frontiers | Frontiers in Future Transportation

TYPE Review
PUBLISHED 07 August 2025
DOI 10.3389/ffutr.2025.1630011

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OPEN ACCESS

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RECEIVED 16 May 2025
ACCEPTED 16 July 2025
PUBLISHED 07 August 2025

CITATION
Omido N, Luke R, Mageto J and Ombati T (2025) Industry 4.0 in commercial airlines: a bibliometric analysis.
Front. Future Transp. 6:1630011.
doi: 10.3389/ffutr.2025.1630011

Industry 4.0 in commercial airlines: a bibliometric analysis

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Commercial airlines face numerous challenges related to operational inefficiencies, poor maintenance practices, overcrowding of airports, supply chain complexity, lack of seamless customer experience, safety issues, data privacy and security issues, increasing fuel prices, and sustainability issues; however, Industry 4.0 technologies are widely regarded as a transformative solution, offering advanced tools and methodologies to address these challenges effectively. Despite the potential benefits of Industry 4.0 technologies, there remains a lack of comprehensive understanding regarding their extent and impact on commercial airlines. The study examined the current state of research on Industry 4.0 in commercial airlines, identified the most significant research topics within this domain, and proposed a future research agenda. The bibliometric analysis was based on 5,113 documents extracted from the Scopus and Web of Science databases, covering 2,109 journals, with an annual publication growth rate of 9.34%. However, Africa's contribution remains minimal, accounting for less than 1% of the total research output analyzed, highlighting a significant research gap on the continent. The contemporary literature has focused on artificial intelligence, automation, big data analytics, the Internet of Things, and integrating Industry 4.0 technologies. The study was also used to identify the future research agenda of Industry 4.0 in commercial airlines, which includes human-centric approaches, integration of advanced technologies, cybersecurity, environmental sustainability, and ethical and legal implications.

KEYWORDS
bibliometric analysis, industry 4.0, big data analytics, artificial intelligence, internet of things, commercial airlines

1 Introduction

Industry 4.0 (I4.0), first conceptualized in 2011, has gained attention due to its ability to improve organizational performance (Tan and Masood, 2021; Bautista-Hernández and Martín-Prats, 2024). The four main technologies driving this revolution are big data analytics (BDA), artificial intelligence (AI), virtual reality (VR) and the Internet of Things (IoT) (Ghosh and Chakraborty, 2018). These technologies can address challenges airlines face, such as maintenance, operational disruptions, environmental pollution, overcrowding of airports, customer service, safety and security, fleet management, personalized experience, training and development, decision-making, and supply chain management (Tan and Masood, 2021). BDA is the process of collecting, pre-processing, analyzing, and interpreting large amounts of data (big data) from multiple sources to identify patterns, trends, and correlations (Qureshi et al., 2024). BDA on its own does not provide much value to an organization; however, when BDA is merged with AI and IoT, organizations are guaranteed to achieve superior returns (Adedoyin et al., 2020). AI is a field of science that focuses on creating computer systems that can think, learn, and act like humans, enabling businesses to automate processes, make decisions, and provide insights that would otherwise be impossible (Sarker, 2022). VR is a technology that immerses users in a simulated, three-dimensional environment and creates an entirely artificial environment that can mimic real-world settings (Tan and Masood, 2021). IoT is a network of interconnected smart devices that can communicate and exchange data, providing valuable insights into user behavior, system performance, and customer preferences (Perera et al., 2014).

Airlines face significant pressure to adopt advanced technologies to ensure their survival due to the growing intricacies of business operations and the incorporation of advanced technologies (Serrano and Kazda, 2020; Yıldırım et al., 2025). The airline industry plays a vital role in the economy as it is the primary linkage between different regions, facilitating the movement of people, goods, ideas, capital, and technology from one country to another (Khanal et al., 2022; Bonser, 2019). The airline industry employs about twenty-nine million people globally. In addition, every year, over four billion passengers travel using airlines, and about sixty-four billion tons of cargo are transported (International Air Transport Association, 2022a). In the United Arab Emirates, the air sector contributes US $47.4 billion (13.3%) to its gross domestic product (GDP) and employs 770,000 people; France, US$105 billion (4.3% of GDP) and 1.1 million jobs; Australia, US$69 billion (5.5% of GDP) and 716,000 jobs; Ethiopia, US$4.5 billion (5.7% of GDP) and 1.1 million jobs; and Kenya, US$3.2 billion (4.6% of GDP) and 410,000 jobs (International Air Transport Association, 2022b). However, the COVID-19 pandemic severely disrupted the global airline industry, resulting in significant declines in passenger volumes, flight cancellations, and substantial revenue losses. This disruption not only exposed the vulnerabilities within airline operations but also intensified the need for resilient, technology-driven solutions. As the industry recovers, the adoption of Industry 4.0 technologies has become increasingly critical to improve operational efficiency, enhance safety protocols, and support the revival of tourism-dependent economies in a post-pandemic environment (Amankwah-Amoah, 2021).

I4.0 technologies hold significant promise for commercial airlines, including enhanced operational efficiency, predictive maintenance, and seamless customer experiences (Qureshi et al., 2024; Bhatia et al., 2024). I4.0 technologies can uncover inefficiencies, optimize flight routes, reduce fuel consumption, and minimize delays, leading to improved profitability and economic growth (Simonetto et al., 2022). Predictive maintenance initiatives, such as real-time monitoring of critical components, minimizing downtime and increasing aircraft availability, ensuring reliable and safe operations (Stanton et al., 2023). Additionally, efficient booking processes, personalized services, enhanced in-flight experiences, and improved baggage handling can provide seamless customer experiences (Al-Khatib, 2023). Cost optimization through reduced fuel consumption, lower maintenance and repair costs, and optimized resource allocation can also enhance airline profitability and contribute to overall economic sustainability (Rath et al., 2025). I4.0 technologies significantly benefit commercial airlines (Tan and Masood, 2021; Chakraborty et al., 2021).

Despite the valuable contributions of I4.0 in airlines, the technology is relatively new and a largely unexplored area of research. While several studies have explored the applications and impacts of I4.0 technologies in airlines, there remains a significant gap in understanding the extent and implications of these advancements. Previous research has provided valuable insights into specific aspects, such as the use of big data, artificial intelligence (AI), and the Internet of Things (IoT) in enhancing various facets of airline operations. Some of the notable studies include Dou (2020), who examined the impact of big data on the airline industry in and Alansari et al. (2019), who studied how big data can be used to help the development of smart airports. Chang et al. (2022) examined an analytics method that utilizes big data to extract valuable information from 23 global airlines between 2013 and 2017. Hausladen and Schosser (2020) studied the use of BDA to create efficiency in the airline industry. Singh and Gupta (2021) examined the use of AI in the aviation industry. Chakraborty et al. (2021) examined the use of IoT, AI, and BDA-driven sustainable practices in airlines. Aigbavboa et al. (2023) studied the growth potential for airlines in South Africa in the era of fourth industrial revolution (4IR) technologies. Saadi et al. (2020) studied the use of AI and IoT to improve the customer journey. Zamani et al. (2022) examined literature review on the impact of AI on and Bi et al. (2023) examined the potential of IoT to provide a wealth of data for BDA.

Despite the significance of the papers to the current research, there is a need for a bibliometric analysis of I4.0 in commercial airlines to identify current and future research trends in the field of I4.0 in commercial airlines to provide valuable insights for researchers, industry practitioners and policymakers. The existing literature has primarily focused on isolated aspects of I4.0 implementation, such as its impact on operational efficiency, customer experience enhancement, and the potential for airline growth. While these studies offer valuable insights, they fall short of providing a holistic understanding of the broader landscape of I4.0 adoption and its implications for the airline industry. The current study establishes research trends and suggests future research directions on I4.0 in commercial airlines. The findings of this paper contribute to the existing body of knowledge on I4.0 in commercial airlines by elucidating current research trends and identifying key areas for further investigation. Moreover, the paper provides clear direction for future research endeavors, outlining potential research directions and areas that warrant subsequent research. Thus, this study contributes to advancing knowledge in the field and serves as a roadmap for future research initiatives aimed at harnessing the full potential of I4.0 in commercial airlines. The bibliometric analysis addressed the following research questions: (1) What is the current state of research on I4.0 in commercial airlines? (2) What are the most significant research topics within the domain of I4.0 in commercial airlines? (3) What should be the future research agenda for Industry 4.0 in commercial airlines?

The paper is structured as follows: Section 2 examines the existing literature review of I4.0. Section 3 describes the methodological approach employed for the bibliometric review. Section 4 presents the review's outcomes, including a summary of the major findings and implications of the study, as well as trends and researcher collaborations. Section 5 presents the discussion, and Section 6 provides the paper's conclusion by summarizing the study's major findings and implications.

2 Literature review

I4.0 technologies are revolutionizing the airline industry by enabling data-driven strategies aligned with transport economics principles (Kamble et al., 2024). This convergence enhances efficiency, competitiveness, and sustainability through real-time data analytics and advanced technological innovations (Malik et al., 2020; Tang et al., 2023). Commercial airlines play a pivotal role in global economic development by providing essential connectivity, facilitating the movement of people and goods, and fostering international trade and cooperation (International Air Transport Association, 2022b). The industry also generates employment across various sectors, including pilots, cabin crew, ground staff, maintenance professionals, and administrative roles, while creating a ripple effect in related industries such as tourism and hospitality (Zamani et al., 2022). To maintain their economic impact and competitiveness, airlines are increasingly adopting I4.0 technologies such as BDA, AI, and IoT (Tan and Masood, 2021).

