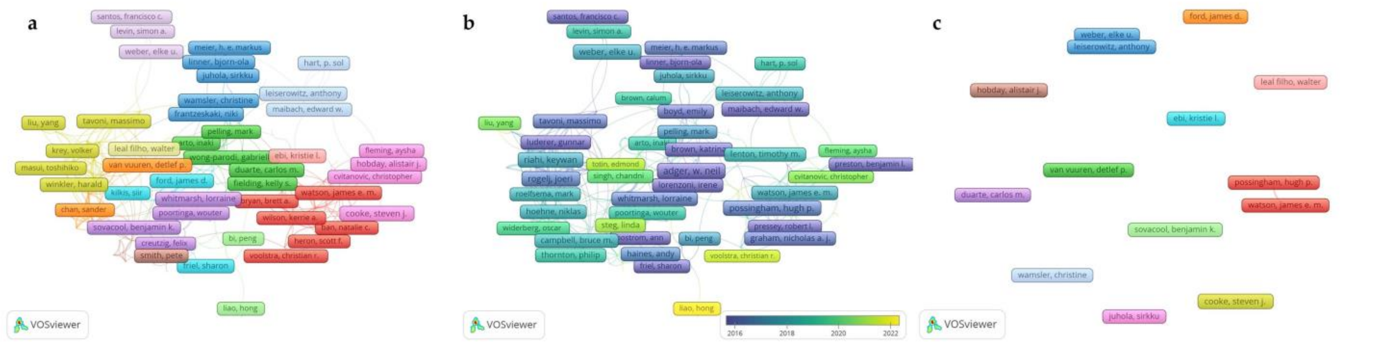

Figure 2. Co-authorship visualization network. (**a**) Network visualization map (document weights); (**b**) overlay visualization network map (citation weights); (**c**) visualization network of largest academic circle (document weights).

When the threshold value was established at 10, a total of 213 authors met this criterion, representing 0.22% of the total. Additionally, 33 authors contributed six papers focused on climate action, accounting for 0.27%, while six authors published 10 papers on the same subject. By setting this threshold to 10, a partnership network diagram was generated. In Figure 2a, it is shown that the network comprises 163 distinct projects. Figure 2b illustrates a superimposed visual representation of the network, while Figure 2c highlights the largest academic circle within the network, which included 11 authors. The overall strength of collaboration among the 163 authors and their connections to other authors is documented in the accompanying column.

The collaborative cluster illustrated in Figure 2a is depicted using various colors, showcasing 163 interconnected items through 394 links, resulting in a total connection strength of 809. These clusters served to illuminate significant academic relationships and the researchers involved within the network. In this collaborative framework, the size of each node reflected the number of publications attributed to each individual. The principal investigators included Cooke, Steven J.; Possingham, Hugh P.; Watson, James E. M.; Van Vuuren, Detlef P.; Ford, James D.; Ebi, Kristie L.; Riahi, Keywan; Hobday, Alistair J.; Juhola, Sirkku; Weber, Elke U.; Duarte, Carlos M.; Leiserowitz, Anthony; Sovacool, Benjamin K.; Wamsler, Christine; and Leal Filho, Walter.

In Figure 2b, the authors present a visualization network characterized by a spectrum of colors, each indicative of the citation frequency over time. Certain authors, such as Possingham, Hugh P.; Watson, James E. M.; Van Vuuren, Detlef P.; Riahi, Keywan; Weber, Elke U.; and Leiserowitz, Anthony, were notably more prominent than others. Recently, several institutions have released new publications focused on climate action, including works by Havlik, Peter; Feldman, Lauren; and Hoehne, Niklas. Figure 2c illustrates the fifteen most prolific scholars in this domain. The findings revealed that the majority of researchers in this area tend to pursue independent studies, with infrequent collaboration among peers. However, the internal cooperative academic groups that can be identified are Possingham, Hugh P.; Watson, James E. M.; Van Vuuren, Detlef P.; and Riahi, Keywan. Each academic group and individual have made significant contributions to the field of climate change. Table 2 enumerates the top fifteen most prolific authors, as identified by VOSviewer.

Table 2. The top 15 most prolific authors.

Serial Number	Author	Documents	Citations	Total Link Strength	Average Publication Year
1	Cooke, Steven J.	29	3015	0	2020
2	Possingham, Hugh P.	27	3331	8	2016
3	Watson, James E. M.	25	3018	8	2017
4	Van Vuuren, Detlef P.	25	2817	5	2017
5	Ford, James D.	25	2020	0	2017
6	Ebi, Kristie L.	24	2514	0	2017
7	Riahi, Keywan	22	4779	5	2018
8	Hobday, Alistair J.	22	1068	0	2018
9	Juhola, Sirkku	21	1063	0	2018
10	Weber, Elke U.	20	3360	1	2018
11	Duarte, Carlos M.	20	3213	0	2017
12	Leiserowitz, Anthony	20	1954	1	2015
13	Sovacool, Benjamin K.	20	1186	0	2020
14	Wamsler, Christine	20	852	0	2020
15	Leal Filho, Walter	20	417	0	2020

Van Vuuren, Detlef P. has published 25 articles on climate action, several of which were co-authored with Keywan Riahi. Keywan Riahi has authored 22 articles focused on climate action, with notable scientific contributions including the coordination and development of representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs). These frameworks have significantly advanced the comprehensive analysis of climate change response strategies within the scientific community [65]. Possingham, Hugh P. has also made substantial contributions to this field, particularly through his research in decision theory as it pertains to conservation biology, which seeks to safeguard biodiversity in the context of climate change. Dr. Watson focuses on protected area effectiveness, biodiversity conservation, and the impact of climate change on ecosystems. As indicated in Table 2, there has been notable collaboration among the top 15 prolific authors over the past decade. The extensive citation of their works suggests a burgeoning interest and activity in climate action research.

3.3. Country and Regional Cooperation Analysis

Investigating the impact of research outputs on the economic growth of countries is one of the important topics in the field of economic sciences [66]. Whether research output significantly impacts economic growth and which research areas/fields of science matter the most to improve the economic performance of countries stand as fundamental endeavors of scientific inquiry [67]. Research output is a key element of economic growth, and many researchers have conducted a lot of research on the effect of research outputs on economic growth. Price (1978) investigated the relationship between the effect of the quality of research on economic growth, where the quantity of research output is usually measured by the number of publications per year. Romer (1986) and Lucas (1988) investigated the relationship between knowledge and economic growth. Vinkler [68], through disparities in publication metrics between CEE and EUJ countries, quantified them via a new "Mean Structural Difference" index. Yearly GDP is not closely tied to publication numbers in EUJ countries, although historic GDP correlates with total publications. Wealthier countries often dedicate larger budgets to research despite no direct GDP–research expenditure linkage, indicating possible misalignment with actual demands. It may be assumed that grants for R&D do not actually depend on real needs, but the fact is that rich countries can afford to spend more whilst poor countries have less money to spend on scientific research. Most of the further research in this field is performed using the fitting and analysis of regression models based on which the effect of research outputs on economic growth and development can be studied [69,70].

This study used VOSviewer to analyze the relationship between socioeconomic factors and research output. The analysis presented in Figure 3 illustrates the collaborative landscape of countries and regions as depicted through co-created web visualization maps generated by VOSviewer. The criterion for inclusion was set at a minimum of ten documents per country, resulting in 126 out of 199 countries meeting this threshold and being represented on the visualization map. This visualization highlighted the countries with the highest total link strength, indicating robust collaborative networks.

