Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1629319

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 8 - Issue 2: 524-536/ March 2025

FROM SIMULATORS TO SKIES: ENGINEERING AND EDUCATIONAL ADVANCEMENTS IN PILOT TRAINING: A BIBLIOMETRIC PERSPECTIVE

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Abstract: The integration of advanced engineering innovations into pilot training has brought transformative changes to aviation education, emphasizing the role of technologies such as flight simulators, virtual reality (VR), augmented reality (AR), and artificial intelligence (AI). This study employs a bibliometric analysis to explore research trends, influential contributors, and thematic focuses in pilot training from 2000 to 2025, using data from 350 peer-reviewed articles indexed in the Web of Science. Findings reveal a significant rise in publications during the last decade, driven by advancements in simulation technologies, competency-based training, and human factors research. While the field has experienced rapid technological evolution, challenges such as cost barriers, integration complexities, and gaps in long-term performance evaluation remain. This paper highlights emerging trends, including competency-based training and assessment (CBTA) and scenario-based training (SBT) as well as physiological monitoring, offering a comprehensive roadmap for future research and innovation in aviation training.

Keywords: Flight simulation, Virtual reality (VR), Artificial Intelligence (AI), Competency-based training, Human factors in aviation training

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Received: January 29, 2025
Accepted: March 01, 2025
Published: March 15, 2025

Cite as: Yilmaz AA. 2025. From simulators to skies: Engineering and educational advancements in pilot training: A bibliometric perspective. BSJ Eng Sci, 8(2): 524-536.

1. Introduction

The aviation industry has consistently emphasized the critical role of pilot training in ensuring safety, operational efficiency, and adaptability in increasingly complex flight environments. Over the decades, advancements in training methodologies have been instrumental in reducing human error, which remains a leading factor in aviation incidents and accidents (Helmreich et al., 1999). Engineering innovations, particularly the development and refinement of simulation technologies, have revolutionized traditional pilot training practices. These technologies provide realistic and risk-free environments for trainees to master critical skills and experience a wide range of scenarios, including emergency situations, adverse weather conditions, and equipment failures (Salas et al., 2010). As the aviation industry continues to expand, especially in emerging markets, the demand for efficient, scalable, and innovative training solutions has grown significantly (ICAO, 2018).

The integration of virtual reality (VR) and augmented reality (AR) into training programs has further enhanced the immersive quality of these technologies, enabling pilots to engage in highly interactive and lifelike training exercises. VR-based training modules, for example, have been shown to improve situational awareness, decision-making, and overall pilot performance (Zhu et al., 2021). Similarly, AR applications, such as cockpit overlays and real-time system monitoring, have bridged the gap between theoretical learning and practical application, offering dynamic and context-rich educational experiences (Gavrilov et al., 2020). These advancements align with broader trends in CBTA, which focus on measurable learning outcomes and align with international aviation standards (ICAO, 2018).

Artificial intelligence (AI) represents another transformative force in pilot training, enabling the development of adaptive learning systems that personalize training based on individual performance metrics. AI-driven simulators analyse trainee behaviour in real-time, identifying weaknesses and tailoring training modules to address specific needs. Such systems not only enhance learning efficiency but also contribute to early identification of potential deficiencies that could impact long-term performance (Rathinam et al., 2019). Additionally, AI-powered predictive analytics have been employed to optimize training schedules, improve resource allocation, and anticipate trainee performance trends, making pilot training programs more efficient and data-driven (Endsley, 1995).

Despite these advancements, several challenges persist. The high cost of high-fidelity simulators, VR systems, and AI-driven tools presents financial barriers, particularly for smaller training institutions in developing regions. Furthermore, the integration of these technologies into traditional curricula requires significant organizational readiness and expertise, which can hinder widespread adoption (Zhu et al., 2021). In addition, human factors such as stress, cognitive overload, and fatigue remain critical considerations in the design and implementation of training programs (Helmreich et al., 1999). Addressing these challenges will require not only technological innovation but also a comprehensive understanding of the psychological, organizational, and regulatory dimensions of pilot training.

Given these trends, this study aims to examine the convergence of engineering innovations and educational methodologies in pilot training using a bibliometric approach. By analysing 350 peer-reviewed articles published between 2000 and 2025, this paper identifies dominant research themes, leading contributors, and future research directions. Through this lens, it seeks to provide a roadmap for addressing existing challenges while capitalizing on emerging opportunities to enhance the safety, efficiency, and scalability of pilot training programs. This bibliometric analysis contributes to the broader discourse on the role of engineering in advancing aviation education, highlighting the synergies between technological innovation and pedagogical practice in shaping the future of flight training.

2. Literature Review

2.1. The Evolution of Pilot Training

Pilot training is a critical component of aviation safety and efficiency, and its evolution reflects technological and educational advancements over the decades. Traditional pilot training methods primarily relied on classroom instruction and basic in-flight exercises, often with limited opportunities for trainees to practice complex scenarios. However, the integration of engineering advancements, particularly simulation technologies, has revolutionized this field. Initial pilot training programs were designed around a teacher-centred approach, emphasizing rote learning of procedures and theoretical knowledge. Practical exposure was restricted to actual flights, which carried significant risks for both trainees and equipment (Lintern et al., 2000). The introduction of flight simulators marked a paradigm shift, allowing trainees to practice in a controlled environment that mimicked real-world conditions. Today, pilot training incorporates state-of-the-art technologies such as high-fidelity flight simulators, virtual reality (VR), and augmented reality (AR). These tools enable immersive training experiences, significantly reducing risks while improving knowledge retention and skill transferability (Salas et al., 2010). The evolution of pilot training reflects a broader shift toward competency-based education, where the focus is on measurable outcomes rather than time spent in training (Airbus, 2023; Boeing, 2023; Boeing and Airbus. 2023). ICAO has also been updating its documents to include competency based training and assessment programs (Tuncal and Çınar, 2024).

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2.2. Engineering Innovations in Pilot Training

2.2.1. Flight simulators

Flight simulators are one of the most impactful engineering contributions to pilot training (IATA, 2023). These devices replicate aircraft systems and flight conditions, enabling trainees to practice a range of scenarios, from routine procedures to emergency situations. High-fidelity simulators, equipped with motion platforms and realistic visuals, provide an unparalleled level of immersion (Zhu et al., 2021). Research by Salas et al. (2010) highlights the effectiveness of simulators in reducing training costs while maintaining high safety standards. Advanced simulators allow for SBT, where trainees practice handling rare but critical events such as engine failures or extreme weather conditions (Kanki et al., 2019). These capabilities make simulators an indispensable tool in modern pilot training.