AI has emerged as a transformative technology in the aviation industry, with significant potential to improve safety, efficiency, and cost savings. Singh and Gupta (2021) reviewed AI applications in aviation from 1950 to 2012, concluding that AI can revolutionize the industry by enhancing operational efficiency and safety. However, their analysis was limited to literature up to 2012, potentially missing recent advancements and applications. More recently, Bautista-Hernández and Martín-Prats (2024) investigated the use of AI for error mitigation in aerospace, focusing on military aircraft. Their findings demonstrated a 90% reduction in errors and a 93% decrease in processing time using AI techniques such as support vector machines and logistic regression. While these findings are promising, the study's focus on military applications limits its generalizability to commercial aviation.

BDA has become a vital tool for improving efficiency and decision-making in the airline industry. Taliah and Zervopoulos (2024) investigated the use of Data Envelopment Analysis (DEA) in assessing airline efficiency within the context of BDA. The study highlighted DEA as a robust methodological approach for benchmarking airline performance, identifying inefficiencies, and optimizing operational strategies. The findings emphasized the potential of DEA to provide data-driven insights that enable airlines to enhance productivity and competitiveness in a rapidly evolving industry. However, the study focused on a specific dataset and did not explore the integration of I4.0 technologies beyond BDA. Similarly, Hausladen and Schosser (2020) used DEA to assess the efficiency of a sample of airlines between 2017 and 2019, highlighting BDA's potential to enhance operational efficiency and provide insights into consumer behavior. However, the study was limited by specific timeframes and sample sizes, reducing the generalizability of the findings. Zhang et al. (2021) conducted a bibliometric review of BDA in business research from 2010 to 2019, revealing a significant increase in BDA-related publications, with 23,764 articles published during this period. However, the review did not specifically address the aviation sector.

IoT has the potential to provide a wealth of real-time data, enabling more informed decision-making and operational efficiency in the airline industry. Bi et al. (2023) examined the role of IoT in generating data for BDA, concluding that IoT can significantly enhance decision-making processes. Their findings were corroborated by Priyanka et al. (2021), who concluded that IoT enhances BDA capabilities by providing high-quality real-time data. However, these studies primarily focused on theoretical applications and lacked empirical validation in airline operations. Zamani et al. (2022) explored the impact of AI on BDA, highlighting that as organizations accumulate vast amounts of data, AI-driven analytics become essential for processing and interpreting this information effectively. Similarly, Demigha (2020) emphasized AI's role in strengthening BDA capabilities, demonstrating that AI can enhance predictive modelling and operational insights. Despite these contributions, the studies did not examine how AI and BDA collectively improve airline efficiency.

The integration of AI, IoT, and BDA offers significant opportunities to enhance customer experience, operational efficiency, and sustainability in the airline industry. Zaki (2019) examined the potential of IoT and AI to improve customer experience, enhance loyalty, and increase revenue, concluding that these technologies can deliver personalized services and drive customer satisfaction. Chakraborty et al. (2021) explored the use of AI and IoT to enable sustainable practices in the airline industry, finding that these technologies can lead to increased customer satisfaction and positive word-of-mouth. Similarly, Saadi et al. (2020) highlighted the benefits of AI and IoT in enhancing the customer journey, including improved operational efficiency and cost savings. While these studies demonstrate the potential of integrated I4.0 technologies, they often focus on isolated implementation aspects, lacking a holistic view of the broader landscape.

3 Materials and methods

The study adopted a quantitative approach that was based on bibliometric analysis. Bibliometric analysis is an approach that utilizes quantitative methods to analyze enormous data sets and disclose gaps in knowledge, thereby establishing the intended contribution of researchers and providing insights into emerging fields of study (Linnenluecke et al., 2020; Donthu et al., 2021). This approach was adopted to explore the current state of I4.0 in commercial airlines, examine the most significant research topics and identify the new and upcoming research areas within the field. Bibliometric analysis can be presented as performance analysis, science mapping, and network analysis, as described in Figure 1 Performance analysis evaluates the impact, influence, and productivity of researchers, institutions, journals, and specific research areas (Donthu et al., 2020). Science mapping, also known as knowledge mapping or research mapping, investigates the interrelationships of research constituents (Baker et al., 2020). Network metrics elucidate the significance of research constituents (e.g., authors, countries, institutions) that may not be reflected through citations or publications (Andersen, 2021).

The search strategy included selecting and optimizing keywords, selecting an appropriate database, configuring filters for search

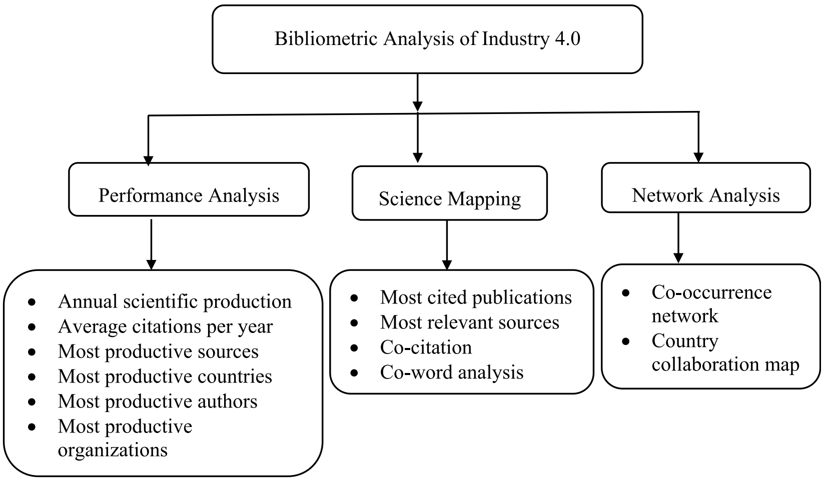

FIGURE 1
Bibliometric performance metrics used in analyzing industry 4.0 literature. Source: (Donthu et al., 2020; Mageto, 2022; Janik et al., 2021).

parameters, and determining the pertinent analysis timeframe (Zupic and Čater, 2015). The researchers applied a combination of I4.0 and commercial airlines that formed the following keywords: ("Industry 4.0″OR "fourth industrial revolution" OR "industrial revolution" OR ″4IR" OR "digital transformation" OR "big data" OR "big data analytics" OR "BDA" OR "data analytics" OR "Internet of Things" OR "IoT" OR "artificial intelligence" OR "machine learning" OR "data mining" OR "AI") AND ("airline" OR "commercial airlines" OR "aviation" OR "air cargo" OR "air passenger" OR "air transportation" OR "air transport" OR "airport"). To ensure the relevance and coverage of these keywords, a pilot search was conducted in both Scopus and Web of Science. The initial results were reviewed to assess the suitability of the search string and the clarity of retrieved documents. Based on this pilot phase, minor adjustments were made to the Boolean structure to improve specificity and reduce irrelevant results. Furthermore, three academic supervisors acted as independent validators, reviewing the pilot outputs and confirming the adequacy and alignment of the final search strategy with the study's objectives.

Scopus and Web of Sciences were chosen as the primary database for this study due to their extensive coverage of high-quality, peer-reviewed publications and their strong representation in technology related fields (Baas et al., 2020). The search was conducted on 17 March 2025, at 4:08 p.m. (EAT), and the researchers obtained 7,114 publications, comprising 5,412 from Scopus and 1,702 from Web of Science from 1978 to 17 March 2025. The search comprised articles, conference papers, review papers, book chapters, and books published in business, transport, and technology subject areas. In addition, the search encompassed complete records of author, article title, abstract, affiliations, and country. Only publications written in English were considered. The documents were filtered by excluding publications from the following fields: chemical engineering, material science, energy, physics and astronomy, chemistry, biochemistry, genetics and molecular biology, physiology, agriculture, biological sciences, and health. These exclusions were necessary to maintain the study's focus on business, transport, and technology applications in aviation, as research in the excluded fields often diverges from the direct application of I4.0 technologies in commercial air-lines. This reduced the number of publications to 5,625, the remaining publications, each abstract was meticulously examined for relevance and suitability for the study. This reduced the number of publications to 5,113, comprising 3,956 from Scopus and 1,157 from Web of Science, representing 71.9%, which were exported as a CSV Excel file. The results were analyzed using VOSviewer version 1.6.19 and Biblioshiny via the Bibliometrix R package in RStudio. Biblioshiny was accessed through the R environment by executing the bibliometrix:biblioshiny () command, which provided an interactive interface for bibliometric analysis. VOSviewer was used to visually present complex relationships, co-authorship networks, co-citation patterns, and thematic clusters, enhancing the depth of the insights gained. The analysis included co-authorship analysis, keyword co-occurrence analysis, and co-citation analysis. For all analyses, the minimum keyword occurrence threshold was set at five, with full counting applied as the counting method. Co-occurrence analysis was based on author keywords, while co-citation analysis was performed using cited references. The minimum number of documents per author for co-authorship analysis was set at three to ensure the relevance and strength of collaborative links.

4 Results

This section presents the results and discussion of a bibliometric analysis of I4.0 and the performance of commercial airlines. The section is divided into three sub-sections: performance analysis, science mapping, and network analysis, as well as discussion of the results. The section concludes by highlighting emerging trends and providing insights into the evolving discourse and future directions of I4.0 research in commercial airlines. The research documents extracted from Scopus and Web of Science were related to I4.0 and

TABLE 1 Main information about the data.

Description	Results
Main information about the data	
Timespan	1978:2025
Sources (Journals, Books, etc.)	2,109
Documents	5,113
Annual Growth Rate %	9.4
Document Average Age	7
Average citations per doc	7.3
References	138,777
Document contents	
Keywords Plus (ID)	21,298
Author's Keywords (DE)	10,075
Authors	
Authors	11,702
Authors of single-authored docs	493
Author's collaboration	
Single-authored docs	548
Co-Authors per Doc	3.3
International co-authorships %	16.4
Document types	
Article	1710
article in press	1
Book	22
book chapter	188
conference paper	2,752
conference review	273

Source: Data compiled from Scopus and Web of Science (2025).

the performance of commercial airlines, as per the search criteria. The documents span from 1978 to 2025, with an average citation of 7.331 per article and 138,777 references, as summarized in Table 1.

