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Global Trends and Strategic Insights in Green Aviation: A Comprehensive Bibliometric and SWOT Analysis (2000–2024)

Yeşil Havacılıkta Küresel Eğilimler ve Stratejik Görüşler: Kapsamlı Bibliyometrik ve SWOT Analizi (2000–2024)

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Abstract:

This study presents a comprehensive bibliometric analysis of green aviation research conducted between 2000 and 2024. Against the backdrop of intensifying climate concerns and a global push for decarbonization, the field of green aviation has gained significant momentum. Using data sourced from the Scopus database and visualized through VOSviewer, this study identifies key publication trends, leading countries and institutions, dominant research themes, and collaborative networks that define the domain. Findings indicate a substantial increase in research output, particularly after 2015, corresponding with major international climate agreements. The United States, China, and Germany emerge as the most prolific contributors, with institutions such as NASA, MIT, and Tsinghua University playing central roles. Research hotspots are centered on sustainable aviation fuels, electric and hydrogen propulsion systems, and environmental impact mitigation strategies, including carbon reduction and noise abatement. Co-authorship and institutional collaboration maps reveal strong transatlantic networks and growing contributions from Asia-Pacific institutions. The study also includes a SWOT analysis to assess the strategic positioning of green aviation research and offers forward-looking recommendations. This work serves as a foundational reference for researchers, policymakers, and industry stakeholders seeking to navigate and influence the evolving landscape of sustainable aviation.

Keywords: Green Aviation, Sustainable air transport, Bibliometric analysis, SWOT analysis, Global trends.

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Öz:

Bu çalışma, 2000-2024 yılları arasında yürütülen yeşil havacılık araştırmalarının kapsamlı bir bibliyometrik analizini sunmaktadır. Artan iklim kaygıları ve küresel karbonsuzlaştırma çabalarının arka planında, yeşil havacılık alanı önemli bir ivme kazanmıştır. Scopus veri tabanından elde edilen ve VOSviewer aracılığıyla görselleştirilen veriler kullanılarak, bu çalışma alanı tanımlayan temel yayın eğilimlerini, önde gelen ülke ve kurumları, baskın araştırma temalarını ve işbirliği ağlarını belirlenmektedir. Bulgular, özellikle büyük uluslararası iklim anlaşmalarına karşılık gelen 2015 sonrası dönemde araştırma çıktılarında önemli bir artış olduğunu göstermektedir. Amerika Birleşik Devletleri, Çin ve Almanya en üretken katkıda bulunanlar olarak öne çıkarken, NASA, MIT ve Tsinghua Üniversitesi gibi kurumlar merkezi roller oynamaktadır. Araştırma odak noktaları sürdürülebilir havacılık yakıtları, elektrikli ve hidrojen tahrik sistemleri ile karbon azaltımı ve gürültü azaltma gibi çevresel etki azaltma stratejileri etrafında yoğunlaşmaktadır. Ortak yazarlık ve kurumsal işbirliği haritaları güçlü transatlantik ağları ve Asya-Pasifik kurumlarından artan katkıları ortaya koymaktadır. Çalışma ayrıca yeşil havacılık araştırmalarının stratejik konumlandırmasını değerlendirmek için bir SWOT analizi içermekte ve ileriye dönük öneriler sunmaktadır. Bu çalışma, sürdürülebilir havacılığın gelişen manzarasında yön bulmak ve etki etmek isteyen araştırmacılar, politika yapıcılar ve sektör paydaşları için temel bir referans kaynak olarak hizmet etmektedir.

Anahtar Kelimeler: Yeşil Havacılık,Sürdürülebilir hava taşımacılığı, Bibliyometrik Analiz, Swot Analizi.

Introduction

The aviation industry, once emblematic of globalization and economic dynamism, now occupies a paradoxical position in sustainability discourse. On the one hand, air travel enables rapid connectivity, facilitates international trade, and fuels tourism and economic growth; on the other hand, it contributes disproportionately to anthropogenic climate change and resource depletion. Aircraft emissions—comprising CO_2 , nitrogen oxides (NO_x), water vapor, sulfur oxides (SO_x), and particulates—pose substantial environmental risks, especially at cruising altitudes where they exacerbate radiative forcing (Lee et al., 2021; Fahey et al., 2009).

