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Evolution of Fatigue Research in the Aviation Sector: A Bibliometric Study

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Abstract

Fatigue is widely recognized as a critical human factor in aviation, influencing flight safety, crew performance, and operational efficiency. This study presents a comprehensive bibliometric analysis of peer-reviewed and open-access publications on aviation-related fatigue between 1995 and May 31, 2025, based on 228 articles indexed in the Web of Science Core Collection. Using VOSviewer software, data were analyzed through performance metrics, co-authorship, and citation networks, bibliographic coupling, and keyword co-occurrence mapping. Findings reveal a significant increase in publication output after 2020, highlighting growing academic and regulatory attention to fatigue risk management, especially in the context of extended flight duties and cognitive performance deterioration. Highly cited publications emphasize the physiological and neurocognitive consequences of fatigue, while the most central authors and clusters point to increasing interdisciplinary collaboration. Keyword co-occurrence mapping revealed prominent conceptual clusters around human fatigue, operational safety, fatigue management strategies, and detection technologies, reflecting the multifaceted nature of fatigue-related research in aviation. The study contributes to a deeper understanding of the structural evolution of fatigue literature in aviation, offering methodological clarity and highlighting key research gaps. These results provide actionable insights for aviation stakeholders seeking evidence-based strategies to manage fatigue and support human-centered safety systems.

1. Introduction

Fatigue is considered a critical human factor in terms of flight safety in the aviation industry. According to the International Civil Aviation Organization [ICAO] (2020), fatigue is "*A physiological state of reduced mental or physical performance capability resulting from sleep loss, extended wakefulness, circadian phase, and/or workload (mental and/or physical activity) that can impair a person's alertness and ability to perform safety-related operational duties*". This can negatively affect the alertness of the aviation professionals (such as pilots, air traffic controllers, aircraft maintenance engineers) and their ability to safely perform tasks that ensure aviation safety. Fatigue has been reported as a direct or indirect cause of many aircraft accidents and serious incidents (Caldwell, 2012; National Transportation Safety Board [NTSB], 2017).

Fatigue is one of the most significant human factors that threaten operational safety in aviation and can lead to serious flight accidents through effects such as decreased cognitive capacity, distraction, prolonged reaction time, and judgment errors (Basner et al., 2013; Caldwell, 2005). Wingelaar-Jagt et al. (2021) found that fatigue cannot be completely prevented, and therefore pharmacological interventions and preventive strategies play a critical role. In this context, it was stated that there is a need for risk reduction systems based not only on regulatory limitations but also on operational realities. Many accident investigations conducted in recent years have revealed that fatigue is a critical variable contributing to unsafe conditions in both civil and military aviation. For example, in the accident in 2010 when Air India Express Flight 812 went off the runway during landing and disintegrated, resulting in the death of 158 people, it was determined that the captain was asleep for most of the flight and made decision-making errors after waking up (Directorate General of Civil Aviation, 2010). Similarly, in the accident of Colgan Air Flight 3407 in 2009, it was determined that the flight crew was both tired and sleep-deprived, and it was reported that this situation led to incorrect landing configuration and delayed engine responses (NTSB, 2010). The impact of fatigue on accidents is not limited to civil flights; a review by the United States Air Force (USAF) found that approximately one-quarter of the most serious Class A accidents were attributed to fatigue (Gaines et al., 2020). Fatigue has also been considered a contributing factor to decision-making in complex mission environments, such as the Libyan Arab Airlines Flight 1103 accident (Libyan Civil Aviation Authority, 2017). Fatigue Risk Management System (FRMS), one of the most discussed and implemented systems in the management of fatigue today, has been spread throughout the sector with the guide published by ICAO in

2011. Instead of focusing only on flight/rest times, this system adopts a proactive approach supported by operational data and aims to reduce fatigue risk at the corporate level (ICAO, 2020). In the FRMS handbook published in 2020, EASA recommends that this system be integrated and culturally adopted at all levels of flight operations (EASA, 2020).

Fatigue is a risk factor that needs to be addressed at organizational and system levels, beyond its effects on individual performance. NTSB has included fatigue in its "Most Wanted" list since 1990 and has published hundreds of safety recommendations in this context (Marcus & Rosekind, 2017). However, despite the measures taken, a significant decrease in fatigue-related incident rates has not been achieved. This situation has shown that fatigue management should be supported not only by regulatory frameworks but also by scientifically based strategic approaches. In this context, analyzing the evolution of academic knowledge on fatigue over time, prominent thematic focuses, and research collaborations fills an important gap in understanding the current status of the field.