4.1 Initiative performance analysis

Performance analysis examined journal, author, country, and affiliation contributions to examine the current state of research on I4.0 in commercial airlines. A total of 5,113 documents were analyzed, predominantly comprising 2,752 conference papers, 1,710 articles, 273 conference reviews, 188 book chapters, and 22 books, as illustrated in Table 1.

The research published on I4.0 in commercial airlines started in 1978 with Preiss's article (Preiss, 1980). The article proposed a data-driven approach to modelling the engineering design process, emphasizing the need to transition from passive computer tool usage to active computer-driven design processes, leveraging electronic information systems and potentially integrating AI advancements. The number of documents has gradually increased to 538 publications per year by 2024, up from 1 article in 1978. As shown in Figure 2 the period 2010–2024 has over 88% of the published publications, suggesting a continued upward trajectory in publications in the foreseeable future. The rapid increase in the number of documents published in I4.0 since 2010 is attributed mainly to technological advancements and economic and social factors (Khan et al., 2017).

The 2010 period saw the rapid development and adoption of key technologies such as IoT, BDA, and AI, enabling automation, data-driven decision-making, and intelligent systems, contributing to increased research and publications (Meindl et al., 2021). On the economic and social factors, the 2008 financial crisis highlighted the need for greater efficiency and adaptability in industries. I4.0 concepts offered promising solutions for resilience and competitive advantage, driving research and investments in the field (Serumaga-Zake and van der Poll, 2021). In addition, initiatives like Germany's I4.0 strategy and the World Economic Forum's Industrial Internet of Things project raised global awareness of the potential benefits of Industry 4.0, leading to increased research and publications across countries and sectors (Zhang et al., 2021).

4.1.1 Total citations and impact per journal

The productivity and influence of the published research on I4.0 in commercial airlines were examined using the h_index. H_index is a metric that combines both the number of publications and the number of citations to measure the impact and productivity of a researcher, author, or journal (Ali, 2021).

The top 20 publications by citations were ranked as illustrated in Table 2. The most influential source was the Transportation Research Part C: Emerging Technologies journal, with an *h*_index of 21 and an impact factor of 33 (*g*_index), followed by the Journal of Air Transport Management with *h*_index of 19 and *g*_index of 32. The Lecture Notes in Computer Science was third, with *h*_index 16 and *g*_index 28. The journal Transportation Research Part E: Logistics and Transportation Review ranked fourth with *h*_index of 13 and *g*_index of 15. Lastly, Aerospace, AIAA/IEEE Digital Avionics Systems Conference–Proceedings, Expert Systems with Applications, and Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining journals were ranked fifth with *h*_index of 12. Conferences like the AIAA SciTech 2019 Forum and AIAA SciTech 2020 Forum have lower *h*_index but are more recent, suggesting they might gain influence over time.

I4.0 research is undertaken in diverse areas, as indicated in Table 2, reflecting the interdisciplinary nature of research in this field. The areas covered include transportation, computer science, aerospace, AI, air traffic management, integrated communication, navigation, and surveillance in airlines, BDA, and logistics and transportation. Journals with high citation counts can be attributed to several factors. First, journals like Transportation Research Part C: Emerging Technologies and Journal of Air Transport Management focus on ML and predictive analytics for air traffic flow, flight delays, weather impact, and smart aviation technologies, making them reputable outlets within transportation

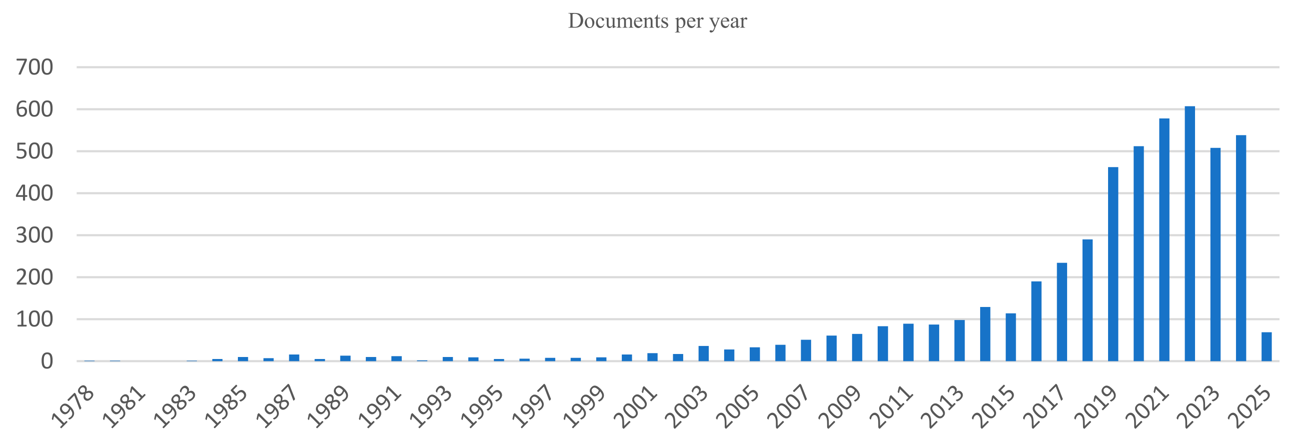

FIGURE 2
Documents per year. Source: Data compiled from Scopus and Web of Science (2025).

and air transport management. Second, Lecture Notes in Computer Science and Expert Systems with Applications address AI-driven aviation applications, including deep learning for flight delay prediction, blockchain for aircraft parts tracking, and fuzzy logic models in airline management, which are essential to developing and implementing I4.0 technologies in commercial aviation. Lastly, conferences such as the AIAA/IEEE Digital Avionics Systems Conference - Proceedings and AIAA SciTech Forums provide platforms for machine learning applications in air traffic management, flight safety, autonomous navigation, and predictive maintenance in aviation systems.

4.1.2 Source growth

The Journal of Lecture Notes in Computer Science had the earliest publication in the research area in 1993 with a paper on integrating AI and fuzzy patterns, as illustrated in Figure 3. The journal was the sole publication outlet that released articles before 2000, accumulating a total of 20 publications between 1993 and 1999. AIAA/IEEE Digital Avionics Systems Conference Proceeding had its first publications in 2000 with three articles. The number of publications in the journal steadily increased, becoming the second most published journal in the field of Industry 4.0. The ACM International Conference Proceeding Series followed, publishing its first two articles in 2006. Lecture Notes in Networks and Systems and Advances in Intelligent Systems and Computing are recent journals with their first publications in 2017 and 2013, respectively.

The number of publications experienced significant growth in 2011. Journals such as Lecture Notes in Computer Science and AIAA/IEEE Digital Avionics Systems Conference Proceedings achieved faster growth and are stronger in Industry 4.0 technologies research due to their role as early contributors to the field. Other journals, like the ACM International Conference Proceeding Series, cover a wider range of technology topics, making them suitable for research that spans different fields and interdisciplinary studies. This period of journal growth aligns with the key milestone in developing and adopting Industry 4.0. Industrie 4.0 was introduced in 2011 by the German government as part of the High-Tech Strategy for German Manufacturing (Yang and Gu, 2021). This initiative prompted the adoption of I4.0 technologies in the airline sector, aiming to improve efficiency and drive innovation within the industry (Tan and Masood, 2021). Simultaneously, rapid advancements in key technologies such as AI, robotics, IoT, cloud computing, and BDA laid the groundwork for creating and implementing smart interconnected systems within factories and across industries.

4.1.3 Most productive authors in industry 4.0

Table 3 displays bibliometric metrics for the most productive authors. The metrics include the author's h-index, g-index, m-index, total citations (TC), number of publications (NP), and the year their publishing records began (PY-Start).

A total of 7,563 authors contributed to the 4,501 publications analyzed, with only 422 (9.4%) documents being single-authored, revealing that the predominant mode of research in the field of I4.0 in commercial airlines is through collaborative efforts. Liu Y emerged as a pioneer researcher in I4.0 in commercial airlines with 475 citations, h_index 14, and an impact factor of 21 (g_index) since 2004. Liu Y research focused on IoT incremental learning and use of BDA to improve airline operations. Key findings included enhancing data operational efficiency and decision making through data driven insights. Mavris Dn was the second most influential author, with h_index 11 and 353 citations. Marvis Dn focused on safety prediction, data mining for flight delays, and machine learning techniques to enhance aviation safety and operations. A gap exists in adapting these models for evolving safety threats and integrating them into predictive maintenance. Puranik Tg was the third most influential author with h_index 11 and 305 citations. The author focused on research in data-driven environmental impact assessment and machine learning applications for predicting safety events, further research is need to refine predictive accuracy across varying environmental conditions and integrate real-time environmental data for proactive responses. Chen H was the fourth most influential author, with a h_index of 10 and 418 citations. Chen H focused on research in personalized travel forecasting, airport security systems, airspace operation, and air passenger index prediction. There is a need to expand on the interoperability between

TABLE 2 Citations and publications per journal.