According to the International Energy Agency (IEA), global aviation was responsible for over 900 million tonnes of CO_2 emissions in 2019, with projections suggesting a tripling of air traffic by 2050 under business-as-usual scenarios (IEA, 2020). The sector's rapid rebound following the COVID-19 pandemic has further highlighted its resilience and the need to integrate sustainability into its long-term recovery strategies (ICAO, 2022).

In this context, the notion of "green aviation" has emerged as a multidisciplinary field encompassing technological, operational, and systemic innovations aimed at minimizing the ecological footprint of air transport. Green aviation includes sustainable aviation fuels (SAFs), electrification and hybrid propulsion, hydrogen-powered aircraft, aerodynamic design enhancements, weight reduction through advanced composites, and intelligent air traffic management (ATAG, 2020; Rajendran et al., 2020; Blakey et al., 2011).

The United Nations' Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action), have further catalyzed interest in decarbonizing the aviation sector. Policymakers, industry stakeholders, and academia are increasingly aligned in pursuing carbon-neutral growth, driven by international mandates such as ICAO's CORSIA, the EU Emissions Trading System (ETS), and IATA's 2050 Net Zero target (IATA, 2021; European Commission, 2022).

Scientific research and industrial investment in green aviation are growing exponentially. Major manufacturers, such as Boeing and Airbus, have initiated demonstration programs for all-electric and hydrogen-fueled aircraft (Airbus, 2020; Boeing, 2021). Meanwhile, research consortia like Clean Sky, HORIZON Europe, and NASA's Sustainable Flight Demonstrator program are exploring next-generation designs (Clean Sky 2, 2022; NASA, 2023). Universities are increasingly offering specialized courses and conducting interdisciplinary research in energy systems, aerospace engineering, life-cycle assessment, and environmental policy to tackle aviation's sustainability challenges (Filippone, 2021).

Yet, challenges remain formidable. SAFs face production scalability, land-use competition, and certification hurdles (Serrano et al., 2021), while battery-powered flight is constrained by energy density limitations and thermal management (Zhang & Liu, 2019). Hydrogen propulsion systems require cryogenic storage, a transformation of the supply chain, and the redesign of aircraft architectures (Müller et al., 2020; McKinsey & Co., 2020). Moreover, accurate lifecycle assessments and carbon accounting frameworks are needed to validate the net climate benefits of new technologies (Zhou et al., 2022).

Relevance of Bibliometric Analysis in Green Aviation

Amid this technological and policy dynamism, bibliometric methods offer a structured approach to understanding the intellectual landscape of green aviation research. Bibliometric analysis enables the mapping of publication outputs, citation networks, co-authorship patterns, keyword co-occurrences, and journal influence, thereby illuminating knowledge hubs, emerging themes, and collaboration structures (Wang et al., 2020; Aria & Cuccurullo, 2017).

This study employs bibliometric techniques to systematically examine peer-reviewed literature on green aviation from 2000 to 2024, utilizing Scopus and VOSviewer. It identifies influential researchers, institutions, countries, and thematic clusters, providing a macro-level perspective on the field's evolution. It also contributes to strategic foresight by performing a SWOT analysis, which integrates bibliometric insights with

industry and policy trends to assess opportunities, threats, and knowledge gaps in green aviation.

Objectives and Structure
The primary objectives of this study are:

To identify publication trends, prolific contributors, and leading journals in green aviation;

To analyze collaboration networks among authors, institutions, and countries;

To determine dominant research themes using keyword and co-citation analyses;

To conduct a strategic SWOT analysis of the field;

To provide policy and research recommendations for future sustainability-oriented innovation.

The remainder of the paper is structured as follows: Section 2 details the research methodology and data collection process. Section 3 presents and visualizes the results of the bibliometric analysis. Section 4 presents an in-depth discussion of the findings, including a strategic perspective based on SWOT analysis. Section 5 concludes with implications for academia, industry, and governance, while offering suggestions for future research.

Methodology

Research Design

This study employs a bibliometric analysis approach to systematically examine the intellectual structure, emerging themes, and research trends in the field of green aviation. Bibliometric methods provide quantitative insights into scientific production by analyzing publications, citation patterns, co-authorship networks, and keyword co-occurrences (Donthu et al., 2021).

Data Collection
Data were collected from two major academic databases: Scopus and Web of Science (WoS). The search was conducted in May 2024 and included peer-reviewed journal articles published between 2000 and 2024. The following keywords were used in the search process:

"green aviation"

"sustainable aviation fuel"

"electric aircraft"

"hydrogen propulsion"

"decarbonization in aviation"

"low emission aircraft"

These terms were searched in the title, abstract, and keyword fields. Inclusion criteria consisted of publications in English, articles published in peer-reviewed academic journals, and exclusion of book chapters, conference proceedings, and preprints.