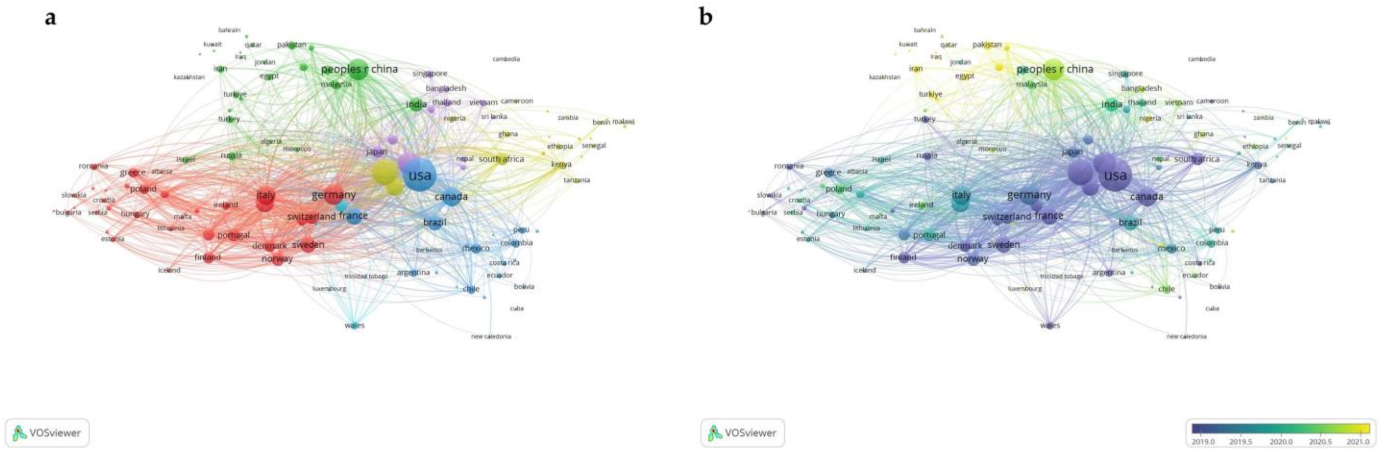

Figure 3. Co-author network maps of countries and regions. (**a**) Network visualization map (document weights); (**b**) overlay visualization map (document weights).

In Figure 3a, the circle node size describes the number of articles, and they were proportional to each other. The 126 countries were divided into five clusters, indicating that they worked closely together. In cluster 1 (blue lines), the USA, Canada, France, Brazil, Mexico, and others collaborated on many works. In Cluster 2 (green lines), China, India, Malaysia, Saudi Arabia, Pakistan, and Turkey had a high level of cooperation. In the third cluster (red lines), there was a lot of cooperation between Germany, Italy, Switzerland, Sweden, Norway, Portugal, Ireland, Denmark, and other countries. There were still low link strength clusters, cluster 4 (purple lines) and cluster 5 (yellow lines), both of which made significant contributions to climate action research. The data showed that collaboration between different countries has a significant impact on research output. For example, the United States, Canada, France, and other countries have close cooperation in the field of climate action research, which shows that international cooperation can promote increased research output. Countries such as China, India, and Malaysia also show a high level of cooperation in the field of climate action research, which may be related to economic growth and increased concern for environmental issues in these countries.

At the bottom of Figure 3b, a ribbon transitioning from purple to yellow illustrates the document release dates by country. The overlay visualization network depicted in Figure 3b reveals that prior to 2019, countries such as the USA, Britain, Australia, Canada, South Africa, the Netherlands, Scotland, France, Sweden, Demark, Norway, Argentina, and others (represented as purple nodes) produced a significant number of documents addressing climate action. In 2019, Britain saw the publication of several influential books on climate action. The following year, 2020, marked a notable increase in publications from Germany, Italy, Spain, Portugal, Ireland, Brazil, Mexico, and other nations (indicated by dark green nodes) focusing on climate action. Additionally, countries and regions like China, Malaysia, India, Thailand, Singapore, Bangladesh, et al. (shown as light green nodes) began to prioritize climate action research in 2020, which may be related to the increased emphasis and economic investment in climate action in these countries. Since 1970, the USA and other global powers have enacted various environmental laws, leading to a growing recognition among nations of the critical need to protect our planet. This awareness has culminated in the acknowledgment that climate change represents one of the most pressing challenges facing the Earth today. For instance, in Figure 3b, the countries highlighted in yellow include Pakistan, Saudi Arabia, Egypt, U Arab Emirates, et al. The larger nodes representing the USA, Britain, and China indicated their extensive collaboration with other nations or regions, positioning them as leaders in cooperative climate action research efforts.

As detailed in Table 3, the USA stands out as a pioneering nation in the realm of climate action research, leading in both the volume of published papers and citation counts compared to its counterparts. Following closely were Britain, Australia, China and Germany. Countries such as the United States, the United Kingdom, and China lead in research output and citations, which may be related to their leading positions in research investment, economic power, and policy support. China emerged as the most active contributor in the average publication year after 2018, underscoring the importance China places on climate action research.

Table 3. Top 10 countries with largest number of documents.

Position	Country	Documents	Citations	Total Link Strength	Average Publication Year
1	USA	8168	363,441	9085	2018
2	Britain	3963	201,258	8162	2018
3	Australia	2962	155,305	5012	2018
4	China	2603	94,825	3413	2020
5	Germany	2468	104,027	5978	2019
6	Canada	2051	97,169	3627	2018
7	Italy	1864	69,258	3891	2019
8	Spain	1716	56,237	3600	2019
9	The Netherlands	1564	79,807	4067	2019
10	France	1404	68,406	4311	2018

3.4. Organizational Cooperation Analysis

This section examined the collaborative efforts of organizations engaged in climate action. Current statistics indicate that there are 20,958 organizations involved in this endeavor. By setting the “Minimum number of documents for an organization” criterion to 10, we found that 1289 influential organizations, approximately 6.14%, meet this threshold. For these 1289 organizations, we calculated the total link strength in relation to one another. The total link strength of these 426 prominent entities is illustrated in Figure 4.

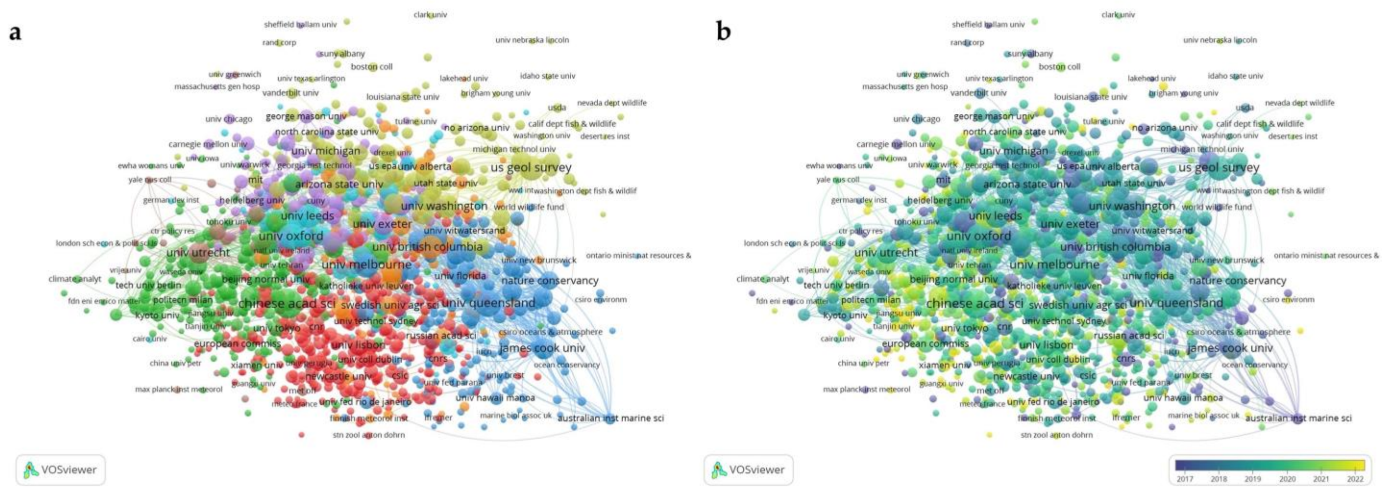

Figure 4. Organization visualization network. (**a**) Network visualization graph (document weights); (**b**) overlay visualization graph (document weights).