Element	*h*_index	*g*_index	*m*_index	TC	NP	PY_start	Research 22topics
a)							
Transportation Research Part C: Emerging Technologies	21	33	1.5	1,141	45	2010	ML and predictive analytics for air traffic flow, flight delays, weather impact, and anomaly detection
Journal of Air Transport Management	19	32	0.8	1,049	45	2000	BDA, ML, IoT blockchain, and predictive analytics in the airline industry
Lecture Notes in Computer Science	16	28	0.5	1,221	215	1993	AI and deep learning for flight delay prediction, crew scheduling, and aviation applications
Transportation Research Part E: Logistics and Transportation Review	13	15	2.2	400	15	2018	AI for air traffic flow, trajectory prediction, and fuel consumption analysis
Aerospace	12	21	2	490	43	2018	AI for aviation safety event detection
AIAA/IEEE Digital Avionics Systems Conference – Proceedings	12	24	0.5	822	160	2000	ML for flight delays, aviation data mining, air traffic modernization, and security
Expert Systems with Applications	12	24	0.4	750	24	1996	AI for service quality, blockchain for aircraft parts, and fuzzy cognitive models
ACM SIGKDD International Conference on Knowledge Discovery and Data Mining	12	15	0.6	552	15	2003	AI for flight anomaly detection, dynamic pricing, and airline revenue optimization
AIAA SciTech 2019 Forum	10	15	2	291	50	2019	Flight Safety and Delay Prediction, ML and AI Applications and Human Factors and Training
AIAA SciTech 2020 Forum	9	15	2.3	360	59	2020	AI in autonomous navigation and aviation applications
Element	*h*_index	*g*_index	*m*_index	TC	NP	PY_start	Research topics
b)							
ACM International Conference Proceeding Series	8	13	0.4	251	120	2006	AI in UAV operations, security, and air traffic decision support
Journal of Aerospace Information Systems	8	15	0.7	246	20	2013	AI for predictive maintenance, safety event detection, and runway anomaly prediction

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TABLE 2 (*Continued*) Citations and publications per journal.

Element	*h*_index	*g*_index	*m*_index	TC	NP	PY_start	Research 22topics
Procedia Computer Science	8	12	0.9	156	16	2015	ML for air traffic delay prediction and aviation decision-making
Integrated Communications, Navigation and Surveillance Conference, ICNS	7	10	0.6	134	34	2013	AI for risk assessment and predictive analytics in flight operations
Multimedia Tools and Applications	7	9	0.8	187	9	2016	IoT and blockchain in UAV logistics, ML for demand forecasting and passenger behavior
Proceedings of the National Conference on AI	7	16	0.2	297	16	1994	AI and expert systems in air traffic management
SESAR Innovation Days	7	9	0.8	152	42	2015	AI/ML for air traffic efficiency and airline disruption management
Transportation Research Procedia	7	10	0.9	113	18	2016	AI for airport digital transformation, delay prediction, and efficiency
13th USA/Europe Air Traffic Management Research and Development Seminar 2019	6	9	1.2	102	11	2019	AI for weather impact, flight conflict resolution, and ATC automation

Source: Data compiled from Scopus and Web of Science (2025).

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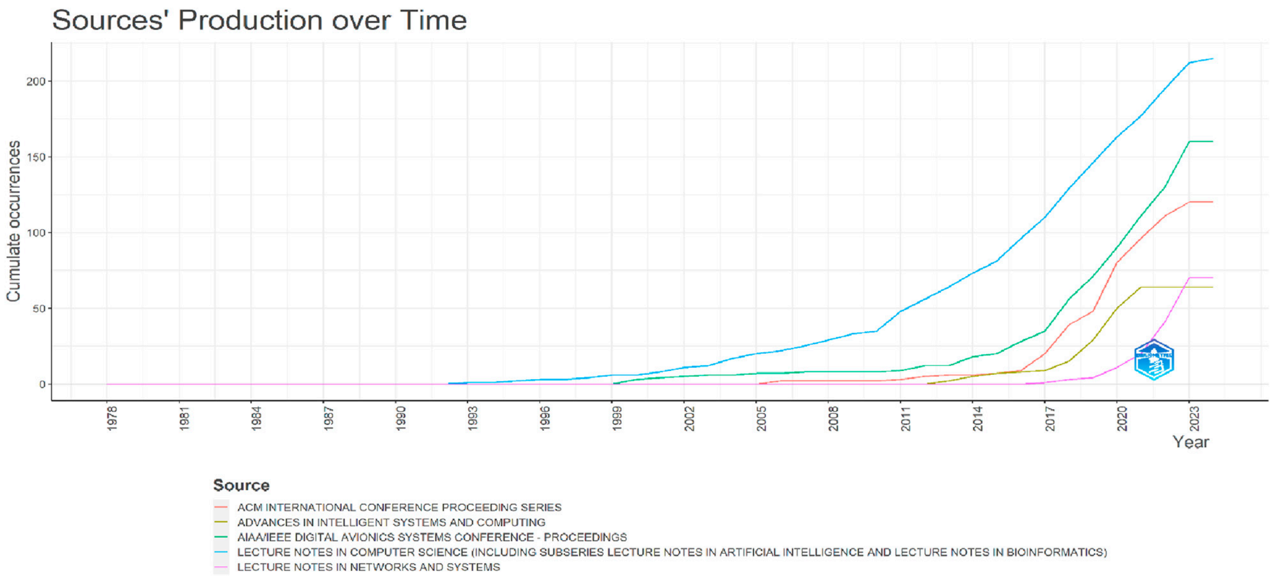

FIGURE 3
Source growth between 1993–2024. Source: Data compiled from Scopus and Web of Science (2025).

TABLE 3 Most productive authors.

Element	*h*_index	*g*_index	*m*_index	TC	NP	PY_start	Key research areas
Liu Y	14	21	0.7	475	40	2004	IoT incremental learning, BDA in airline operations, data-driven decision-making
Mavris Dn	11	17	0.6	353	36	2006	Safety prediction, data mining for flight delays, ML for aviation safety, predictive maintenance integration
Puranik Tg	11	17	1.6	305	24	2017	ML for safety event prediction
Chen H	10	20	1.1	418	28	2015	Airport security, airspace operations, air passenger index prediction
Alam S	9	14	0.6	267	33	2010	Aircraft maneuver detection, air traffic complexity reduction
Li Y	9	15	0.5	261	48	2006	Aviation operations, aircraft performance
MatthewsB	9	17	0.8	310	22	2012	Machine learning in aerospace, predictive maintenance
Wang J	9	19	0.6	396	32	2010	Flight trajectory optimization, air traffic modeling
Li J	8	16	0.4	295	33	2005	Big data analytics in aviation, airline operations
Tambe M	8	16	0.5	962	16	2008	AI applications in aviation, autonomous systems
Wang X	8	11	0.5	159	34	2007	Airspace traffic management, decision support systems
Chen J	7	13	0.5	174	14	2010	Aviation cybersecurity, risk assessment
DelahayeD	7	14	1	212	20	2017	AI in air traffic control, automation in aviation
Li L	7	10	0.4	1,200	10	2004	Smart aviation systems, digital transformation
Liou Jjh	7	7	0.5	407	7	2009	Aviation safety modeling, risk analysis
Olive X	7	8	1.4	187	8	2019	Air traffic efficiency, real-time monitoring
Oza N	7	10	0.5	210	10	2009	AI in air transport, deep learning models
Wang C	7	15	0.4	235	19	2008	Pilot decision-making support, intelligent transport systems
Wang Y	7	15	0.5	253	48	2009	Human factors in aviation, cockpit automation

Source: Data compiled from Scopus and Web of Science (2025).

TABLE 4 Publications per institution.

Affiliation	Country	Publications
Nanjing University of Aeronautics and Astronautics	China	189
Civil Aviation University of China	China	110
Beihang University	China	102
The Hong Kong Polytechnic University	Hong Kong	65
Civil Aviation Flight University of China	China	49
NASA Ames Research Center	USA	45
Purdue University	USA	39
Shanghai Jiao Tong University	China	34
Tsinghua University	China	34
Universidad Politécnica De Madrid	Spain	34
Delft University of Technology	Netherlands	33
Georgia Institute of Technology	USA	33
Air Force Engineering University	China	32
Tongji University	China	31
Northwestern Polytechnical University	China	30
Embry-Riddle Aeronautical University	USA	29
Massachusetts Institute of Technology	USA	28
State Key Laboratory of Air Traffic Management System and Technology	China	28
Arizona State University	USA	27
University of California	USA	26

Source: Data compiled from Scopus and Web of Science (2025).

personalized forecasting systems and real-time airport operations for holistic improvements. Alam S was the fifth most influential author, with a h_index of 9 and 267 citations. The author's research focused on optimizing arrival procedures for environmental sustainability, detecting aircraft maneuvers, and reducing air traffic complexity. The most influential authors collectively addressed key areas such as safety, efficiency, environmental impact, and the integration of advanced technologies.

4.1.4 Author affiliations

The affiliations list the institutions where the authors are employed and their respective countries of origin. Nanjing University of Aeronautics and Astronautics from China had the highest contribution to I4.0 in commercial airlines with 189 articles, followed by Civil Aviation University of China (110) and Beihang University (102), as illustrated in Table 4.

Ten Chinese institutions were among the top twenty contributors, indicating that most of the research on I4.0 in commercial airlines is conducted in China. The USA followed closely with seven institutions, also making a significant contribution. Many of these institutions, particularly in China and the USA, host strong aviation academies and research centers, driving innovation in the field. Additionally, institutions in Hong Kong, Spain, and the Netherlands have made valuable contributions, reflecting global participation in advancing research on I4.0 in commercial airlines. Chinese institutions in the top 20 contributed to 639 articles, representing 63.9% of the total articles from the 20 institutions. The substantial contribution from Chinese institutions is attributed to the government of China allocating substantial funding to support scientific and technological advancements (Xie and Freeman, 2019). Other institutions such as the USA (227), Hong Kong (65), Spain (34) and the Netherlands (33) also made significant contributions, signifying international collaboration and knowledge sharing in advancing I4.0 within commercial airlines.

4.1.5 Contribution by country

The USA had the highest total number of citations, with a total of 6,374 citations. On average, each article from the USA received approximately 15.9 citations, as depicted in Table 5. The USA's highest contribution is attributed to its history of investing in research and development. As the headquarters for global aerospace companies like Boeing and Airbus, the companies have the resources and expertise to lead research in the adoption of I4.0 technologies in the design, manufacturing, and operation of aircraft. China follows with a total of 3,370 citations and an average article citation of 5.2, highlighting the strong impact of its research outputs. India (1,338), France (1,175), Singapore (956), the United Kingdom (845), Hong Kong (739), Germany (707), and Italy (644) closely followed in that order in the top ten.

