How does green innovation support carbon neutrality? A global bibliometric analysis of research trends and thematic evolution

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ABSTRACT

Global attention is shifting to climate change, with carbon neutrality acting as a global development strategy since the Paris Agreement to emphasize the strict control and mitigation of emissions. This phenomenon allows the international community to explore carbon neutrality from different disciplines. The unavailability of a cross-database bibliometric perspective on carbon neutrality since Paris Agreement adoption created a wide opportunity to explore new knowledge. Therefore, this study aimed to present a comprehensive visualization and analysis of carbon neutrality research from the Scopus database. For acquiring data, we use the PRISMA Protocol by considering factors such as search period, document type and source, language, and keywords. This led to 1,017 data samples processed using VOS viewer and R-tools. The results showed that publication trends, recent analyses, journals, authors, institutions, and countries contributed the most to carbon neutrality research. We explore the areas and topics under investigation and conclude future research opportunities through thematic analysis, including historical development process, research hotspots, and research frontiers. We identified carbon neutrality, renewable energy, green innovation, green hydrogen, and electric vehicles as emerging areas that need more attention. Our study is useful for academics and policymakers to prioritize their research and policy to achieve carbon neutrality.

Keywords: Carbon neutrality, climate change, bibliometric, Paris Agreement, innovation

Introduction

The most urgent environmental problem and major socioeconomic concern of the world at the moment is climate change caused by increased carbon emissions ([1]). The worldwide land-ocean temperature index in 2020 was about 1.2°C higher than in 1880, based on the most recent statistics. This exceeds the mean temperature variations of the earth over the last 10,000 years. The Paris Agreement was adopted in 2015 by 197 countries of the Paris Climate Change Conference (PCCC) in response to the rising global carbon emissions and the anomalous climate change ([2]). This agreement desires to control the rise in the average world temperature to 1.5°C over pre-industrial levels [3]. The concept of "carbon neutrality" is a crucial component of international development strategy, which calls for rigorous control and mitigation of emissions in all sectors and regions. A new climate governance system requires each country to update the Nationally Determined Contribution (NDC) progressively and set the carbon neutrality targets. This phenomenon has led institutional and academic research in various countries to place new emphasis on exploring carbon neutrality from different disciplines and related issues.

Countries all across the world have made commitments to technological innovation in recent years in an effort to bring carbon emissions down to neutral levels. Numerous specialists and scholars have conducted research to balance economic and environmental factors as well as promote innovation, particularly in the adoption of contemporary low-carbon technologies [4], [5]. [6] confirmed that implementing green innovation through environmentally friendly technology reduces carbon emissions. The disparity between industrialized and developing nations' approaches to reducing carbon emissions is becoming more apparent. Most developed countries worldwide are controlling energy consumption with strict targets. A range of technologies, including clean and low-carbon energy, have been developed and adapted to an electricity-based energy foundation. Due to their dependency on energy consumption and their hurried pursuit of net-zero emissions, emerging nations may experience carbon lock-in, stranded assets, and significant economic losses [7]. In this context, sustainable energy consumption growth is driven by economic growth. Despite the fact that progress in lowering carbon emissions varies, there are several innovations in energy consumption, resident lifestyles, as well as process reengineering to meet carbon neutrality objectives.

Theoretically and practically, an important grasp of carbon neutrality research is significantly valuable. We observed a long track record and various research focuses in this field. Experts concentrate on developing scientific theories for carbon neutrality and emission reduction, while governments prioritize policy formulation [8], [9]. These include research on reduction policies and social impacts [10], [11], [12], decarbonization and negative emission technologies [13], [14], [15] carbon emission reduction and low-carbon development [13], [16], as well as neutrality and net-zero emissions [17], [18]. We also found limited bibliometric analysis in previous studies, for example, exploration of technology innovation *technology innovation* [19], *bioenergy carbon capture and storage* [20], renewable energy in COVID-19 condition [21]

A variety of contributions has been made to the literature. The result shows the originality and outlines the knowledge of carbon neutrality to analyze the shortcomings of earlier research. Additional research will be performed on tools for reducing carbon emissions that use innovative technologies and the contribution of green innovation to carbon neutrality targets. The main contributions are summarized as follows (1) International collaborations on carbon neutrality research are visualized and analyzed to further promote cross-country collaboration, (2) A bibliometric framework is designed to deliver a method as well as the visualization for research hotspots, developments, and trends on carbon neutrality in various fields, and (3) A visual analysis of carbon neutrality research developments is carried out to document themes and potentials in the future as well as prioritized different areas. The methodology, results, thematic analysis, and conclusion are described in the second, third, fourth, and fifth sections, respectively. The third and fourth parts present the results and theme analysis, the second section describes the method and data, and the fifth section presents the conclusions.

Materials and methods

Bibliometrics is quantitative research used to analyze the characteristics of certain journal publications [22], [23], [24], [25] as well as show the characteristics, development trends, and priorities of publications in a particular field [17], [26], [27]. The analysis is a suitable method for analyzing and evaluating scientific data [28]. This method explains the limits in examining complexities and evolutionary history. The intricacies of the evolutionary history are explored in a particular field to identify existing focal points, investigate the evolution of academic fields, and predict future research directions [29], [30], [31], [32].

We use the Scopus database for bibliometric analysis as a more comprehensive citation [28], [33], [34]. We follow the PRISMA protocol for data acquisition by considering factors such as search period, document and source types, search language, and keywords (Table 1). The Scopus database is exclusively used to ensure completeness and high quality of articles [35], [36]. Other databases are not used in this study, such as Google Scholar (consideration of overall article quality). Although the entire papers on Web of Science are of high quality and are readily available, Scopus offers a more comprehensive representation of the publications [37], [38], [39]Additionally, Scopus applies strict indexing requirements to increase the quality of published articles. Data exploration only includes articles and reviews in journals, excluding other publications such as book series, chapters, and conference proceedings. This is because articles and reviews published in journals are subjected to more rigorous peer review than other sources [37]. English is exclusively used as the search language to avoid bias in bibliometric analysis [40], [41]. The search period spans 2015 to 2024, covering the initial implementation of the Paris Agreement as well as the various carbon emission policies and regulations development, including the Talanoa Dialogue and the Katowice Rulebook (2018). In 2021, different countries were committed to increasing emission reduction targets through NDC.

Table 1. PRiSMa Protocol

Stage	Description	Results
Identification Data were retrieved on December, 29 2024:	Keyword searched: "emissions intensity target" or "1.5 °C target" or "emissions reduction target" or "climate neutral*" or "carbon neutral*" or "net-zero emissions" or "zero carbon" or "emission control" or “decarbonization” or “carbon offset*” AND “green innovation" or “green research and development” or “green research & development” or “green R&D” or “green technolog*” or “green engineering” or “low-carbon innovation”	1.322 publications
Screening	Screening criteria: 1. Year: 2015-2024 2. Document type: article & review 3. Source type: journal 4. Language: English	Screened and excluded (N=305) 1. Year= 67 2. Doc type= 136 3. Source type= 50 4. Language= 52
Eligibility & Inclusion	Validation process and bibliometric analysis	1017 articles were eligible

Initially, bibliometrics consisted of measuring attributes and processes related to documents, namely word frequency, citation, and co-word examination, as well as uncomplicated document counting [42]. For performance and science mapping, the bibliometric analysis proposed by [33], [43] was used to comprehend the demographic production of research in carbon neutrality. The performance analysis included yearly scientific production graphs and the total number of publications generated by institutions, nations, and national collaboration networks. The journals, citations, and articles fractionated are analyzed to identify leading documents in carbon neutrality. Therefore, this research aimed to determine the conceptual context and suggested future lines of inquiry for carbon neutrality. To achieve this objective, we utilize science mapping in bibliometric analysis, such as word cloud, factorial analysis, thematic map, trend topics, and thematic evolution, based on keywords' author.

We use VOSviewer because different studies have repeatedly verified the software and the map results are reliable. VOS viewer is used because different studies have repeatedly verified the software and the map results are reliable. The software also helps academics analyze past studies and comprehensively assess prospects [44]. Furthermore, our study is strengthened by the R-tool, which has gained wide recognition and support from international academics [43], [45].

Document general characteristics

Table 2 displays the characteristics overview of the data employed. The investigation focuses on global emission decrease as well as innovation-related literature on carbon neutrality topics over the past decade, characterized by globalization and rapid technological progress. Following strict criteria, 1,017 articles are selected from 423 journals. The average annual growth of carbon neutrality publications and citations per document reaches 55.4% and 20.25. In this context, 3,328 keywords and 2,968 authors contributed to the bibliometric analysis and other relevant information.