These 1289 organizations are categorized into eight distinct clusters. As depicted in Figure 4a, these organizations collectively possess 138,742 links, resulting in a total link strength of 372,368. In Figure 4, the size of each node corresponds to the number of publications related to climate action, while the length of the connections between nodes reflects the academic proximity of the two organizations. A larger node signifies a greater number of published articles, whereas a shorter connection indicates a stronger academic relationship between the institutions. Numerous organizations have made substantial contributions to climate action research. Notably, 12 institutions stand out for their prolific output, namely the University of Queensland, the University of Oxford, the University of Utrecht, James Cook University, the University of Melbourne, the University of Leeds, the Australian National University, Columbia University, the University of Exeter, the University of Washington, the University of British Columbia, and the University of Stockholm. Additionally, the presence of various clusters of organizations suggested that a significant number were actively investigating the topic of climate action.

In Figure 4b, the purple nodes represent institutions that initiated their climate action research earlier, including Columbia University, the University of English, Princeton University, the U.S. Forest Service, and NASA. The Sustainable Development Goals (SDGs), proposed by the United Nations in 2015, aim to comprehensively address the three dimensions of social, economic, and environmental development from 2015 to 2030 and to transition towards a path of sustainable development. The urgency of the call for action on climate change and its impacts has prompted numerous institutions to initiate climate action research, as evidenced by the yellow nodes in Figure 4b, which include Tsinghua University, Aarhus University, and New York University, among others.

3.5. Co-Citation Journal Analysis

Co-citation analysis can conduct research frontier analysis and domain analysis to provide a basis for research and evaluation [71]. Co-citation journal analysis (JCA) is developed on the basis of co-citation analysis, that is, the literature of two journals is cited by other academic journals at the same time, and the number of citations by other journals is the co-citation intensity of the journal [72].

In this study, the literature was meticulously selected from a pool of 402,372 sources. By establishing a threshold of 20 for the "Minimum number of references to sources", we identified 7031 sources that met this criterion. As illustrated in Figure 5, the journal co-citation network delineated the 7031 most cited journals in the realm of climate action research, which are organized into eight distinct clusters. The node sizes depicted in Figure 5a correspond to the number of published journals, with "*Science*" emerging as the most frequently cited journal, followed closely by "*Global Environ Change*", "*Nature*", "*P Natl Acad Sci USA*", "*Climate Change*" and "*Plos One*", among others. The 18 most cited journals in climate action research are detailed in Table 4.

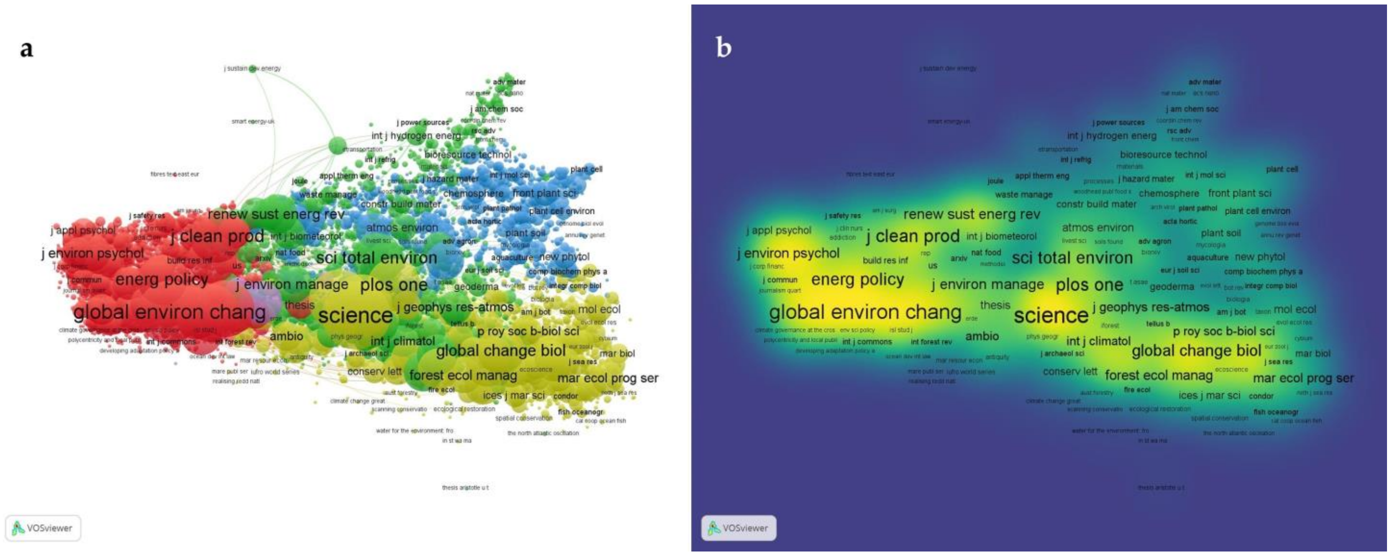

Figure 5. Journal co-citation network. (**a**) Journal network visualization map; (**b**) journal density map.

Table 4. The top 18 journals cited the most in climate action.

Source	Citations	Total Link Strength
Science	23,558	1,860,287
Global Environ Change	19,134	1,154,349
Nature	18,806	1,476,731
P Natl Acad Sci USA	18,423	1,508,318
Climatic Change	15,490	966,642
Nat Clim Change	15,265	1,033,376
Plos One	12,760	1,085,252
J Clean Prod	12,725	823,131
Sci Total Environment	11,905	998,705
Energy Policy	11,089	605,442
Sustainability-Basel	10,678	707,203
Global Change Biology	9574	849,929
Biological Conservation	7968	634,612
Environmental Research Letters	7826	578,456
Environmental Sci Policy	7392	467,891
Ecological Economics	7191	469,951
Conservation Biology	7159	553,219
Ecol Soc	6964	475,696

3.6. Citation Reference Analysis

This paper adopted the citation reference analysis method. Figure 6 shows the 25 strongest references detected by the analysis. In Figure 6, the red part is the time period when the article was cited most times, and the blue part is the publication time of the article. The node type was the reference.

