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Advancements and Trends in Global Low-Carbon Aviation: A CiteSpace Knowledge Map Analysis

Meng Shang[1*], Manqiu Zhu[1], Litian Ren[1], Yongho Shin[2]

[1] School of Flight, Anyang Institute of Technology, 455000 Anyang, China
[2] Department of Business, Yeungnam University, 38541 Gyeongsan, Korea

[*] Correspondence: Meng Shang (20192052@ayit.edu.cn)

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Abstract: The realm of low-carbon aviation, a critical sector in the construction of a low-carbon economy, has consistently garnered extensive attention. This study, utilizing bibliometric analysis and employing the visualization software CiteSpace, constructs knowledge maps based on data sourced from 358 core journal articles and (Chinese Social Sciences Citation Indexed) CSSCI articles in the China National Knowledge Infrastructure (CNKI) and 270 articles from the Web of Science (WOS) Core Collection. These maps elucidate the dynamics of research hotspots and evolutionary trends in the global low-carbon aviation industry by visualizing elements such as researchers, institutions, co-occurring keywords, surging keywords, and clustering time zones. The analysis reveals a dispersed pattern of domestic researchers with a need for enhanced collaboration, in contrast to more frequent collaborations among international researchers. Key issues such as fuel, carbon emissions, and environmental protection emerge as common focal points in both domestic and international contexts. Trends in aviation transportation and emission reduction are identified as converging research trajectories, with significant influence on the scholarly discourse and practical resolutions in the low-carbon aviation sector. The outcomes of this study hold substantial value for guiding academic research and addressing real-world challenges in the low-carbon aviation industry globally.

Keywords: CiteSpace; Global aviation industry; Sustainable development; Carbon emissions

1 Introduction

Accompanying the comprehensive implementation of the "Five-in-One" strategy and the long-term stable growth of the economy, both domestic and international attention towards the low-carbon aviation industry has been increasingly intensifying, with the problems associated with this field also attracting growing interest from scholars. In 1979, following the First World Climate Conference, it was identified that the main cause of global warming is the increase in carbon emissions. Since then, various international environmental organizations aiming to reduce global carbon emissions have successively emerged [1]. After the 2009 Copenhagen Climate Change Conference, the concept of a "low-carbon economy" has become a consensus among nations. Concurrently, the idea of low-carbon consumption has gradually taken root in people's minds, becoming a new lifestyle. In 2020, the ocean temperature continued to rise, marking the warmest year for the oceans in recent years. In light of this, the aviation industry should also actively participate, strengthening its energy-saving and emission reduction efforts. The *Civil Aviation Administration's Guidelines on Accelerating the Promotion of Energy Conservation and Emission Reduction in the Industry* proposed that by 2020, the energy intensity/carbon intensity of China's civil aviation should be reduced by 22% compared to 2005 [2]. Wang and Sun [3] proposed the construction of green airports; Guo [4] suggested optimizing air traffic management routes to achieve the purpose of saving fuel and reducing consumption. In 2022, the globalization of economic trade brought about the vigorous development of the transportation industry and the growing demand for transportation. Under this trend, energy consumption increased, and environmental pollution became increasingly serious, hence Zhang [5] proposed that it is necessary to vigorously develop "low-carbon transportation." Low-carbon economy is the inevitable choice for the future development of the world economy, and Schmalensee et al. [6] proposed to innovate the performance evaluation system to meet the needs of low-carbon economic construction. The issues of global aviation carbon emissions and carbon offset legal regulation are becoming increasingly prominent, İlbasmış et al. [7] suggested that it is very necessary to explore the legal regulation of global aviation carbon emissions and carbon offset. The above measures and reports further strengthen the low-carbon sustainable development of the aviation industry, laying a solid foundation for research on low-carbon aviation both domestically and internationally. The development of the low-carbon aviation industry at home and abroad is still in its initial stages, but has already accumulated certain experiences and results.

The software CiteSpace, developed by Chen [8] in 2006, is a Java-based information visualization tool applicable across various fields, including the history of philosophy, science history, social sciences, management, natural sciences, and social networks. It has now become a widely used method among scholars for analyzing the development status of a field, popular both domestically and internationally. Zhang and Zhu [9] utilized bibliometric analysis to visually analyze the current state, hotspots, and frontier trends of osteoporosis research in recent years. Yin et al. [10] conducted a study and analysis of the trajectory and dynamics of the development of demography in China based on bibliometrics. Ding and Zhang [11] used bibliometric analysis to dissect the current state of culturally responsive teaching and deduced future trends. Garousi and Mäntylä [12] employed bibliometric analysis to explore and analyze popular research topics in software engineering and the most active countries in the field. Si [13] comprehensively analyzed the current state of research and application prospects of Radix Paeoniae Alba in tumor prevention and treatment using bibliometric analysis. Pan [14] explored the development context, evolutionary path, research hotspots, and trends in aerobics teaching using bibliometric analysis, comprehensively understanding the overall situation of aerobics teaching research in this period, grasping the research dynamics, finding themes and focuses that fit the current development, and predicting future trends to provide a theoretical reference for subsequent research. Therefore, conducting a bibliometric analysis of the low-carbon aviation industry both domestically and internationally is imperative and a trend.

Against the backdrop of global warming and various national measures to provide substantial support, systematically combing through the characteristics of the low-carbon aviation industry can point the way for future research and exploration. According to existing literature, there is almost no analysis and summary of the research hotspots and frontier trends in the low-carbon aviation industry both domestically and internationally. To more comprehensively and thoroughly analyze issues such as the hotspots, current state, and evolution of the low-carbon aviation industry at home and abroad, this study uses CNKI and the WOS Core Database as research subjects. Based on bibliometric methods and using CiteSpace software, the study analyzes the scientific knowledge map of this field, systematically summarizes it, and thus better reflects the research hotspots and frontier trends in this field, to facilitate further research by scholars on the development of low-carbon aviation both domestically and internationally. Firstly, this paper organizes and analyzes related literature on low-carbon aviation both domestically and internationally, comprehensively interpreting and analyzing the field through the number of publications, authors, and co-occurrence analysis of institutions. Secondly, it uses bibliometric analysis for keyword co-occurrence, keyword clustering, surges in keywords, and time zone view analysis. Finally, it summarizes the current state, hotspots, and evolutionary trends of the low-carbon aviation industry both domestically and internationally.

2 Data Sources and Research Methodology

2.1 Data Sources

To ensure comprehensiveness and accuracy of data, this paper selects the literature from the largest and most authoritative databases: China National Knowledge Infrastructure (CNKI) and the WOS developed by the American Institute of Scientific Information. As stated by the Chinese government, "Promoting the greening and low-carbon development of economic and social progression is a key link in achieving high-quality development." With the optimization of energy structure, the proportion of civil aviation in the transportation industry and national carbon emissions will continue to rise. The aviation industry plays a crucial role in global cooperation and economic development. At the same time, the difficulty in decarbonizing aviation and its global nature of carbon emissions across countries and regions have made carbon reduction in aviation a focal point of attention. Concepts such as green and low-carbon sustainable development, reduction in carbon consumption, energy conservation, and emission reduction have emerged to serve the healthy development of the aviation industry. Therefore, when collecting data from the CNKI journal database, searches were conducted with themes like "Aviation + Low Carbon," "Aviation + Green," "Aviation + Energy Saving," "Aviation + Consumption Reduction," or "Aviation + Sustainable Development," targeting the period from 2000 to 2022, focusing on core journals and CSSCI journals, with the parameter set to Top N=50. A total of 418 documents were obtained. After manually filtering out 60 documents that did not meet the criteria, a final sample of 358 relevant documents was established. For international research, the WOS database was searched using terms like "Green" Near "Aviation," "Airline Industry + Emission Reduction," "Green Aviation," or "Sustainable Aviation," with the document type set to "Article" and the timeframe spanning from 1993 to 2022, with the parameter set to Top N=50. After manual screening of the documents, 270 relevant samples were obtained.

The data processing procedure using CiteSpace software is as follows:

(1) Data Export. Literature data filtered from four journals are downloaded via CNKI, and the CNKI citation

format is converted to a format recognizable and processable by CiteSpace. First, rename the exported and merged citation document in the format “download_XXX.txt” (CiteSpace requires the input file to start with ‘download’). Create a folder to serve as the working directory, named in English. After entering the folder, create four new folders named: data, input, output, project. Here, the input folder stores original data like those initially exported from the CNKI database; the output stores data after format conversion and deduplication; data holds the processed data; project is the project directory, saving the results of later analysis and some records.