2.2.2. Virtual reality (VR) and augmented reality (AR)

The application of VR and AR technologies in pilot training has gained traction in recent years. VR offers fully immersive environments where trainees can practice cockpit procedures and emergency responses without the need for physical equipment. For example, Zhu et al. (2021) found that VR-based training improved pilot decision-making and situational awareness. AR complements VR by overlaying digital information onto the real world, enhancing the learning experience. Gavrilov et al. (2020) explored the use of AR in navigation training and found it particularly effective for understanding complex systems and spatial relationships. These technologies bridge the gap between theoretical knowledge and practical application, making them valuable tools for both novice and experienced pilots.

2.2.3. Artificial intelligence (AI)

AI-powered systems are increasingly being used to enhance pilot training by personalizing learning experiences. AI algorithms analyse trainee performance, identify weaknesses, and adjust training modules accordingly. Rathinam et al. (2019) demonstrated the potential of AI-driven simulators to improve training outcomes by providing real-time feedback and adaptive scenarios. These systems also enable predictive analytics, helping identify trainees who may need additional support.

2.3. Educational Trends in Aviation

2.3.1. Competency-based training and assessment (CBTA)

CBTA has emerged as a cornerstone of aviation education, shifting the focus from time-based to outcome-based training. According to the International Civil Aviation Organization (ICAO, 2018), CBTA ensures that trainees acquire the skills and competencies required for safe and efficient flight operations. This approach is particularly effective when combined with engineering innovations such as simulators and VR, which provide measurable outcomes for skill assessment (Flight Safety Foundation, 2022).

2.3.2. Scenario-based training (SBT)

Scenario-based training involves realistic exercises that mimic real-world challenges, enhancing decision-making and problem-solving skills. Wiggins (2015) emphasized the importance of SBT in preparing pilots for high-stress situations, such as engine failures or runway incursions. SBT is widely used in conjunction with simulation technologies, providing a safe environment for trainees to practice critical skills.

2.3.3. Crew resource management (CRM)

CRM training addresses the human factors that contribute to aviation safety, including communication, teamwork, and decision-making. Helmreich et al. (1999) noted that CRM has evolved from a focus on interpersonal skills to a comprehensive approach that includes error management and leadership. Advances in simulation technology have enabled more realistic CRM training scenarios, improving the transfer of these skills to real-world operations.

2.4. Challenges and Opportunities

2.4.1. Challenges

One of the primary challenges in modern pilot training is the cost of technology. High-fidelity simulators, virtual reality (VR) systems, and artificial intelligence (AI)-driven tools are expensive to develop, procure, and maintain. This creates significant financial barriers, especially for smaller institutions or training centres in developing countries (Salas et al., 2010). The initial investment and ongoing operational expenses often limit access to these advanced technologies, which can result in disparities in training quality worldwide.

Another challenge is the complexity of integration. Advanced technologies, while beneficial, require significant changes to existing training programs and infrastructures. Incorporating tools such as AI-powered systems or VR simulations into traditional curricula demands specialized expertise and resources. Zhu et al. (2021) emphasize that integrating such technologies can disrupt established methods and require substantial organizational adjustments to align with technological innovations.

Despite the advantages of engineering advancements, human factors continue to be a critical concern. Stress, fatigue, and cognitive overload remain significant obstacles, even in highly controlled training environments. These factors can impact trainees' performance and their ability to absorb and apply new skills effectively (Endsley, 1995). Additionally, cybersickness, often associated with VR-based training, poses a challenge to trainee comfort and acceptance of the technology (Marron and Dungan, 2023a).

2.4.2. Opportunities

The integration of engineering innovations also presents opportunities to enhance training effectiveness. Advanced tools such as simulators and AI-driven adaptive systems allow for personalized and immersive learning experiences. These technologies enable trainees to practice high-risk scenarios in a safe, controlled environment, improving both skill acquisition and retention (Zhu et al., 2021). Additionally, VR and AR technologies offer a sustainable approach to training by reducing the need for physical aircraft, thereby lowering costs and environmental impact (Marron and Dungan, 2023b).

Another significant opportunity lies in global standardization. CBTA and other outcome-based methodologies provide frameworks to unify pilot training standards worldwide. These approaches align training programs with international safety and proficiency benchmarks, as recommended by the International Civil Aviation Organization (ICAO, 2018). By leveraging these frameworks, training organizations can enhance global aviation safety and ensure consistent pilot competency across regions. While challenges persist, the opportunities for technological advancements to transform pilot training are immense. With strategic investment and innovation, the aviation industry can overcome these obstacles and continue to advance the quality and accessibility of training worldwide.

Despite significant advancements in pilot training through engineering innovations and educational methodologies, several research gaps persist in the literature. First, the long-term impact of VR and AR technologies on pilot skill retention and real-world performance remains underexplored. While studies have demonstrated the short-term benefits of these technologies, their effectiveness in ensuring long-term competency and adaptability in real-world flight conditions requires further investigation (Zhu et al., 2021). Second, the effectiveness of AI-driven adaptive learning systems in addressing individual differences among trainees is another area that warrants deeper exploration. While AI shows promise in tailoring training modules to individual needs, there is limited empirical evidence on how well these systems accommodate varying cognitive and emotional profiles among pilot trainees (Rathinam et al., 2019). Third, the role of organizational culture and regulatory frameworks in the adoption of engineering innovations in pilot training is poorly understood. The successful implementation of advanced technologies often depends on institutional support, regulatory compliance, and cultural acceptance within training organizations (ICAO, 2018). These factors are critical in determining the scalability and sustainability of technological adoption across diverse regions.

Given these gaps, the following research question emerges:

"How do engineering innovations such as VR, AR, and AI impact long-term skill retention, trainee adaptability, and organizational readiness in pilot training programs?" Addressing this question requires a comprehensive approach that combines bibliometric analysis with thematic exploration to uncover existing trends, research gaps, and influential contributors in the field. The next section outlines the methodology employed to systematically examine the academic literature and answer this research question.

3. Materials and Methods

This study employs a bibliometric analysis to systematically explore the academic literature on engineering innovations and educational advancements in pilot training. The methodology is designed to address the research question: “How do engineering innovations such as VR, AR, and AI impact long-term skill retention, trainee adaptability, and organizational readiness in pilot training programs? “The bibliometric approach provides a comprehensive overview of publication trends, key contributors, thematic focuses, and research gaps in the many areas of the science (Bozkurt Uzan et al., 2025; Önder, 2025).