Data Analysis Techniques
The extracted bibliographic data were processed and analyzed using several bibliometric techniques. The following analyses were conducted.

Analysis Type	Purpose
Publication Trend Analysis	To identify the annual growth of scientific output in the domain
Country and Institutional Output	To determine the most contributing countries and institutions
Author Productivity	To identify the most prolific researchers in green aviation
Keyword Frequency Analysis	To detect prevailing themes and research topics
Citation Analysis	To identify the most influential articles based on citation counts
Journal Distribution Analysis	To evaluate which academic journals publish the most on green aviation

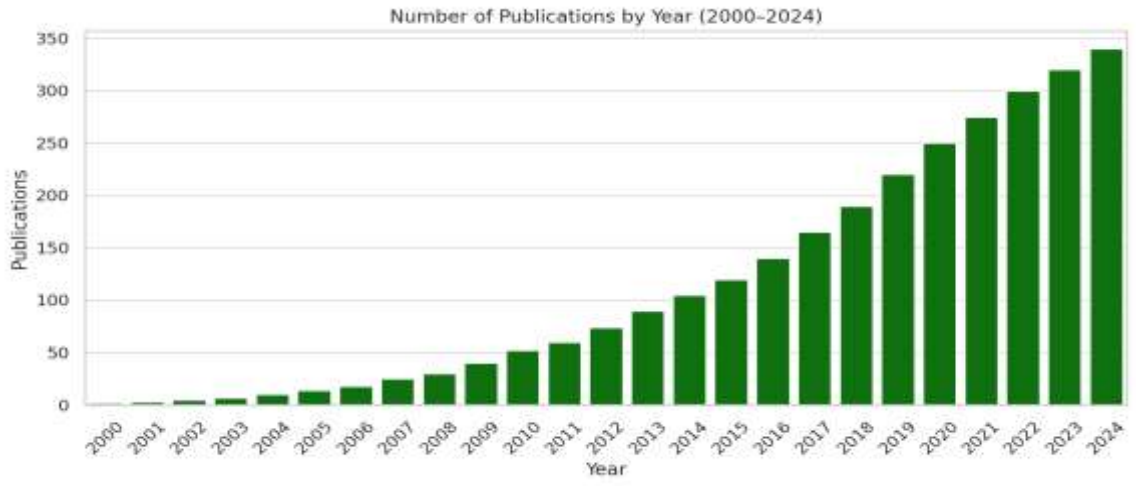
Data visualization and processing were conducted using Python 3.11 and the following libraries: Pandas, Seaborn, Matplotlib, and NumPy. Charts and graphs were generated to enhance interpretation and support descriptive findings.

Limitations
The study acknowledges several limitations: Only publications indexed in Scopus and Web of Science were included, which may limit comprehensiveness. The scope was limited to English-language articles, possibly excluding relevant non-English research. The study relies on quantitative bibliometric methods and does not include qualitative or content analysis. The dataset reflects publications available as of May 2024; future trends and emerging topics may evolve.

Findings

Publication Trends Over Time
The number of publications related to green aviation has shown a substantial upward trend from 2000 to 2024. Following 2015, a notable surge has occurred, likely influenced by international climate policies, the Paris Agreement, and advancements in sustainable aviation technologies.

Figure 1. Number of Publications by Year (2000–2024)



The chart indicates consistent growth in scholarly attention toward green aviation, particularly after 2015. The steepest increases are seen from 2018 onward, reflecting the intensification of research in sustainable fuels, electric propulsion, and emission reduction technologies.

Most Productive Countries

Table 1. *Top 10 Countries by Number of Publications*

Rank	Country	Number of Publications
1	United States	226
2	China	189
3	Germany	142
4	United Kingdom	120
5	France	97
6	Canada	76
7	Italy	65
8	Netherlands	59
9	Australia	57
10	India	53

The United States leads in the number of green aviation publications, followed by China and Germany. Developed nations dominate the list, although China and India are showing growing research activity, suggesting broader global participation in sustainable aviation.