For each page of the retrieved data literature, select all and export in groups of 10 pages (CNKI allows a maximum export of 500 documents at a time). After selection, click on “Export/Reference”, choose “Refworks”, and click “Export” to complete the download. The data includes authors, titles, source journals, keywords, abstracts, etc. After downloading the search results, rename the files as “download_XXX” and save them in the “input” folder.

(2) Data Conversion. After downloading the data text, run CiteSpace software and click “New” to create a new project. Select the previously established folder path, operating only the first four items: ①Title (project name); ②Project Home (project working directory); ③Data Directory (project data directory); ④Data Source (data source), and then click “Save”. After creating a new project, begin processing the data. Click the “Data” button, then Import/Export, and select the corresponding database platform. After selection, directly click the conversion button [CNKI Format Conversion (2.0)] to successfully convert. The converted data will be output in the previously selected Output folder.

(3) Parameter Settings. Import the data from the “output” folder into CiteSpace software and create a new Demo file. Then, select node types for analysis in the relevant function interface of the software, set the time interval, and define it as a one-year time zone slice. Based on the research purpose, choose appropriate functions like “Keyword”. To ensure a clear and intuitive map, select “Pathfinder” (pathfinding algorithm) and “Pruning Visualization” for data normalization operations, and then click “Visualize” to generate a knowledge map related to the low-carbon aviation field. Choose “Burst Detection” (burst monitoring) and “TimeZone” (time zone evolution) presentation methods to obtain a visualization map of research hotspots and a time zone view of the evolutionary context, showing the research dynamics of low-carbon aviation both domestically and internationally.

(4) Analyzing and Interpreting the Knowledge Map. Adjust functions and parameters as needed for research, to optimize the map view, identify research hotspots based on high-frequency keywords shown in the map, and then grasp the emergence and focus of keywords in each period.

2.2 Research Methodology

Analyzing papers on domestic and international low-carbon aviation can summarize the main contents of the low-carbon aviation industry. However, extracting effective information through reading each paper is impractical due to the sheer volume of literature. The challenges include: 1) the overwhelming number of articles to read; 2) the difficulty in manually determining the interconnections between multiple articles, leading to potential subjectivity; 3) the complexity in uncovering the information reflected in the interrelations among references within the articles. Therefore, the choice of research methodology must consider scientific validity, effectiveness, and efficiency.

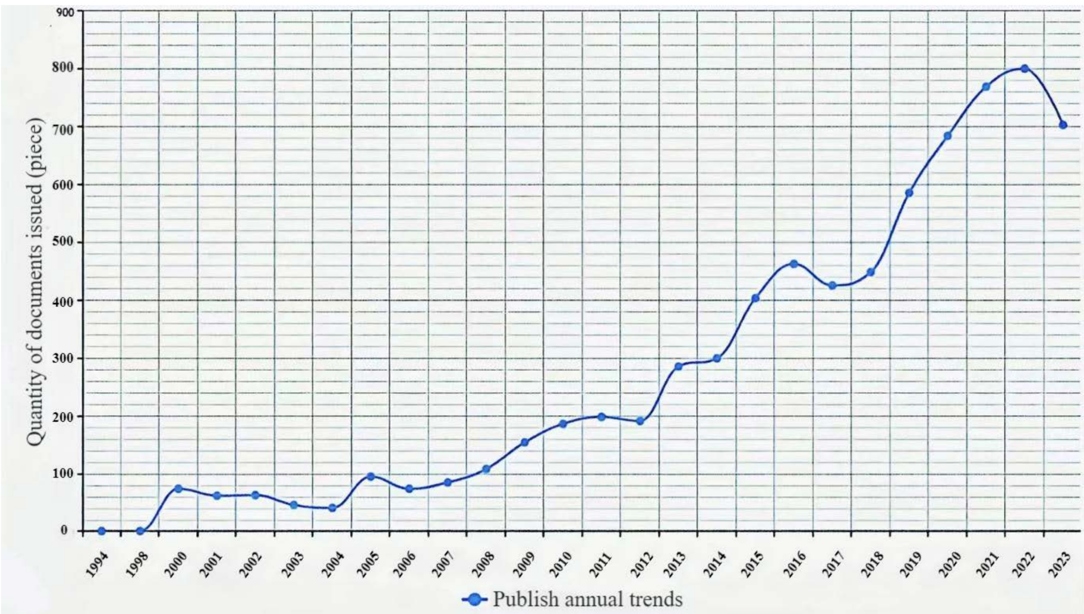

Figure 1. Statistical chart of the number of papers conducting research using bibliometrics

With the continual advancement of information technology, large data repositories contain rich research information. Bibliometrics, aided by bibliometric tools, demonstrates significant analytical advantages. It employs mathematically related algorithms to objectively present the interconnections between literatures. A search for the keyword "Bibliometrics" on the CNKI, followed by a distribution of relevant literature by publication year, results in Figure 1.

This study utilizes bibliometrics, primarily employing the data statistical software SPSS and the scientific knowledge map software CiteSpace for scientometric analysis of domestic and international literature. CiteSpace is capable of identifying and displaying new trends and dynamics in scientific literature, aiding in finding the research progress and current frontiers of a particular discipline, as well as its underlying knowledge base. First, SPSS software is used to calculate the annual publication volume in databases, understanding the temporal distribution characteristics of domestic and international low-carbon aviation logistics research. Next, CiteSpace is utilized to conduct metric analysis on aspects like research institutions and their cooperation relationships, and the distribution and cooperation of authors, to understand the spatial distribution of low-carbon aviation logistics research. Finally, the co-occurrence network of high-frequency keywords and the surge of emerging words are used to display the hotspot distribution, development trends, and sudden changes in the field.

A scientometric analysis of authors and institutions, and keywords of domestic and international low-carbon aviation research literature is conducted. By drawing co-occurrence and clustering maps and other scientific knowledge maps, the study reveals relationships between changes in publication volume, author and institution characteristics, content and thematic evolution in the field of low-carbon aviation, research hotspots under different backgrounds, and future research frontiers. The study provides an in-depth interpretation of the research development and evolution in this field.

Bibliometrics focuses on the "quantitative" aspect, mainly studying the distribution number, distribution, and changes from a quantitative perspective, thereby playing an important role in predicting research trends. This study did not employ a combined approach of quantitative and qualitative research methods, failing to supplement the numerical data with descriptive information, which could have led to richer and more credible research results. Consequently, this may affect the conclusions drawn.

3 Structural Characteristics of Domestic and International Low-Carbon Aviation Industry Research Literature

3.1 Temporal Distribution Characteristics of Domestic and International Low-Carbon Aviation Industry Research

The number of publications is an important indicator reflecting the development of research in a field and serves as a crucial basis for analyzing the evolutionary trends of that field. This study is based on 307 core journal articles and CSSCI journal articles on low-carbon economy research in the aviation industry, as well as articles from the WOS core database. Using SPSS software, the annual publication volume trend line was drawn (see Figure 2). The publication characteristics and trends both domestically and internationally show significant differences.

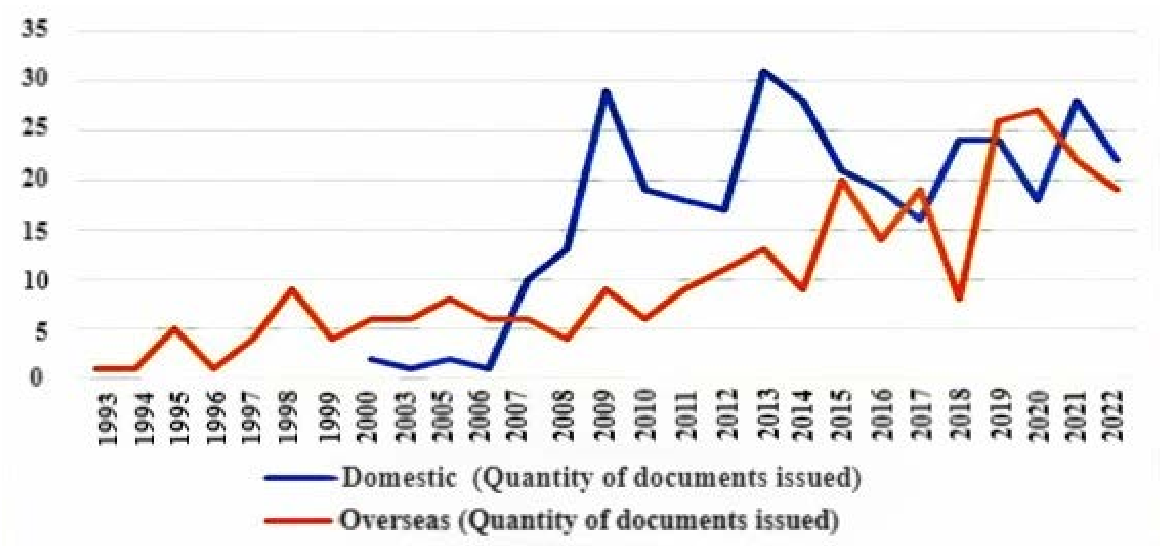

Figure 2. Distribution of domestic and international low-carbon aviation industry research literature (2000-2022)