3.1. Data Collection

The bibliometric analysis for this study was conducted using the Web of Science (WoS) database, renowned for its comprehensive coverage of peer-reviewed academic literature. WoS was chosen for its ability to provide high-quality metadata and access to a wide range of scholarly publications relevant to engineering and aviation education. To ensure the relevance and accuracy of the dataset, a systematic approach was adopted, comprising several key steps.

The first step involved the development of a targeted search query to capture the intersection of engineering innovations and pilot training. The query was designed to include specific terms reflecting the technological and educational aspects of the field. The following Boolean search string was used:

TS=("pilot training" OR "aviation education") AND TS=("virtual reality" OR "augmented reality" OR "artificial intelligence" OR "simulation technology"). This search strategy ensured that the dataset focused on studies integrating advanced technologies, such as virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and simulation systems, within the context of aviation training. The search was restricted to publications between 2000 and 2025, reflecting the most recent and relevant research developments. Additionally, only peer-reviewed articles, reviews, and conference proceedings written in English were included to maintain the quality and consistency of the dataset. To further refine the dataset, inclusion and exclusion criteria were applied. Studies selected for inclusion had to focus explicitly on pilot training and the application of engineering technologies, addressing topics such as skill retention, learning adaptability, or organizational frameworks in aviation education. Moreover, the selected articles were required to be published in high-impact journals or presented at reputable conferences in the fields of aviation and engineering. Conversely, studies unrelated to aviation or pilot training were excluded, along with duplicate entries and articles with incomplete metadata, to ensure the integrity and reliability of the dataset.

After applying these criteria, a final dataset comprising 350 records was extracted. Each record included metadata such as publication titles, abstracts, keywords, authors, institutions, journals, and citation count. This comprehensive dataset provided a solid foundation for conducting a detailed bibliometric analysis.

3.2. Data Analysis

The data collected from the WoS database were subjected to rigorous quantitative bibliometric techniques to identify key trends and relationships within the literature. Various analytical dimensions were explored to gain a holistic understanding of the academic landscape surrounding engineering-driven pilot training.

The first dimension of analysis focused on publication trends over time. The distribution of articles by year was examined to identify growth patterns, milestone years, and potential shifts in research priorities. This temporal analysis provided insights into how research interest in the field has evolved, highlighting periods of rapid growth, peak activity, and potential decline.

Next, authorship and institutional contributions were analysed to identify the most prolific researchers, influential institutions, and patterns of international collaboration. This analysis provided a clear picture of the key contributors driving advancements in the field, as well as the collaborative networks that underpin much of the research.

Keyword co-occurrence analysis was another critical component of the bibliometric analysis. Frequently used keywords were examined to identify thematic clusters and emerging research topics. By visualizing the co-occurrence of keywords using tools like VOS viewer, this analysis revealed the interconnectedness of various themes, such as VR, AR, AI, human factors, and competency-based training. The resulting network maps highlighted central topics and potential research gaps.

Citation and co-citation analysis were conducted to assess the impact of individual articles and references within the field. Highly cited articles and frequently co-cited references were identified, shedding light on foundational studies and influential works that have shaped the discourse around engineering innovations in pilot training.

Finally, thematic evolution over time was explored to capture shifts in research focus. This dimension of analysis highlighted the transition from traditional training methods to the integration of advanced technologies, such as AI-driven adaptive systems, digital twins, and immersive simulations. By mapping these thematic changes, the analysis provided a dynamic view of the field's development.

3.3. Statistical Analyses

To ensure the accuracy and depth of the analysis, several specialized tools and software were employed. The Web of Science Analytics platform was used for data retrieval and initial citation analysis, offering robust tools for identifying publication trends and key contributors.

VOSviewer, a widely used tool for bibliometric visualization, was utilized to generate keyword co-occurrence maps, co-citation networks, and thematic clusters. This software allowed for a clear graphical representation of the relationships between various research themes, enabling a deeper understanding of the field's structure.

Additionally, the Bibliometrix R package was employed to perform advanced statistical analyses on the bibliometric data. This open-source package provided extensive functionality for descriptive and inferential analysis, enhancing the rigor and comprehensiveness of the study.

By combining these tools and techniques, the bibliometric analysis offered a detailed and multifaceted perspective on the academic literature, uncovering trends, contributors, and research gaps in the integration of engineering innovations into pilot training.

4. Results

The findings of this bibliometric analysis shed light on the evolving landscape of engineering innovations and educational methodologies in pilot training. By examining 350 publications spanning from 2000 to 2025, the analysis identifies key research trends, influential contributors, and thematic clusters in the field. Significant growth in publications over the years reflects an increasing interest in integrating technologies such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) into aviation education. This section presents insights into publication trends, author contributions, institutional influence, and keyword co-occurrence, revealing the interconnectedness of emerging technologies and educational practices in shaping modern pilot training programs.

4.1. Publication Trends over Time

As shown in Figure 1, the analysis reveals four distinct phases in publication activity: the early years (1989–2016), a growth period (2017–2021), peak activity (2022–2023), and a recent decline (2024–2025). Each phase is marked by unique characteristics that reflect shifts in research focus, technological advancements, and industry needs.

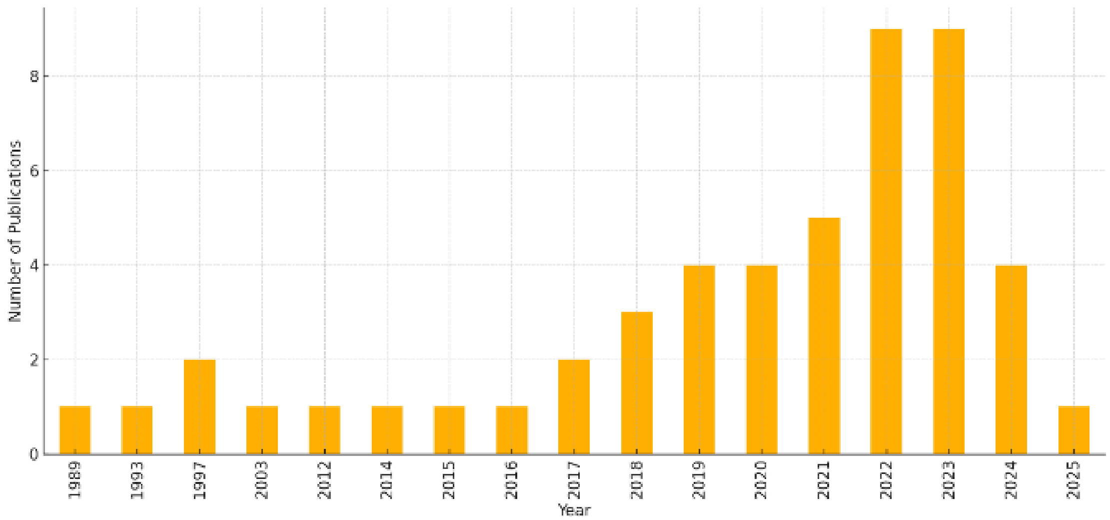

Figure 1. Publication trends over time.