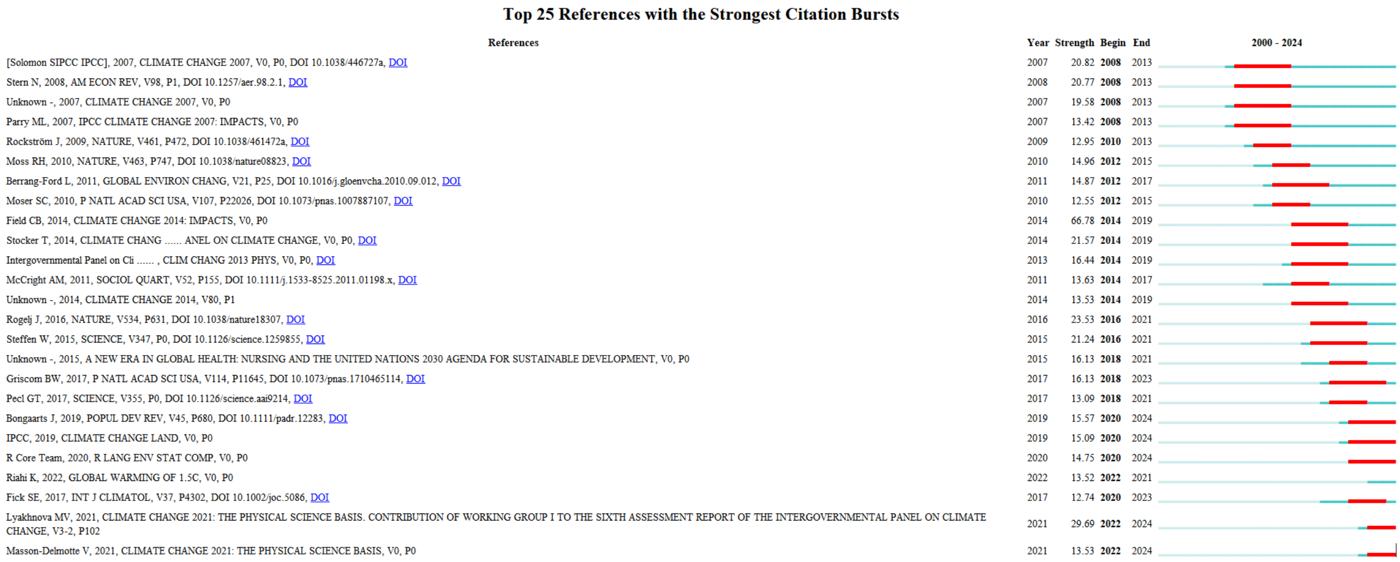

Figure 6. The top 25 references with the strongest citation bursts.

As can be seen from Figure 6, the longest time for the literature citation outbreak was 5 years and the shortest time was 2 years. These 25 articles were all published after 2007 and have been cited since 2008. Among them, there were seven papers on the topic of "climate change", and it was precisely in order to deal with "climate change" and its effects; there was an urgent need to study "climate action". Thus, climate change was a major problem facing mankind, and climate action was an important solution for mankind.

3.7. Co-Keywords and Keyword Citation Burst Analysis

Keywords are important indicators of information measurement research. They succinctly sum up the essence of the whole article. Frequent keywords indicate the central focus of a topic and can help identify research hotspots and development trends in a specific research field [73]. Keywords are selected from the title, abstract, and body of the publication to provide a comprehensive summary of the article [64]. Co-keyword analysis is similar to calculating how often a group of keywords appear in the same document. Affinity is evaluated based on the frequency of co-occurrence. Bibliometric data showed that there were 80,209 keywords. VOSviewer was used to generate a keyword co-occurrence web map to identify research hotspots in the field of climate action research. With a minimum requirement of 15 keywords, 2455 items were visualized in the map. Figure 7 depicts the collaborative keyword network.

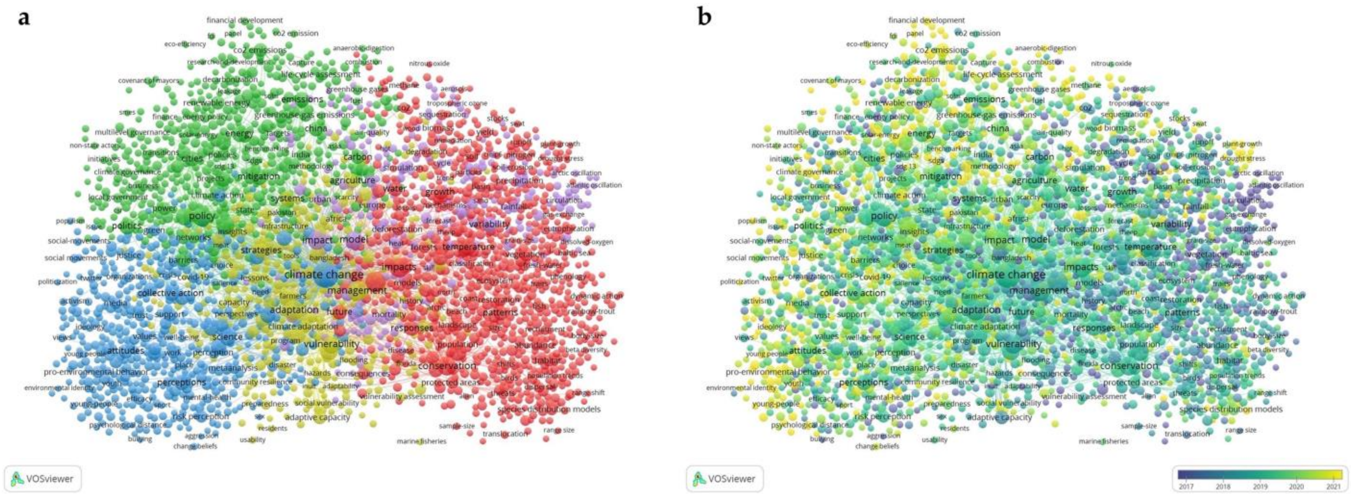

Figure 7. Co-keyword network visualization. (**a**) Network visualization map (occurrence weights); (**b**) overlay visualization map (occurrence weights).

In Figure 7a, the node size represents the keyword frequency. The larger the node, the more co-occurrences. It is worth mentioning that the largest node is "climate change", which is located in the middle of the other nodes. The same nodes are clustered together, they display similar topics, and are most closely related. In Figure 7a, the keywords are organized into five clusters, represented by five different colors. Each cluster corresponds to a subfield within the field of climate action research. By analyzing the five primary cluster nodes, you can assign appropriate labels to the primary cluster.

In the first group (red), there were 861 items. The big node keywords were impacts, climate, conservation, biodiversity, temperature, ecosystem services, dynamics, water, land use, and growth, all related to "ecosystems". Researchers should pay attention to the impacts of climate change on ecosystems and use research results to ameliorate the effects of climate change.

In the second group (green), there were 535 items. Keywords with large nodes in cluster 2 were policy, sustainability, governance, mitigation, sustainable development, energy, emissions, power, renewable energy, barriers, and carbon. These are all related to "air pollution and policy response". One direct manifestation of climate change is atmospheric change. To reduce the impact of pollution, the researchers analyzed the effects of climate change on pollution and the policies implemented to combat climate change.

The third group (blue) had 512 items. The big nodes in Group 3 were climate change, science, knowledge, environmental, performance, meta-analysis, behavior, values, support, collective action, attitudes, and COVID-19, with a focus on the "science and technology". Research should address how the next generation of new technologies will operate in a climate changing environment and how ecosystem design can be enhanced through the creative creation and application of ecosystems.

Group 4 (yellow) had 317 items. Keywords with larger nodes in cluster 4 were management, adaptation, vulnerability, resilience, framework, strategies, challenges, system, agriculture, food security, infrastructure, risk, and level, all related to "agriculture" to study the impact of climate change on agricultural production, improve agricultural productivity, and improve people's living standards.

In group 5 (purple), there were 230 items. The keywords in cluster 5 were as follows: impact, model, variability, simulation, mortality, rainfall, trends, index, circulation, heat, precipitation, climate variability, urban, rainfall, design, and air quality. These are all related to the "water cycle". It focuses on the impact of climate change on surface water flow and studies the influencing factors such as precipitation and drought.

Both link and total link strength were standard weight attributes. According to the VOSviewer manual, "a link was a connection or relationship between two items.". Total link strength refers to "the total strength of links from one item to another item" [74]. For example, for co-occurrence links between keywords, "links" refer to the number of co-occurrence links between a keyword and other keywords. The total link strength of keywords refers to the total strength of links that occur between keywords. Specifically, the higher the value, the stronger the association. Table 5 shows that new research hotspots mainly focus on climate change, management, adaptation, impacts, policies, vulnerability, conservation, and biodiversity. Future research will focus on "adaptation and conservation".