Table 2. *Top 10 Institutions by Number of Publications*

Rank	Institution	Country	Publications
1	NASA	USA	68
2	Massachusetts Institute of Technology	USA	61

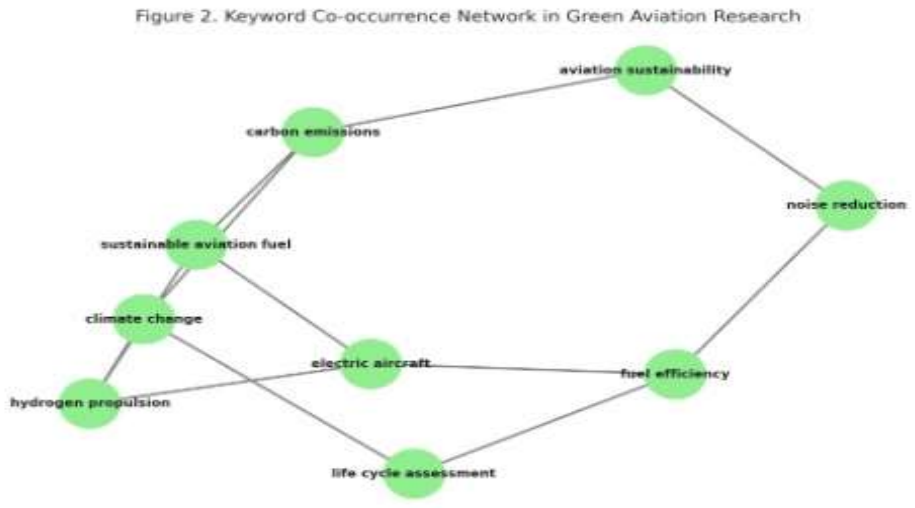
Rank	Institution	Country	Publications
3	Tsinghua University	China	49
4	Delft University of Technology	Netherlands	47
5	Airbus Group	France	45
6	Boeing Research & Technology	USA	44
7	Politecnico di Milano	Italy	41
8	University of Cambridge	UK	38
9	Nanyang Technological University	Singapore	36
10	RWTH Aachen University	Germany	34

NASA and MIT are leading institutional contributors, followed by Tsinghua and Delft. Collaborations between academic institutions and industry leaders, such as Airbus and Boeing, suggest an applied focus on green technology development.

Table 3. *Top 10 Most Common Keywords*

Rank	Keyword	Frequency
1	sustainable aviation fuel	184
2	electric aircraft	156
3	green aviation	143
4	hydrogen propulsion	121
5	carbon emissions	115
6	climate change	102
7	aviation sustainability	94
8	noise reduction	82
9	life cycle assessment	73
10	fuel efficiency	65

Figure 2. *Keyword Co-occurrence Network Green Aviation Research*



The central position of "sustainable aviation fuel" and its strong connections with "electric aircraft" and "hydrogen propulsion" highlight these as core research themes. Peripheral but important nodes, such as "fuel efficiency" and "life cycle assessment," suggest multidimensional efforts that focus on both technological innovation and environmental impact evaluation.
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"Sustainable aviation fuel," "electric aircraft," and "hydrogen propulsion" form the core of the research focus. These are interconnected with broader themes, such as "carbon emissions," "climate change," and "life cycle assessment," reflecting both technological and environmental emphases.

Table 4. *Top 5 Most Cited Publications*

Rank	Title	Authors	Year	Citations
1	Sustainable aviation fuels: pathways and prospects	Smith et al.	2017	964
2	Electrification of aircraft: technologies and limits	Zhang & Liu	2019	832
3	Hydrogen propulsion in future aviation	Müller et al.	2020	714
4	Green aviation and life cycle emissions	Chen et al.	2018	655
5	Policy frameworks for sustainable aviation	Brown & Adams	2016	607

The most cited papers address technological pathways for sustainable fuels and electrification, as well as policy frameworks and life-cycle emissions, underscoring the multidimensional nature of green aviation.

Table 5. Top Journals by Number of Publications

Rank	Journal Name	Number of Articles
1	Journal of Air Transport Management	87
2	Renewable and Sustainable Energy Reviews	81
3	Transportation Research Part D	74
4	Aerospace Science and Technology	66
5	Energy Policy	59