Table 2. Document-level characteristics

Description	Results	Description	Results
Main information about data		Authors	
Timespan	2015:2024	Authors	2968
Sources (Journals)	423	Authors of single-authored docs	81
Documents	1017	Authors collaboration	

Annual Growth Rate %	55.4	Single-authored docs	84
Document Average Age	1.36	Co-Authors per Doc	4.18
Average citations per doc	20.25		
References	71895	International co-authorships %	31.37
Document contents		Document types	
Keywords Plus (ID)	5435	Article	848
Author's Keywords (DE)	3328	Review	169

Results

Scientific research production

(Insert Fig. 1)

Fig. 1 shows the growth in the publications' digits with citations in carbon neutrality research. In 2015, there were 7 documents and the number steadily increased throughout the research period until 2024 by 370 (36.4%). Meanwhile, there has been a rise in the number of publications directly relevant to global carbon neutrality. By 2060 and 2050, China and the EU hope to achieve carbon neutrality, respectively [46]. The necessity of reducing carbon emissions has been reported by global environmental issues [47]. This sense of urgency contributes positively to reaching carbon neutrality. According to [48], technological innovation plays a significant role in reducing global emissions. Technological developments, decarbonization, and the monumental global agreement to address climate change have increased publications over the past 10 years. Fig. 2 shows a strong drive in the scientific community to explore innovative solutions and new technologies to reduce carbon emissions. Therefore, research on carbon neutrality will develop rapidly in the future, and more academics are expected to participate in the domain to encourage the growth of a sustainable environment, society, and economy [49], [50], [51].

Furthermore, Fig. 1 shows that the average citations per year are decreasing since the concept is time-dependent. Articles published a long time ago tend to have more citations. However, new publications must greatly impact and gain attention in the short term. In this context, future research needs to be more innovative and explore important areas that are not well-established. The highest average citation was in 2018 with 12 publications but declined in the following years, where production increased until the average citation was below 10, 7.79, and 3.07 for 2022, 2023, and 2024, respectively.

We divide it into three stages for further analysis. Stage 1- Since the Paris Agreement, there has been a substantial increase in publications regarding carbon neutrality. Between 2015 and 2017, (e.g. [52] concentrated on creating novel scenarios in accordance with national policy to investigate different facets of the carbon cycle and the influence on climate change. [53] addressed the difficulty of reaching neutrality and showed various carbon cycle reactions to climatic changes. Therefore, this period marked an increase in academic literature focusing on the challenges and strategies to achieve carbon neutrality in line with the global ambition set out in the Paris Agreement.

Stage 2- From 2018 to 2020, following the launch of the Talanoa Dialogue (COP23) as well as the Katowice Rulebook (COP 24), there was a significant surge in publications about carbon neutrality and climate change mitigation methods. The Talanoa Dialogue aimed to improve the climate action's ambition by promoting inclusive discussions among stakeholders and catalyzing broader engagement in climate change research [54]. Scientific publications evaluating the effects of the Paris Agreement and exploring novel approaches to achieving carbon neutrality, such as non-market and market-based processes, increased over this time [55]. Different countries have improved transparency and accountability in emissions reporting, as reported in the Katowice Rulebook governing the technical implementation of the Paris Agreement. Therefore, the academic community has yielded a wide range of research contributing to understanding the complexities of carbon neutrality to reflect a growing recognition of the need for urgent and collaborative climate action ([55]

Stage 3- From 2021 to 2024, following the COP26 conference, there has been a substantial increase in publications examining carbon neutrality, specifically the concept focusing on implementing NDC to lessen GHG emissions. COP26 emphasized the urgency of improving emission reduction targets to fulfill the Paris Agreement goals, leading to enhanced strategies for reaching net-zero emissions [10]. According to earlier research, adopting renewable energy and switching to low-carbon technology are crucial parts of national strategy to meet the objectives. Furthermore, the commitment to carbon neutrality has evoked research on the implications of pledges for global climate action, with a substantial increase in collaborative efforts and knowledge sharing [56] ; [57]. The literature from this era indicates the necessity for a comprehensive strategy to achieve carbon neutrality and represents the developing understanding of the connections between economic development, technological innovation, as well as climate policy [58]

We also see that in the last five years, previous studies have contributed to the literature, such as proposing 6 configuration pathways to provide a new perspective on carbon emission decrease. This was pushed by ambidextrous green innovation plans[59] to examine the role of emission reduction technological innovation in influencing carbon trading and designing effective carbon trading parameters [60], recommend the government to adopt carbon emission reduction technology innovation in facilitating the Pathways to 2050 carbon-neutrality agenda in Argentina [61], adopt the Malmquist–Luenberger (MML) metafrontier index to examine the feasibility of green cultural revolution regulatory policies to achieve 2050 carbon-neutral economy in Korea [62] and provide a policy priority framework for the commercialization of Carbon Capture and

Storage (CCS) developed by the Global Institute [9]. Therefore, technological advancements contribute to driving carbon emission reduction practices toward neutrality, attracting different stakeholders.

Documents

Table 3 provides the 10 most quoted academic papers with excellent reference value. These papers examine technological innovation and carbon neutrality as ways to reduce emissions. Table 3 provides an overview of the importance of decarbonization [63], [64], carbon neutral fuel synthesis [65]; sustainable energy technology development [66], [67], [68], as well as policy, implementation path, and future transition toward carbon neutrality [64], [69], [70], [71], [72].

Table 3. Most significant articles

No	Title	Author	Significant contribution	TC	Avg. Year
1	Science and technology of ammonia combustion	(Kobayashi et al., 2019)	Exploring the importance of decarbonization through the development of ammonia combustion technology as a carbon-neutral fuel.	1396	232.67
2	Net-zero emissions energy systems	(Davis et al., 2018)	Reviewing the factors needed to achieve decarbonization of the energy system	1350	192.86
3	A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement	(Bataille et al., 2018)	Reviewing policy options to encourage innovation and investment in decarbonization technologies to achieve net zero emissions by 2035-2060	358	51.14
4	Carbon peak and carbon neutrality in China: Goals, implementation path and prospects	(Wang et al., 2021)	Discussing 4 main implementation pathways for carbon peak and neutrality by accelerating green technology innovation.	344	86
5	Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems	(Dowling et al., 2020)	Exploring that long-term storage technology makes the lowest-cost electricity system.	295	59
6	The co-evolution of policy mixes and socio-technical systems: Towards a conceptual framework of policy mix feedback in sustainability transitions	(Edmondson et al., 2019)	Proposing a new conceptual framework to conceptualize the co-evolutionary dynamics of policy mix and socio-technical systems.	270	45

7	Carbon-neutral sustainable energy technology: Direct ethanol fuel cells	(An et al., 2015)	Providing an overview of the current innovations in DEFC technology and the prospects.	267	26.7
8	Review on available biogas upgrading technologies and innovations towards advanced solutions	(Miltner et al., 2017)	Proposing innovative and effective technologies along the biomethane production chain, namely desulfurization, and gaspermeation.	265	33.13
9	The nexuses between energy investments, technological innovations, emission taxes, and carbon emissions in China	(Ma et al., 2021)	Analyzing macroeconomic determinants of reducing carbon emissions in China.	258	64.5
10	Exploring the role of green innovation and investment in energy for environmental quality: An empirical appraisal from provincial data of China	(Guo et al., 2021)	Investigating the impact of green innovation and investment in the energy industry	233	58.25

Leading Journals

(Insert Fig. 2)

Fig. 2 provides the Bradford Law sources clustering result, which aim to visually convey the documents' distribution across multiple journals. A total of 1,017 publications were obtained from 423 journals, where the carbon neutrality discipline area is published in 14 core sources. The decrease in the graph after the core zone shows that other journals contribute a small number of articles outside the scope. The quantity of publications specifies the impact of journals and directly connects with the citations. Meanwhile, the total number obtained is used to find the most important sources. Energy and environmental science comprise the bulk of the periodicals. For 43 articles in the discipline, the "Journal of Cleaner Production" receives 1554 citations. There are very few articles in some journals, such as "Sustainable Energy Reviews" and "Journal of Environmental Management and Renewable." However, the publications receive a large amount of citations and are well respected in the subject of carbon neutrality. Table 4 shows top 10 the most relevant journals that relate with carbon neutrality and green innovation. The IF2023 shows the absolute potency in the scope, "Renewable and Sustainable Energy Reviews", which has the highest IF at 16.3.