During the early years (1989–2016), the number of publications remained consistently low, with fewer than two articles published annually. Research in this phase primarily focused on traditional simulation techniques and the initial adoption of computer-based training methods. The limited technological advancements in virtual reality (VR) and artificial intelligence (AI) during this period contributed to the modest research activity. Despite the slow growth, foundational studies on human factors and basic flight simulation methodologies laid the groundwork for future advancements in the field.

The growth period from 2017 to 2021 marked a significant increase in research activity, reflecting rapid advancements in high-fidelity simulations, VR, and AI technologies. These developments were accompanied by heightened industry demand for innovative and cost-effective pilot training solutions. Key research topics during this period included SBT, CBTA, and immersive learning environments. The substantial growth in publications highlights the growing recognition of engineering innovations as critical to modernizing pilot education.

Peak activity was observed during 2022 and 2023, with a dramatic increase in publication numbers. This heightened research interest can be attributed to several factors, including the integration of AI for personalized training, the widespread adoption of VR/AR technologies, and increased collaboration between academic and industry stakeholders. The COVID-19 pandemic further accelerated innovation in training methodologies, emphasizing the importance of remote and virtual learning tools. Research themes during this period expanded to include digital twins, adaptive learning systems, and advanced training technologies, underscoring the field's dynamic nature.

In contrast, the years 2024 and 2025 saw a decline in research activity, with a sharper drop in 2025. This decline may reflect saturation in certain areas of study, shifts in funding priorities, or a transition toward emerging fields such as UAV training and autonomous systems. Despite this downturn, opportunities remain to explore under-researched topics, including the long-term impact of VR/AR tools and AI systems on pilot skill retention. These areas hold significant potential for driving the next wave of innovation in pilot training methodologies.

4.2. Most Prolific Contributors

The chart highlights the top 10 most prolific authors contributing to the field of pilot training and associated technologies. These authors have significantly shaped the research landscape by exploring diverse themes such as engineering innovations, training methodologies, and simulation technologies.

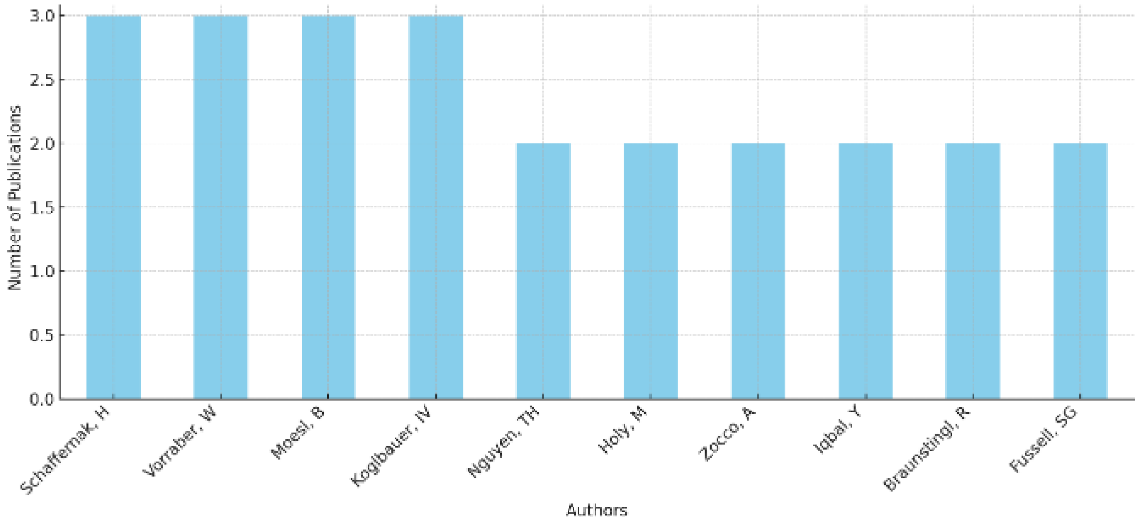

Figure 2. Top 10 most prolific author.

As seen Figure 2, the bibliometric analysis identifies several prolific authors who have significantly contributed to the field of pilot training and its associated technologies. Leading the list is Schaffenrok and Vorraber (2022), who has authored three publications, focusing primarily on the intersection of simulation technologies and human-machine interaction in pilot training. His research provides critical insights into how engineering advancements can enhance training methodologies, particularly in reducing errors and improving situational awareness.

Wolfgang Vorraber shares the top spot with Schaffenrok and Vorraber (2022), demonstrating expertise in virtual reality (VR) and augmented reality (AR) applications within competency-based training programs. His work highlights the growing importance of immersive technologies in modernizing pilot education and creating measurable learning outcomes. These contributions underscore his significant influence in integrating advanced engineering solutions into aviation training practices.

Another notable contributor is Birgit Moesl, who brings extensive expertise in aviation psychology. Her research focuses on crew resource management (CRM) and decision-making in high-stress scenarios, reflecting a strong emphasis on human factors in aviation safety. By addressing psychological and interpersonal dimensions of pilot training, her work complements technological advancements and emphasizes the importance of human-centric approaches.

Robert Koglbauer is recognized for his work on human factors, particularly in exploring how simulation technologies enhance situational awareness and minimize errors during training. His contributions bridge the gap between engineering advancements and cognitive performance, ensuring that training tools align with the psychological needs of trainees.

T. H. Nguyen is another key contributor whose research focuses on advanced engineering applications such as artificial intelligence (AI) in adaptive learning systems. His work highlights the potential of AI to personalize training modules based on individual performance, improving skill retention and adaptability. Nguyen's studies represent a forward-looking approach to leveraging AI in aviation education.

M. Holy has made significant contributions to understanding the effectiveness of immersive technologies in improving pilot skill retention. His work aligns closely with educational trends, emphasizing the use of VR and AR to create engaging and effective learning experiences. This focus on immersive tools highlights their growing relevance in pilot training.