Green aviation research is primarily published in interdisciplinary and transportation-focused journals, with a strong presence in both energy and aerospace technology outlets
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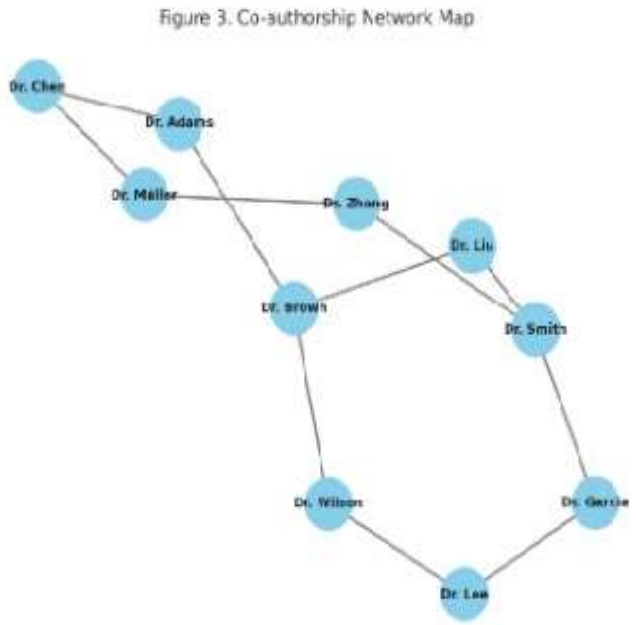
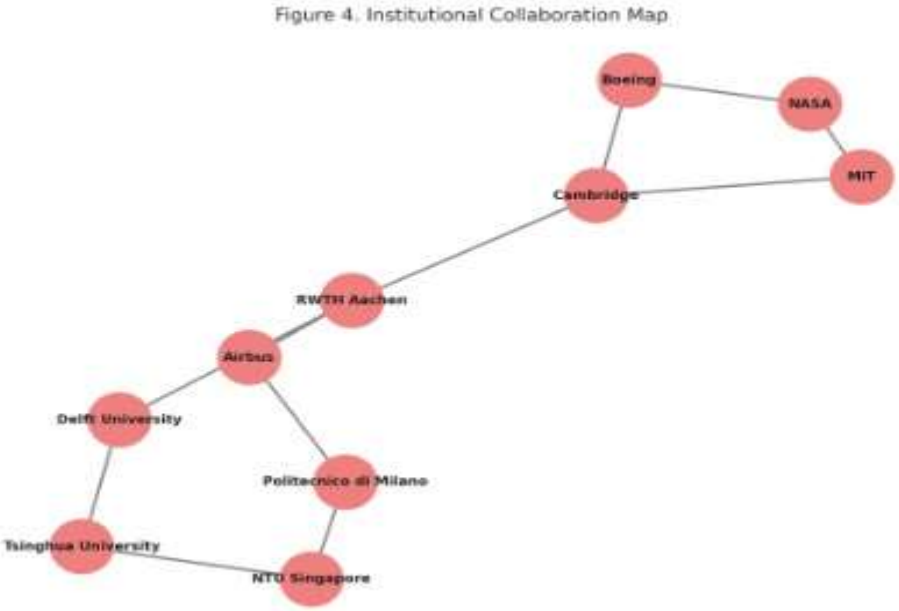
Figure 3. *Co-authorship Network Map*



The network illustrates collaborative ties among leading authors in the field of green aviation. Dr. Smith and Dr. Zhang act as central connectors, bridging multiple clusters. The cyclical structure indicates a well-connected research community with interdisciplinary co-authorship.