TABLE 5 Most cited countries.

Country	Total citations	Average publication citations
USA	6,374	15.9
China	3,370	5.2
India	1,338	5.6
France	1,175	19.6
Singapore	956	43.5
United Kingdom	845	10.4
Hong Kong	739	16.1
Germany	707	7.8
Italy	644	11.3
Spain	637	8.7
Australia	630	12.6
Finland	533	41.0
Turkey	506	6.7
Korea	503	11.2
Belgium	416	41.6
Netherlands	412	10.6
Brazil	407	8.5
Iran	290	9.4
Sweden	271	27.1
Canada	242	5.3

Source: Data compiled from Scopus and Web of Science (2025).

4.2 Science mapping

Science mapping investigates co-citation, citation, thematic clusters, co-word, and co-authorship analysis. Collaborations between countries on I4.0 in commercial airlines revealed that China and the USA have numerous collaborations with various countries, indicating a significant global influence in I4.0 research. A significant amount of research on Industry 4.0 in commercial airlines is conducted in North America (6,569), Asia (6,464), Europe (4,733), Oceania (594), and South America (391). The high research volume in North America, Asia, Europe, and Oceania indicates a strong global focus on I4.0 in the commercial airline sector. However, Africa does not appear among the top 20 most cited countries, reflecting a potential research gap or limited emphasis on I4.0 within the continent. Nonetheless, a few African countries have contributed to this research, with Morocco leading with 51 citations, followed closely by Egypt (45 citations). Other contributors include South Africa (30), Algeria (20), Nigeria (17), Ethiopia (6), Ghana (6), Botswana (3), Guinea (2), and Sudan (2), with Kenya and Rwanda each having one documented article, as illustrated in Figure 4.

China collaborates extensively with Hong Kong, Singapore, and the United Kingdom, while the USA has strong ties with Canada, China, and the United Kingdom. European countries, including Germany, France, and the United Kingdom, collaborate substantially within the region and with other continents. Germany collaborates extensively with France, the Netherlands, and Switzerland, while the United Kingdom has notable collaborations with the USA, Spain, and Italy. The collaborative relationships between countries are multifaceted and driven by various factors. China collaborates with Hong Kong, Singapore, and the United Kingdom due to their advanced technological capabilities, access to financial resources, and established research infrastructure (Wong et al., 2018). Similarly, the USA collaborates with Canada, China, and the United Kingdom to leverage each other's strengths in technology innovation, research funding, and market access (Pei et al., 2024).

In the Asia-Pacific region, Australia collaborates with a diverse range of countries, including Belgium, Brazil, Canada, and Egypt. Singapore has collaborations with various countries, particularly Australia, China, and the United Kingdom, emphasizing its role as a hub for research and innovation in the Asia-Pacific region. The Middle East region, represented by the United Arab Emirates and Saudi Arabia, collaborates with European nations, India, and the USA. In the Latin America region, Brazil collaborates with Belgium, Mexico, and Portugal, while in Africa, collaborations include Morocco with Belgium, Egypt with Jordan, and South Africa with Nigeria and Qatar. Additionally, Algeria collaborates with Australia, Canada, and Saudi Arabia. Intra-African collaborations are very few; similarly, Africa-international collaborations are also

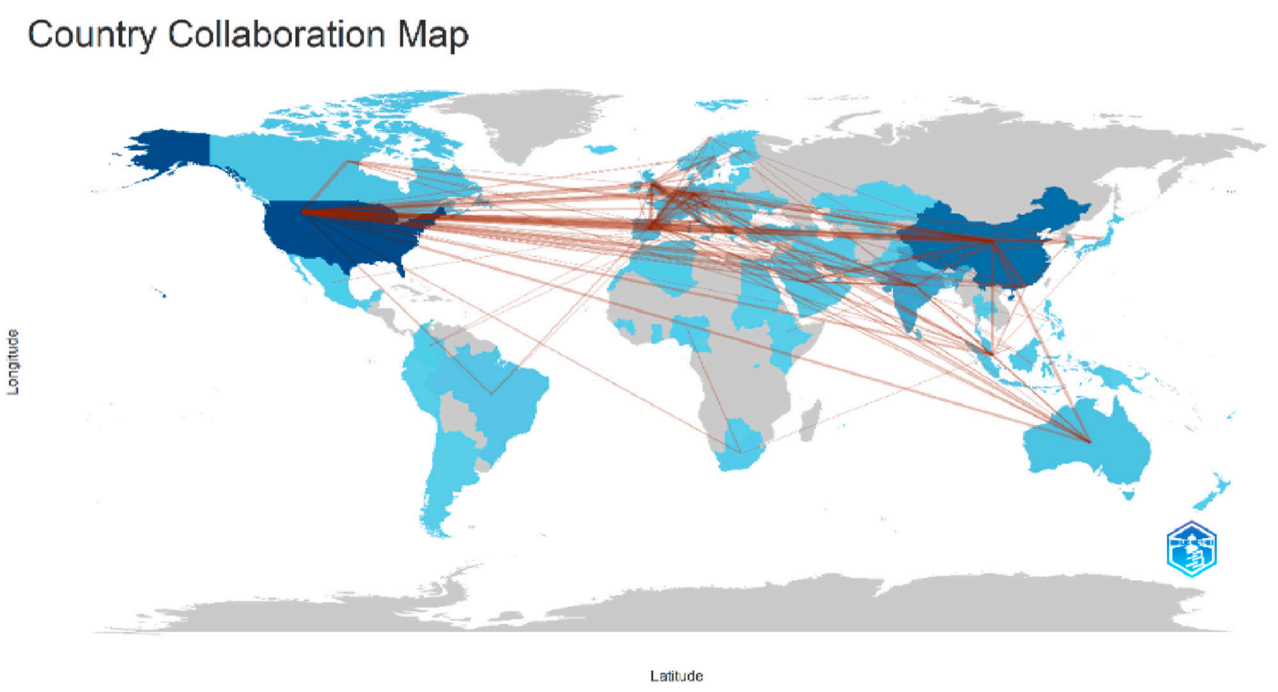

FIGURE 4
Country collaborations. Source: Data compiled from Scopus and Web of Science (2025).

weak. This could be attributed to the lack of robust research infrastructure and inconsistent funding in developed nations, coupled with the prioritization of immediate development challenges such as poverty reduction and healthcare (Ndzendze et al., 2024). Despite the lack of collaborations in Africa, some countries, such as Kenya and Ethiopia, are experiencing strong airline growth due to key geographical positioning within Africa (Samunderu, 2023).

4.2.1 Co-word analysis

Co-word analysis aids in recognizing emerging themes, which can serve as indicators for future research directions within the field of study. The analysis revealed 66,960 keywords that appeared in I4.0 in commercial airline publications, as indexed in the Scopus and Web of Science databases. Table 6 presents the top 50 most frequent words extracted from publications: article title, abstract, and keywords.

Big data analytics, with 1,138 occurrences, AI (971), machine learning (941), air transportation (929), aviation industry (926) and air traffic control (908) are the most frequently mentioned words, indicating the airline industry's significant reliance on these advanced technologies. Keywords like data analytics, big data, and data handling further emphasize the industry's strategic focus on leveraging data for decision-making and operational improvements. The commitment to safety and security is evident through terms such as safety engineering, aviation safety, and accident prevention. The operational and business aspects of aviation, including transportation services and airport operations, are evident through terms such as air transportation, airports, the aviation industry, and the airline industry. The integration of various technological applications, such as IoT, digital avionics, UAV, and network security, further demonstrates the industry's commitment to staying at the forefront of technological advancements. The keywords illustrate an airline industry embracing I4.0 for data-driven decision-making, operational efficiency, enhanced safety and security, and technological advancements.

4.3 Network analysis

Network analysis is a powerful tool for visualizing and understanding the relationships and patterns within complex systems, such as research domains. In bibliometric studies, network analysis helps uncover the structure of knowledge by mapping connections between entities such as authors, institutions, countries, or keywords. These connections can reveal collaboration patterns, thematic clusters, and the evolution of research trends over time (Baker et al., 2020). One of the most widely used techniques in network analysis is the co-occurrence network, which examines the frequency and relationships between specific terms or keywords within a body of literature (Donthu et al., 2021).

4.3.1 Co-occurrence network

The co-occurrence network is an analysis of the author's keywords. In a co-occurrence analysis, if the "author keywords" are not available, significant words can be obtained from "article titles," "abstracts," and "full texts" to use in the analysis (Donthu et al., 2021). The minimum number of occurrences of keywords was set at eight; out of 24,741 keywords, only 1,100 met the threshold. The analysis revealed eight major subthemes of research in

TABLE 6 Most frequent words.

S/no	Words	Occurrences	S/no	Words	Occurrences
1	Big data analytics	1,138	26	Remote sensing	81
2	Artificial intelligence	971	27	Monitoring	80
3	Machine learning	941	28	Reinforcement learning	79
4	Air transportation	929	29	NASA	78
5	Aviation industry	926	30	Flight delays	77
6	Air traffic control	908	31	Flight simulators	77
7	Decision-making systems	898	32	Performance	74
8	Aircraft safety	876	33	Social networking	74
9	Airport	765	34	Scheduling	71
10	Neural networks	695	35	Maintenance	71
11	Prediction	523	36	Fighter aircraft	71
12	Algorithms	450	37	Computer simulation	68
13	Deep learning	424	38	Traffic management	67
14	Security systems	384	39	Digital storage	66
15	Information systems	352	40	Complex networks	65
16	Automation	130	41	Genetic algorithms	65
17	Aircraft engines	100	42	Real-time systems	65
18	Accident prevention	91	43	Federal aviation administration	64
19	Costs	90	44	Efficiency	60
20	Intelligent systems	88	45	Military aviation	59
21	Predictive analytics	87	46	Clustering algorithms	58
22	Convolutional neural networks	87	47	Uncertainty analysis	58
23	Random forests	86	48	Feature extraction	56
24	Digital avionics	84	49	Traffic congestion	55
25	Trajectories	82	50	Computer vision	54

Source: Data compiled from Scopus and Web of Science (2025).