Systematic and objective evaluation of scientific literature is critical to understanding the direction and dynamics of knowledge production, especially in multidisciplinary fields (Aria & Cuccurullo, 2017). In this context, bibliometric analysis stands out as a powerful method that enables measuring academic productivity, collaborations, conceptual developments, and research trends through the examination of bibliographic data related to scientific publications with mathematical and statistical techniques (Broadus, 1987; van Eck & Waltman, 2010). In recent years, the use of this method has become widespread, especially in fields such as health sciences, management, engineering, and aviation, and has become an effective tool for mapping both interdisciplinary knowledge flows and research clusters in a particular field (Moral-Muñoz et al., 2020; Yeung et al., 2019). In applied fields such as human factors and aviation safety, bibliometric analysis provides important contributions in determining research priorities, developing evidence-based recommendations for policymakers, and identifying academic gaps (Xie et al., 2020).

A limited number of bibliometric analysis studies are available on the subject of fatigue in the context of human factors in aviation. However, there are studies in the literature examining the theme of fatigue under different subheadings. Tuncal and Altıntaş (2025) conducted a bibliometric analysis of the literature on human factors in aviation and demonstrated that the term "fatigue" is conceptually associated with safety-critical issues such as "accident," "aircraft," and "work." Their findings highlight the increasing academic interest in human factors and the need for more in-depth investigations within this domain. In addition, Gomes de Carvalho et al. (2023) conducted a bibliometric analysis examining fatigue assessment methods specific to air traffic control activities and revealed that current assessment approaches are mostly based on subjective methods, and objective measurement tools are used limitedly. In the review study conducted by Wingelaar-Jagt et al. (2023), it was emphasized that fatigue cannot be completely prevented, especially in military aviation due to operational restrictions, and therefore pharmacological interventions and preventive strategies play a critical role. Similarly, Göker (2023) discussed the effects of fatigue on cognitive functions and the subjective and objective methods for assessing fatigue and stated that neurophysiological-based measurements in particular need to be used more widely in aviation applications. On the other hand, Bendak and Rashid (2020) comprehensively analyzed the risks of fatigue in aviation operations through a systematic review study and revealed that duty periods longer than 16 hours and pre-sleep rest periods shorter than six hours increase the risk level. Although these studies provide in-depth information on measurement, management, and prevention strategies related to fatigue, they have not yet addressed the structure of scientific production on fatigue in aviation on a global scale, in which conceptual focuses are prominent and the development over time through a systematic bibliometric analysis. This study aims to analyze scientific production on the subject of fatigue, which directly affects aviation safety, using the bibliometric method. The theme of fatigue, which is increasingly addressed in the literature, has become a critical research area, especially in the context of operational conditions that push the limits of human performance.

The study aims to analyze scientific production on the subject of fatigue, which directly affects aviation safety, using the bibliometric method. To this end, the study seeks to reveal the structural characteristics of the literature by determining the position of the concept of fatigue within the aviation discipline, its development over time, and the most prominent researchers, institutions, and countries. Additionally, it systematically maps research trends in this field by identifying the most studied themes, frequently cited publications, and influential journals. The theme of fatigue, which is increasingly addressed in the literature, has become a critical research area, especially in the context of operational conditions that push the limits of human performance. The findings obtained not only provide an academic resource map but also aim to support more effective fatigue management in aviation and the reinforcement of safety culture by guiding future studies focused on human factors.

2. Materials and Methods

This research aims to examine academic publications addressing the subject of fatigue in aviation using the bibliometric analysis method. Bibliometric analysis is an approach that systematically examines trends, research clusters, citation relationships, and collaborations in scientific literature through quantitative data. Within the scope of the study, publications from the period between 1995 and May 31, 2025 were scanned to reveal how the theme of fatigue in aviation was addressed in a scientific context.

2.1. Research Questions

The research seeks answers to the following questions:

- Which are the most cited studies published between 1995 and 2025?
- Who are the most productive and influential authors, and is there a significant relationship between the number of citations and the number of publications?
- Which countries and institutions publish the most in this field?
- What are the most frequently used keywords in the literature, and what kind of relational clusters are there between these concepts?

2.2. Records Collection and Analysis

The dataset of this study was created via the Web of Science (WoS) Core Collection database, connected to the university campus network via the Istanbul University VETIS database. A structured topic search query was employed using the keyword sequence ((("pilot fatigue" OR "crew fatigue" OR "air traffic controller fatigue" OR "aviation fatigue" OR "flight fatigue" OR "cabin crew fatigue" OR "fatigue risk management") AND ("aviation" OR "flight crew" OR "air traffic control" OR pilot* OR "air traffic controller*" OR "cabin crew" OR cockpit OR airline*))) to retrieve relevant bibliographic records from the WoS. The search was limited to publications published between 1995 and 2025. 5,842 publications were reached in the first search conducted as of May 31, 2025. Only peer-reviewed articles, English language publications, and open-access ones were filtered and 228 articles were selected for analysis. The obtained records were transferred to EndNote 21.5 software for resource management purposes.