Table 4 Most relevant journals

No	Journal name	NP	IF 2023	CS 2023	TC	Initial Year
1	Journal of Cleaner Production	43	9.8	20.4	1554	2017
2	Journal of Environmental Management	29	8.0	13.7	1475	2020
3	Renewable And Sustainable Energy Reviews	14	16.3	31.2	980	2016
4	Energy Policy	16	9.3	17.3	881	2015
5	Environmental Science and Pollution Research	39	5.8*	8.7	574	2021
6	Sustainability	55	3.3	6.8	569	2019
7	Energy Research And Social Science	14	6.9	14.0	558	2015
8	Frontiers in Environmental Science	31	3.3	4.5	407	2021
9	Energies	35	3.0	6.2	332	2018
10	Energy	15	9.0	15.3	160	2022

* IF 2022; IF 2023 is not available.

Authors

Table 5 shows an index of the most productive as well as influential authors in carbon neutrality research. The quantity of research, total citations, G-index, as well as H-index are the four primary indicators acting as the focus of the analysis. The research with citation counts equal to or higher than H are considered to have an H-index [73]. Meanwhile, the G-index, which is the derivative of H-index can "average" the number of citations in publications [74]. Wang Y is the most prominent in the discipline, with 38 publications, 1,127 citations, and 13 impacts out of the 2968 authors. Wang Y has received great attention through research on insulating materials for realizing carbon neutrality. This is achieved by addressing the challenges and opportunities in electrical equipment and electrified transportation systems. In second place, with 26 publications and 650 citations, Li Y examined green innovation and environmental standards in China.

Additionally, expertise from various disciplines was applied to neutrality to promote the carbon-neutral economy's development worldwide.

Tabel 5.

Most contributing authors

No	Name	NP	TC	H-index	G index	No	Name	NP	TC	H-index	G-index
1	Wang, Y.	38	1127	13	33	6	Li, J	17	177	6	13
2	Li, Yaya	26	650	10	25	7	Zhang, X	17	124	6	11
3	Wang, X.	25	195	6	13	8	Zhang, J	16	158	6	12
4	Wang, J.	20	413	6	20	9	Chen, J	14	257	6	14
5	Zhang, Y.	18	207	7	14	10	Wang, L	14	184	6	13

(Insert Fig. 3 here)

Fig. 3 visualizes the collaboration network to produce more outstanding publications. Larger related nodes in the collaboration network show more publications co-authored with others. Authors with at least 5 publications are selected to be grouped into 7 clusters. In addition, Wang Y (h-13), Wang X (h-6), and Li Y (h-10) are good collaborative network nodes. Research collaborations enhance the understanding and discussion in the articles and expand the network. Fig. 3 is consistent with Table 5 where the top 3 authors show strong intermediary centrality. Energy transition, carbon accounting, footprint impacts, as well as the climate change impact on everyday behavioral choices are the main topics. There are major financial and environmental advantages to the creation and use of new energy. The quality of the research types also concentrates on sustainable governance and environmental behavioral decision-making to attain carbon neutrality.

(Insert Fig. 4 here)

Achieving carbon neutrality includes a comprehensive knowledge framework, enabling scholars and academics to shift from isolated research to increasingly collaborative efforts. In addition, the analysis shows the dynamics of collaboration and shifting developments among stakeholders in the field. Fig. 4 reports global collaboration and communication among countries, with China and Pakistan leading with 22 joint publications. This is followed by China and the UK (20), China and Australia (16), China and Hong Kong (15), as well as China and the US (15). Fig. 5 shows institutional collaborations ranked by betweenness, identifying Tsinghua University, North China Electric Power University, and Imperial College London as major collaborators, with the National Renewable Energy Laboratory and the Institute of Petroleum Exploration and Development. The complex network states that carbon neutrality has developed into a globally cooperative and participatory research domain. However, collaboration is rarely strengthened and there are very few exchanges between nations in South America, Africa, and other regions. Academics from all nations should actively collaborate and share ideas to advance the development of global carbon neutrality, safeguard the environment, and reduce emissions.

Institutions and countries

Table 6 and Fig. 5 show the top 10 most productive institutions and collaborations, reporting the significance of carbon neutrality as a major concern for academics globally. Tsinghua University in China tops the list on the topic with 48 publications. Imperial College London and North China Electric Power University in UK (22) and China (34) are the next in line. The 7 of the top 10 institutions are in China, totaling the 22.5% of all publications. This is supported by Table 7, where China ranks first in the most publications. The influence of emission taxes, R&D investment, technical innovation, as well as the utilization of renewable energy sources to reduce carbon dioxide emissions is a significant article from Tsinghua University [75]. Numerous facets of carbon neutrality have been examined, such as creating CCS technology, urging the renewable energy sources utilization, calculating GHG emissions, and significantly impacting the field. Similarly, substantial progress in carbon emission research has attracted the attention of various stakeholders due to the positive impact on corporate sustainability performance. well-designed carbon emission reduction strategy can fulfill stakeholders' expectations to enhance corporate reputation.

Table 6. Top ten institutions with the most publications.

No	Affiliation	Negara	NP
1	Tsinghua University	China	48
2	North China Electric Power University	China	34
3	Imperial College London	UK	33
4	National Renewable Energy Laboratory	USA	33
5	Institute of Petroleum Exploration and Development	China	32
6	Chongqing University	China	31
7	Tongji University	China	29
8	Qingdao University	China	28
9	Nanjing University	China	27
10	University of California	USA	26

(Insert Fig. 5 here)

The next stage is the selection of organizations with more than 5 publications for collaborative network investigation. Fig. 5 reports the degree of collaboration with other universities shown by the node size, and the same color denotes clusters. As the backbone of a cooperative network to expand influence in the area, Tsinghua University and North China Electric Power University have a large quantity of publications and solid connections with other academic institutions. The objective of the partnership is to provide novel solutions, and support international initiatives. Academics from various universities should actively engage in interaction and idea sharing to increase the attainment of global carbon neutrality. This is because inter-institutional interactions and partnerships greatly enhance the advancement of research.

Table 7 lists the top 10 countries by publication output, reporting that 8 countries excluding India and the Netherlands have a stronger Single Country Publication (SCP) than Multiple Country Publication (MCP). This shows a preference for domestic collaboration over international partnerships and reports the need to enhance global research collaboration. Regarding publications, China is ahead of other countries, ranking first with 467 articles (SCP: 363, MCP: 104). The country has become a center for carbon emission mitigation research and the largest energy consumer, attracting global attention [76], [77], [78]. The objectives of "carbon peak" and "carbon neutrality" have been reported to undertake a number of policies for carbon mitigation in important industries such as power generation, coal mining, electricity, transportation, and building [79], [80]. The governments and industries of all stripes should cut carbon emissions and offer financial incentives with the development of low-carbon technology [81], [82]. The UK and the US have 77 and 43 publications at 7.57% and 4.23%, respectively. In a broad collaborative relationship, the topics are not limited to a country or continent but are evenly distributed globally.

Table 7 Top 10 countries with the most publications.

No	Countries	NP	%	SCP	MCP	GDP (2023) ranking
1	China	467	45.92	363	104	2
2	United Kingdom	77	7.57	51	26	6
3	USA	43	4.23	33	10	1
4	Germany	29	2.85	15	14	3
5	Italy	23	2.26	17	6	8
6	India	19	1.87	8	11	5
7	Australia	18	1.77	11	7	13
8	Netherlands	17	1.67	8	9	17
9	Korea	15	1.47	11	4	14
10	Hongkong	14	1.38	8	6	39

In addition, we see eight developed and two developing countries, as reported in Table 7. The urgency of emission reduction varies, where emission reduction is an urgent challenge and requires greater focus for developing countries. Developed and developing nations prioritize economic growth and have decades of experience in reducing carbon emissions. To steer clear of pitfalls on emission reduction, Developing nations should optimize policies and learn from the governance experience of developed nations.

(Insert Fig. 6 here)

This result is consistent with Fig. 6 which shows the potential gap in research contributions between developed and developing nations. Due to the volume of publications, China is the only developing nation with the most citations, while the other 9 are found in developed nations. For example, the US has more innovative research topics and trends such as sustainability issues related to carbon emissions. Sustainability issues have received great attention in recent years among the worsening climate change, waste, and emissions [83]. Nowadays, discussion has been performed on carbon neutrality, green innovation, carbon capture, and circular economy. Therefore, developed countries dominate the list of countries with the most citations, showing substantial contributions to emission control compared to developing countries. The UK was among the first to encourage studies on net zero emissions. Study on carbon neutrality in the US is primarily concerned with technological and scientific issues. In recent years, study on climate change and low carbon has been a priority for China, the US, and Europe. Other countries investing in net zero-emission research include Germany (29), Italy (23), India (19), Australia (18), the Netherlands (17), Korea (15), and Hong Kong (14).