I4.0 literature, which were distinguished by their colors in the network. The larger circles correspond to the keywords that were chosen more often by the authors, while the lines between them represent the co-occurrences of the keywords in publications. The width of the lines indicates the number of these co-occurrences, with wider lines meaning more frequent co-occurrences, as depicted in Figure 5.

The eight clusters represent themes in I4.0 technologies applied in commercial airline literature. The red cluster comprises sub-themes such as advanced analytics, AI, data mining, accident prevention, BDA, aircraft maintenance, baggage handling systems, business intelligence and transportation. The cluster demonstrates the integration of advanced analytics, AI, and safety measures in the aviation industry, aiming to improve operational efficiency, profitability, passenger experience, and safety. The green cluster comprises sub-themes such as machine learning, airports, prediction, data science, environmental monitoring radar, and weather information systems. The cluster highlights the use of data-driven intelligence in improving air traffic management and aviation operations, enhancing prediction accuracy, decision-making, efficiency, safety, and resilience.

The dark blue cluster comprises sub-themes such as IoT, airport security, UAV, autonomous systems, BDA, augmented reality and air passengers. The cluster aims to enhance aviation security and passenger experience by integrating interconnected technologies and smart systems. The yellow cluster represents a thematic grouping of sub-themes related to air transportation, airport passengers, data-driven, collision avoidance and airline operations. The cluster focuses on enhancing air transportation efficiency, safety, and overall experience through data-driven approaches and optimization techniques. The purple cluster comprises air traffic control, air navigation, airport capacity and aircraft trajectory. The cluster is centered around the critical areas of air traffic flow management and airspace optimization.

The light blue cluster comprises sub-themes such as flight delay, accurate prediction, airline services and tickets. The cluster focuses

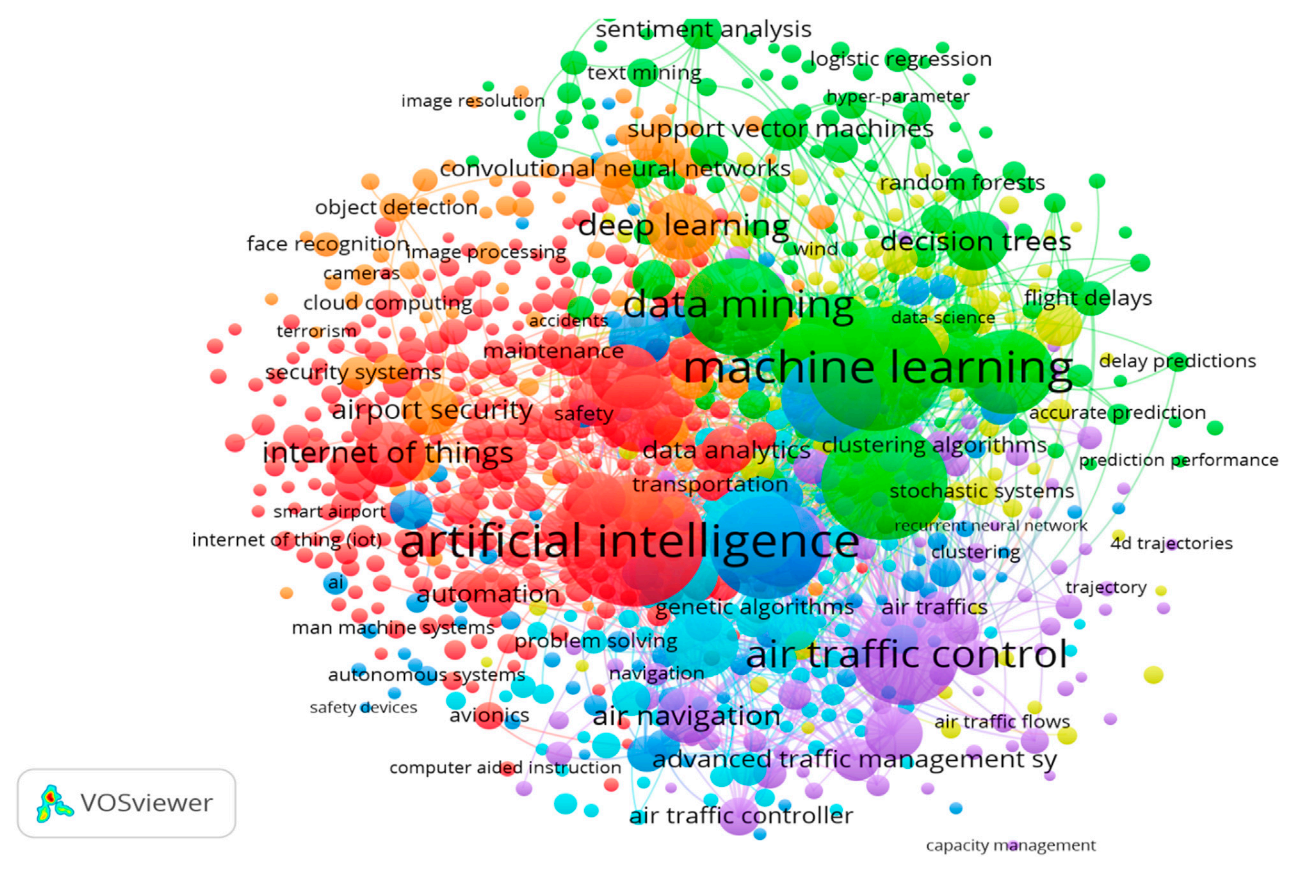

FIGURE 5
I4.0 themes network. Source: Data compiled from Scopus and Web of Science (2025).

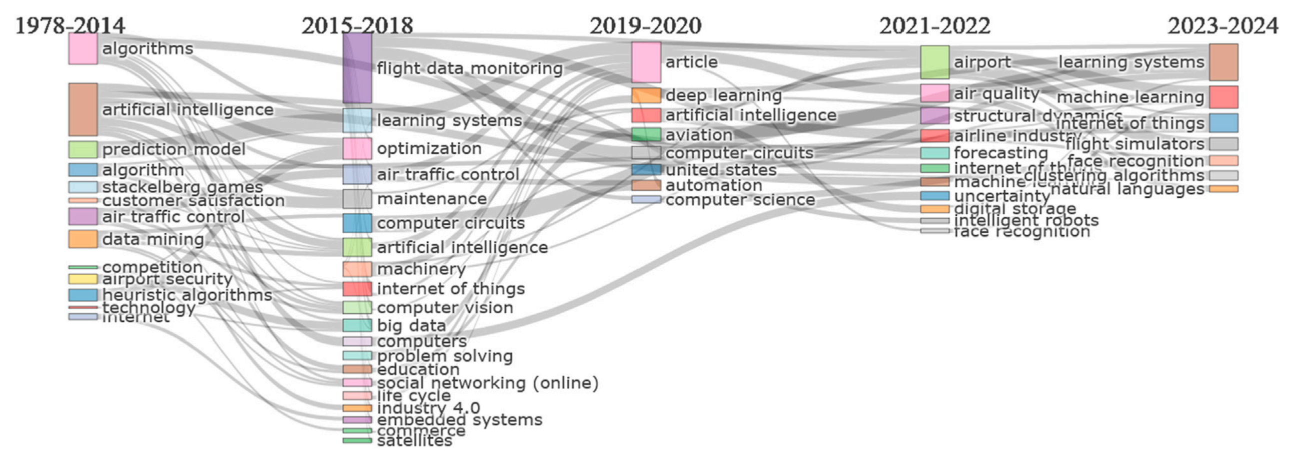

FIGURE 6
Thematic evolution of I4.0. Source: Data compiled from Scopus and Web of Science (2025).

on using data and predictive analytics to gain insights into enhancing customer experience and business outcomes. The orange cluster represents sub-themes such as aerodynamics, aircraft control, aviation safety and flight data monitoring. The cluster aims to enhance aviation safety through accident prevention and technical advancements. Lastly, the brown cluster comprises sub-themes such as aviation security, expert systems, pattern recognition and algorithms. The cluster focuses on applying expert systems and advanced algorithms to enhance aviation. The eight themes indicate that the airline industry is actively embracing I4.0 technologies to create a safer, more efficient, and passenger-friendly air travel environment. The integration of advanced analytics, AI, IoT, and predictive analytics reflects a forward-looking approach to addressing challenges and leveraging opportunities in the aviation sector.

4.4 Emerging themes and trends

The thematic evolution is discussed in four periods 1978–2014, 2015–2018, 2019–2020 and 2021–2022, as depicted in Figure 6. As the years progress, the duration shortens because of the rapid technological advances and the increase in publications.

The period from 1978 to 2014 primarily focused on research in air traffic control, with an emphasis on control towers, trajectories, and cybernetics. The period introduced emerging themes such as AI, big data, optimization, algorithms and security. Although emergent themes such as AI and big data had not reached prominence, they laid the foundation for future advancements. For instance, research on collision avoidance systems with the help of AI by NASA (Vranish et al., 1991) laid the foundation for today's automated flight safety platforms. In addition, advancements in optimization algorithms led to improved flow management systems, while studies on human factors in control towers enhanced safety protocols.

The period from 2015 to 2018 witnessed a notable evolution in commercial airline research, with a continued emphasis on traditional themes while witnessing an increased integration of emerging technologies. AI research explored decision support systems, information management, digital avionics, and data analytics. Big data gained substantial attention, especially in the intersection with AI, contributing to topics like airport security, cloud computing, and real-time systems. Additionally, integrating IoT in flight safety and information systems became a prominent theme, indicating a broader adoption of interconnected technologies in air traffic management. The period also marked significant progress in learning systems, extensively exploring machine learning algorithms, forecasting, and predictive analytics for improving air traffic control operations. The infusion of I4.0 and augmented reality hinted at a growing trend of incorporating advanced technologies into air traffic control systems. This period marked a transition towards a more technology-driven and interconnected approach to commercial airline research, with AI, big data and IoT playing pivotal roles.