Zocco et al. (2023) is known for his exploration of training standardization and the integration of international frameworks such as the International Civil Aviation Organization's (ICAO) competency-based training guidelines. His work emphasizes the importance of aligning training methodologies with global standards, ensuring consistency and quality across diverse regions.

Y. Iqbal has contributed to studies on the global implications of innovative training technologies, particularly their adoption in developing regions. His research underscores the importance of making advanced training tools accessible to underserved areas, addressing disparities in aviation education worldwide.

Braunstingl et al. (2023) focuses on SBT, with a particular emphasis on emergency response and teamwork skills. His work highlights the role of realistic scenarios in preparing pilots for high-stress situations, contributing to the development of robust and practical training programs.

Finally, Fussell and Vorraber (2021) has contributed significantly to the development of high-fidelity simulation systems for pilot decision-making in dynamic environments. His work emphasizes the importance of accurate and immersive simulations in improving trainee performance and confidence.

Several observations emerge from analyzing the contributions of these authors. First, many of these researchers collaborate with institutions and industry stakeholders, reflecting the applied nature of their work. This collaboration ensures that their research addresses real-world challenges and contributes directly to advancements in pilot training technologies.

The thematic focus of these authors spans diverse areas, including VR/AR integration, AI-driven learning systems, and human factors in training. Scenario-based training and competency-based frameworks are recurring themes, highlighting their centrality to modern pilot education. This thematic diversity demonstrates how engineering innovations intersect with educational practices to create comprehensive training methodologies.

These authors also have a notable global influence. Their work is recognized across academic and industrial contexts, emphasizing the relevance of their contributions to both research and practice. The international scope of their research underscores the universal challenges and opportunities in aviation education.

4.3. Top Ten Contributing Instutitions

4.3.1. Leading institutions

The analysis highlights key institutions that have emerged as leaders in the domain of aviation and engineering research, particularly in pilot training. Among the top contributors, institutions based in Toulouse, France, such as ISAE SUPAERO and affiliated research centres, play a prominent role. Their focus on aeronautical sciences and pilot education positions them at the forefront of engineering-driven advancements in aviation. These institutions are recognized for their expertise in simulation technologies, virtual reality (VR), and competency-based training, reflecting their commitment to enhancing pilot education methodologies.

Prominent individual researchers, including Schaffenrok and Vorraber (2022), are affiliated with institutions that emphasize robust aviation engineering programs. Their recurring contributions to the field further underscore the importance of institutional support in driving impactful research. Similarly, Zhang Chen from Shenyang Aerospace University in China represents the growing influence of Asian institutions in aviation innovation. Shenyang Aerospace University has made significant strides in integrating human factors into aviation education, highlighting its contribution to the interdisciplinary nature of pilot training research.

The global distribution of contributing institutions demonstrates the international scope of aviation research. Institutions from Europe, such as those in France and Germany, and Asia, particularly China, dominate the landscape. This geographic diversity underscores the universal relevance of pilot training innovations and the need for collaborative approaches to address global challenges in the field.

4.3.2. Institutional impact

Institutions contributing to pilot training research often operate within extensive collaborative networks. These networks involve universities, private companies, and aviation authorities, creating a synergy that accelerates the development and implementation of cutting-edge technologies. Collaborative research efforts have been instrumental in advancing simulation technologies, VR applications, and artificial intelligence (AI)-driven systems, addressing critical needs in modern pilot education.

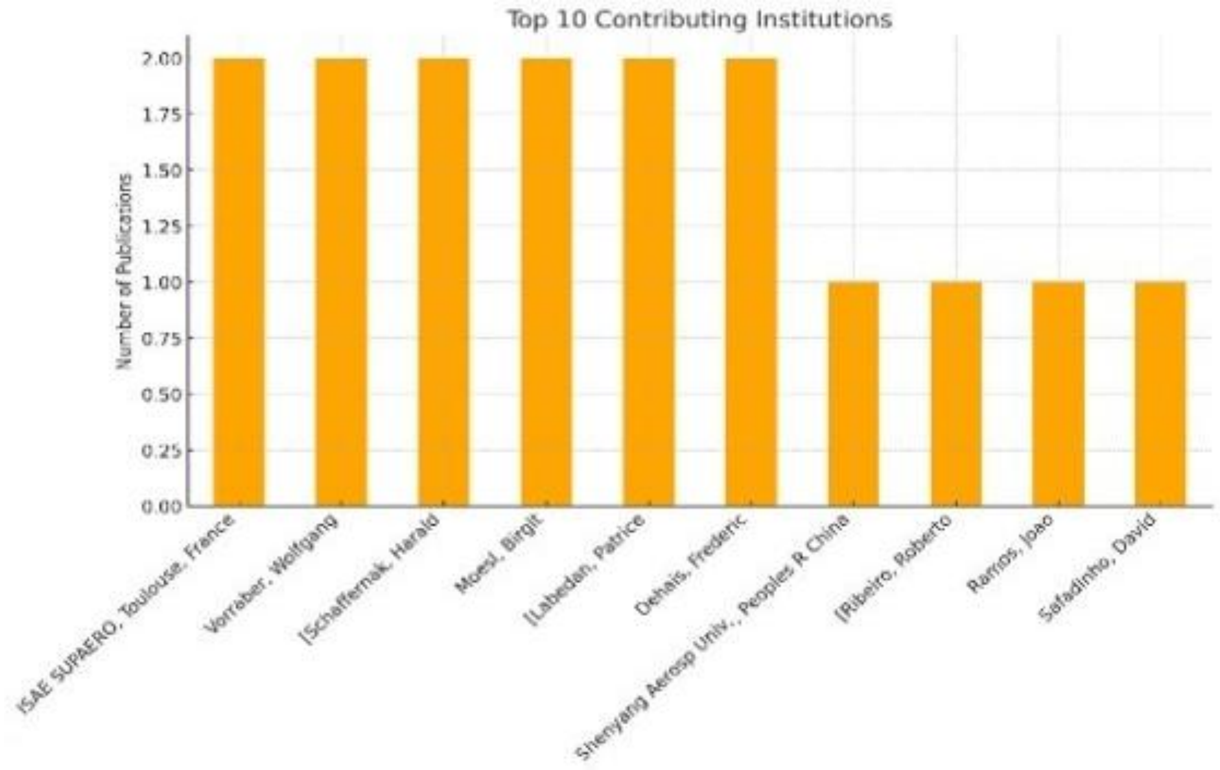

Figure 3. Top ten contributing institutions.