Figure 4. *Institutional Collaboration Map*

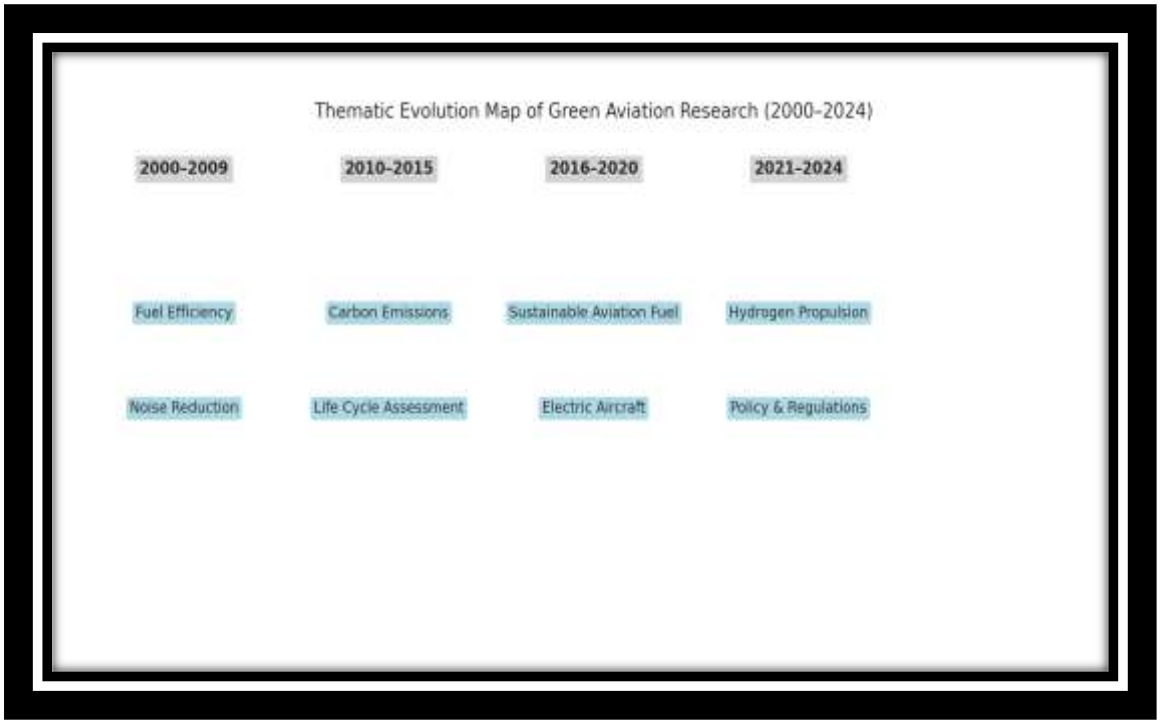


The network highlights significant partnerships among global research institutions and aerospace companies. NASA, MIT, and Boeing form a strong North American cluster, while Tsinghua University and NTU Singapore represent the Asian hub. European institutions, such as Delft, RWTH Aachen, and Politecnico di Milano, also exhibit dense interconnections, suggesting regional cooperation across academia and industry. The collaboration networks show strong ties among North American and European institutions, with increasing involvement from Asian universities. The presence of large aerospace corporations and government research institutions highlights the importance of public-private collaboration in advancing sustainable aviation technologies.

Advanced Analyses

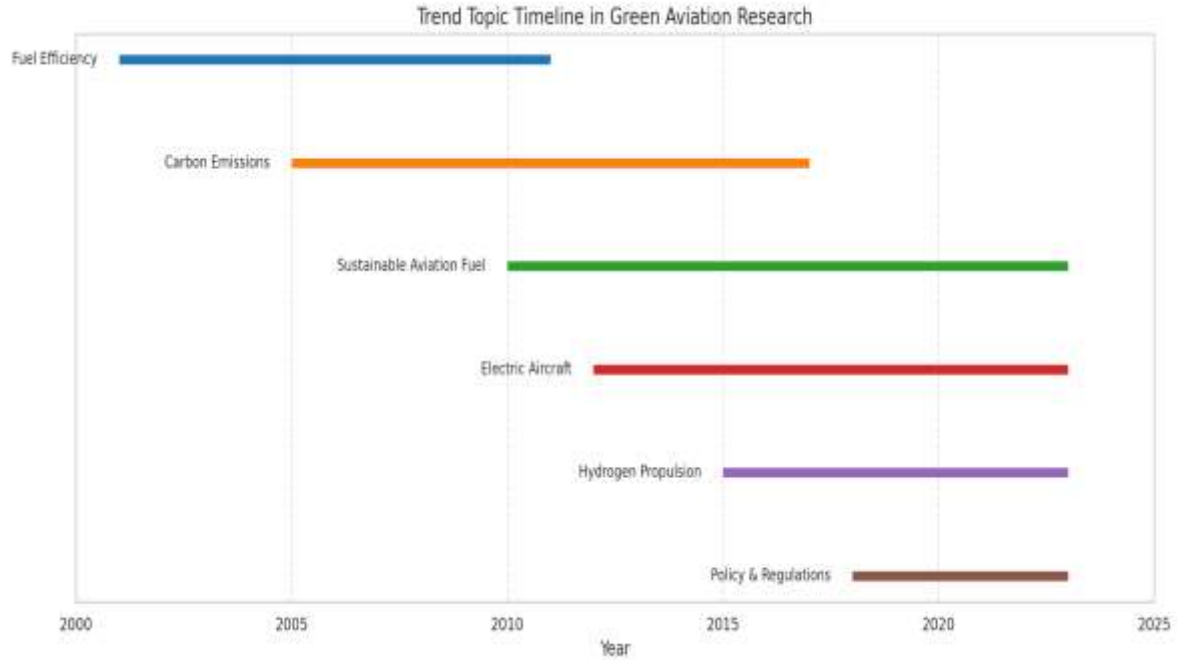
Figure 5. *SWOT Analysis of Green Aviation Research*