The third period, from 2019 to 2020, experienced a significant expansion and diversification of research themes in commercial airlines. AI continued to play a central role, with a strong focus on applications in various fields in commercial airlines. The integration of AI into the aviation sector focused on areas such as aviation safety, flight simulators, optimization, and decision-making processes. The intersection of AI with IoT gained prominence, leading to studies on information management, airport security, UAVs and risk assessment. Automation, particularly in the context of air traffic control and aviation, saw notable developments during this period. Automation, coupled with AI, played a crucial role in enhancing various aspects of aviation operations, ranging from surveillance to transportation planning. Moreover, the integration of deep learning into air traffic control research marked a notable shift, with a focus on image enhancement, object detection, and recognition. The 2019–2020 period showcased a dynamic and interdisciplinary approach to air traffic control research, with a convergence of AI, automation, deep learning, and IoT, reflecting the ongoing efforts to enhance safety, efficiency, and innovation in the aviation industry.

In the fourth period, from 2012 to 2022, research continued to explore the intersection of emerging technologies with various domains in commercial airlines. The airline industry witnessed an integration of clustering algorithms and decision support systems, particularly focusing on remote sensing and forecasting methods for weather-related challenges. IoT research diversified into economic and social effects, cybersecurity, and the application of IoT in areas such as airport security, UAVs, and maintenance. Forecasting techniques continued to be a focal point, employing machine learning algorithms for applications ranging from environmental impact assessment to energy efficiency. Machine learning, a key player in this period, found applications in diverse areas, including aviation safety, air traffic control, decision-making processes, and risk management. This period marked a transformative era in commercial airlines, characterized by the synergy of diverse technologies, from AI-powered systems to human-centered design, driving unprecedented levels of efficiency, safety, and passenger comfort.

In summary, the themes shifted from a foundational focus on air traffic control to a more technology-driven approach. The integration of AI, big data, IoT, and machine learning became increasingly prominent, demonstrating a shift towards adopting I4.0 technologies by commercial airlines. A human-centric approach gained importance, reflecting a holistic understanding of the role of technology and human factors in commercial airlines. The future direction suggests that research in commercial airlines is heading towards a more technologically advanced, interconnected, and human-centric approach, with a continued emphasis on leveraging emerging technologies to enhance safety, efficiency, and innovation in commercial airlines.

5 Discussion

The main objectives of this bibliometric analysis were first to provide an understanding of the current state of research on I4.0 in commercial airlines. Second, identify the most significant research topics within the domain of I4.0 in the commercial airline industry. Third, to propose a possible future research agenda of I4.0 in commercial airlines. I4.0 technology research started in 1978 with one article by Preiss (1980). The article proposed a data-driven approach to modelling the engineering design process, emphasizing the need to transition from passive computer tool usage to active computer-driven design processes, leveraging electronic information systems and the potential integration of AI advancements. While AI, a fundamental component of Industry 4.0, originated much earlier, dating back to the 1950s (Azeem et al., 2022), its role in industrial automation evolved over time. The number of articles experienced exponential growth, from 89 in 2011 to 508 in 2023. The exponential growth during this period was attributed to the German government formulating a high-tech German manufacturing strategy based on I4.0. Concurrently, there were significant advancements in relevant technologies to support the implementation of I4.0. The interest in I4.0 research indicates how important the technologies are to the airline industry (Pandya and Kumar, 2023). Productivity analysis revealed that Lecture Notes in Computer Science, AIAA/IEEE Digital Avionics Systems Conference Proceedings and AIAA SciTech Forum were the top journals based on the number of publications. Notably, I4.0 research spans diverse thematic areas, demonstrating the interdisciplinary nature of this field. I4.0 is characterized by the integration and convergence of various technologies and disciplines, including AI, data analytics, cyber-physical systems, digital transformation, sustainability, safety, and security measures in commercial airlines. Abbasnejad et al. (2024) argue that the diverse thematic areas covered by I4.0 provide valuable resources and knowledge to various researchers in the aviation industry.

The most productive scholars revealed clusters that contribute significantly to the diverse challenges and advancements within I4.0. The clusters addressed critical areas in commercial airlines, such as safety, efficiency, environmental impact, and the integration of advanced technologies. The collaborative and multidisciplinary approach observed among these scholars emphasizes the significance of teamwork and shared expertise in advancing research and innovation within each thematic cluster. Moreover, it highlights the maturity of research in this field, especially among the collaborating countries. These collaborative models not only enrich the understanding of I4.0 but also reinforce the importance of interconnected efforts in shaping the future of the aviation sector. The scholars that emerged as the most influential include Liu Y, Mavris Dn, Puranik Tg, Chen H, and Alam S. Their contributions to I4.0 span critical areas such as flight safety, security, predictive maintenance, predictive analytics, and operational efficiency. The authors' affiliations revealed the dominance of Chinese institutions, highlighting China's strong commitment to I4.0 and aviation-related research. This dominance can be attributed to strategic state investments, supportive policy frameworks such as "Made in China 2025", high academic productivity, and strong institutional backing. However, this output is complemented by a global network of collaborating institutions from countries such as the United States, Hong Kong, Spain, and the Netherlands. This international spread of collaboration presents opportunities for global partnerships and knowledge exchange in I4.0 and aviation. Notwithstanding the dominance of Chinese institutions, the USA had the highest number of citations, thus making a substantial contribution to I4.0 in commercial airlines. While China is more prolific in output, studies from the USA are cited more frequently, possibly reflecting their perceived quality, applicability, or foundational significance in I4.0 for commercial airlines. This is evident because North America was leading in the quantity of research published per continent, followed by Asia and Europe. This is attributed to USA researchers frequently publishing in high-impact journals, which increases the likelihood of their work being cited by other authors. The USA invests significantly in research and development across various sectors, including aerospace and technology. Additionally, a strong culture of private-sector innovation, exemplified by firms such as Boeing, a flexible regulatory environment that supports experimentation, and an academic emphasis on research quality and rigour all contribute to the production of impactful research (Yang and Gu, 2021). These investments are driven by the substantial impact of Industry 4.0 technologies, which have enhanced operational efficiency, passenger experience, safety, environmental sustainability, data-driven decision-making, and regulatory compliance (Aigbavboa et al., 2023). Well-funded research institutions and government agencies provide ample resources for conducting research in areas related to I4.0 (Yang and Gu, 2021).

The second objective aimed to identify the most significant research topics within the domain of I4.0 in commercial airlines. Co-occurrence analysis of the extracted documents revealed that researchers have focused on five main areas: AI, automation, BDA, the Internet of Things, and integrating I4.0 technologies. Past research in AI focused on its applications across various fields of aviation, including machine learning, decision support systems, BDA, aviation safety, flight simulators, optimization, decision-making processes, and civil aviation. The past research demonstrated AI's role in ensuring an optimal supply of air transport services, improving efficiency, enhancing air transport user experience and improving air transport safety. Recently, researchers have focused on integrating AI and IoT for comprehensive information management, enhanced airline security, operational efficiency, UAV support, and proactive risk assessment (Heger et al., 2021). For instance, Ghosh and Chakraborty (2018) highlighted the transformative role of AI in IoT applications, particularly its ability to optimize real-time data processing for aviation security and operational efficiency. Similarly, Saadi et al. (2020) examined how AI and IoT integration is revolutionizing the customer journey in the airline industry, enabling predictive analytics, automated responses, and improved service delivery. The integration of AI and IoT enhances operational efficiency and reduces costs, directly impacting the economics of air transport by influencing ticket pricing and market competition. Studies by Lampropoulos et al. (2022) and Olaganathan et al. (2020) support the findings by asserting that AI and IoT contribute to airports' and airlines' efficiency, profitability and safety.

Past research in automation focused on contributing to the efficiency and safety of commercial airlines (Belo-Pereira, 2022). Research on air traffic control and aviation aimed at developing and implementing automated systems that utilize remote sensing technologies, advanced algorithms, and numerical models. These technologies contributed to real-time data acquisition and analysis, allowing for optimized flight trajectories and effective management of airspace, particularly during challenging weather conditions. The findings were collaborated by Kosovic et al. (2020) and Kim et al. (2022). Additionally, research demonstrated how machine learning was applied to international airport operations, streamlining processes such as baggage handling and security checks. Recently, researchers have focused on integrating deep learning techniques in image enhancement, object detection, and recognition, elevating the sophistication of monitoring and control systems. This was collaborated with McBrideet and Phillippou (2023). Research on BDA in commercial airlines focused on safety, predictive maintenance, and product optimization. The findings are supported by Khanal et al. (2022) whose study found that BDA and machine learning achieved high accuracy in weather prediction.

Research on IoT focused on how IoT can be used to improve airport security through smart cameras and sensors that detect anomalies, automate security checks, and track passenger movement. Furthermore, the application of IoT in predictive maintenance has been a significant area of investigation. This involved embedding sensors in aircraft components that transmit real-time data, enabling AI to predict potential failures and schedule preventive maintenance. Integrating IoT into security protocols and airport maintenance enhances safety for passengers and staff, mitigating risks effectively. Hence, contributing to the overall economic sustainability of the transportation sector (Koroniotis et al., 2020). Additionally, researchers also focused on the economic and social benefits of IoT, such as improved passenger experience, airport operations, and sustainability practices (Baláž et al., 2023; He et al., 2024). Lastly, integrating I4.0 technologies such as AI, BDA, and IoT has recently been the focus of several studies. This convergence creates a synergistic effect, where each technology enhances the capabilities of the others. This integration fosters advancements in predictive maintenance, risk assessment, and personalized passenger experiences, ultimately contributing to a smarter, safer, and more efficient aviation ecosystem. However, research in I4.0 is still growing exponentially, and more researchers are investigating the adoption of this technology in different fields. Lampropoulos et al. (2022) argued that integrating AI and BDA technologies offers a more personalized and customized experience to the customers and, in addition, improves organization performance.