Before 2006, domestic research on the low-carbon aviation industry was sparse. It began to gain more attention and research from 2007, but over these 20 years, the publication volume fluctuated slightly, peaking twice - first in 2009 and then in 2013. In 2009, China's civil aviation implemented the *Civil Aviation Industry Energy Conservation* *and Emission Reduction Plan*, which had a noticeable impact. In July of that year, the *Civil Airport Management Regulations* were officially implemented, playing a crucial role in the future construction, management, operation, reform, and development of airports in China, hence the increased research attention that year. In 2013, the State Council and the Central Military Commission formulated the *Opinions on Deepening the Reform of China's Low-altitude Airspace Management* (referred to as the *Reform Opinions*), which made explicit deployments for deepening the reform of low-altitude airspace management in China, promoting the development of the aviation industry. Additionally, China issued programmatic documents like the *Guidance on Accelerating Energy Conservation and Emission Reduction in the Industry* and *Notification on Comprehensive Energy Conservation and Emission Reduction in the Civil Aviation Industry*, outlining methods for energy conservation and emission reduction by the International Civil Aviation Organization and directing the development of the low-carbon aviation industry. As a result, there was a relative increase in research in this field in that year. However, due to several air disasters in 2014, the research heat on aviation slightly decreased compared to 2013. The research on low-carbon aviation started to pick up again in 2019. Thus, it is evident that the national political situation and development planning significantly influence the volume of literature published in the domestic low-carbon aviation research field.

The research by foreign scholars on low-carbon aviation can be divided into two phases. The first phase (1993–2010): Slow development, with an annual publication volume of less than ten papers from 1993 to 2010, indicating a low level of attention to this field by foreign scholars during these years. The second phase (2011–2022): Steady development, with an average annual publication volume of about 16 papers.

It can be observed that the progress of research on the low-carbon aviation industry is different domestically and internationally, which can be summarized in three points: First, domestic research progress is closely related to the national political situation and policies, while international research in this field is more stable than domestic. Second, the annual publication volume fluctuates more in China, while it shows a steady upward trend internationally. Third, foreign scholars began researching the low-carbon aviation industry earlier, with relevant literature appearing as early as 1993, while domestic research in this field started later. However, the growth rate of domestic publications was faster, and during its peak periods, the publication volume was about three times that of foreign countries. In recent years, the publication volumes domestically and internationally have been roughly equivalent, results in Figure 2.

3.2 Spatial Distribution Characteristics of Low-Carbon Logistics Industry Research

3.2.1 Analysis of literature authors and their collaboration relationships

Figure 3. Domestic authors co-occurrence map

Effectively analyzing literature authors and their collaboration relationships helps to comprehensively grasp the core academic groups and high-yield authors in the field of low-carbon logistics research. By running CiteSpace software and importing the standardized data of the sample literature into CiteSpace, with the analysis item set to "authors," the co-occurrence maps of authors related to low-carbon aviation industry research both domestically and internationally can be drawn (see Figure 3) for the years 2000-2022 and 1993-2022, respectively. Each node in the map represents an author, and the connections between nodes reflect the collaboration relationships between different authors. The results show a node count of N=533, a link count of E=775, and a network density of Density=0.0055. This indicates that 533 authors and 775 links between authors have been selected in the co-occurrence knowledge map of researchers in the field of low-carbon aviation. From Figure 3, it is evident that there is a lack of close collaboration among researchers who have made significant contributions to this field.

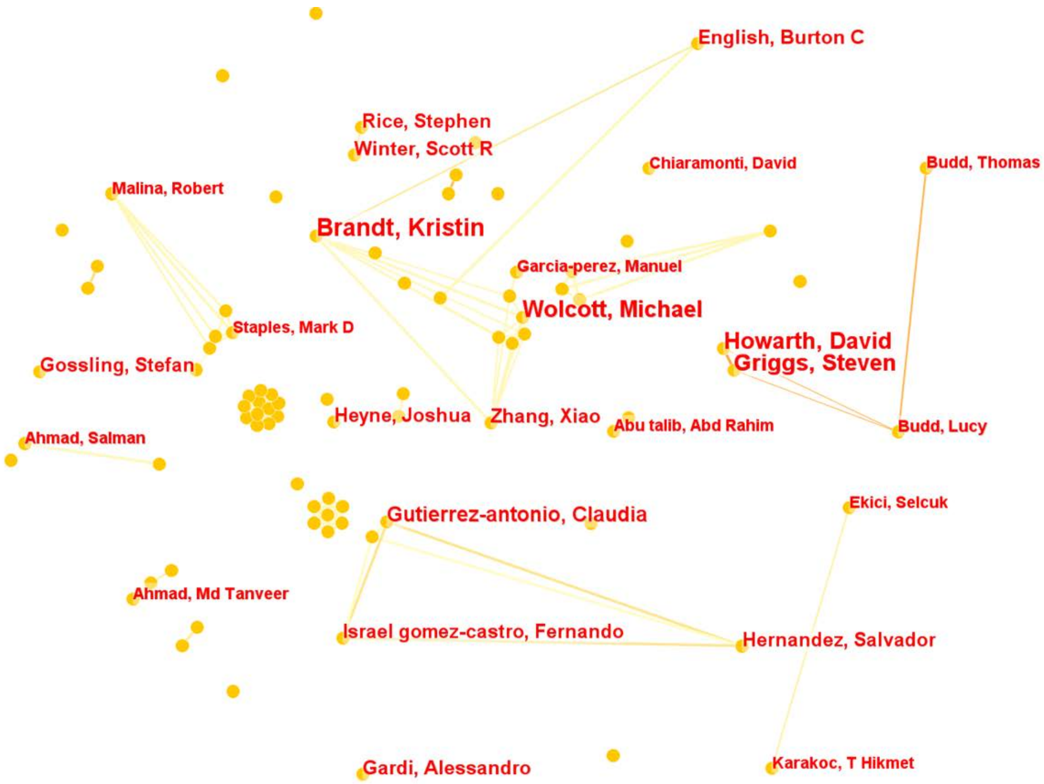

Figure 4. International authors co-occurrence map

Table 1 and Table 2 list the top 10 main researchers in the field of domestic and international low-carbon aviation industry. By synthesizing Figure 3, Figure 4, Table 1, and Table 2, the following characteristics of authors and their collaboration in low-carbon aviation industry research can be observed:

Table 1. Distribution of top 10 domestic authors in low-carbon aviation industry by publication volume (2000—2022)

No.	Author	Publication Volume
1	Jingbo Deng	16
2	Lijun Tian	6
3	Jian Yu	4
4	Yan Lu	3
5	Junfeng Zhang	3
6	Jingjie Chen	3
7	Hao He	3
8	Jie Li	3
9	Rong Hu	3
10	Xiangjie Li	3

Table 2. Distribution of top 10 international authors in low-carbon aviation industry by publication volume (1993—2022)

No.	Author	Publication Volume
1	BRANDT KRISTIN	7
2	WOLCOTT MICHAEL	6
3	HOWARTH DAVID	6
4	GRIGGS STEVEN	6
5	GUTIERREZ-ANTONIO.CLAUDIA	5
6	RICE STEPHEN	4
7	HEYNE JOSHUA	4
8	HERNANDEZ SALVADOR	2
9	GOSSLING STEFAN	2
10	ZHANG XIAO	2