Discussion

Research hotspots

Keyword cluster analysis provides important insights into the field of carbon neutrality, enhancing comprehension of subjects and research objectives for different nations. Fig. 7 reports word cloud analysis where the font size reflects the frequency of the keywords. The analysis identifies the five most frequent topics functioning as key research hotspots, including carbon neutrality (134), renewable energy (59), climate change (53), green innovation (51), and sustainability (49) (Table 8). The transition is increasingly recognized as essential to mitigate climate change, which requires adopting of renewable energy sources as well as cross-sectors' innovative practices. Different types of research are identifying and developing effective strategies to achieve this goal. For example, green innovation has been shown to improve organizational performance by integrating sustainable practices into business models [84], [85]. Companies with a strong green learning orientation are positioned to implement innovative solutions in line with sustainable performance metrics to strengthen the connection between green innovation and sustainability[86]. Finally, green innovation is essential for driving the shift to renewable energy as well as achieving sustainability [87], [88].

Table 8. Global carbon neutrality research hotspots, 2015–2024.

No	Terms	Freq.	No	Terms	Freq.
1	carbon neutrality	134	11	energy efficiency	29
2	renewable energy	59	12	circular economy	27
3	climate change	53	13	carbon emissions	26
4	green innovation	51	14	decarbonization	26
5	sustainaibility	49	15	energy transition	23
6	china	39	16	co2 emissions	22
7	innovation	39	17	net zero	20
8	technological innovation	34	18	hydrogen	16
9	sustainable development	31	19	carbon footprint	14
10	green technology innovation	22	20	energy policy	14

(Insert Fig. 7 here)

Some research reported that investment in renewable energy was positively associated with carbon neutrality, by providing a framework for the development and implementation of clean technologies [16], [89], [90]. Research that advances the green innovation as well as renewable energy policy knowledge to attain carbon neutrality and show the best practices used by different industries is a current and growing area of interest [91], [92], [93]. Therefore, further investigation is suggested to explore the utilization of government policies to promote green innovation and renewable energy usage, as well as the impact on achieving sustainability targets and reducing carbon emissions.

Research frontiers

The word cloud analysis results contain numerous keywords with the potential to obfuscate crucial information and create noise. Similar to Principal Component Analysis (PCA), the Factorial Analysis is performed to reduce the dimensionality of data in multivariate statistical analysis. This enables the classification and refinement of pertinent variables to show the underlying factors (Fig. 8) [94]. Economic and technological development, the green economy, and environmental variables such as economics, policy, and protection are important components for global carbon neutrality. In addition, environmental methods from economic, policy, and protection perspectives are the focus of global carbon neutrality research. Factorial analysis offers insightful information about important areas of focus and identifies possible underlying components. In this context, the environment should be considered when maximizing energy efficiency and lowering carbon emissions.

(Insert Fig 8 here)

(Insert Fig 9 here)

According to [95] thematic maps identify and document themes, patterns, and as well as trends in a topic of study. In Fig. 9, significant and well-developed themes are summarized in quadrant 1 (motor themes), while highly developed and isolated ideas are reported in quadrant 2 (niche themes). Quadrant 3 (declining themes) shows increasing or decreasing themes in the earlier stages. Additionally, quadrant 4 (basic themes) is significant to the area but the themes have not been completely explored and are typically relate to basic notions. There is no distinct topic serving as the motivating factor of the field in quadrant 1. Energy, climate, and emissions are at the intersection between motor and niche themes. In quadrant 2, electrocatalysis, carbon dioxide, and SDG9 are not relevant to achieving carbon neutrality. Therefore, academic research should distinguish the significant themes and focus on further development. Themes related to carbon capture, CCUS, and environment show lower centrality in quadrant 3. Carbon neutrality, renewable energy, green innovation, climate change, sustainability, and innovation show practical relevance in basing further research on fundamental concepts in quadrant 4. These themes need a bridge between academic innovation and practical application to increase relevance on a global scale.

(Insert Fig. 10 here)

The next application of the Trend Topics module analyzes the keyword development. The length of the line segment shows the years covered by the high frequency, while the size of the blue node indicates the frequency of the associated terms (Fig.10). The trend of the high-frequency keywords has changed since 2018, with increased concentration in 2022–2024. The range of the year is the development expansion and deepening phase. Early publications focused more on emission reduction targets, including the effects of transportation policies on costs and mitigation potential of the 2°C &1.5°C targets [80], [90], energy systems with net-zero emissions [63], as well as options for deep decarbonization pathways [64]. The scope of the carbon neutrality examination has shifted to economics, sustainability, and environmental policy in Europe to implement green strategies [96], [97], [98] and extend into business model innovation. Carbon emission reduction, technology development, [99], [100], green economy, resource efficiency, as well as social welfare [85], [101], [102] have been developed as interesting research areas.

(Insert Fig. 11 here)

Fig. 11 shows the flow of research contributions from specific themes and the distribution across countries. Chen H, Wang G, and Zhang Y have significant contributions to key themes, such as carbon neutrality, renewable energy, sustainability, green innovation, and climate change.

The themes represent topics of great interest in current research. Chinese academics form the bulk of the 2968 writers, covering all topics and giving particular attention to carbon neutrality, renewable energy, green innovation, technical innovation, and green technology innovation. This shows the emphasis on cutting carbon emissions through sustainable development and innovation in renewable energy. Additionally, the US and the UK report worldwide contributions to the development of green technology, focusing on technical innovation and the circular economy. The outputs from other nations are more evenly distributed and cover fewer themes.

Fig. 11 lists authors, subjects, and nations to identify research focal points and areas of interest in sustainability and green innovation. Academics are expected to find interdisciplinary possibilities, possible partners, and patterns of communication and knowledge dissemination across areas. This has been helpful in promoting academic collaboration and multidisciplinary research.

Future research

Comprehensive transformations in all facets of the economy and society are initiated by net-zero emissions [103] . The method of comprehending carbon neutrality is changing as the research grows more varied and comprehensive, as demonstrated by the evolving thematic map shown in Fig 9.

Optimal path to achieve carbon neutrality

Research on the best strategies to become carbon neutral is essential in the context of global climate change. A multipronged method is required to develop renewable energy technology, boost energy efficiency, and put regulations for facilitating the shift to a low-carbon economy. [104] and [105] emphasized that research in sustainable energy technologies and synthesizing carbon-neutral fuels required further exploration, considering the challenges faced in transitioning to carbon neutrality. Scenario analysis also considers the growth of renewable energy sources as well as the decrease of carbon emissions in transportation and industry to determine the most effective and sustainable routes [106]. Technology developments, community inclusion, and an assessment of the social and economic effects of suggested policies are among the additional elements [107]. Future research should be carried out to fully comprehend the effects of carbon taxes and trading policies, which successfully lower emissions in a number of nations [108]. Innovative technologies such as CCS as well as Bioenergy with Carbon Capture and Storage (BECCS) have also been identified as potential solutions [109], [110]. Therefore, suggestions for further research include a deeper exploration of the integration of various technologies and policies for effectively and efficiently supporting the transition to carbon neutrality effectively and efficiently.

Clean renewable energy vs CCUS(Carbon Capture, Utilization, and Storage)

CCUS, parallel techniques, and the clean renewable energy sector are taken into consideration in the context of emission reduction. CCUS is essential to reaching net-zero emission goals because it permits the continuous use of fossil fuels while lessening their environmental effect [16], [111] . The shift to a renewable energy industry is essential to reduce dependence on carbon-based energy sources, which dominate the global system[112]. However, major challenges remain, including high investment costs and dependence on existing infrastructure. CCUS has been developed as a key technology enabling the sustainable use of fossil fuels and significantly reducing carbon emissions. Technology development has shown rapid progress with great potential to support emission reduction efforts [111], [113]. In order to encourage the implementation of the technology, it frequently depends on suitable government regulations and incentives [88], [111]. A parallel method combining the strategies may offer a more comprehensive solution, where renewable energy directly reduces emissions, while CCUS captures unavoidable emissions from sectors relying on fossil fuels [86]. Therefore, further research should explore the synergies between these methods and to develop policies that support an effective shift to a low-carbon economy.

Green innovation and carbon neutrality

Further research on the relationship between green innovation and carbon neutrality should focus on developing more efficient green innovation technologies implemented under stringent environmental policies. Since sustainability is increasingly recognized, green innovation is becoming essential to corporate operational strategies, in line with global efforts to mitigate climate change. According to previous research, boosting efficiency may help many industrial sectors meet carbon neutrality objectives. Therefore, green technology innovation plays a key role in reducing emissions [20], [114], [115]. To support the development of low-carbon technologies, the relationship between green innovation and financing should be investigated[116], [117]. Government initiatives that can promote businesses to invest in green innovation, including progressive carbon taxes, should also be analyzed research [83]. In this context, a multidimensional method combining technological, economic, and policy aspects provides more comprehensive insights into the contribution of green innovation to achieve carbon neutrality effectively and sustainably.