In the data analysis and visualization process, VOSviewer version 1.6.20 was used to map scientific collaborations, citation relationships, and conceptual connections. This software graphically represents bibliometric data sets, making structural relationships in the literature more understandable (Van Eck & Waltman, 2010). Within the scope of the study, co-authorship analysis, citation analysis, and text-mining methods were applied. The analysis parameters were determined: a maximum of 15 authors for each author, a minimum of 1 document produced, and a minimum of 1 citation criterion. In line with these criteria, influential researchers, institutional collaborations, and thematic density areas in the literature were visually presented.

3. Results

3.1. Annual Distribution of Articles

Within the scope of this study, 228 articles published between 1995 and May 31, 2025 were evaluated. Figure 1 shows the distribution of these publications by year. A remarkable increase in the number of publications has been observed, especially since 2020. In recent years, studies on fatigue in aviation have intensified, and academic production in this field has gained momentum. The trend line in the figure statistically supports the increase in the volume of publications and the increase in research interest in this direction.

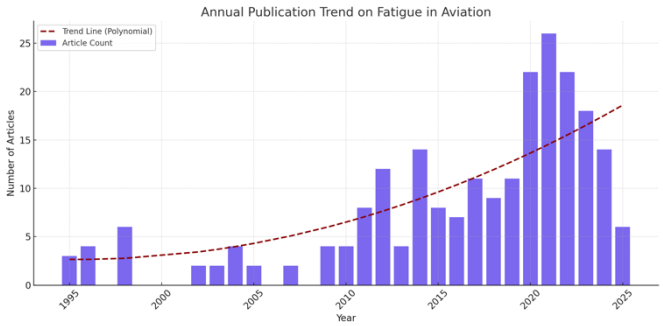

Figure 1. Distribution of Articles Per Year

3.2. Co-authorship Analysis of Authors

Co-authorship analysis was evaluated with the collaboration relationships established by each author with other authors (Melin & Persson, 1996). Within the scope of this analysis, the minimum number of publications that an author must have in order to be included was determined as 1, and the minimum number of citations was determined as 1. In line with these threshold values, 123 authors out of a total of 706 authors were evaluated within the scope of the analysis. The group that formed the largest connected network structure among these authors consisted of 35 authors, and 264 links and a total link strength of 513 were determined in this network, as shown in Figure 2. The most cited authors in the co-authorship network are J. Lynn Caldwell, (230 citations), John A. Caldwell, (223 citations), Hans P. A. Van Dongen, (87 citations), and Peter McCauley, (59 citations). These researchers not only represent the most influential contributors in terms of citation impact but also occupy central positions in the collaboration map, forming the densest and most interconnected parts of the network. Particularly, J. Lynn Caldwell, and John A. Caldwell, demonstrate strong mutual collaboration and serve as a bridge between other author clusters. In contrast, although authors such as Jillian Dorrian, Adam Fletcher, and Peter Page appear in the same co-authorship cluster, their citation impact remains relatively lower and their collaborative connections are more limited within the overall structure of the network.