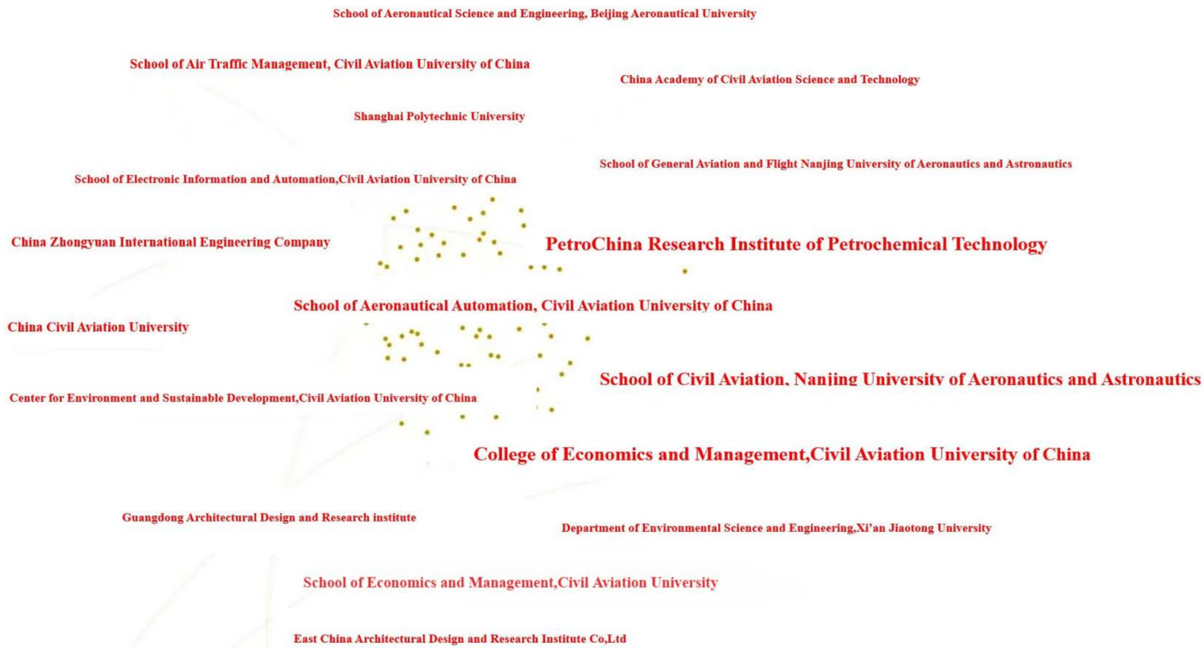

Figure 5. Domestic institutions co-occurrence knowledge map

First, from the perspective of the number of publications by authors, only a few researchers have shown a high level of attention to the low-carbon aviation industry. The rest of the scholars have relatively less research in this field. By 2022, domestically, researchers with a larger number of publications include Jingbo Deng, Lijun Tian, Jian Yu and Yan Lu. Notably, Jingbo Deng has 16 publications, and Lijun Tian has 6. Internationally, researchers with more publications in this field include BRANDT KRISTIN, WOLCOTT MICHAEL, HOWARTH DAVID, GRIGGS STEVEN and GUTIERREZ-ANTONIO.CLAUDIA, with 7, 6, 6, 6 and 5 publications, respectively. It is noticeable from the map that there are more domestic researchers in this field compared to international researchers.

Second, regarding collaboration, domestic researchers tend to work independently, while international researchers show more collaboration. From Figure 3 and Figure 4, they can be seen that there are relatively more authors focused on low-carbon aviation industry research. However, most nodes representing domestic scholars are isolated, indicating a lack of collaborative relationships between most authors. Some scholars frequently publish independently, while international researchers have more connections, suggesting closer collaborative relationships among them.

3.2.2 Analysis of research institutions and their collaboration relationships

To comprehensively understand the research influence and strength of institutions related to the low-carbon aviation industry, a statistical analysis of research institutions and their collaboration situations was conducted. After standardizing the selected literature data, it was imported into CiteSpace software, with the analysis item set to "institutions." For domestic literature, the timeframe was chosen as 2000-2022 to draw a co-occurrence map of research institutions related to the low-carbon aviation industry. Each node in the map represents a research institution, and the lines between nodes reflect the collaboration relationships between different institutions. The results showed a node count of N=248 and a link count of E=123, with a network density of Density=0.004. This indicates that 248 institutions and 123 links between institutions were selected in the co-occurrence knowledge map of research institutions in the low-carbon aviation industry. For international literature, the timeframe was set as 1993-2022, and a similar co-occurrence map was drawn, showing a node count of N=336 and a link count of E=162, with a network density of Density=0.0047.

Figure 6. International institutions co-occurrence knowledge map

Table 3. Top ten domestic research institutions in low-carbon aviation industry by publication volume (2000—2022)

No.	Institution Name	Publication Volume (Papers)
1	College of Economics and Management, Civil Aviation University of China	9
2	Civil Aviation College, Nanjing Univ of Aeronaut & Astronaut	5
3	College of Aviation Automation, Civil Aviation University of China	4
4	Civil Aviation University of China	3
5	China Zhongyuan International Engineering Company	3
6	Chengdu Aviation Vocational and Technical College	3
7	China National Petroleum Corporation Limited	3
8	Air Traffic Management College, Civil Aviation University of China	3
9	East China Architectural Design and Research Institute	2
10	Guangdong General Institute of Architectural Design Research	2

Table 4. Top ten international research institutions in low-carbon aviation industry by publication volume (1993—2022)

No.	Institution Name	Publication Volume (Papers)
1	Univ. Utrecht	2
2	Univ. Guanajuato	2
3	Univ. Autonoma Queretaro	2
4	Univ. Sydney	2
5	Tech. Univ. Carolo Wilhelmina B.	2
6	Univ. Kebangsaan Malaysia	1
7	Qingdao Univ. Sci. & Technol.	1
8	Budapest Univ. Technol. & Econ.	1
9	Swiss Fed. Inst. Technol.	1
10	Florida Inst. Technol.	1

From Figure 5, it can be seen that domestically, the institutions with the most publications include College of Economics and Management, Civil Aviation University of China, Civil Aviation College, Nanjing Univ. of Aeronaut & Astronaut, and College of Aviation Automation, Civil Aviation University of China. Others include Civil Aviation University of China, China Zhongyuan International Engineering Company, Chengdu Aviation Vocational and Technical College, China National Petroleum Corporation Limited, Air Traffic Management College, Civil Aviation University of China, East China Architectural Design and Research Institute, and Guangdong General Institute of Architectural Design Research. From Figure 6, internationally, the institutions with the most publications include the Univ. Utrecht, Univ. Guanajuato, Univ. Autonoma Queretaro, Univ. Sydney and Tech. Univ. Carolo Wilhelmina B, followed by Univ. Kebangsaan Malaysia, Qingdao Univ. Sci. & Technol., Budapest Univ. Technol. & Econ., Swiss Fed. Inst. Technol., Florida Inst. Technol. The specific publication volumes are listed in Table 3 and Table 4.

An analysis of Figure 4 reveals that domestic institutions have lower frequency of collaboration compared to international institutions, which exhibit closer cooperation. Institutions located geographically closer tend to have more collaborations, while those farther apart have fewer collaborations.

4 Visualization Analysis of Research Hotspots and Evolutionary Trends in Domestic and International Low-Carbon Aviation Industry