Carbon neutrality and sustainability

Carbon neutrality and sustainability follow a multipronged method incorporating governmental reform, technical innovation, and societal transformation as key objectives in the global response to climate change. Achieving net-zero carbon emissions, or carbon neutrality, is essential for reducing the negative effects of climate change and advancing sustainable development. Future research could focus on the relationship by exploring the different strategies needed to achieve both goals across sectors. For example, institutions can play a critical role in promoting sustainability initiatives to support greenhouse gas emission reductions and increase energy efficiency [118], [119]. Furthermore, research on the development of new technologies, such as the use of hydrogen fuel, provide insights into the transformation of industries towards sustainability [120]. Policy and technology-based methods, such as the adoption of renewable energy and the development of sustainable supply chain models, are also critical to achieving synergies [121], [122]. Future research integrating multiple disciplines and industry sectors is invaluable in understanding and addressing carbon neutrality and sustainability challenges.

Green hydrogen, electric vehicles, dan carbon neutrality

Future research on the connection between carbon neutrality, electric cars, as well as green hydrogen should create integrated energy systems. Green hydrogen is used as the primary energy source for electric vehicles and sustainable transportation infrastructure. The manufacture is accomplished by electrolyzing water through renewable energy in shifting carbon-neutral society to lower dependency on fossil fuels and carbon emissions [123], [124]. Hydrogen-powered (FCEVs) and electric cars worked within the larger transportation system due to energy management rules and strategies [125], [126]. The challenges and opportunities associated with the development of hydrogen infrastructure were also analyzed, including the production, storage, and distribution, as well as the impact on energy and environmental policies [127], [128]. Deeper insight should be provided into the synergistic contribution of green hydrogen and electric vehicles to achieve global carbon neutrality goals.

Conclusion

Climate change demands massive implementation of more sustainable innovations, especially since many countries adopted the Paris Agreement. The keyword "carbon neutrality" received attention from different disciplines. This research mapped the intellectual terrain of scientific advancement in carbon neutrality using bibliometric analysis. From 2015 to 2020, 1,017 research publications were gathered from 423 journals. Even though the term carbon neutrality recently appeared in academic literature, the results increased exponentially since 2020. As a multidisciplinary area, the majority of the research on carbon neutrality was published in publications related to sustainability and the environment. According to the justification, this research offered intriguing new perspectives on the present carbon neutrality boom. Academics should also concentrate more on reducing carbon emissions, developing new technologies, using clean energy, and the effects on the environment, society, and economy. The different areas requiring further attention included carbon neutrality, renewable energy, green innovation, green hydrogen, and electric vehicles. Scientific collaborations from different countries could ensure a comprehensive and diverse understanding since carbon neutrality was reported as a global issue. This research helped policymakers prioritize analyses to attain carbon neutrality.

A number of recommendations were made, including a review of the best method to reach carbon neutrality, evaluation of the clean renewable industry and CCUS synergy, investigation into the role of green innovation in reaching carbon neutrality, exploration of the different strategies required to achieve sustainability and carbon neutrality, and analysis of the complementary contributions of green hydrogen and electric vehicles in reaching global carbon neutrality objectives.

The results assisted policymakers in making informed decisions and prioritizing policies to achieve carbon neutrality. For example, policies were created to increase demand for decarbonization-related investments, promote more green innovation, and provide greater cost-cutting incentives for sectors using green technologies, renewable energy, and sustainable growth. Studies on collaboration networks encouraged cooperation between government organizations, academia, as well as industry stakeholders to close the gap between research, policy, and improve policy outcomes.

The results of this analysis might be affected by subjective search methods and data selection standards. The inclusion of inappropriate or omission of relevant keywords affected the determination of clusters and themes. Despite the limitations, this research exploration provided an overview and comprehensive review as well as contributed to future directions related to carbon neutrality.

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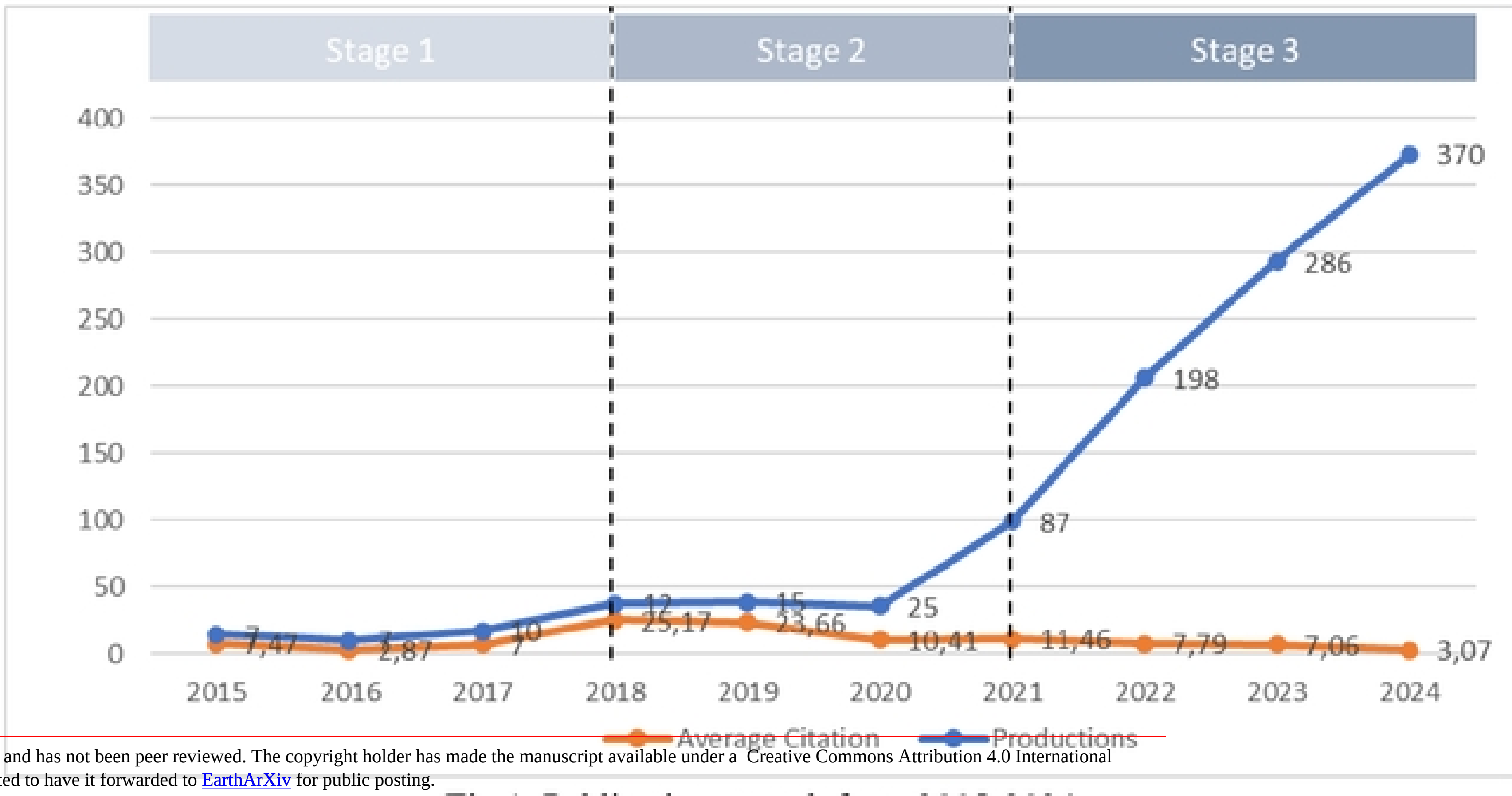