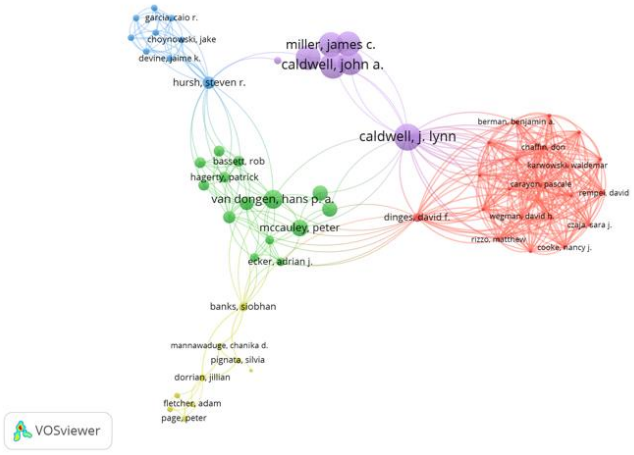

Figure 2. Co-Authorship Network of Authors

3.3. Citation-based Findings

Citation analysis is an important method for determining the most influential publications and authors in a particular research area (Vasudevan et al., 2016). This analysis reveals the level of scientific contribution and visibility in the literature through the citations that publications receive over time. In this study, 228 articles published between 1995 and 2025 were evaluated and it was determined that 131 of them received at least one citation. Table 1 displays the top ten most cited articles in the field of fatigue within aviation. Unlike general discussions on human factors, all of these studies directly address fatigue, particularly in operational flight contexts, and contribute significantly to the development of fatigue risk management strategies. The most cited work is the comprehensive position paper by Caldwell et al. (2009), with 179 citations, which synthesizes the scientific understanding of fatigue and critiques existing civil and military regulations, offering policy-level recommendations. Following this, the study by Hu and Lodewijks (2020), with 144 citations, provides an in-depth evaluation of non-invasive physiological and behavioral indicators of fatigue, particularly distinguishing between sleepiness and mental fatigue—an important differentiation for pilot monitoring systems. Morris and Miller (1996), ranked third with 138 citations, focus on electrooculographic indicators and simulator performance under fatigue, revealing early psychophysiological markers of degraded performance. Goode's (2003) empirical analysis, with 108 citations, establishes a statistically significant

link between long duty hours and accident probability, making a direct regulatory impact. Similarly, Petrilli et al. (2006) and Caldwell et al. (2004) address international operations and sustained wakefulness respectively, offering robust evidence on how disrupted sleep and long-range flights impair pilot vigilance. Studies by Neri et al. (2002), Powell et al. (2007), Gander et al. (2013), and Honn et al. (2016) extend these insights by testing fatigue countermeasures, such as in-flight breaks, segment-based scheduling, and in-flight sleep optimization. Together, these articles underscore fatigue as a central operational and safety-critical issue in aviation, providing foundational evidence for the refinement of duty time regulations and fatigue risk management systems (FRMS).

Table 1. Most Cited Articles on Fatigue

Ranking	Article	Citations
1	Caldwell J.A. et al. (2009)	179
2	Hu & Lodewijks (2020)	144
3	Morris & Miller (1996)	138
4	Goode (2003)	108
5	Petrilli et al. (2006)	89
6	Caldwell et al. (2004)	86
7	Neri et el. (2002)	71
8	Powell et al. (2007)	63
9	Gander et al. (2013)	57
10	Honn et al. (2016)	50

Citation networks were determined with at least 1 publication and at least 1 citation criteria, and a network map was created for author citation analysis. In the study conducted on 113 units that were seen to be connected, a total of 12 clusters, 1256 links, and a total link strength of 3235 were determined. The most cited authors were Philippa Gander with 261 citations, J. Lynn Caldwell with 230 citations, and Drew Dawson with 145 citations. These three authors are also among the top three in terms of total connection strength (Figure 3).

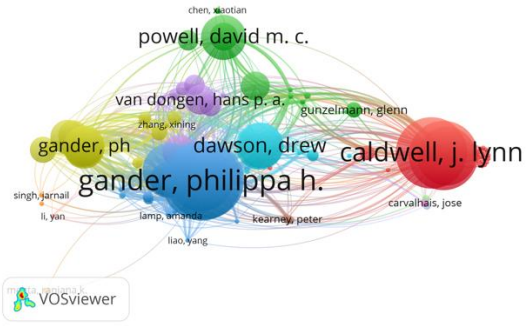

Figure 3. Citation of Authors

The network map of the citations received by the publications according to their country of origin was analyzed on 39 observation units that were related to each other within the scope of the criteria of at least 1 work published and 1 citation received by a country. 6 clusters, 92 links, and 632 total link strengths were identified. The countries with the most citations were the United States (USA) (1341 citations), Australia (411 citations) and China (217 citations). These countries are in the top three in terms of total link strength. In terms of the number of works, the ranking is as follows: United States (USA) (74 publications), China (45 publications) and New Zealand (24 publications) (Figure 4).