4.1 Research Hotspot Analysis

4.1.1 Keyword co-occurrence analysis

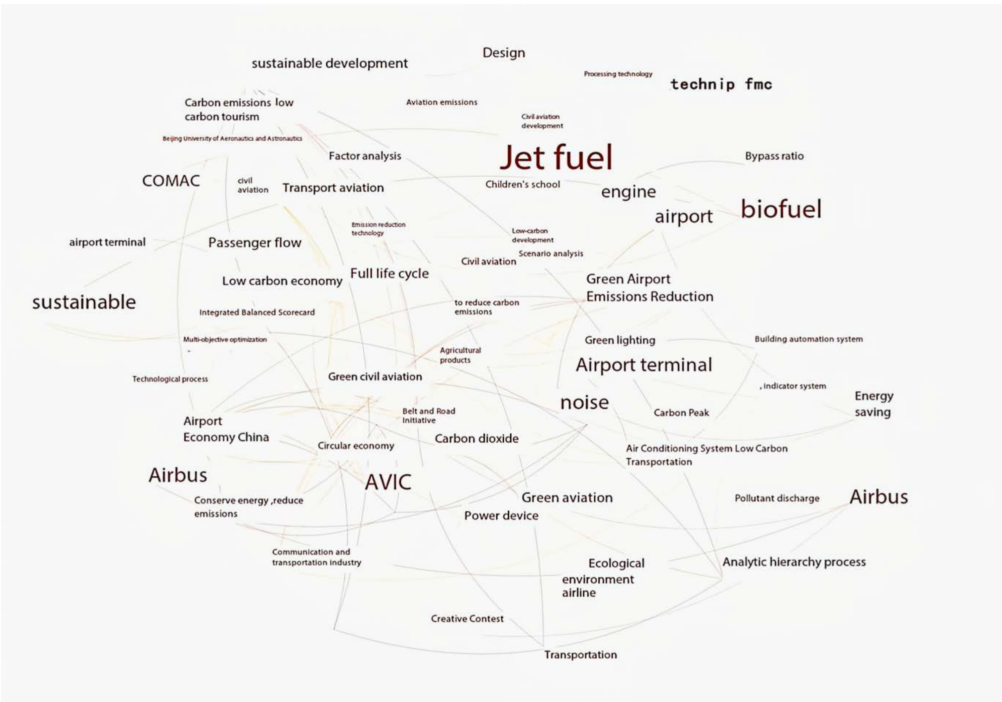

Figure 7. Domestic keyword co-occurrence map

Keyword co-occurrence analysis is a crucial step in analyzing the research hotspots of a given field. In this study, the keyword knowledge map for domestic and international low-carbon aviation industry research was created using CiteSpace. After standardizing the sample literature data, it was imported into CiteSpace, with the data cluster point type set to "keyword." For domestic literature, the timeframe was set to 2000—2022, and for international literature, it was set to 1993-2022, thus creating a co-occurrence map of research keywords in the low-carbon aviation industry (see Figure 7 and Figure 8). Analyzing these figures lead to several conclusions: Firstly, the term "Jet fuel" appears most frequently in domestic research, with 9 occurrences and a centrality of 0.29. In contrast, "Bioma" appears 21 times with a centrality of 0.51 in international research; Secondly, the quantity of keywords in domestic research is slightly less than in international research, indicating that international research has a higher intensity than domestic; Lastly, the connections between keywords are denser in international research, suggesting that these interconnected keywords are often cited together by international scholars, indicating a higher relevance among them.

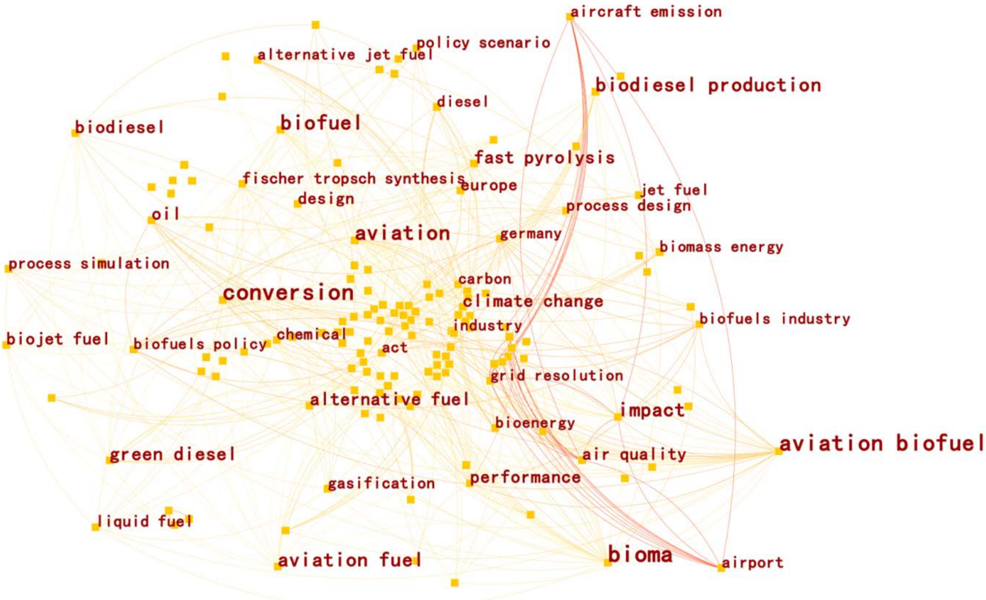

Figure 8. International keyword co-occurrence map

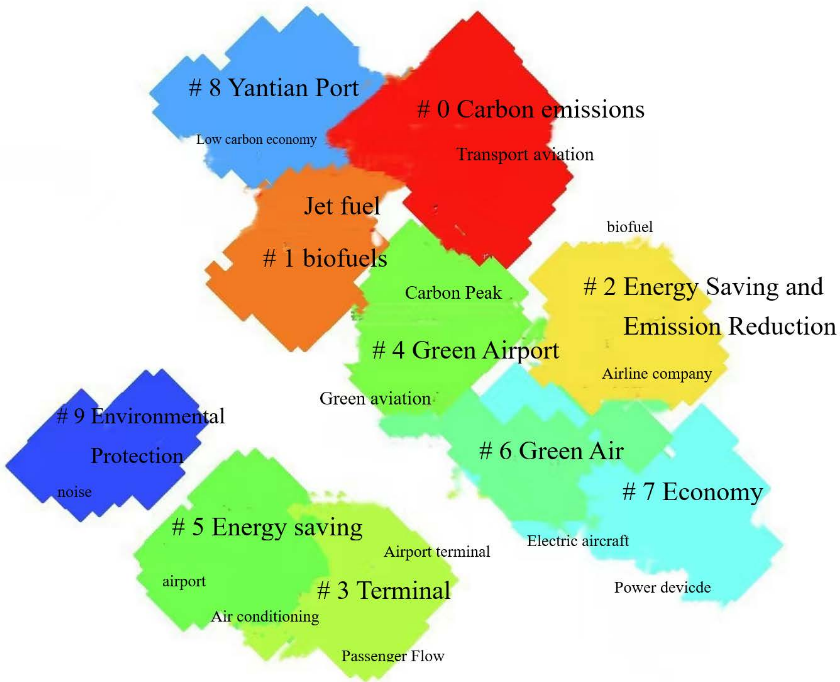

Figure 9. Domestic keywords cluster map

4.1.2 Keyword clustering analysis

Keyword clustering involves summarizing and extracting research themes from the keyword co-occurrence knowledge map, visually displaying the research fields [15]. After importing and running domestic and international data separately in CiteSpace, the keyword clustering map (shown below) can be obtained. From Figure 9, the clustering modularity values for both domestic and international research are greater than 0.3, indicating significant clustering structures. The average silhouette values (S) are greater than 0.7, suggesting that the clustering results are credible and convincing.

(1) Domestic Low-Carbon Aviation Industry Research Cluster Analysis

From the cluster map, it can be observed that there are ten major clusters: Carbon emissions, Biofuels, Energy saving and emission reduction, Terminal, Green airport, Energy saving, Green aviation, Economy, Yantian port and Environmental protection. This indicates that domestic research in the low-carbon aviation industry is closely related to civil aviation, aircraft fuels, emissions, and green environmental practices. The largest cluster (#0) consists of 49 members with a silhouette value of 0.97. The second-largest cluster (#1) has 31 members with a silhouette value of 0.974. The third-largest cluster (#2) comprises 30 members with a silhouette value of 0.957. The fourth-largest cluster (#3) includes 27 members with a silhouette value of 0.976. The main cluster members are listed in the Table 5 below:

Table 5. Main cluster members of domestic keywords

Cluster	Main Cluster Members
Carbon emissions	carbon emissions, carbon reduction, air transport, low-carbon transport, geographical, fleet
Biofuels	alternative fuels, jet fuels, biofuels, sustainable, comac
Energy saving and emission reduction	energy saving, factor analysis, fuel saving, airline, energy saving
Terminal	terminal building, ventilation, air conditioning system, natural lighting; Natural ventilation
Green airport	airport, green airport, airport economy, circular economy, energy saving and consumption reduction
Energy saving	energy saving, airport, large, cooling water, retrofit
Green aviation	avic, green aviation, combination of industry and finance, laminar flow wing, intelligence
Economy	economy, power unit, electric aircraft, engine, business jet
Yantian port	carbon tax, Civil Aviation, Yantian port, logistics park, China civil Aviation Industry
Environmental protection	engine, noise, bypass ratio, energy saving, fan blades, pollution emission, low emission, environmental protection, legal system

(2) International Low-Carbon Aviation Industry Research Cluster Analysis

The cluster map reveals that there are nine major clusters in international research on the low-carbon aviation industry. These clusters are Aviation Fuel, Renewable Jet Fuel, Alcohols, Greenhouse Gas Emissions, Process Simulation, Aircraft Emissions, Biokerosene, Reactive Distillation and Hydrogen Storage Tank Structure. It is evident that international research in the low-carbon aviation industry is closely related to civil aviation fuel and emissions. The largest cluster (#0) consists of 27 members with a silhouette value of 0.877. The second-largest cluster (#1) includes 21 members with a silhouette value of 0.94. The third-largest cluster (#2) is composed of 19 members with a silhouette value of 0.956. The fourth-largest cluster (#3) has 18 members with a silhouette value of 0.855. The fifth-largest cluster (#4) also includes 14 members, but with a silhouette value of 0.909. The sixth-largest cluster (#5) comprises 12 members with a silhouette value of 1. The main members of each cluster are detailed in Table 6.