Table 5. The top 9 occurrence keywords.

Rank	Keyword	Cluster id	Links	Total Link Strength	Occurrence	Average Publication Year
1	Climate change	3	2374	39,990	5998	2019
2	Climate	1	2063	13,316	2122	2018
3	Impacts	1	1915	13,753	1790	2019
4	Adaption	4	1789	17,427	2183	2019
5	Model	5	1638	7533	1165	2018
6	Conservation	1	1608	11,448	1516	2019
7	Sustainability	2	1607	10,078	1382	2020
8	Biodiversity	1	1445	9130	1163	2019
9	Science	2	1308	6670	874	2018

Keyword reference bursts were those keywords that had a sharp increase in the number of citations. Burst detection was a valuable analytical technique that aided in discovering keywords gaining significant attention in relevant scientific fields within a specific timeframe. Keyword outbursts, an important indicator, helped to identify emerging or declining research trends in a given field [75]. Therefore, keyword analysis can reveal many interesting topics. To gain a deeper understanding of the dynamics of climate action research and to explore detailed research directions, CiteSpace was used to identify emerging keywords. CiteSpace detected 25 keywords with the strongest reference bursts (Figure 8) (year parameter settings for each article: 1; Node type: Key words; top N per tablet: 50; The first N%: 10%). Keywords that cited the strongest outbreaks were divided into two phases based on the outbreak year, namely phase I (red) and phase II (green). In the field of climate action, some hot research topics have attracted great attention. The most frequently cited keywords mean that certain words have changed significantly in a short period of time, reflecting emerging research topics and cutting-edge directions. Keywords that cite eruptions in the field of climate action were sorted by starting year, as shown in Figure 8. The research frontier for climate action was largely theoretical in its early stages. Some papers focused on the need for climate action. For example, the keywords of the previous decade were global warming (2008), variability (2011), climate change (2004), sustainable development (2008), uncertainty (2002), and governance (2012). In recent years, carbon footprint (2020), pro environmental behavior (2020), sustainable development goals (2020), young people (2020), and life circle assessment (2020) were new research topics.

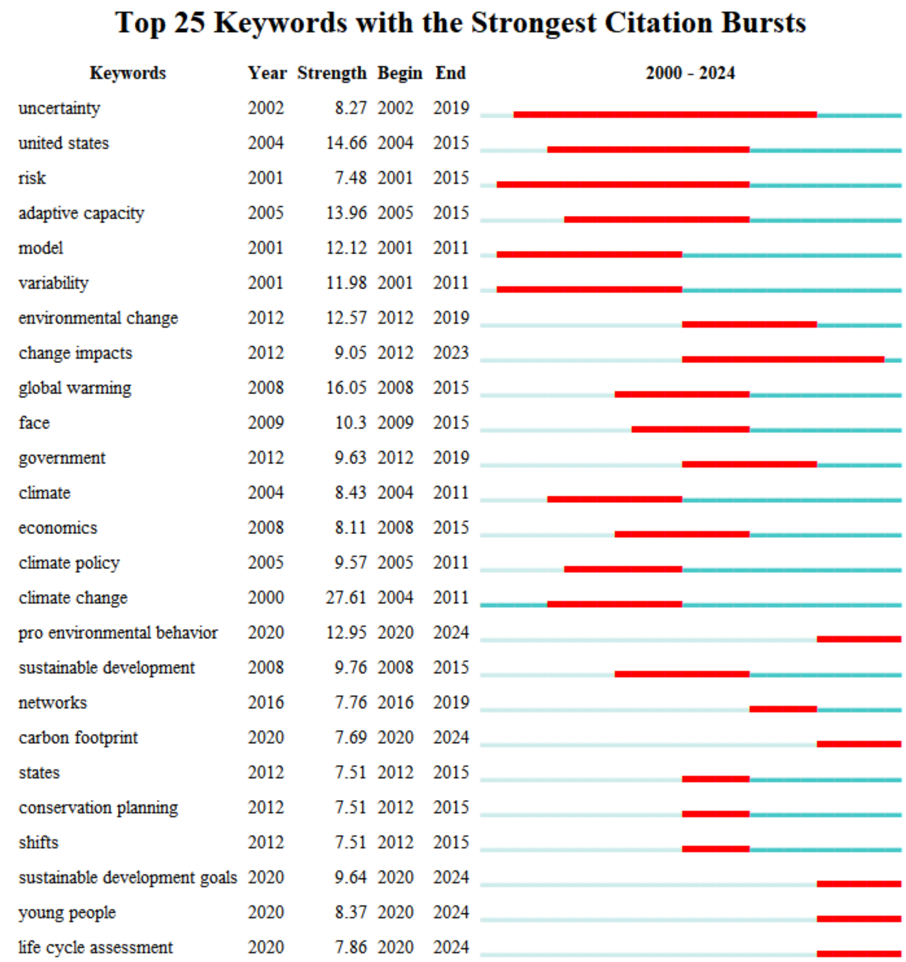

Figure 8. The top 25 keywords with the strongest citation bursts, sorted by the beginning year of the burst.

3.8. Funding Agencies

With the availability of large-scale funding information provided in authoritative bibliographic databases, this new data source has attracted wide attention from policy-makers to academic researchers [76]. Liu et al. [77] examined recently updated grant data of WoS, investigating the characteristics and distribution of FA data across the four WoS citation indexes. Studies have shown persistent differences in FA information coverage in these indices, influenced by time, language, and document type. There is evidence of enhanced FA data collection in the humanities and social sciences. Since many documents only provide details of the funding agency or grant number, the grant text (FT) alone is not sufficient to retrieve and analyze grant information. Notably, Chinese articles showed a higher FA presence than other non-English WoS publications. This latest study summarizes new findings and practical recommendations for the future retrieval and analysis of funded research. Scopus, another competing database of Web of Science, is also increasingly used in academic research and research evaluation practices [78,79]. Liu [80] studied the accuracy of autonomous information by comparing two databases, Web of Science and Scopus. The case study, which analyzed 26 English-language papers published between 2014 and 2019, demonstrated that the accuracy of research funding information collected by Web of Science was superior to that of Scopus. It is noteworthy that there are persistent discrepancies in the grant confirmation text and grant agency fields in Scopus. Despite the limitations of grant confirmation data on the Web of Science (WoS), the use of grant confirmation information has exploded in recent years.

Therefore, this study selected and analyzed the Funding agencies and Funding Agencies Count data of 28,457 articles from 2000 to 2024 in the Wos database. Based on the data in Table 6, it is evident that research funding agencies from multiple countries and regions play a significant role in climate action funding. For instance, the European Union (EU) tops the list, with 1169 instances of funding, followed by the National Natural Science Foundation of China (NSFC) and the National Science Foundation (NSF) in the United States, with 1166 and 1151 instances of funding, respectively. These figures underscore the global emphasis on climate action research and the distribution of financial investments in this field.

Table 6. Top 10 funding agencies for climate action research.