Fig 1. Publication growth from 2015-2024

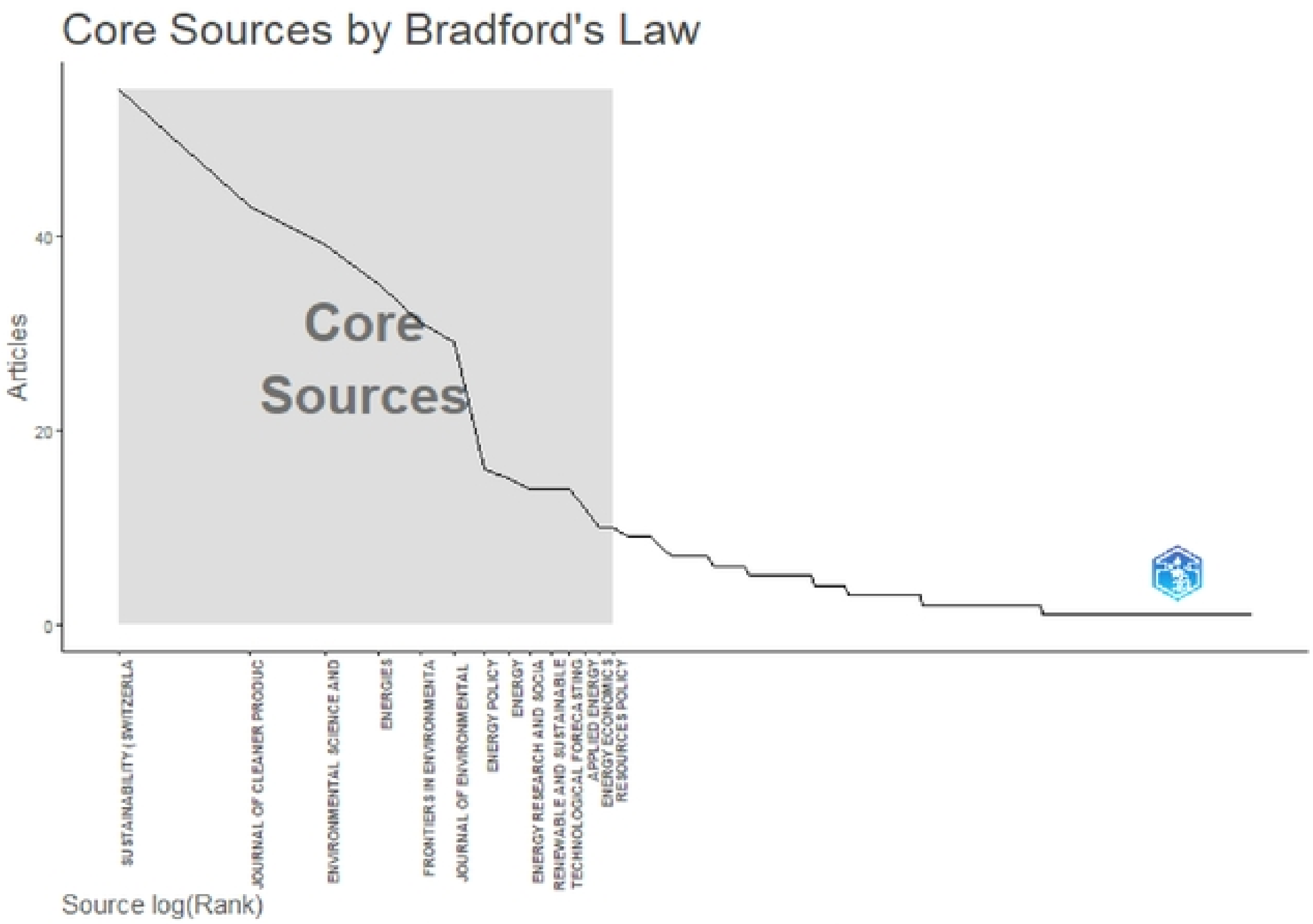

Fig. 2. Core sources according to Bradford's Law.