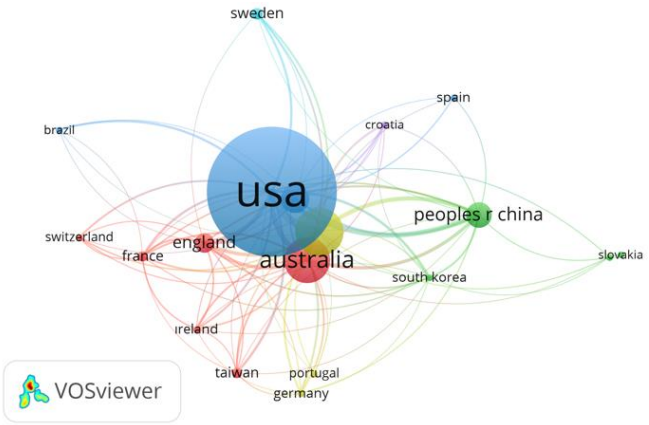

Figure 4. Citation of Countries

Bibliometric coupling analysis reveals that when two publications cite the same studies as sources, these publications are content-wise similar (Zupic & Čater, 2015). Within the scope of this analysis, the largest connected cluster was determined, consisting of 155 authors out of a total of 170 authors. Figure 5 visually presents the bibliometric connections between authors. As a result of the analysis, it was determined that 11 different clusters were formed, there were 3.647 links between authors, and a total link strength of 7.374 was obtained. These findings reveal the structural density of academic collaborations in the literature and the strength of thematic clusters. The publications with the highest number of bibliographic matches were John A. Caldwell (2009) with 179 citations, Xinyun Hu (2020) with 144 citations, and Philippa Gander (2013) with 45 citations.

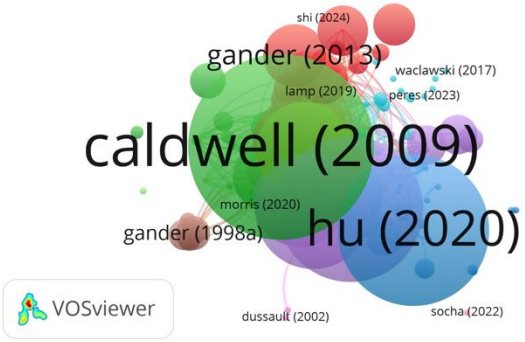

Figure 5. Bibliometric Coupling of Authors

3.4. Text Mining in Title and Abstract Fields

The text mining method analyzes the relationships between the terms that occur together in the documents and creates two-dimensional conceptual maps between these terms. The smaller the physical distance between the terms on the map, the stronger their conceptual relationships are considered (Cobo et al., 2011). This method allows the visual display of the basic concepts, thematic densities, and research trends in a certain field. In this study, keyword analysis conducted on scientific publications on the subject of fatigue published between 1995 and 2025 revealed conceptual densities and thematic clusters in the field. In the co-occurrence analysis conducted with VOSviewer software, the word “fatigue” stood out as the concept with the highest frequency with 59 repetitions. This was followed by “pilot fatigue” (16

repetitions), "fatigue risk management", sleep (14) and "aviation" (14 repetitions each).

The keyword co-occurrence Cluster Map illustrates the conceptual structure of the literature by grouping frequently co-occurring terms into thematic clusters. As shown in Figure 6, the central cluster (red) is built around the core concept of "fatigue" and includes closely related terms such as "alertness," "sleep," and "flight crew," emphasizing its strong association with physiological states and human performance. The green cluster reveals the domain-specific context of aviation, including terms like "aviation," "flight fatigue," and "pilots," which reflect operational applications of fatigue research. Meanwhile, the blue cluster highlights the link between fatigue and safety outcomes, with terms such as "pilot fatigue," "flight safety," and "fatigue detection." The yellow cluster focuses on "fatigue risk management" and regulatory approaches, pointing to applied models in aviation safety systems.

The Density Map further supports these findings by visually reinforcing the centrality of "fatigue" in the research domain. As shown in Figure 7, keywords such as "fatigue," "aviation," "pilot fatigue," "fatigue risk management," and "alertness" form a dense conceptual core, suggesting that recent studies predominantly concentrate on the interface between fatigue and human factors in aviation contexts. The intensity of density around these terms also indicates an increased scholarly focus on real-world risk mitigation strategies in flight operations and aircrew management. Together, these maps confirm that the literature is heavily oriented toward human performance, operational safety, and fatigue management within the aviation industry.