Specialization als lefines the impact of leading institutions. For instance, ISAE SUPAERO is renowned for its focus on competency-based pilot training, scenario-based learning, and the integration of advanced engineering solutions into educational frameworks. Such institutions play a pivotal role in setting standards and benchmarks for effective training methodologies.

Emerging regions, particularly in Asia, are becoming increasingly prominent contributors. Chinese institutions, such as Shenyang Aerospace University, have shown a rapid increase in their research output. This growth is driven by the country's expanding aviation sector and its investment in research-led innovation. These institutions are shaping the future of aviation training by introducing innovative approaches that address both regional and global challenges.

4.3.3. Research themes and focus areas

The research themes explored by leading institutions reflect the multidisciplinary nature of pilot training innovations. A significant emphasis is placed on human factors and training, with studies prioritizing human-machine interaction, situational awareness, and overall training efficiency. These areas are critical in ensuring that technological advancements align with the cognitive and psychological needs of trainees.

The integration of VR and AR technologies is another focal area for many institutions. Immersive technologies are being utilized to create dynamic and interactive learning environments, enhancing the effectiveness of pilot training programs. These contributions underscore the potential of VR and AR to bridge the gap between theoretical knowledge and practical application.

Additionally, competency-based training has emerged as a key research focus. Institutions aim to develop frameworks that ensure measurable outcomes for pilot proficiency. This approach aligns with international standards, such as those set by the International Civil Aviation Organization (ICAO) and highlights the importance of creating globally consistent training methodologies.

4.4. Keyword Co-occurrence Analysis

As seen in Figure 4 the keyword co-occurrence network provides valuable insights into the thematic structure and research priorities in pilot training and its associated technologies. The network, composed of nodes and edges, reflects the frequency and strength of connections between keywords in academic literature. Larger nodes and stronger edges signify highly researched areas and their interdependencies, offering a clear representation of dominant themes and emerging trends in the field.

4.4.1. Core themes

A detailed analysis of the network reveals several core themes that dominate the research landscape. One of the most prominent themes is Simulation and Virtual Reality (VR).

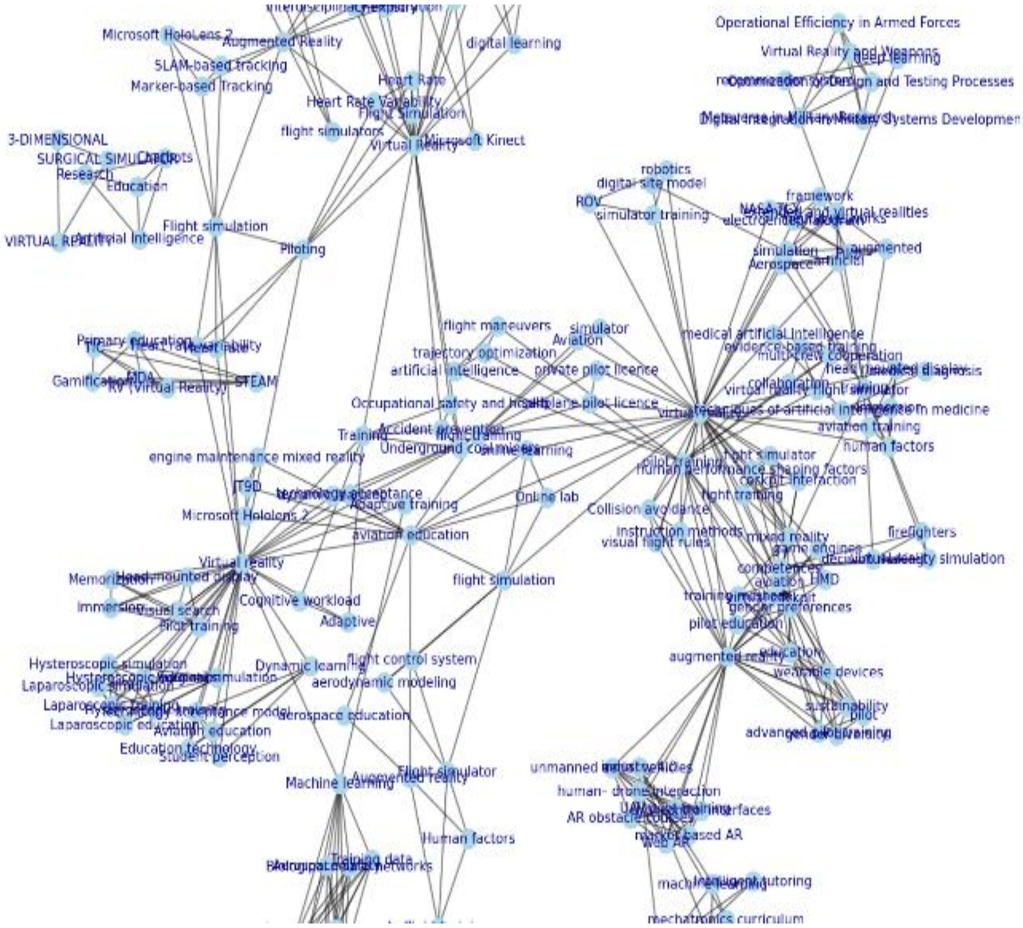

Figure 4. Keyword co-occurrence analysis.

Keywords such as "flight simulation," "virtual reality," and "augmented reality" form a dense cluster, underscoring the central role of immersive technologies in improving pilot training outcomes. These tools are widely recognized for their ability to replicate real-world scenarios in controlled environments, thereby reducing risks and enhancing skill development. The cluster's strong connections to "cognitive workload" and "human factors" further highlight the importance of VR in addressing psychological aspects of pilot training, such as stress management and decision-making under pressure.

Another significant theme is Artificial Intelligence (AI) and Machine Learning, which reflects the growing interest in personalized and adaptive training solutions. Keywords like "artificial intelligence," "machine learning," and "adaptive systems" appear prominently, pointing to the use of AI for tailoring training programs to individual needs. The close links between AI-related keywords and "trajectory optimization" and "human-machine interaction" emphasize the role of AI in improving decision-making, flight manoeuvre training, and overall operational efficiency.

The theme of Human Factors and Safety is also prominent, with keywords such as "human factors," "occupational safety," and "situational awareness" forming a cohesive cluster. These studies are essential for understanding and mitigating human error, which remains a critical challenge in aviation safety. Research in this area often overlaps with Crew Resource Management (CRM), highlighting the importance of teamwork, communication, and leadership in training programs.