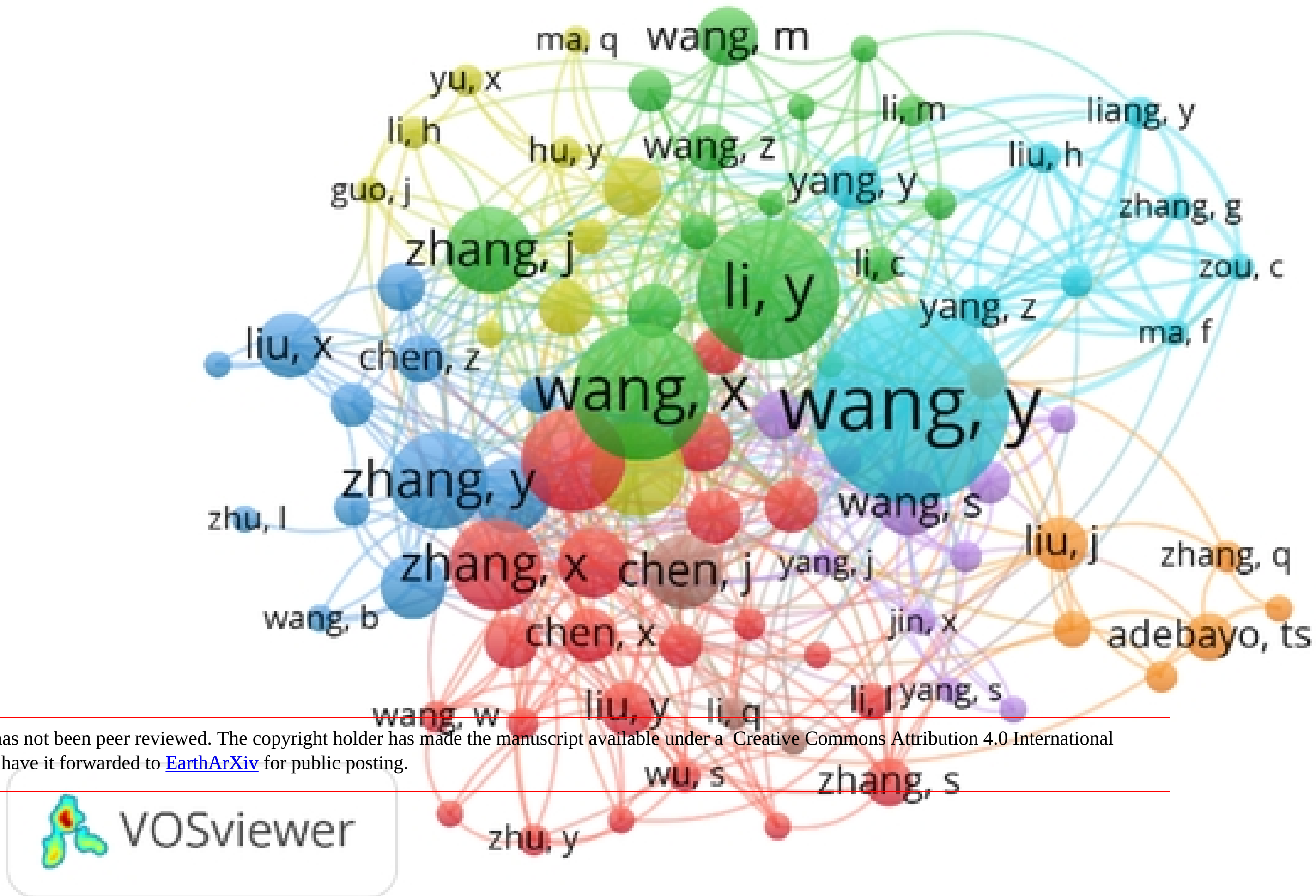

Fig 3. Author cooperation network

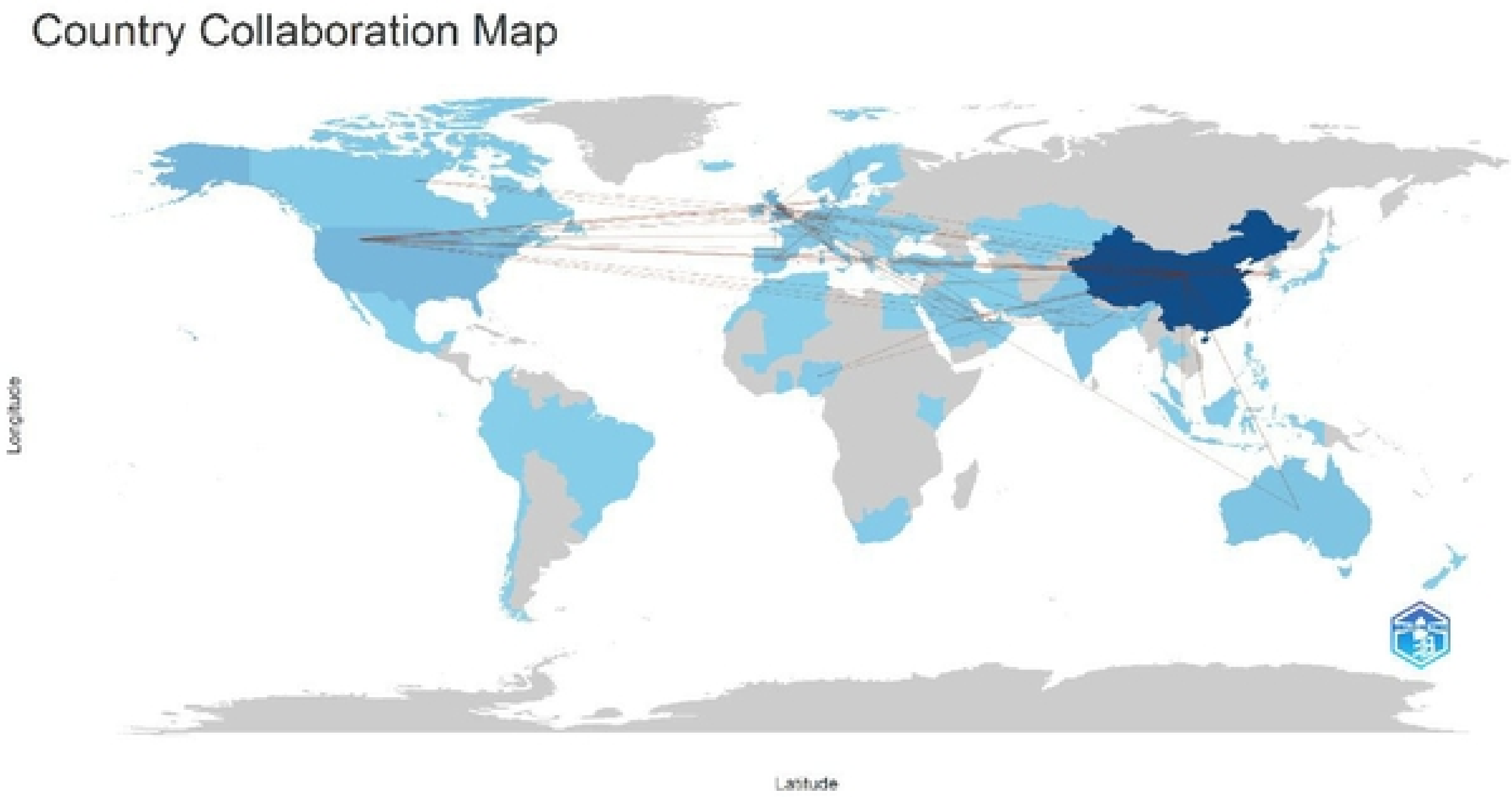

Fig 4. Country collaboration

Fig. 5. Institutions cooperation network

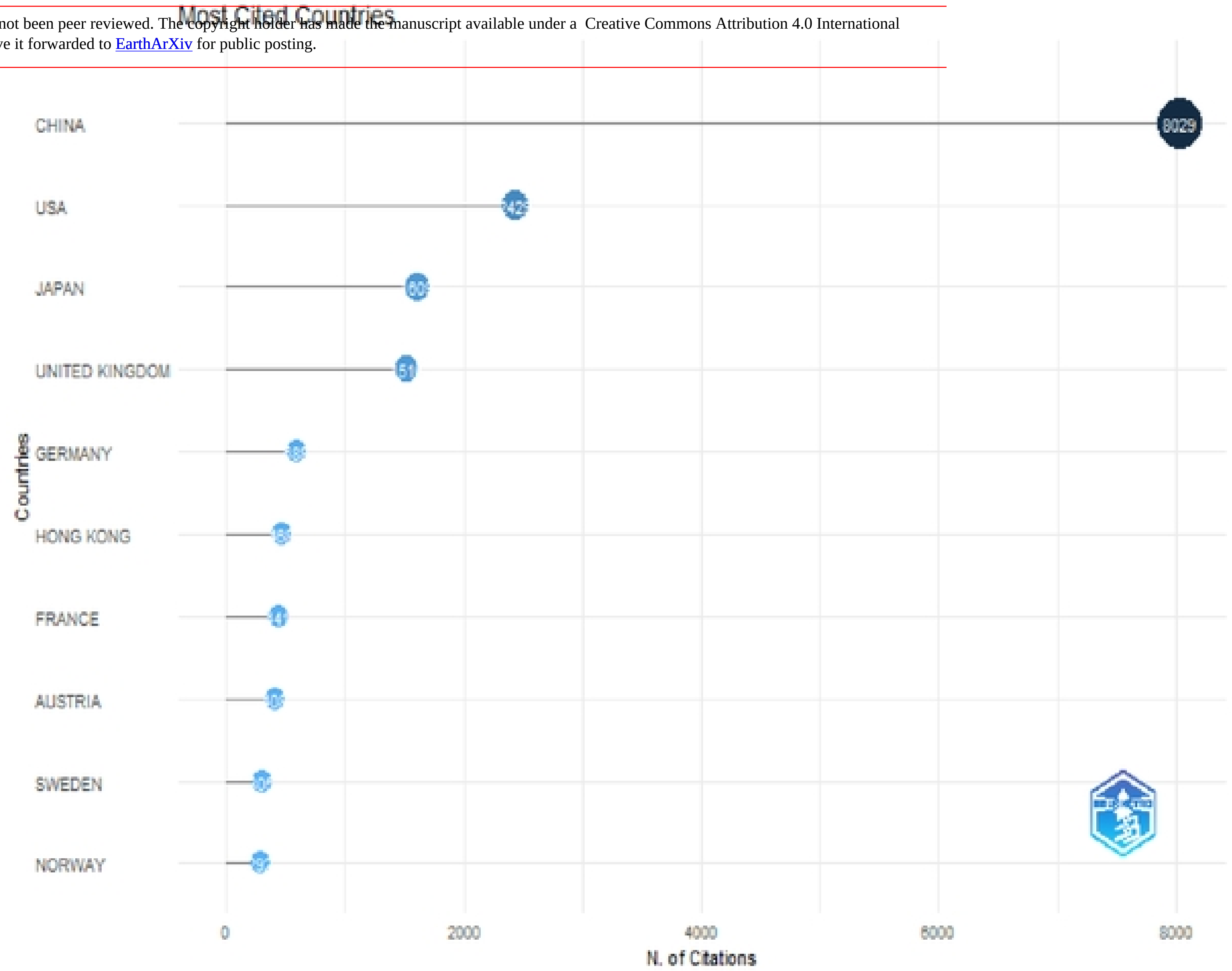

Fig. 6. Most cited countries