Funding Agencies	Funding Agencies Count
European Union, EU	1169
National Natural Science Foundation Of China, NSFC	1166
National Science Foundation, NSF	1151
UK Research Innovation, UKRI	1126
Natural Environment Research Council, NERC	506
Spanish Government	451
Australian Research Council	446
Conselho Nacional De Desenvolvimento Cientifico E Technologico, CNPQ	397
Fundacao Para A Ciencia E A Tecnologia, FCT	364
Economic Social Research Council, ESRC	341

3.9. Emerging Trends

Hot topics were not enough to reflect the research trends in the academic field, because the "timeliness of different literatures" was not taken into account [81]. To address this, we used CiteSpace to perform a cluster analysis of keywords to identify emerging trends and cutting-edge keywords in the field of climate action. Cluster analysis was a valuable tool for understanding the whole picture of the field from different perspectives [81]. In CiteSpace, we set the parameters as follows: Node type: keyword; g-index: k= 10; Top N: 20, years per slice: 1. Then, we obtained the keyword clustering network diagram (Figure 9), where modularity $Q = 0.36$ and weighted mean silhouette $S = 0.6787 > 0.5$. These significant values indicated that the clustering effect was good and the outline was clear. CiteSpace generated seven clusters. Some terms may overlap between different categories.

There were six clusters, including Adaption, Climate change, Paris agreement, Climate change adaption, Climate justice, Nitrous oxide, etc. (Figure 9). The specific information of keyword clusters is listed in Table 7.

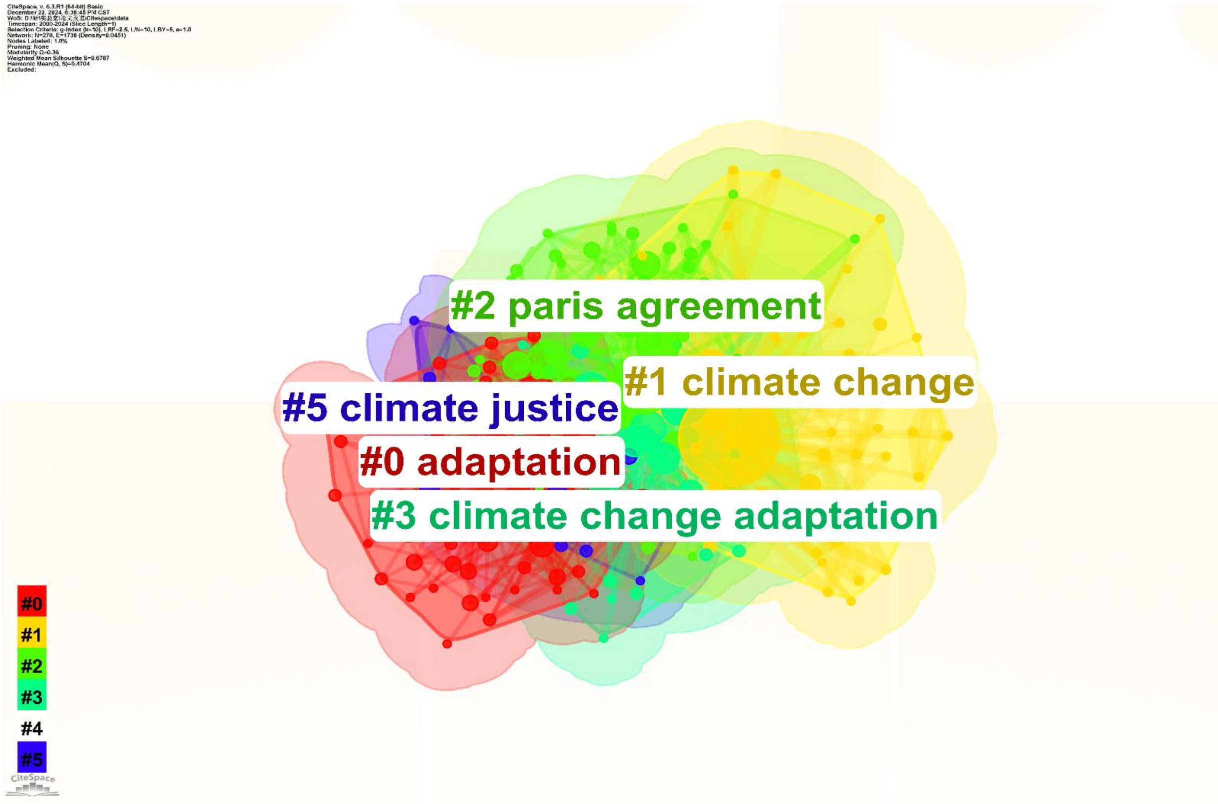

Figure 9. Clusters of climate action keywords.

Table 7. Key labels of the climate action research topics.

Cluster ID	Label (LSI)	Size	Silhouette	Mean (Year)	Label (LLR)
0	Adaption	70	0.588	2018	adaptation (19.12, 1.0 × 10^{-4}); climate change (17.43, 1.0 × 10^{-4}); determinants (17.14, 1.0 × 10^{-4}); pro environmental behavior (17.14, 1.0 × 10^{-4}); social identity (17.14, 1.0 × 10^{-4})
1	Climate change	60	0.691	2009	climate change (85.07, 1.0 × 10^{-4}); public health (24.88, 1.0 × 10^{-4}); air pollution (15.28, 1.0 × 10^{-4}); sustainable development (13.04, 0.001); impacts (10.88, 0.001)
2	Paris agreement	56	0.628	2015	paris agreement (42.07, 1.0 × 10^{-4}); climate change mitigation (20.53, 1.0 × 10^{-4}); climate action (20.51, 1.0 × 10^{-4}); climate policy (17.1, 1.0 × 10^{-4}); climate governance (15.65, 1.0 × 10^{-4})
3	Climate change adaption	49	0.761	2014	climate change adaptation (25.62, 1.0 × 10^{-4}); vulnerability (18.24, 1.0 × 10^{-4}); adaptation (14.89, 0.001); adaptive capacity (14.75, 0.001); management (12.31, 0.001)
4	Climate justice	12	0.865	2018	climate justice (38.71, 1.0 × 10^{-4}); system change (11.34, 0.001); behavior change (9.07, 0.005); carbon footprint (9.07, 0.005); climate change (7.7, 0.01)
5	Nitrous oxide	7	0.997	2006	nitrous oxide (11.23, 0.001); methane (11.23, 0.001); emission scenario (11.23, 0.001); energy choices (11.23, 0.001); community-based action (11.23, 0.001)

Clusters 0 and 3 are marked as "Adaption" and "Climate change adaption". In order to cope with the phenomenon of rapid climate change, it has become a hot topic to study and improve the resilience of cities, crops, and farmers to the climate. As far as "cities" are concerned, disaster risks from climate change are increasingly prominent as populations rapidly urbanize. Many international cities develop and implement plans to adapt to climate change, build “resilient cities”, and improve the resilience of cities to disasters [82], which has been studied by many researchers.

Cluster 1 is labeled “climate change” and it focuses on the public health, air pollution, sustainable development, and impacts. Cluster 5 is labeled as Nitrous oxide and focuses on energy use and value. It shows that the pollution of climate change will be paid attention to and gradually solved in the research process, energy utilization efficiency will also be paid attention, and economic benefits will be further improved. Scholars underscore the pivotal role of forests in nurturing the terrestrial biosphere’s well-being. According to Portela et al., forests’ prowess in moderating greenhouse gasses emerges as the cardinal ecosystem service they furnish. Streck et al. elaborate on the manifold co-benefits accruing from forest-centric climate change abatement efforts, encapsulating the preservation of biodiversity, desertification deterrent measures, and the fulfillment of Millennium Development Goals. In recent years, the development of a theoretical framework for climate action has emerged as a pivotal focus within this domain [83].

Cluster 3 is labeled “Paris agreement” and Cluster 6 is labeled “Climate justice”. These two clusters show that climate change is a growing problem and has become a global problem. On 12 December 2015, the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) concluded in Paris with the adoption of a historic new global agreement on climate change, the Paris Agreement. According to the agreement, all parties will strengthen the global response to the threat of climate change, ensure that the global average temperature rise is kept below 2 °C above pre-industrial levels, and strive to limit the temperature rise to 1.5 °C. The problem of climate change is pointed out, arousing the attention of the world. The climate harm can be further reduced, as well as the treatment cost.