Competency-Based Training represents another core theme, focusing on measurable training outcomes. Keywords like "competency-based training," "scenario-based training," and "evaluation processes" are closely linked, indicating an emphasis on aligning training methodologies with international standards. Connections to "digital learning" and "online labs" further demonstrate the shift toward remote and technology-driven education, which has gained prominence in response to global challenges such as the COVID-19 pandemic.

4.4.2. Emerging trends

Beyond the core themes, the network reveals several emerging research areas that indicate the future direction of pilot training innovations. One notable trend is the growing interest in Digital Twins and Advanced Engineering. Keywords such as "digital twins," "advanced engineering," and "mechatronics education" highlight efforts to integrate physical and virtual systems for error-free training. These technologies are strongly connected to "maintenance simulation" and "engine performance modelling," reflecting their applications in technical and operational training.

Augmented Reality (AR) also stands out as an emerging trend, with keywords like "augmented reality," "Microsoft HoloLens," and "mixed reality" indicating an increased focus on enhancing situational awareness and interactive learning experiences. AR technologies offer unique advantages by overlaying digital information onto the real world, making them particularly effective for navigation training and understanding complex systems.

Another emerging theme is Health and Performance Monitoring, which involves integrating physiological monitoring into training systems. Keywords such as "heart rate variability," "sensor fusion," and "cognitive workload" suggest a growing interest in assessing and optimizing trainee performance. These tools enable trainers to measure stress levels, fatigue, and other factors that impact learning and operational efficiency.

4.4.3. Interconnections and clusters

The keyword co-occurrence network also reveals interconnected clusters that reflect the multidisciplinary nature of pilot training research. The first major cluster revolves around Simulation and VR, which forms the foundation of modern training methodologies. This cluster is connected to both AI and safety-related themes, demonstrating its multifaceted applications in addressing technical, cognitive, and operational challenges.

The second cluster focuses on Adaptive and Personalized Training, encompassing keywords such as "adaptive systems" and "personalized training." This cluster highlights the growing emphasis on trainee-centric approaches, where training programs are tailored to individual strengths, weaknesses, and learning styles.

The third cluster, centered on Human-Drone Interaction, points to an emerging focus on training for unmanned aerial vehicle (UAV) operators. Keywords like "human-drone interaction" and "unmanned systems" suggest that researchers are increasingly exploring the unique challenges and requirements of UAV training, which is expected to become a critical component of aviation education in the coming years.

5. Discussion

The findings of this bibliometric analysis reveal the dynamic and evolving nature of research on engineering-driven pilot training. The trends in publication activity provide a clear picture of how interest in this field has grown over time, shaped by technological advancements, industry needs, and global challenges. In the early years, spanning from 1989 to 2016, research output remained relatively low, reflecting the nascent stage of pilot training innovations. During this period, traditional simulation techniques and basic computer-based training dominated the landscape. Limited technological progress in virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) constrained the scope of academic exploration, resulting in fewer than two publications annually. However, foundational studies focusing on human factors and basic simulation methodologies laid the groundwork for future advancements.

A turning point occurred between 2017 and 2021, marking a period of significant growth in research activity. This coincided with rapid advancements in high-fidelity flight simulators, VR, and AI technologies, as well as increasing demand from the aviation industry for innovative and cost-effective training solutions. Research during this time emphasized immersive learning environments, SBT, and CBTA. The integration of these advanced tools into training methodologies addressed critical gaps in pilot preparation, paving the way for safer and more effective training protocols. By 2021, research output had reached a level indicative of sustained academic and industry interest, with new studies focusing on tailoring training programs to meet evolving needs.

The period of peak activity, from 2022 to 2023, saw a dramatic increase in publication numbers, reflecting a heightened focus on integrating cutting-edge technologies into pilot training. This surge can be attributed to several factors, including the growing adoption of digital twins, adaptive learning systems, and AI-driven training tools. These years also witnessed increased collaboration between academia and industry, enabling researchers to address real-world challenges with innovative solutions. The COVID-19 pandemic played a pivotal role in accelerating research on remote and virtual training methods, as traditional in-person training faced significant disruptions. Key themes during this time expanded to include the role of AI in personalized training, the effectiveness of VR/AR in skill development, and the use of digital twins for error-free simulation.

Despite this peak, a decline in research activity is observed in the years 2024 and 2025. This may be indicative of saturation in certain areas of study, a shift in focus toward emerging fields such as unmanned aerial vehicle (UAV) training, or changes in funding priorities. However, this decline also underscores opportunities to explore under-researched areas, such as the long-term impact of VR/AR technologies on skill retention and the organizational readiness required for systemic adoption of AI-driven tools in training programs. These areas remain critical for advancing pilot training methodologies and ensuring their relevance in a rapidly evolving aviation landscape.

In terms of author contributions, the analysis highlights the significant impact of a select group of researchers who have shaped the field through their innovative studies. Leading contributors, such as Schaffenrok and Vorraber (2022), have focused on simulation technologies and the application of VR/AR in competency-based training programs. Their work, along with that of other prolific authors, such as Birgit Moesl and Robert Koglbauer, underscores the importance of human factors in training. Research by these authors spans diverse themes, including scenario-based training, AI-driven learning, and the psychological dimensions of pilot education. Collaborative networks among these researchers and their institutions reflect the applied nature of their work, which bridges the gap between academic theory and industry practice.

Institutional contributions further illustrate the global nature of this research field. Leading institutions, such as ISAE SUPAERO in Toulouse, France, and Shenyang Aerospace University in China, have played pivotal roles in advancing pilot training research. Their focus on engineering innovations, immersive learning, and human factors demonstrates their commitment to addressing critical challenges in aviation education. Collaborative efforts between universities, private companies, and aviation authorities have led to significant advancements in simulation technologies, VR/AR integration, and AI applications. The rise of Chinese institutions, in particular, highlights a shift in the global research landscape, emphasizing the importance of fostering international collaboration to address shared challenges, such as pilot shortages and training standardization.

The keyword co-occurrence analysis provides deeper insights into the thematic structure of this research field. Central themes, such as flight simulation, virtual reality, and augmented reality, dominate the landscape, reflecting their foundational role in pilot training innovations. These themes are closely connected to human factors and cognitive workload, highlighting the multidisciplinary nature of this research. Emerging trends, such as digital twins, advanced engineering, and physiological monitoring, point to the field's evolution toward integrating physical and virtual systems for seamless training. However, the analysis also reveals gaps, such as limited studies on the long-term effectiveness of VR/AR and AI in real-world applications, and the lack of focus on regulatory frameworks and institutional readiness for adopting these technologies.