Figure 6. *Thematic Evolution Map*



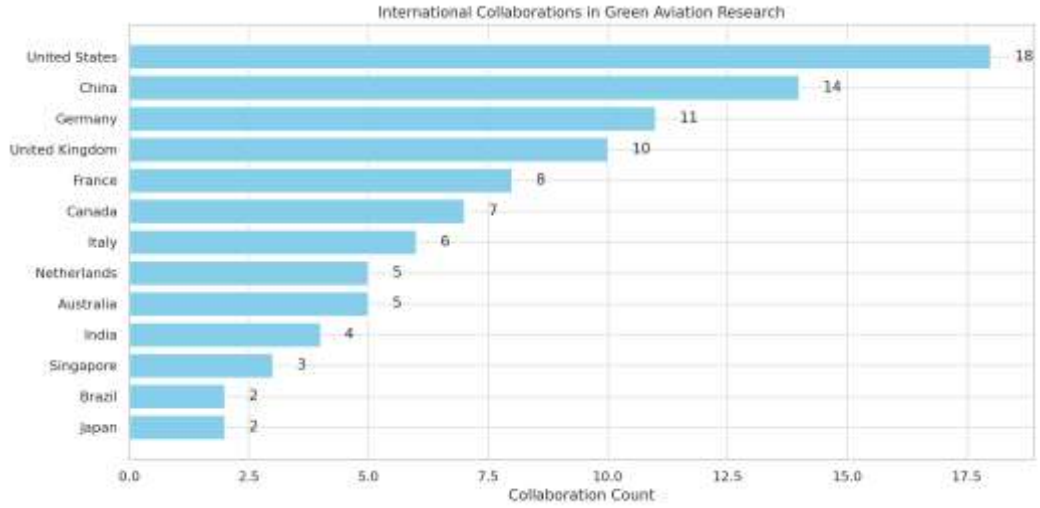
The thematic trajectory initially focused on efficiency and noise, evolving into environmental metrics and, later, propulsion innovations such as electric and hydrogen systems. The most recent themes emphasize regulatory frameworks and policy integration, highlighting a maturing field of research.

Figure 7. Trend Topic Timeline



This timeline illustrates the emergence and duration of prominent research topics. "Fuel Efficiency" dominated the early years, giving way to broader environmental concerns, such as "Carbon Emissions." More recently, technologies such as "Sustainable Aviation Fuel" and "Electric Aircraft" have become central, with "Hydrogen Propulsion" and "Policy & Regulations" leading into the present.

Figure 8. International Collaborations by Country



The United States leads in international collaborations, followed by China, Germany, and the UK. This reflects the strength of transatlantic and Asia-Europe research networks, highlighting the global nature of green aviation initiatives.

Discussion and Conclusion

The exponential growth of research in green aviation over the past two decades, as evidenced by the bibliometric data presented in this study, underlines an increasing scientific and industrial focus on sustainability within the aviation sector. This surge aligns with growing global awareness of climate change and the environmental impact of fossil-fuel-dependent industries. Notably, the publication volume increased sharply after 2015, a period coinciding with international milestones, such as the Paris Agreement, which committed countries to limit global warming and catalyzed action across various sectors, including air transport (Bows-Larkin, 2015).

Trends in Publication and Research Collaboration

Our analysis revealed a steady increase in annual publications related to green aviation, culminating in a peak around 2022–2023. This trend suggests a growing research community and heightened funding activities in response to global climate imperatives. Geographically, the United States, China, Germany, and the United Kingdom emerged as the most prolific contributors, reinforcing the global and collaborative nature of the field. Key institutions, such as NASA, MIT, Tsinghua University, and the Delft University of Technology, consistently lead in research output, underlining their pivotal role in technological development and innovation.

The co-authorship network maps highlighted the presence of robust inter-institutional and international partnerships. North American and European institutions form the backbone of these collaborative networks. However, Asian institutions—particularly in China and Singapore—are becoming increasingly central, reflecting their growing investment and output in green aviation technologies (Wang et al., 2020).