3.10. Knowledge Structure for Climate Action

According to the knowledge graph construction method of previous studies [84,85], the knowledge base generated by bibliometrics (keywords related to research topics), knowledge domain (key research focus), and knowledge evolution (keywords with citation outburst) is integrated to build the knowledge structure map of climate action (Figure 10).

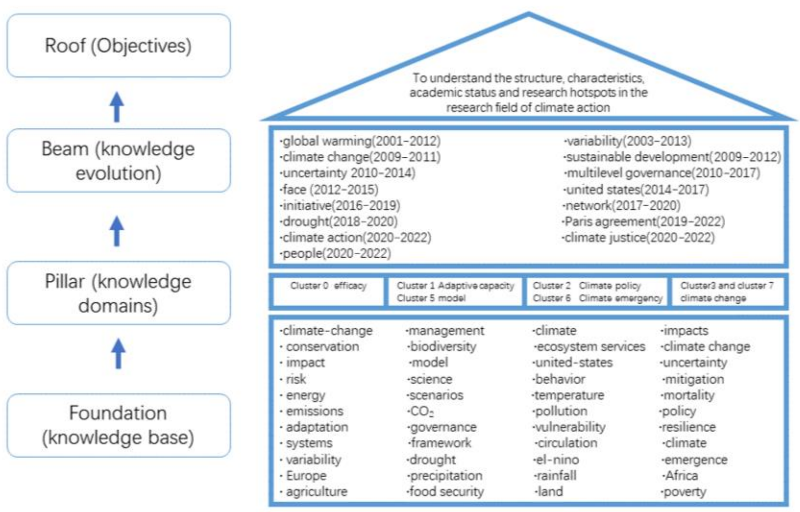

Figure 10. Climate action integrated knowledge structure map.

The climate action knowledge base is developed from keywords derived from the co-occurrence network. These four domains serve as foundational pillars for the implementation of climate action. The evolution of knowledge in this field encompasses cluster analysis and citation burst analysis. The trajectory of climate action knowledge has unfolded as follows: initial research predominantly concentrated on theoretical frameworks, addressing topics such as global warming (2001–2012), variability (2003–2013), climate change (2009–2011), sustainable development (2009–2012), uncertainty (2010–2014), and multi-level governance (2010–2017). As the impacts of climate change have intensified, research has increasingly focused on disasters, with significant attention given to themes such as face (2012–2015), the United States (2014–2017), and drought (2018–2020). A critical challenge remained in translating climate action theory into practical applications. Research that bridges theory and practice was essential and represented a key frontier in the field, with emerging topics including initiatives (2016–2019), networks (2017–2024), the Paris Agreement (2019–2024), climate action (2019–2024), climate justice (2020–2024), and the role of people (2020–2024).

Analyzing the comprehensive knowledge map of climate action provides a deeper understanding of the structure and evolution of the knowledge framework in the field. Given the rapid advances in information technology, climate action is expected to undergo rapid renewal, leading to changes in the knowledge base, domain, and evolutionary structure. Future research should look at the field of theoretical research as a whole and aim to formulate more "smart" actions.

4. Discussion

Compared with the literature analysis methods of traditional models, the use of bibliometrics to focus on the key factors of climate action has a strong role in promoting the research of climate action-related issues [86]. The traditional literature analysis methods are often one-sided, because authors and researchers read and selected a limited number of studies, which prevents a comprehensive analysis and leads to bias. In contrast, bibliometric analysis shows more advantages in climate action research. The overall situation of the field can be systematically analyzed; a general overview of past research and an overview of future research development trends can be made to make accurate predictions.

Question 1: what are the trends in publication and citations of articles related to climate action? A comprehensive analysis of findings, as well as publication growth trends and classification, shows that the number of research and publications related to climate action continues to increase. This upward trend shows that climate action research is attracting increasing attention from the academic community. It is worth noting that climate action research focuses on megacities, urban greenhouse gas emissions, government policy regulation, and sustainable development. In these studies, key questions are the role of urbanization, technological innovation, and policy frameworks. The cited literature analysis shows that the 15 most cited articles are mainly related to the topic of "climate change". In general, the content of climate action includes climate change, energy conservation and emissions reduction, biodiversity protection, ocean protection, climate warming, and other environmental issues. This reflects the main goal of climate action, which is to combat climate change and create a livable planet [87].

Question 2: how do keywords such as carbon neutrality, climate change, and global climate governance emerge and relate to each other in climate action? Keywords such as carbon neutrality, climate change, and global climate governance are interlinked in climate action. Carbon neutrality is an effort to reduce and offset emissions by addressing the main causes of climate change. Global climate governance refers to the international frameworks and policies (such as the Paris Agreement) that guide these efforts. Taken together, the concepts emphasize the coordination of international strategies, technological innovation, and equitable action to mitigate climate risks and achieve long-term sustainability goals. They represent shared priorities in policy reform, technology deployment, and social adaptation. In addition, co-keywords and keyword citation outbreak analysis can help researchers understand the emerging hotspots and development trends in the current field. From the keyword analysis, the current emerging hotspots focus on climate change, management, climate adaptation, policy, vulnerability, conservation, and biodiversity. As an emerging hot science and technology, big data analysis and machine learning are widely used in the analysis and prediction of climate change. Big data analysis technology, through the analysis of climate big data for government organizations to formulate appropriate policies, expose the impact of climate change in various climate data and accelerate the response to climate change movement [88]. Artificial intelligence (AI) holds a pivotal position in climate action research, given its capacity to process and analyze vast quantities of intricate environmental data, forecast climate change trajectories, and simulate the impacts of climate change on various regions [89]. AI technologies augment our understanding of the climate system, enhance energy efficiency, curb carbon emissions, and facilitate progress towards achieving the Sustainable Development Goals. AI algorithms adeptly analyze climate models to pinpoint zones anticipated to undergo shifts in temperature and precipitation patterns. As an illustration, the DeepSD framework employs AI to examine climate model outputs to predict temperature and precipitation fluctuations on a regional scale. In the domain of renewable energy, AI plays a significant role, encompassing the deployment of data-integrated renewable energy networks, the assessment and projection of solar and wind resource availability, and microgrid management. AI has proven instrumental in appraising and refining carbon markets, engendering more accurate carbon pricing paradigms, inclusive of dynamic carbon pricing schemes and sturdier comparative models for carbon price predictions. Machine learning and AI offer potent utilities for environmental monitoring and data analysis, enabling enhanced forecasting, real-time monitoring, and an exhaustive examination of amalgamated datasets. Despite AI's considerable potential for climate action, it presents methodological biases and ethical concerns. AI systems may mirror biases embedded in training data, potentially yielding unforeseen repercussions and amplifying pre-existing inequalities. Consequently, it is imperative that AI-driven climate action tactics are inclusive, transparent, and equitable [89,90].

Question 3: what is the relationship between the year of publication of climate action literature and the year of policy reform (e.g., the 2015 Paris Agreement)? Our research shows that the relationship between the year of publication of the climate action literature and the year of policy reform tends to show temporal consistency, with key scientific insights and trends in climate action research influencing the timing of international and national policy reform; significant research findings published in the climate action literature tend to precede or coincide with pivotal reforms, However, after the policy reform, the targeted research results will show an explosive growth in the short term (1–2 years). Additionally, while major global events such as the signing of the Paris Agreement in 2015 and the 2019 UN Climate Action Summit have played an important role in motivating research efforts, it is important to recognize that there are multiple factors driving this growth.