Fig. 7 Word cloud analysis

Fig. 8. Factorial analysis

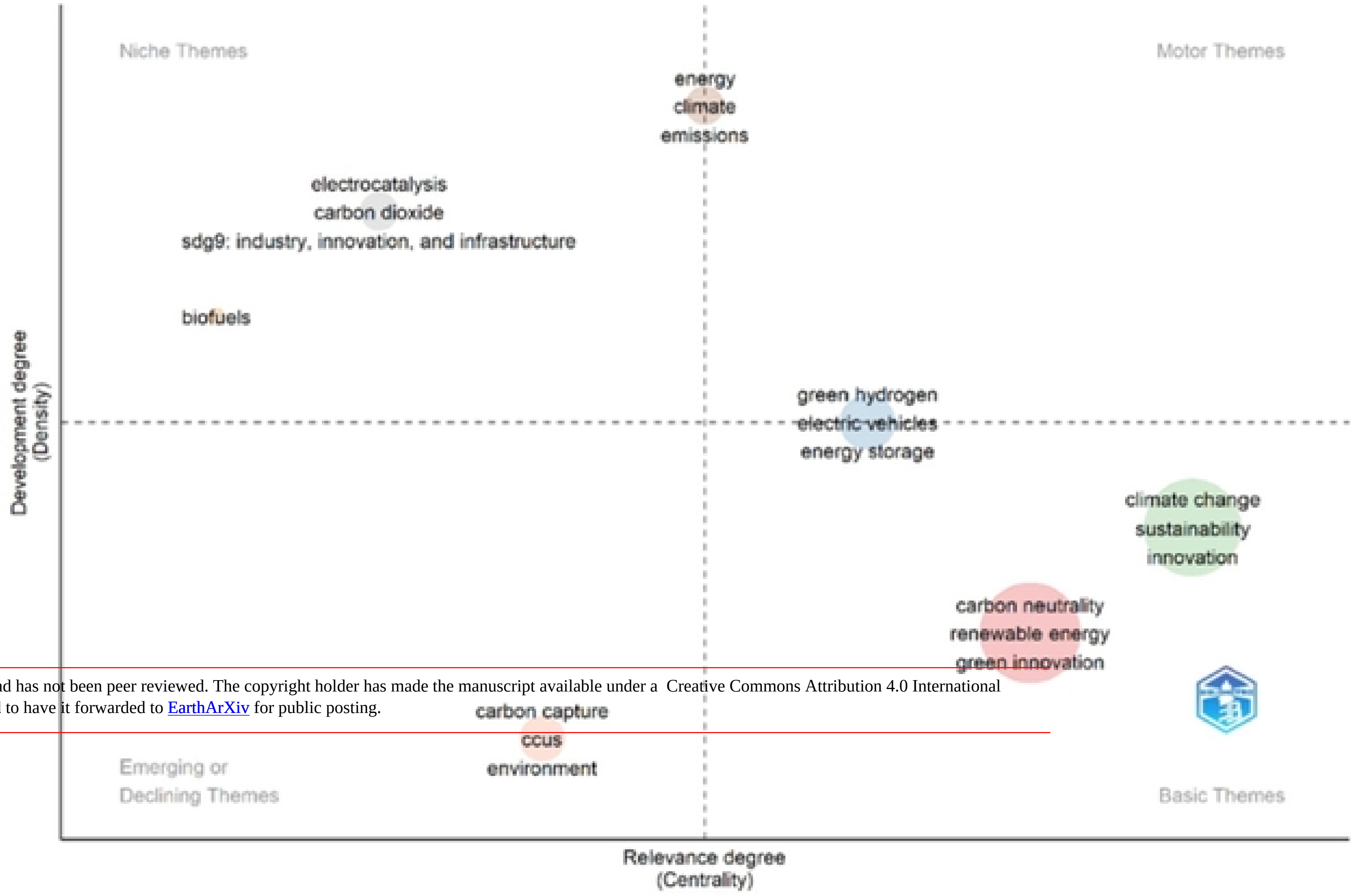

Fig. 9. Thematic map

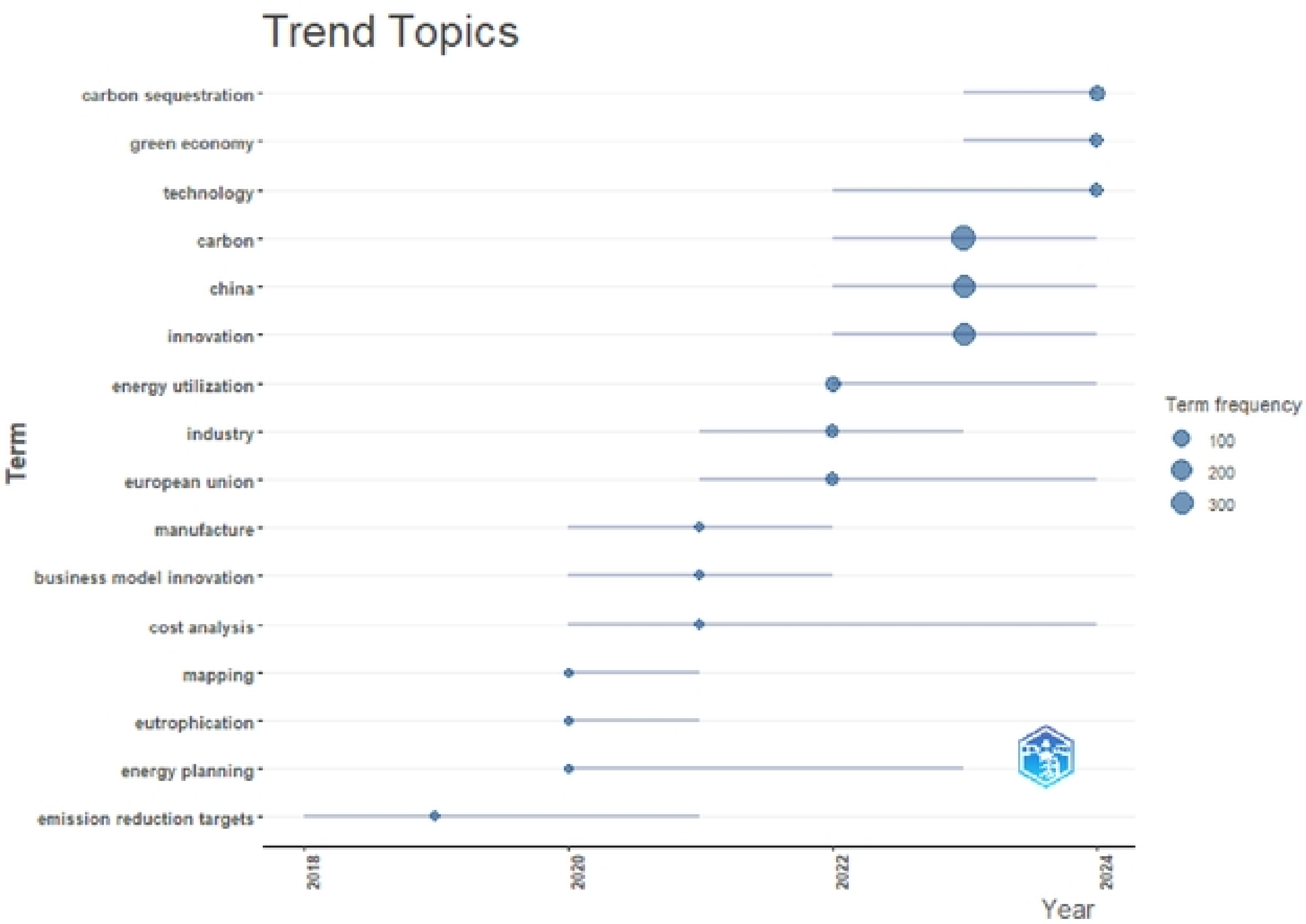

Fig. 10. Trend topics

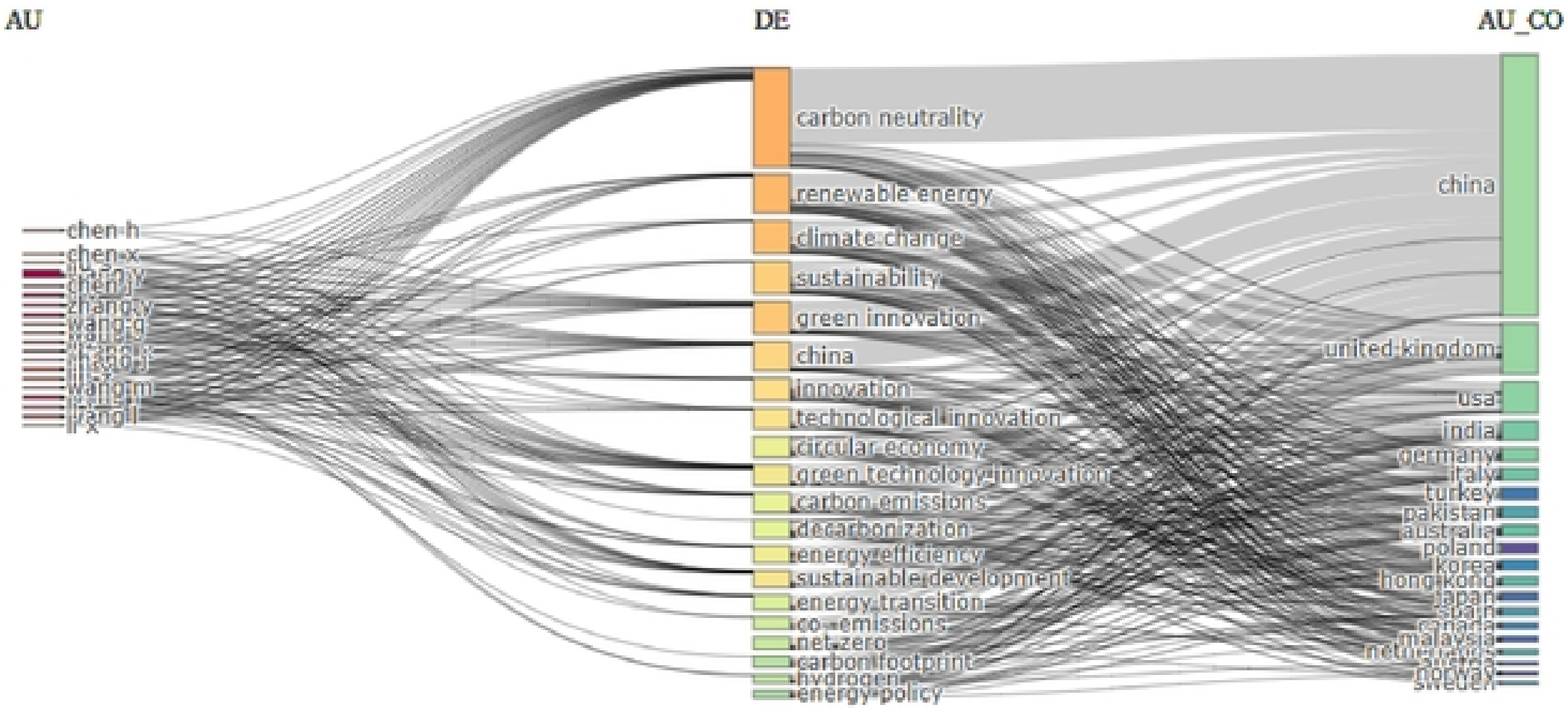

Fig. 11. Thematic evolution map