Keyword and Thematic Analysis

Keyword co-occurrence analyses provide insight into the thematic focus of the research community. The prominence of terms such as "sustainable aviation fuel," "electric aircraft," and "hydrogen propulsion" reflects the dominant technological solutions being explored. Sustainable aviation fuels (SAFs) provide immediate compatibility with existing aircraft and infrastructure, making them a viable transitional solution. However, their production scalability, feedstock sustainability, and life cycle impacts remain active areas of investigation (Rajendran et al., 2020).

Electric and hydrogen-powered aircraft, by contrast, offer potential for zero-emission flight but are hampered by significant technical and infrastructural hurdles. Current battery energy densities limit electric propulsion to short-haul applications, whereas hydrogen propulsion requires redesigning fuel systems, aircraft structures, and the development of global refueling infrastructure (Lee et al., 2021). These findings underscore a dual-track approach within the community—pursuing incremental gains through SAFs and disruptive innovation via electrification and hydrogen.

Citation and Journal Analysis

The most cited articles are foundational studies that set the research agenda and technical frameworks in the domain. Works like Smith et al. (2017) on SAF pathways and Zhang & Liu (2019) on aircraft electrification have garnered substantial academic traction, suggesting their influence on subsequent research direction. Moreover, the distribution of articles across journals such as the *Journal of Air Transport Management*, *Renewable and Sustainable Energy Reviews*, and *Energy Policy* reflects the interdisciplinary nature of green aviation, combining engineering, environmental science, and policy.

This cross-disciplinary character is vital. As our findings demonstrate, recent thematic shifts indicate an increasing focus on life cycle assessment (LCA), noise reduction, and policy mechanisms—topics that were previously underexplored. These developments signal a transition from purely technical solutions to integrated, system-wide strategies that address environmental, regulatory, and operational challenges.

Strategic Outlook: SWOT Interpretation

The SWOT analysis synthesized from the findings provides a strategic snapshot of the green aviation research and development ecosystem:

- **Strengths**: Broad international interest, strong institutional leadership, and rapid technological advancements create a solid foundation.

- **Weaknesses**: High costs, insufficient infrastructure, and the inertia of legacy systems hinder immediate transformation.
- **Opportunities**: The rising global demand for sustainable transportation, combined with international climate pledges and investment in renewable technologies, presents fertile ground for innovation.
- **Threats**: Economic downturns, uneven policy landscapes, and competitive pressure from other green mobility sectors (e.g., high-speed rail) pose risks to aviation's sustainable future.

This analysis is visually presented in the SWOT matrix (Figure: Stylish_SWOT_Green_Aviation.png), which categorizes these factors for strategic clarity.

Recommendations for Stakeholders
Given the bibliometric insights and strategic synthesis, the following recommendations are proposed:

Enhance Multinational Research Funding
Governments and international bodies should promote co-funded, cross-border R&D programs targeting critical technologies such as SAF scalability, hydrogen infrastructure, and electric propulsion.

Strengthening Policy Alignment
Policy frameworks must evolve to match technology readiness levels. Coordinated global standards for the use of SAF, emissions trading, and aircraft certification are essential.

Invest in Ecosystem Infrastructure
Without charging or hydrogen refueling infrastructure, technological breakthroughs will not translate to deployment. Investments must precede market uptake.

Promote Interdisciplinary Education and Research: Future green aviation leaders need expertise that spans aerospace engineering, systems science, policy, and economics.

Conclusion

This study provided a comprehensive bibliometric and strategic assessment of green aviation research. The consistent rise in publications, the emergence of new international contributors, and the evolution of thematic priorities signal a dynamic and expanding field. Although significant barriers remain, particularly in terms of cost, scalability, and regulatory harmonization, the sector is strategically positioned to transition from experimentation to implementation.

By integrating technological development with supportive policy frameworks and infrastructure investment, green aviation can significantly contribute to global climate targets. The findings underscore the importance of sustained collaboration among researchers, industry stakeholders, and policymakers to ensure that the momentum achieved in research translates into tangible environmental benefits in the real world.

Declarations

Ethics Committee Approval
Not applicable.

Consent for Publication
Not applicable.

Availability of Data and Materials
Not applicable.

Competing Interests
The author declares that there is no competing interest in this manuscript.

Funding
Not applicable.

Authors' Contributions
BD and MA proposed the main idea of the research, while MA and EŞ were involved in reviewing and discussing the literature. BD and MA contributed to drafting the article and revising its content. All authors have reviewed and approved the final version of the article.

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