Overall, the findings of this analysis underscore the transformative impact of engineering innovations on pilot training. While significant progress has been made, the field continues to evolve, presenting new challenges and opportunities. Future research must focus on interdisciplinary collaboration, the exploration of emerging technologies, and the development of global standards to ensure that pilot training remains effective, accessible, and aligned with the demands of modern aviation. These efforts will not only enhance the safety and efficiency of pilot training programs but also ensure their continued relevance in an era of rapid technological change.

6. Conclusion

The integration of engineering innovations into pilot training represents a significant evolution in aviation education, blending technological advancements with educational methodologies to enhance pilot competency, safety, and efficiency. This bibliometric study provides a comprehensive analysis of the key trends, research contributions, and emerging technologies that have shaped modern pilot training programs. By analysing 350 peer-reviewed articles from 2000 to 2025, this study highlights the transformative role of flight simulation technologies, virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and competency-based training (CBT) in aviation education.

6.1. Engineering Innovations and Pilot Training Advancements

The findings reveal a progressive shift from traditional training methods—which relied heavily on in-flight training and theoretical instruction—to high-fidelity simulation environments, AI-driven learning models, and immersive VR/AR systems (Salas et al., 2010). Flight simulators, a longstanding component of pilot training, have evolved into highly sophisticated, full-motion systems that allow pilots to experience realistic, high-risk scenarios without exposure to physical danger (Lintern et al., 2000). SBT within these simulators has been particularly effective in developing decision-making skills, situational awareness, and crisis management abilities (Kanki et al., 2019).

The emergence of virtual reality (VR) and augmented reality (AR) in aviation training has introduced new levels of immersion and interaction. VR-based training platforms provide 360-degree simulation environments, allowing pilots to practice cockpit procedures, emergency responses, and navigation techniques in a highly controlled, interactive setting (Zhu et al., 2021). AR, on the other hand, overlays real-time information on cockpit displays, enhancing spatial orientation and navigation accuracy (Gavrilov et al., 2020). These technologies bridge the gap between theoretical learning and practical experience, offering a cost-effective and scalable alternative to traditional aircraft-based training.

Artificial intelligence (AI) has further revolutionized pilot education by introducing adaptive learning systems that personalize training based on individual performance metrics (Rathinam et al., 2019). AI-powered simulators analyse trainee behaviour in real-time, adjusting training modules to address knowledge gaps, weaknesses, and cognitive workload limitations (Endsley, 1995). Moreover, AI-based predictive analytics can assess pilot readiness, skill retention, and learning trajectories, helping instructors tailor training programs more effectively (Marron and Dungan, 2023a).

6.2. Challenges in Engineering-Based Pilot Training

Despite these advancements, several challenges hinder the widespread adoption of these technologies in pilot training. The high cost of high-fidelity simulators, VR systems, and AI-driven adaptive learning platforms presents a significant financial barrier for smaller flight training schools and developing aviation markets (Helmreich et al., 1999). The initial investment required for hardware, software integration, and instructor training is often prohibitively expensive, limiting access to cutting-edge aviation education tools (Wiggins, 2015).

Additionally, the complexity of integrating emerging technologies into existing training frameworks presents an organizational and regulatory challenge (ICAO, 2018). Many aviation authorities and training institutions lack the technical expertise and infrastructure necessary to support AI-driven learning models and immersive VR/AR environments. Furthermore, cybersickness and cognitive overload in VR-based training modules remain significant human factors concerns, requiring further research into ergonomic optimization and trainee adaptability (Marron and Dungan, 2023).

This study is limited to 350 articles indexed in the Web of Science (WoS) database, excluding relevant research from other sources such as Scopus, IEEE Xplore, and Google Scholar. Additionally, the analysis covers the period 2000–2025, which may not account for emerging technological developments beyond this timeframe.

6.3. Opportunities for Future Research and Development

Despite these challenges, the opportunities presented by engineering-driven training technologies are substantial. The use of digital twins, CBTA, and AI-powered adaptive learning models is expected to further enhance training effectiveness while reducing operational costs (ICAO, 2018). VR and AR systems offer a sustainable approach to pilot training, minimizing reliance on physical aircraft for training, thus reducing fuel consumption and carbon emissions (Rathinam et al., 2019).

The global push for standardized pilot training frameworks under ICAO's CBTA initiative provides a unique opportunity for research institutions, regulatory bodies, and aviation training centers to develop uniform training methodologies that ensure competency and safety across international aviation markets (ICAO, 2018).

This study highlights several research gaps that require further investigation:

Longitudinal Studies on Skill Retention – While VR, AR, and AI-based training modules have shown short-term improvements in pilot competency, their long-term effectiveness in real-world flight operations remains underexplored (Zhu et al., 2021).

Scalability of AI-Driven Training – The effectiveness of AI-based adaptive learning systems in customizing training for diverse cognitive profiles needs further empirical validation (Rathinam et al., 2019).

Regulatory Challenges in Implementing Advanced Technologies – There is a lack of policy-driven research addressing the regulatory, ethical, and operational challenges of incorporating AI, VR, and digital twins into pilot training curricula (ICAO, 2018).

Human Factors Research in VR-Based Training – More studies are needed to optimize user experience, minimize cybersickness, and assess cognitive workload in VR-based training environments (Endsley, 1995).

AI and Big Data Integration in Flight Training – AI-powered analytics and machine learning algorithms can improve error prediction, skill evaluation, and dynamic training module adjustments, but their real-world application remains limited (Marron and Dungan, 2023b).

The transformative impact of engineering innovations on pilot training is undeniable. Flight simulators, virtual reality, augmented reality, artificial intelligence, and competency-based training methodologies have significantly enhanced pilot education by providing realistic, immersive, and data-driven learning experiences. However, the successful implementation of these technologies requires strategic investment, interdisciplinary research collaboration, and regulatory standardization to maximize their impact.

The aviation industry stands at a critical juncture, where the adoption of advanced training technologies can improve safety, accessibility, and efficiency in pilot education. Future research should focus on long-term effectiveness assessments, scalability across diverse aviation training environments, and the development of standardized frameworks for technology-driven pilot training.

By addressing these challenges and research gaps, the aviation industry can ensure that pilot training remains at the forefront of technological innovation, equipping future pilots with the skills, competences, and adaptability required to navigate an increasingly complex aviation landscape.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	A.A.Y.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study due to there is no experimental study on research material.

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