While these clusters reflect dominant academic themes, they also align with real-world implementation trends across airline types. For instance, flag carriers often invest in advanced tools such as digital twins, AI-based crew scheduling, and predictive maintenance systems (Cheung et al., 2023). In contrast, low-cost carriers (LCCs), operating under tight cost constraints, adopt more affordable solutions like dynamic pricing algorithms, chatbot-based customer service, and IoT-driven fuel monitoring systems (Farahpoor et al., 2024). Meanwhile, cargo airlines are leveraging blockchain for traceability and BDA for optimizing logistics and regulatory compliance (Lau et al., 2024). These operational distinctions help explain why certain research themes are emphasized more than others, revealing how scholarly interest reflects practical needs within the industry. However, the application of these technologies remains uneven globally, particularly in developing countries. Persistent barriers include limited digital infrastructure, high implementation costs, institutional resistance and a shortage of skilled personnel (Pittri et al., 2025; Nosike, 2024). To interpret these disparities, this study draws on two established theoretical frameworks. The Technology Organization Environment (TOE) framework explains how adoption is shaped by technological readiness, organizational capability, and external environmental factors such as regulation and market pressure (Tornatzky and Fleischer, 1990). Similarly, Rogers' Diffusion of Innovations (DOI) theory provides insight into the staggered uptake of I4.0 technologies, with early adoption concentrated in high-income regions and later adoption observed in resource-constrained settings (Rogers, 2003). Together, these frameworks help contextualize why certain technologies dominate academic discourse but remain underutilized in specific regions or airline segments.

The third objective aimed to propose the future research agenda of I4.0 in commercial airlines. The results revealed several gaps and emerging trends that point to key areas for future exploration. First, human-centric approaches emerged as a critical gap. While the analysis highlighted significant advancements in I4.0, there was limited focus on integrating these technologies with human factors to prioritize safety, comfort, and usability (Ghosh and Chakraborty, 2018; Saadi et al., 2020; Yang et al., 2024). Second, cybersecurity was identified as an underexplored area despite its growing importance. The bibliometric analysis revealed that commercial airlines had adopted I4.0 technologies to enhance efficiency, yet research on the cybersecurity risks associated with these advancements remained limited (Bautista-Hernández and Martín-Prats, 2024). Third, environmental sustainability emerged as an area of interest for future research. While the analysis highlighted growing interest in technologies such as predictive maintenance and fuel efficiency optimization, there was limited focus on the broader environmental impact of I4.0 in aviation (Lampropoulos et al., 2022; Zaoui et al., 2024; Dinçer et al., 2024). Finally, ethical and legal implications were identified as an emerging area of concern. The bibliometric analysis revealed that while I4.0 technologies are transforming the airline industry, ethical and legal research remains limited. For instance, the use of AI for decision-making and predictive analytics raises questions about bias, transparency, and accountability. Additionally, the potential impact of automation on employment in the aviation sector remains underexplored. The future research agenda for Industry 4.0 in commercial airlines will likely be multidisciplinary, addressing technical, human, ethical, and business aspects.

6 Conclusion

The bibliometric analysis undertaken in this review provided valuable insights into the state and trajectory of research on I4.0 in commercial airlines. Since 2011, research in this field has experienced exponential growth, driven by government initiatives, technological advancements and the increasing relevance of I4.0 technologies in commercial airlines. A key finding of this review is the multidisciplinary nature of I4.0 research, which reflects the interconnectedness of fields such as AI, BDA and IoT. This interdisciplinary approach underscores the importance of collaborative efforts in shaping the future of aviation and highlights the need for practitioners to leverage diverse expertise to fully realize the benefits of I4.0. While Chinese institutions dominate research in this field, a global network of collaborations is emerging. However, a notable gap in knowledge regarding the application of I4.0 in developing nations was identified, suggesting an area for future research and collaboration. The review identified key research areas within I4.0, including AI, BDA, IoT, machine learning and the integration of I4.0 technologies. However, emerging technologies such as digital twins and blockchains have received less attention due to their novelty and the high infrastructure demands associated with their implementation. The findings of this review highlight the potential of I4.0 technologies to address critical challenges in airline operations, including efficiency, passenger safety, baggage handling, environmental impact, predictive maintenance, airport security, and passenger experience. Based on the identified trends and gaps, a prioritized and time-phased research agenda is proposed as follows:

1. Cybersecurity (High urgency, Medium feasibility | Short-term: 1–2 years). With the rapid digitization of airline systems, cybersecurity risks are immediate. Future research should focus on assessing vulnerabilities in IoT-enabled systems,

AI-driven platforms, and cloud-based data storage. Recommended methodologies include threat modelling and case studies of cybersecurity breaches in aviation. This research should also evaluate regulatory compliance frameworks and propose adaptive security protocols.

2. Integration Challenges (High urgency, High feasibility | Short-to Medium-term: 1–3 years). Integration of I4.0 with legacy systems presents ongoing operational challenges. Research should explore system compatibility, workforce readiness, and change management. Mixed-method approaches combining organizational case studies with technology readiness assessments would be suitable. Action research in collaboration with airline IT departments may provide grounded insights.

3. Impact Assessment (High feasibility, Medium urgency | Short-term: 1–2 years). Evaluating the tangible benefits of I4.0 implementation remains critical. Research should employ longitudinal studies and performance benchmarking using key metrics such as fuel efficiency, maintenance frequency, flight scheduling accuracy, and customer satisfaction. Quantitative methods such as regression analysis, data envelopment analysis (DEA), or multi-criteria decision analysis (MCDA) can be used.

4. Human-Centric Approaches (Medium urgency, Medium feasibility | Medium-term: 2–4 years). As automation increases, human-machine interaction must be optimized for safety and usability. Studies should focus on cockpit ergonomics, AI explainability, decision support systems, and situational awareness. Human factors engineering, usability testing, and simulation studies in airline environments are recommended methodologies.

5. Environmental Sustainability (Medium urgency, Low feasibility | Medium-to Long-term: 3–6 years). Assessing the environmental benefits of I4.0 technologies is crucial but often complex due to indirect effects. Research could involve life cycle assessments (LCA), carbon accounting, and simulation-based models of energy use. Cross-sectional studies of emissions data before and after I4.0 implementation may also provide valuable evidence.

6. Ethical and Legal Implications (Low urgency, Low feasibility | Long-term: 4–7 years). Ethical issues such as algorithmic bias, employee displacement, and decision accountability are growing concerns. This area would benefit from normative analysis, stakeholder engagement studies, and policy review. Legal scholars and ethicists could collaborate with aviation experts to develop guidelines for responsible technology deployment.

Despite its thoroughness, this review has several limitations that should be acknowledged. First, bibliometric analysis relies solely on publication data and does not assess the actual effectiveness or impact of I4.0 implementation in airline operations. Second, there is a publication bias toward reporting successful implementations, which may skew the representation of challenges, failures, or incomplete adoptions of I4.0 technologies. Third, this review excluded grey literature, such as industry white papers, technical reports, and conference presentations, which often contain valuable insights, especially from airline practitioners, regulatory bodies, or tech vendors. Fourth, there is a language bias, as the review focused exclusively on English-language publications. This may have excluded relevant studies published in other languages. Lastly, bibliometric analyses are subject to temporal lag effects. Recent research trends may not be fully captured due to indexing delays, and highly relevant recent publications may not have accumulated enough citations to appear prominently in co-occurrence and impact analyses. The findings of this review can inform strategic decision-making, resource allocation, and investment in I4.0 initiatives within the commercial airline industry. Practitioners can leverage the identified research areas and future research agenda to drive innovation, address industry challenges, and ensure the responsible deployment of emerging technologies.

To support actionable outcomes, airlines can adopt the following strategies:

- Conduct readiness assessments to evaluate current infrastructure and digital maturity.
- Implement pilot projects to integrate technologies like digital twins and blockchain in targeted operational areas.
- Develop training programs to equip staff with the skills needed to work alongside I4.0 technologies.
- Establish performance metrics to track adoption rates and measure performance improvements over time.

For policymakers, the following recommendations are proposed:

- Provide incentives and research grants to promote the development and adoption of I4.0 technologies.
- Develop regulatory frameworks to address data security and privacy concerns.
- Foster collaborative innovation by encouraging partnerships between airlines, research institutions, and technology providers.

In conclusion, this review provides a comprehensive bibliometric analysis of I4.0 research in commercial airlines, revealing significant insights into its current state, trends, gaps and future research directions. The review highlights the field's interdisciplinary nature, with strong connections across AI, BDA, and the IoT, driving innovation in operational efficiency, customer experience, passenger safety, predictive maintenance and sustainability. Despite exponential growth in research since 2011, significant knowledge gaps remain, particularly in the application of I4.0 technologies in developing countries. The review emphasizes the need for further research to examine the application of I4.0 technologies in commercial airlines in developing countries, especially in impact assessment, integration challenges, cybersecurity, human-centric approaches, environmental sustainability and ethical and legal implications. Through addressing these areas, the aviation industry can harness the full potential of I4.0 technologies to create a safer, more efficient, and sustainable future for air travel.

Author contributions

NO: Conceptualization, Writing – review and editing, Investigation, Writing – original draft, Software, Data curation, Visualization, Validation, Formal Analysis, Methodology. RL: Writing – review and editing, Conceptualization, Validation, Supervision. JM: Validation, Supervision, Writing – review and editing, Conceptualization. TO: Writing – review and editing, Validation, Conceptualization, Supervision.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

The authors are incredibly grateful to the department of transport and supply chain management, college of business and economics at the University of Johannesburg for allowing them to carry out this study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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