From Figure 10, it's clear that the degree of connection between different cluster units varies. Clusters like Renewable Jet Fuel (#1), Greenhouse Gas Emissions (#3) overlap significantly, indicating high interrelation and co-citation frequency among these research hotspots, while other more independent keyword clusters have relatively weaker connections. Some clusters contain fewer keywords, suggesting their silhouette values (S) are less than 0.5, making them less significant for cluster research, and thus not displayed in the map. International scholars have formed 9 keyword clusters around low-carbon aviation research, with most keyword clusters overlapping, indicating high interrelation among international keywords.

Table 6. Main cluster members of international keywords

Cluster	Main Cluster Members
Aviation fuel	aviation fuel; zsm-5 nanosheet catalysts; chemical liquid deposition; acid spatial distribution; gas turbine engine performance
Renewable jet fuel	alternative jet fuel; climate change; renewable jet fuel; life-cycle assessment
Alcohols	biofuels policy; aviation biofuels; biofuels industry; sustainable chemistry; techno-economic analysis
Greenhouse gas emissions	renewable energy; international shipping; greenhouse gas
Process simulation	techno-economic analysis; policy scenario; process simulation; aviation biofuel; microalgae species
Aircraft emissions	aircraft emissions; air quality; cmaq; particulate matter; grid resolution; population exposure
Biokerosene reactive distillation	strategic niche management; aviation biofuel; biojet fuel reactive distillation; biojet fuel; hydroprocessing
Hydrogen storage tank structure	hydrogen-powered UAV; hydrogen storage tank structure; composite materials; impact dynamics; crash characteristics analysis

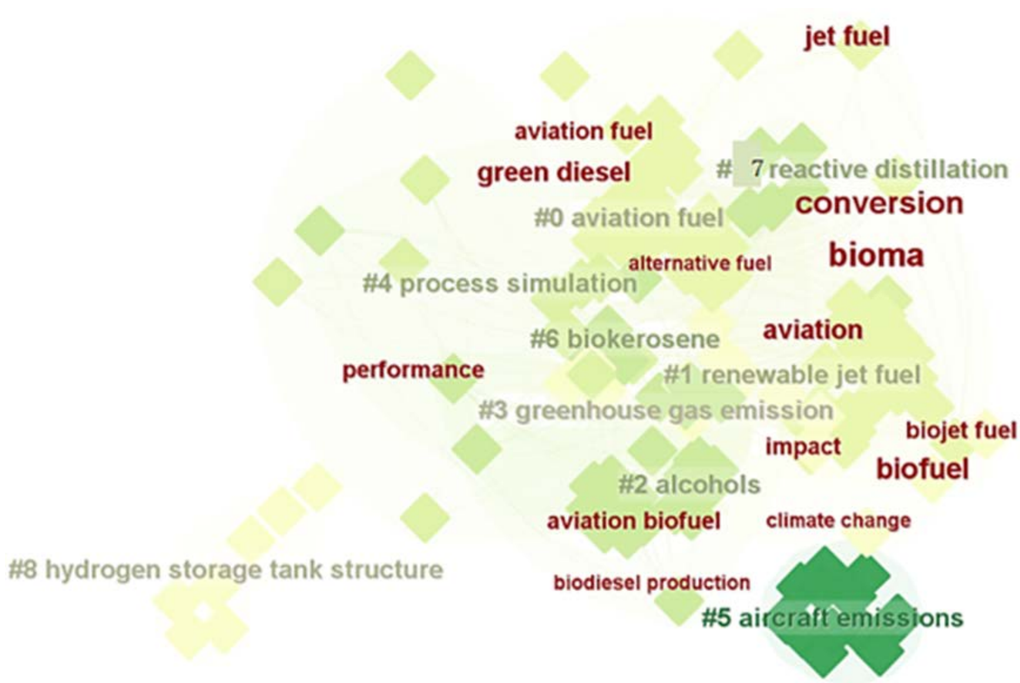

Figure 10. International keyword cluster map

4.2 Research Frontier Trend Analysis

CiteSpace II is a system capable of studying the evolution of any industry or profession and is widely used by scholars. In the same network visualization, research frontiers are identified using trending terms rather than frequently occurring title words, making it more suitable for detecting new trends and shifts [8].

4.2.1 Keyword burst analysis

Keyword burst analysis detects keywords with high frequency change rates, thus determining the cutting-edge content in a research field [16]. The analysis of keyword bursts in the low-carbon aviation industry research field reveals the top six bursting keywords domestically and internationally, as shown in Table 7 and Table 8.

(1) Domestic Keyword Burst Analysis

As seen in Table 7, Energy conservation first became a focus of scholars in 2003. In 2010, with the global growth of biofuels, biofuel also emerged as a research hotspot. In 2017, air transportation started gaining attention. In 2019, the Ministry of Science and Technology and the Ministry of Industry and Information Technology issued the *Twelfth Five-Year Plan for Energy Conservation and Emission Reduction* and the *Energy Conservation and Emission Reduction Technology Special Action Plan*, making energy conservation and emission reduction a research focus. In 2020, the Green Airport Benchmarking System was explicitly proposed, and by 2022, the construction standards for green airports were being researched and refined. The system is expected to be fully established by 2030, with airport green sustainable development anticipated to be fully realized by then. Thus, the focus on green airports has been increasing. Currently, the frontier trends in domestic research on low-carbon aviation include Energy conservation, biofuel, air transportation, energy conservation and emission reduction and green airport.

Table 7. Analysis of domestic citation burst literature

Top 6 Keywords with the Strongest Citation Bursts				
Keywords	**Year**	**Strength**	**Begin**	**End**
energy conservation	2003	2.16	2003	2009
biofuel	2010	2.27	2010	2015
air transportation	2017	1.98	2017	2022
green civil aviation	2018	2.15	2018	2022
energy conservation and emission reduction	2015	2.04	2019	2022
green airport	2009	1.9	2020	2022

Table 8. International burst literature analysis

Top 6 Keywords with the Strongest Citation Bursts				
Keywords	**Year**	**Strength**	**Begin**	**End**
forensic science	1993	2.09	2004	2022
emission	1993	2.25	2011	2022
culture	1993	2.13	2013	2022
safety	1993	2.95	2016	2022
civil aviation safety	1993	2.16	2017	2022
model	1993	3.28	2018	2022

(2) International Keyword Burst Analysis

The analysis of Table 8 reveals the following insights into the international research trends in the low-carbon aviation industry: The keyword with the strongest burst starting in 2018 is “model”. The keyword with the longest burst duration is “forensic science”, before 2011, “forensic science” was the only predominant research area. In 2011, “emission” emerged, marking the start of research into low-carbon sustainable development. In 2013, international researchers began discussing the “culture” of low-carbon aviation. Scholars like Balcerzak [17] addressed issues like reconciling the interests of aviation safety culture, namely a just culture, with the demands of institutions and traders involved in implementing air transportation and exploring aviation measurement effects. By 2016, “safety” became a focus area, in 2016, international scholars began to explore the “safety” domain in greater depth, for instance, South Korean researchers Kim and Yang [18] recognized that aviation safety could vary due to the safety behaviors of individuals. They used survey methods to study perceptions of safety culture and climate in low-cost airlines. This area of research has continued to the present day. For example, Power et al. [19] outlined the agenda for reforming indigenous health and cultural safety courses in Australian higher education institutions. It was not until 2017 that international scholars conducted more detailed exploration in the “safety” field, specifically focusing on “civil aviation safety.” Starting in 2018, “model” emerged as a new research hotspot and has continued to be a focus area. For instance, Paul et al. [20] conducted a comparison between cognitive effect modeling scenarios based on the SAFTE-FAST sleep behavior model and its default settings (pre-coordination) and those based on behaviorally measured sleep. They then coordinated the measured sleep with the predicted sleep to optimize the accuracy of the sleep behavior algorithm. This study aimed to validate the sleep behavior model settings of the fatigue modeling tool (Fatigue Avoidance Scheduling Tool) used in the RCAF, taking into account organizational requirements before and after flights, especially in airborne forces. Currently, the leading trends in international research in the low-carbon aviation industry include forensic science, emission, culture, safety, civil aviation safety, and model.