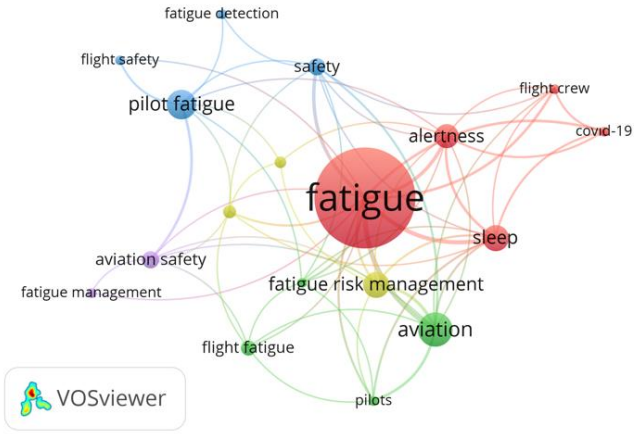

Figure 6. Text Mining Cluster Map

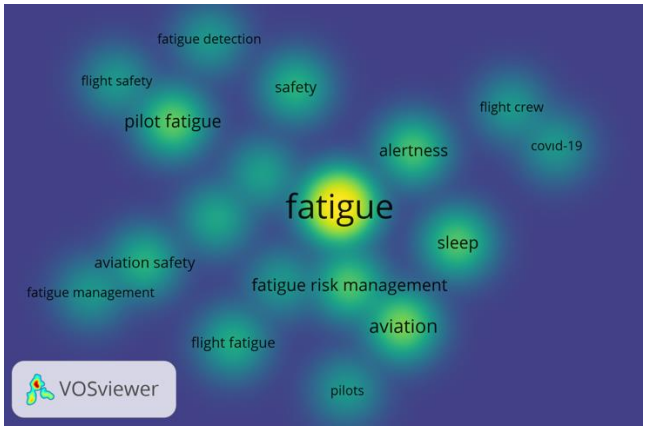

Figure 7. Text Mining Density Map

4. Discussion

The increasing academic interest in the concept of fatigue in the literature in recent years shows how critical an area this subject has become, especially in sectors such as aviation that require high-risk and intense cognitive performance. This increase reflects not only quantitative growth but also the diversification of interdisciplinary approaches. In this context, it is necessary to gain a systematic view of questions such as how fatigue is addressed in aviation, who studies it, which themes it focuses on, and how the research orientation has been shaped over time. In this study, 228 academic articles published in the Web of Science database between 1995 and May 31, 2025 were analyzed, and the development of the research field was evaluated through performance indicators and scientific mapping techniques. The bibliometric analysis conducted using the VOSviewer software revealed multi-dimensional publication trends and conceptual clusters. The findings show that fatigue-themed studies are not limited to physiological effects alone. They also establish strong relationships with areas such as human factors, safety management, artificial intelligence-supported monitoring systems, and ergonomic design.

The bar chart reveals a marked increase in academic publications on aviation fatigue beginning in 2020, suggesting a shift in scholarly and operational focus toward fatigue-related risks in flight operations. This rise corresponds with a wave of research exploring fatigue not only in pilots but also in cabin crew (Van den Berg et al., 2020), air traffic controllers (Huang et al., 2024), and broader operational contexts such as crew rostering and scheduling (Novak et al., 2020). While earlier studies emphasized physiological aspects of fatigue, recent works have adopted interdisciplinary and technological approaches—such as AI-based fatigue detection (Pillai et al., 2020) and biomathematical modeling of subjective and objective fatigue dynamics (McCauley et al., 2021). This growing body of research highlights a deeper understanding of fatigue as a systemic risk that affects safety, decision-making, and well-being across aviation roles. Notably, Bourgeois-Bougrine (2020) critically questioned the bureaucratic limitations of existing FRMS structures, while Guo et al. (2022) and Qin et al. (2021) offered insight into mental fatigue and its psychological mediators. The increase in publication volume, therefore, reflects a research trend that goes beyond traditional perspectives—integrating operational logistics, neurocognitive science, and predictive technologies—to address fatigue as a multifaceted aviation safety issue.

The co-authorship analysis highlights the prominence of J. Lynn Caldwell (230 citations), John A. Caldwell (223 citations), Hans P. A. Van Dongen (87 citations), and Peter McCauley (59 citations) as central figures in the scholarly network on aviation fatigue. These authors not only stand out for their citation impact but also form a densely interconnected core, reflecting long-standing collaborations that have significantly shaped the field. The foundational work of Caldwell et al. (2009) serves as a pivotal reference, offering a comprehensive synthesis of fatigue mechanisms, regulatory frameworks, and operational countermeasures in both civil and military aviation. Their studies emphasize the critical consequences of fatigue—including cognitive slowdown, reduced vigilance, and compromised flight performance particularly under disrupted circadian rhythms and prolonged duty periods. In a related line of inquiry, Caldwell et al. (2004) quantified the deleterious effects of 37 hours of wakefulness on military pilots, revealing measurable declines in mood, cognitive performance, and simulator outcomes, which remain widely cited in operational fatigue modeling. Van Dongen and

McCauley's contributions further expand the scope of fatigue research through the development and refinement of biomathematical models capable of predicting objective and subjective fatigue trajectories, offering crucial insights for fatigue risk management systems (FRMS). These works collectively underscore that fatigue is not merely a physiological limitation but a systemic safety risk that requires multidimensional mitigation strategies. The co-authorship network, therefore, not only visualizes scholarly collaboration but also reveals how a cluster of influential researchers has shaped the scientific understanding and regulatory discourse around fatigue in aviation operations.