Question 4: the emergence and relevance of keywords such as carbon neutrality, climate change, global climate governance, public donations, and UN climate action. The keywords highlight the interconnected efforts to address climate issues. Carbon neutrality aims to achieve net zero emissions through mitigation and offsetting strategies. Climate change is a major environmental issue affecting the global response. Public input is essential to support climate action, and the UN Climate Organization's actions represent a coordinated global effort to implement climate mitigation and adaptation strategies through shared governance. Question 4 also leads to our discussion of collaborative research institutions. The analysis of organizational cooperation shows that there are a total of 426 organizations, with more than five articles on cooperative organizations and 12 organizations with more published articles. They are the University of Queensland, James Cook University, the University of Oxford, the University of Washington, the Australian National University, the University of British Columbia, the University of England, Columbia University, Utrecht University, the United States Forest Service, the University of Exeter, and the University of Melbourne. The results indicate that an increasing number of organizations are intensifying their research on the topic of climate action through clusters. In the analysis of co-cited journals, *Science* was the most cited journal, followed by *Nature*, *P Natl Acad Sci USA*, *Global Environ Change*, *Climate Change*, *Nat Clim Change*, etc. It can be seen that the authors of the literature journals and more cited studies provide a solid theoretical foundation for the research of climate action and make a significant contribution to the development of climate action research.

Question 5: how can countries and researchers promote and influence each other on climate action? The co-author analysis shows the strength of interdisciplinary communication and the connections between the various fields. An analysis of the top ten prolific authors shows that their research cuts across multiple dimensions of climate action, including links to other areas such as shared socioeconomic pathways, biodiversity conservation, and sustainable development. For example, Dr. Rogelj's interdisciplinary work links Earth system science with the study of social change, demonstrating the potential for broader interdisciplinary applications of climate action research [91]. These interdisciplinary collaborations play an important role in expanding the scope and depth of climate action research and promoting comprehensive solutions. Upon examining the analysis of international and regional collaboration, the visualization map produced by VOSviewer reveals a strong cooperative relationship among the countries that exceed the established threshold. Notably, the USA, Australia, Britain, and Canada exhibit the highest levels of cooperation. These nations not only possess advanced levels of development but also demonstrate a significant commitment to climate action research. In terms of the timeline for the publication of national documents, it is evident that developed countries, including the USA, Canada, and Russia, initiated their efforts prior to 2013, significantly ahead of their developing countries [92]. The USA stands out as the nation with the highest volume of published research on climate action, as well as the most frequently cited, underscoring its position as a global leader in this field. This collaborative research among countries is instrumental for scholars, as it enhances the understanding of the spatial and temporal dynamics of climate action initiatives while also uncovering valuable research opportunities and potential partnerships.

Besides the key questions, we also noticed that some technical developments, such as advanced explainable machine learning techniques, achieve high accuracy in weather and climate predictions, improving the credibility and practicality of weather and climate modeling [93]. These studies mainly applied science and technology to the practice of climate change in order to achieve the purpose of protecting the ecological environment [94]. This further illustrates the growing urgency to address climate change, driven by more frequent and severe environmental impacts and increasing funding for research from governments, international organizations, and the private sector. In addition, advances in climate science, data analysis, and interdisciplinary collaboration have enabled a more comprehensive approach to research [95].

The findings from the bibliometric analysis indicate several areas that require further investigation. Notably, there was a scarcity of the literature addressing climate action in China before 2010, and the overall level of research on climate-related issues remained relatively low. Additionally, the analytical depth among co-authors was insufficient, which hampers the ability to align with global leading standards. This brought great challenges to early Chinese researchers but also brought opportunities. They have pursued more comprehensive research and integrated insights from various disciplines. After about seven years, China's annual number of published papers on climate action has entered the top 10 in the world and entered the top five in 2019. With the flourishing of interdisciplinarity, the extent of collaboration in the literature of China must break the limitation, necessitating the establishment of a clear theoretical framework for climate action. This theoretical foundation should then be applied to practical initiatives in energy conservation, emissions reduction, biodiversity protection, and the pursuit of carbon neutrality [96].

5. Conclusions

Based on the bibliometric analysis method, this paper systematically analyzes and summarizes the relevant research literature on climate action as a sustainable development goal. On the basis of a literature review, this paper constructs a research framework for climate action. This study uses VOSviewer and CiteSpace to visually analyze the literature on climate action research, further understand the field of climate action, and draw the structure of climate action. According to the results of bibliometric analysis, this paper puts forward some suggestions. To summarize as follows:

First, all countries should pay attention to the great impact of climate change and continue to pay attention to protecting the environment. Countries have raised the awareness of climate action at home and conducted climate action publicity and education for all ages, so that citizens of all countries realize that protecting the environment and reducing greenhouse gas emissions are inescapable responsibilities.

Second, there can be increased collaboration between scholars in related fields of study. At present, it can be seen from the results of this study that most scholars have conducted independent research. Cooperation and collaboration must be strengthened among researchers to jointly study and propose more reliable and impactful climate action plans and measures. For example, through the use of integrated regional climate big data, combining big data analysis techniques, artificial intelligence, and interpretable machine learning models to analyze and predict climate change movements and to provide government organizations and others the ability to develop appropriate strategies.

Third, countries should strengthen cooperation, build a "community with a shared future for mankind", jointly respond to climate change, and strengthen the development and cooperation of climate action among countries. Climate change is a common problem and challenge facing all countries in the world. Therefore, countries should strengthen cooperation and seek better solutions, helping each other build cleaner, more resilient, and low-carbon economies around the world. Countries should promote each other to incorporate climate change measures into national policies, strategies, and plans.

Fourth, according to the analysis of the above results, developed countries carried out climate action research earlier and published a large number of relevant articles. More developing countries need to step up research on climate action and take action to learn from countries with experience. LDCS and developing countries should accelerate research on climate action, propose solutions tailored to their national circumstances, and promote effective domestic climate change planning and management.

Fifth, countries can encourage domestic enterprises and various organizations to actively participate in the "Act Now" campaign launched by the United Nations. The "Act Now" campaign encourages global participation, urging people worldwide to speak out, participating and calling on governments and businesses to act accordingly. In China, major enterprises and organizations can cooperate with each other to share sustainable life skills through corresponding measures, such as social media platforms, so as to bring more people into action and at the same time, to add more impetus to "immediate action".

Climate action has become a major international focus, with increasing attention globally. Since 2000, research related to climate action has increased year by year, reaching a peak in 2023, and it is expected to reach a new peak in 2025. In the results of this systematic analysis, two possible key research directions for the future of climate action are predicted as follows: (1) Climate change adaptation strategies: in the face of climate change, in addition to slowing down the rate of global warming, people also need to adapt to the impact and consequences of climate change and prepare for the corresponding huge changes. (2) Protect the environment: we must achieve net zero emissions, protect the world's biodiversity, and live in harmony with nature.

Since the data collected in this paper are primarily from the WoS Core Collection, only English literature is studied when using VOSviewer and CiteSpace for visual analysis, and the regional bias and underrepresentation of non-English publications on the Web of Science are not taken into account. In 2024, Toluwase Asubiraro et al. [97] conducted a comparative study of the coverage of academic journals in different regions between Science and Scopus, the two most important citation index databases in the scientific community in the world. The study found that there were significant regional differences between the two databases in representing scholarly journals and that there was a bias in the coverage of non-English publications between WoS and Scopus, which could lead to studies being underrepresented in some regions and languages [98,99,100]. Therefore, the research in this paper has limitations. Subsequent research should also include the relevant research literature from other databases, as well as the use of various bibliometric analysis software programs or websites, such as Histcite, Ucinet, and Gephi.

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