4.2.2 Time zone view analysis

The Time Zone View consists of a series of vertical bands representing different time zones, primarily displaying the evolution of the knowledge map from a temporal perspective. It not only clearly shows the relationships between documents but also vividly presents the updates of the literature. The time zones are arranged from left to right in chronological order, aligning research frontiers with their knowledge bases. The "Time Zone" feature in CiteSpace can display both the referenced terms and the referenced literature, facilitating the mapping of research frontiers to their knowledge bases.

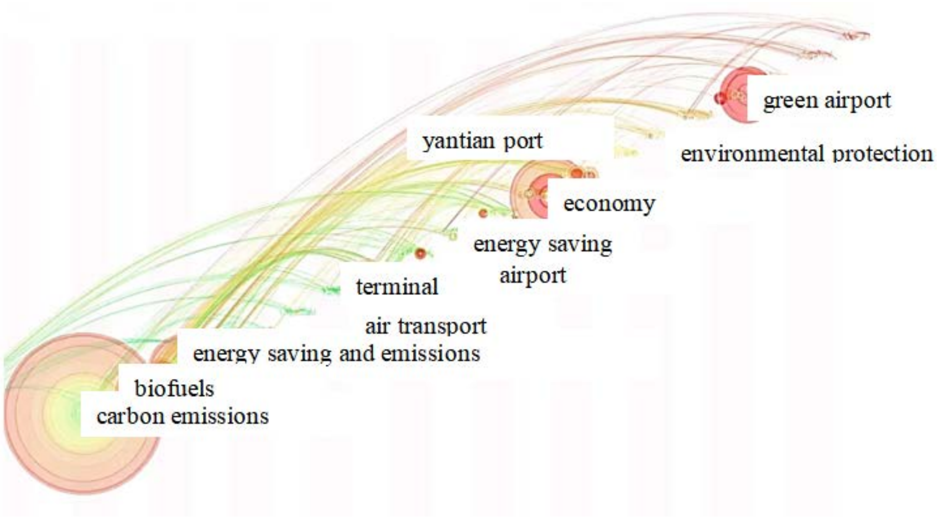

Figure 11. Domestic keyword time zone map

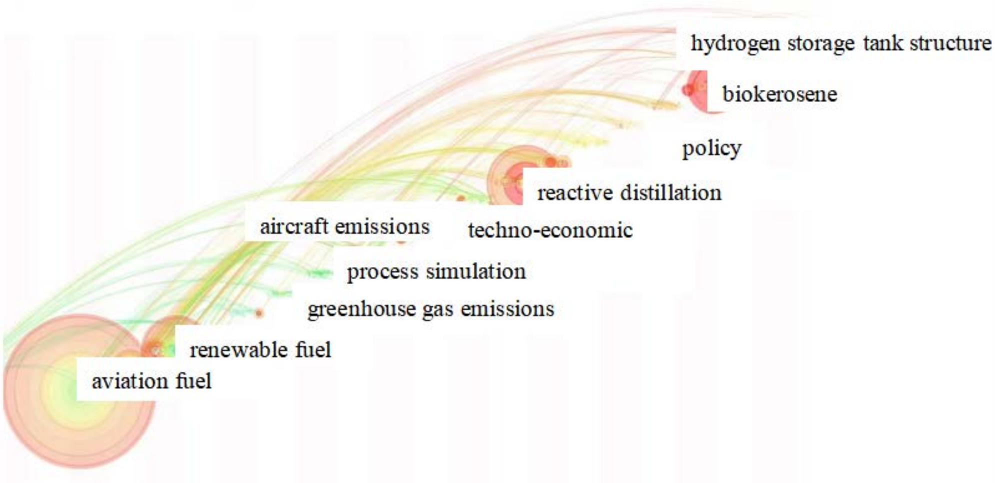

Figure 12. International keyword time zone map

In this study, using the Time Zone function in CiteSpace, the time zone view of domestic and international low-carbon aviation industry keywords was compiled, as shown in Figure 11 and Figure 12. Figure 11 and Figure 12 clearly demonstrate the evolution of research hotspots and frontiers in this field, aiding in predicting the development trends of the domestic and international low-carbon aviation industry in the coming years. An analysis of Figure 11 and Figure 12 lead to the following conclusions: Between 2005 and 2011, scholars mainly focused on the status of carbon dioxide emissions and civil aviation. Starting in 2011, scholars embarked on new directions, delving deeper into the low-carbon aviation industry. In recent years, in line with the development of national policies, topics such as Energy conservation, biofuel, air transportation, energy conservation and emission reduction and green airports have emerged as research frontiers. A comparison of domestic and international time zone views reveals that in recent years, domestic research has shown a higher focus on high-quality development in low-carbon aviation. In the coming years, domestic research on green and sustainable development is expected to exceed the intensity of international research in this field.

5 Publication Volume Prediction

5.1 Exponential Smoothing Method

The Exponential Smoothing Method is a time series analysis and forecasting method developed from the moving average method (Table 9). It involves analyzing the entire historical sequence data of the forecasting object, calculating exponential smoothing values, and using time series prediction models to forecast the development trends of a subject [21]. The selections of the smoothing coefficient and the numbers of smoothing operations are as follows:

Table 9. International burst literature analysis

Exponential Smoothing Forecasting	Determination of Smoothing Coefficient α Value [16] $(0 \le \alpha \le 1)$	1. Determine the range of α value according to the change pattern of the time series	Minor fluctuations	$0.1 - 0.3$
			Clear fluctuation tendencies	$0.6 - 0.9$
		2. Trial calculation, determine α value based on the principle of minimizing forecast error	Select multiple α values for calculation, determine α value	
	Selection of Smoothing Times	Single Exponential Smoothing	Generally used for series without obvious change trends Formula: $\mathrm{Dt(1st)} = \alpha yt + (1-\alpha)\mathrm{Dt} - 1(\mathrm{1st})$	
		Double Exponential Smoothing	Based on single smoothing, generally used for series with linear change trends Formula: $\mathrm{Dt(2nd)} = \alpha \mathrm{Dt(1st)} + (1-\alpha)\mathrm{Dt} - 1(\mathrm{2nd})$	
		Triple Exponential Smoothing	Based on double smoothing, generally used for series with quadratic curve change trends Formula: $\mathrm{Dt(3rd)} = \alpha \mathrm{Dt(2nd)} + (1-\alpha)\mathrm{Dt} - 1(\mathrm{3rd})$	

In the table, Dt is the exponential smoothing value for period t; Dt-1 is the exponential smoothing value for period t-1; α is the smoothing coefficient.

Observing the distribution chart of the number of domestic low-carbon aviation industry research literature, it can be seen that the domestic publication volume shows a quadratic curve change trend. According to the Table 7 above, the triple exponential smoothing method should be used to predict the publication volume.

5.2 Exponential Smoothing Method Forecasting

In the triple exponential smoothing model for each period, there is an alpha value that minimizes the root mean square error (RMSE), which is used to measure the accuracy of the forecast. A smaller RMSE value indicates a better fit. Since the time series of domestic low-carbon aviation industry research publication volume shows a quadratic curve trend, the analysis of the data in Table 10 indicates that the alpha value minimizing the RMSE is 0.2. The highest publication volume domestically was in 2013 with 31 papers, indicating a relatively low level of research intensity in the domestic low-carbon aviation field, suggesting greater potential for development in this area by researchers.

Table 10. Domestic publication volume triple exponential smoothing model RMSE

No.	Initial Value S0	Alpha Value	Smpothing Type	RMSE Value
0	1.5	0.05	Triple Smoothing	9.458
1	1.5	0.1	Triple Smoothing	8.156
2	**1.5**	**0.2**	**Triple Smoothing**	**7.587**
3	1.5	0.3	Triple Smoothing	7.708
4	1.5	0.4	Triple Smoothing	8.301
5	1.5	0.5	Triple Smoothing	9.103
6	1.5	0.6	Triple Smoothing	10.048
7	1.5	0.7	Triple Smoothing	11.181
8	1.5	0.8	Triple Smoothing	12.685
9	1.5	0.9	Triple Smoothing	14.887
10	1.5	0.95	Triple Smoothing	16.389

Note: Blue data represents the best parameter identified by the model.

With the data series between 10-20, the average value of the first two periods is set as the initial value. Among the 11 models predicted, model number 2 with triple exponential smoothing has the smallest RMSE, making it the best model with an initial value of 1.500, alpha value of 0.200, and triple smoothing type, where the RMSE is 7.215. Using these parameters, the model is constructed to obtain the forecasted values (see Table 11).