The citation-based analysis reveals that the most influential studies in aviation fatigue are not only highly cited but also foundational in shaping subsequent research and policy recommendations. Caldwell et al. (2009), with 179 citations, provide a comprehensive review of fatigue countermeasures in both military and civilian aviation, establishing key regulatory and operational frameworks still referenced today. Similarly, Hu and Lodewijks (2020) and Morris and Miller (1996) focus on psychophysiological measures and electrooculographic indicators for fatigue detection—critical contributions to the ongoing development of real-time monitoring systems. Notably, the author citation network reveals Philippa Gander (261 citations), J. Lynn Caldwell (230), and Drew Dawson (145) as the most connected and cited figures, underscoring their centrality in both empirical and theoretical advancements. Gander's extensive work on crew fatigue across various flight types (Gander et al., 1998a; Gander et al., 1998b; Gander et al., 1998c; Gander et al., 1998d; Gander et al., 1998e; Gander et al., 1998f; Gander et al., 2013; Gander et el., 2014; Gander et al., 2018) has illuminated the physiological and circadian disruptions associated with long-haul, short-haul, and overnight operations, emphasizing the need for context-sensitive fatigue risk indicators. Dawson's (2012) reflections on the evolution of fatigue research over two decades advocating for integrative approaches that link laboratory findings with complex operational realities—highlighting persistent challenges in translating performance metrics into effective workplace safety practices. Taken together, these studies demonstrate a shift from descriptive accounts of fatigue to a systems-oriented understanding that encompasses scheduling, individual variability, and technological solutions such as biomathematical modeling and fatigue detection via physiological metrics (McCauley et al., 2021; Qin et al., 2021). This networked structure of influential authors and highly cited articles confirms that the field is both mature and rapidly evolving, with citation strength aligning closely with research utility in safety-critical aviation contexts.

The country-based citation analysis reveals that the United States (USA), Australia, and China are leading contributors to the global literature on aviation fatigue, both in terms of publication volume and citation impact. The USA, with 74 publications and 1341 citations, emerges as the dominant actor, reflecting its long-standing institutional investment in aviation safety research, particularly through entities like NASA Ames Research Center and the U.S. Air Force Research Laboratory (Caldwell et al., 2009; Rosekind et al., 1996). These institutions have pioneered applied studies on fatigue detection, biomathematical modeling, and countermeasure development. Australia follows with 411 citations and a strong tradition of fatigue research grounded in the work of scholars such as Drew Dawson and Philippa Gander, whose collaborations have shaped international fatigue risk management frameworks (Dawson & McCulloch, 2005; Gander et al., 2011). China's emerging presence, with 45 publications and 217 citations, reflects a growing academic and regulatory focus on civil aviation safety, particularly in response to the rapid expansion of its aviation sector (Dai et al., 2020). The network structure also highlights New Zealand's notable influence, especially considering its smaller research base, largely driven by longitudinal field studies led by Gander and colleagues on long-haul and short-haul flight crews (Gander et al., 1998f; 2013). These country-level patterns illustrate not only geographic disparities in research productivity and impact but also the varying institutional strategies for addressing fatigue in aviation ranging from large-scale, data-driven modeling in the U.S. to field-oriented operational assessments in Australia and New Zealand. In alignment with the objectives of this bibliometric study, these findings underscore the importance of cross-national collaboration and knowledge sharing in developing context-specific fatigue risk management systems.

The bibliographic coupling analysis demonstrated a structurally dense and thematically coherent network of academic collaboration in the field of aviation fatigue research. Among 170 authors, a dominant interconnected cluster of 155 researchers was identified, forming 11 distinct clusters with 3,647 total links and a cumulative link strength of 7,374. These findings point to the existence of tightly knit scholarly communities working around shared conceptual frameworks. The high coupling scores of John A. Caldwell (2009), Xinyun Hu (2020), and Philippa Gander (2013) reflect the intellectual centrality of these works in shaping fatigue-related discourse. Hu and Lodewijks (2020) notably contribute by differentiating between mental fatigue and sleepiness, offering a nuanced psychophysiological approach to fatigue detection through EEG, EOG, and eye metrics. In a more recent study, Hu et al. (2024) expanded this work into the domain of air traffic controllers, using fixation and saccade patterns to detect fatigue via machine learning models. These methodologies exemplify the technological shift in the field, moving from traditional subjective self-reports toward automated, sensor-based assessment frameworks. The clustering observed in the current analysis underscores the convergence of scholars around such emerging methods, which bridge cognitive psychology, occupational ergonomics, and data-driven detection technologies an intersection increasingly vital for advancing operational safety in aviation.

The keyword co-occurrence and density analyses provided by this study reveal not only the conceptual framework but also the research orientations that have dominated the fatigue-related aviation literature between 1995 and 2025. The prominence of "fatigue" as the most frequently co-occurring keyword, along with terms such as "pilot fatigue," "sleep," "fatigue risk management," and "aviation," points to the increasing scholarly convergence on human performance and risk mitigation strategies in operational aviation settings. This thematic concentration aligns with the argument made by Caldwell et al. (2009), who emphasized that pilot fatigue, rooted in circadian disruption and sleep deprivation, constitutes a primary risk factor for operational safety. The clustering of "alertness" and "flight crew" around "fatigue" in the red cluster reflects the physiological and cognitive dimensions of fatigue, as previously elaborated by Hu and Lodewijks (2020), who differentiated between mental fatigue and sleepiness to improve detection systems in aviation. In parallel, the green cluster that comprises "aviation," "pilots," and "flight fatigue" corresponds with empirical field studies such as Gander et al. (2013), which demonstrated the cumulative impact of ultra-long-haul flights on sleep quality and psychomotor vigilance. The identification of "fatigue risk management" as a core thematic node, surrounded by regulatory and safety-related terms, highlights the growing

influence of performance-based fatigue mitigation frameworks mirroring international trends such as the ICAO's adoption of Fatigue Risk Management Systems (FRMS) into civil aviation oversight (ICAO, 2011).

The contribution of this analysis lies in its ability to map the evolution and convergence of scholarly interests over time. While earlier studies often treated fatigue as a physiological variable, recent keyword patterns demonstrate a shift toward systemic and organizational interpretations that integrate individual, operational, and regulatory perspectives. As such, the findings confirm that fatigue research in aviation has matured into a multidisciplinary field that now incorporates occupational health, cognitive ergonomics, and data-driven safety management offering a nuanced and strategic outlook that is critical for both academic progress and policy design.

5. Conclusion, Implications and Limitations

This study examined the academic literature produced in the aviation field within the framework of the theme of fatigue between 1995 and May 31, 2025 using bibliometric methods and comprehensively revealed scientific trends, conceptual densities, and collaborative network structures in the field. A total of 228 open-access and peer-reviewed articles were analyzed, revealing a marked increase in publication activity especially after 2020. This upward trend is closely aligned with growing concerns over fatigue-related performance deficits and safety risks in high-responsibility aviation roles. Recent studies employing advanced detection technologies (e.g., Qin et al., 2021; Huang et al., 2024) and fatigue prediction models (e.g., McCauley et al., 2021) have further accelerated the visibility and interdisciplinary integration of fatigue research.

The most frequently cited authors and the publications with the highest bibliometric links underscore the influence of pioneering interdisciplinary works, particularly those integrating physiological, organizational, and operational aspects of fatigue. The keyword analysis reinforces this insight by showing that studies have increasingly moved beyond purely physiological definitions and now address technical, regulatory, and cognitive dimensions of fatigue within aviation systems.

The theoretical contribution of this study is the systematic mapping of structural patterns, collaboration networks, and conceptual clusters in the fatigue-themed aviation literature, providing a methodological foundation for both novice and experienced researchers. The bibliometric approach has identified key publications, prolific authors, and dominant research themes, offering both an introductory guide and a strategic roadmap for identifying emerging gaps and future directions in the field.

From a practical standpoint, the findings contribute to the evidence base needed for strengthening Fatigue Risk Management Systems (FRMS) in aviation. The clustering of key themes such as pilot fatigue, alertness, fatigue detection, and fatigue risk management offers valuable insights for operational decision-making and the development of safety protocols for flight crews, air traffic controllers, and maintenance personnel. In addition, the cross-national collaboration and citation patterns revealed in the study provide a potential framework for enhancing global knowledge-sharing and joint policy initiatives on fatigue management.

The main limitation of this study lies in the use of a single database (Web of Science Core Collection), restricting the dataset to open-access, peer-reviewed articles. As a result, potentially relevant publications from other databases or non-English sources were excluded. Moreover, the analysis is bounded to the 1995–2025-time frame, and the evolving impact of post-2025 developments is not yet captured. Future studies can extend this framework by including multilingual sources, expanding database coverage, and integrating altimetric indicators to assess social and industrial impact more comprehensively.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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