Table 11. Model forecast value table

No.	Initial Value	Forecast Value	Absolute Error
2000	2	2	0
2003	1	1.8	0.8
2005	2	1.38	0.62
2006	1	1.72	0.72
2007	10	1.328	8.672
2008	13	6.487	6.513
2009	29	11.389	17.611
2010	19	23.797	4.797
2011	18	24.992	6.992
2012	17	24.553	7.553
2013	31	23.16	7.84
2014	28	30.261	2.261
2015	21	32.346	11.346
2016	19	28.876	9.876
2017	16	25.076	9.076
2018	24	20.629	3.371
2019	24	22.54	1.46
2020	18	23.616	5.616
2021	28	20.555	7.445
2022	22	24.602	2.602
2023	-	23.415	-
2024	-	23.436	-
2025	-	23.397	-
2026	-	23.297	-
2027	-	23.136	-
2028	-	22.914	-
2029	-	22.632	-
2030	-	22.288	-
2031	-	21.884	-
2032	-	21.419	-
2033	-	20.892	-
2034	-	20.305	-

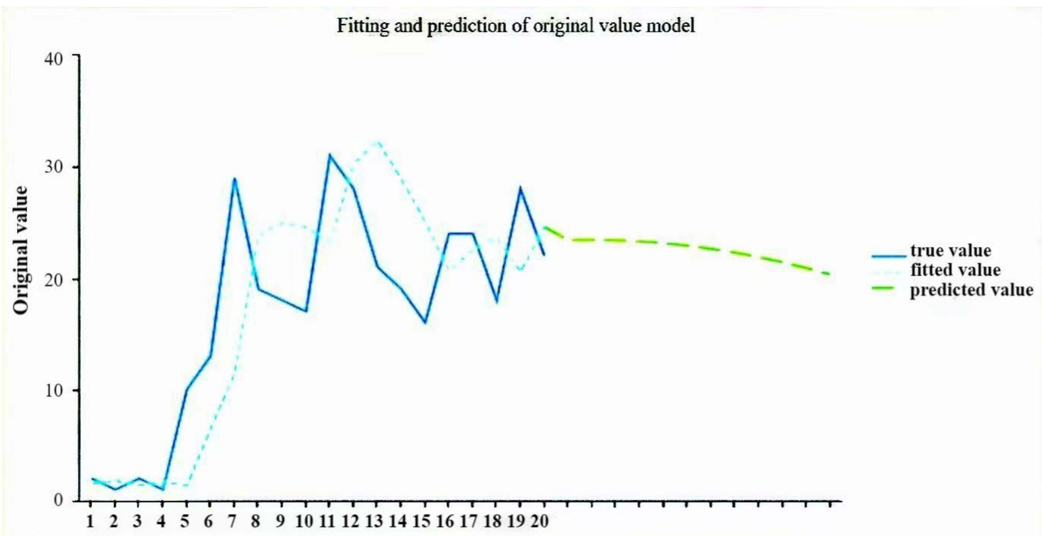

Figure 13. Domestic publication volume forecasting effect fitting chart

From Table 11, it is predicted that the publication volume of domestic research on the low-carbon aviation industry could reach approximately 23 papers annually from 2023 to 2029, around 22 papers in 2030 and 2031, about 21 papers in 2032 and 2033, and around 20 papers in 2034 (The forecasted publication volumes are rounded to the nearest whole number).

Analysis of Figure 13 forecasting effect fitting chart intuitively shows the development pattern of domestic scholars' publication volume in the field of low-carbon aviation industry over time. Additionally, the observation of the chart indicates that the model has a good fit, predicting a gradual yearly decrease in the publication volume by domestic scholars in the low-carbon aviation industry field over the next 12 years.

6 Conclusions and Suggestions

This paper selects literature from core journals and CSSCI journals in the CNKI database and the WOS database, and utilizes CiteSpace bibliometric software to conduct a visual analysis of research hotspots and evolutionary trends in low-carbon aviation industry research literature from 1993 to 2022 [22]. The analysis includes the time series trend of literature publication, authors and their collaboration relationships, research institutions and their collaboration relationships, keyword co-occurrence analysis, keyword clustering analysis, and time zone view analysis. The research hotspots and frontier trend maps of domestic and international low-carbon aviation industry research literature were drawn, leading to the following conclusions: first, the study of the publication time distribution reveals that domestic low-carbon aviation industry research shows slight fluctuation and is closely related to the national economic situation and policies [23, 24]. In contrast, international research in this field shows a steady growth trend. Second, through the analysis of keyword co-occurrence, the research hotspots in the domestic low-carbon aviation industry are mainly focused on Energy conservation, biofuel, air transportation, energy conservation and emission reduction and green airports. In contrast, the international research frontiers are mainly concentrated on forensic science, emission, culture, safety, civil aviation safety, and model. Third, there are fewer collaboration relationships domestically compared to internationally. Therefore, domestic research in the low-carbon aviation field should enhance collaboration for faster development in this area. Fourth, international research in this field started earlier, while domestic research began later, leading to most domestic scholars publishing independently without forming research teams [25].

Through the aforementioned comparative analysis, it can be observed that with the implementation of national policies and economic development, the low-carbon aviation industry is increasingly attracting the attention of scholars both domestically and internationally. Based on the comparative analysis of research hotspots at home and abroad, it can be concluded that domestic research hotspots are somewhat monotonous, mostly focusing on reducing emissions, while international research directions are more diversified. Therefore, domestic scholars could try to explore broader research directions instead of being confined to a narrow scope. This paper analyzes the field of domestic and international low-carbon aviation using bibliometric methods through CiteSpace, aiming to provide researchers in this field with a clearer and more intuitive view of the research hotspots and evolutionary trends. However, considering that the research data only come from two databases, the comprehensiveness of the studied data cannot be fully assured. Additionally, setting different values for various parameters in the CiteSpace process may lead to slightly inconsistent results. Therefore, these factors could result in the research not being entirely precise. Nevertheless, the research findings can still provide some reference for the research hotspots and evolution in the field of low-carbon aviation both domestically and internationally.

Based on the above conclusions, this study's theoretical and practical contributions can be analyzed as follows:

(1) Theoretical Contribution The concept of "low carbon" has been a hot topic in the academic world in recent years. Previous research on low-carbon aviation in China mainly focused on Energy conservation, biofuel, air transportation, energy conservation and emission reduction and green airports. Internationally, the focus was on forensic science, emission, culture, safety, civil aviation safety, and model. This research enriches the theories related to low-carbon aviation, providing new analytical perspectives, expanding new research spaces, and enriching new theoretical materials. On the other hand, studying low-carbon aviation can help the aviation industry combine its strengths, pay timely attention to external factors including national policies and public customs, understand demands, and find suitable development paths. Therefore, researching the hotspots and evolutionary trends of low-carbon aviation can provide references for the development of aviation enterprises and has theoretical significance.

(2) Practical Contribution By reviewing and analyzing literature on low-carbon aviation under the guidance of low-carbon goals, current concentrated research themes were identified. Suggestions were given in line with current market evolution, national policies, and development stages. Facing the current advocacy for a low-carbon environment, this study contributes to the improvement of low-carbon aviation development and the realization of aviation energy conservation and environmental protection goals through visual analysis of existing literature. It also provides reference points for the development of Chinese aviation companies, supplementing the practical application of the low-carbon aviation industry.

In summary, this study proposes the following suggestions: First, improve the quality and depth of research in the low-carbon aviation industry. The field needs more innovative and interdisciplinary research, and enhancing the impact of academic achievements can drive continuous progress in China's low-carbon aviation. Second, strengthen author collaboration, institutional cooperation, and academic exchange in the low-carbon aviation research field. The government should actively guide authors and institutions in research to enhance the quality of research outcomes. Currently, domestic author and institution cooperation is sparse, with small-scale cooperation formed, but there is potential for development. Establishing core academic researchers, building research cooperation platforms, and enhancing the enthusiasm of peripheral researchers for collaboration can promote author cooperation in the field. Outstanding research institutions should strengthen their capacity building and research capabilities, actively build a cooperative system in low-carbon aviation, promote in-depth cooperation among researchers in different regions, achieve mutual benefit, and form systematic and standardized scientific research teams to promote synchronized development in related research areas. Third, keep up with the trend of the times, and expand the research perspectives on hot topics in the low-carbon aviation field. In a series of studies, targeted learn from advanced foreign research experiences and actively explore the value and path of low-carbon aviation in accordance with national policy requirements. Fourth, attempt to use a combination of quantitative and qualitative research methods in designing and conceptualizing research methodologies. The combination of qualitative and quantitative data can complement each other, with qualitative data supplementing the shortcomings of quantitative data, allowing for explanations of issues from different perspectives. Research results supported by various forms of data can lead to creative breakthroughs, making the outcomes more credible and enriched.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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