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Systematic Review

Sustainable Airport Development: A Literature Review Based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses Methodology, Using OpenAlex Database

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Abstract: Airport sustainability has gained increasing attention as the aviation industry faces the challenge of balancing economic growth, environmental responsibility, and social standards. This study conducts a systematic literature review (SLR) using the OpenAlex database. The PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was applied to refine the selection process, resulting in 66 relevant studies. Then, a bibliometric–systematic literature review (B-SLR) approach was employed to analyze trends and identify research gaps. The findings indicate that most studies often focus on two sustainability pillars at a time, while neglecting a fully integrated perspective. Not many research works simultaneously address all three dimensions of sustainability (economic, environmental, and social), leading to fragmented insights into sustainable airport management. Notably, some industry-driven reports are starting to suggest emerging holistic approaches, but the majority of the academic literature remains segmented. Hence, this study highlights the need for a more comprehensive research framework that considers environmental, economic, and social factors concurrently. Future research should integrate these dimensions to develop practical and well-balanced sustainability strategies; while methodological limitations may exist in this work, such as language constraints and dataset selection criteria, this review provides valuable insights into airport sustainability and lays the groundwork for further scientific studies.

Keywords: sustainability; airports; systematic literature review; PRISMA; OpenAlex

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1. Introduction

The topic of sustainability has been in vogue for several years and has been increasingly explored and deepened in a wide variety of sectors and industries. The aviation and airports industry is no exception and airport sustainability is a hot topic that is being raised in different international platforms [1]. However, regardless of the area of study, when it comes to sustainability, its definition always involves the following basic notion: development that meets the needs of the present without compromising the future, incorporating three fundamental dimensions: environmental, social, and economic [2].

Nowadays, airports are vital to global connectivity and economic growth; nevertheless, rising air traffic demand poses significant sustainability challenges for airport managers. While emerging air travel demand induces airport expansions, it also often conflicts with

environmental goals, increasing emissions, noise, and community disruptions. Balancing economic, social, and environmental priorities has become critical, as stricter regulations demand sustainable practices. As airports face difficult trade-offs in defining clear strategies for the future, innovative approaches are needed to align airport development with sustainability goals.

Some of these innovative approaches are already being explored by major industry stakeholders. Therefore, in recent years, sustainability in aviation has evolved from a peripheral concern to a core strategic objective, driven by global climate commitments and increasingly stringent regulatory frameworks. International bodies such as the International Civil Aviation Organization (ICAO) have introduced comprehensive environmental initiatives, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which aims to cap the net carbon emissions from international flights at 2020 levels [3]. CORSIA represents the first global-market-based measure for any sector and, despite being voluntary until 2026, participation will be compulsory from 2027 onward, thus reflecting the urgency of climate action in aviation [3].

Another example of an innovative approach, at a more regional level, is the European Green Deal, which outlines an ambitious path toward carbon neutrality by 2050, with aviation identified as a key sector for decarbonization [4]. These policy efforts are pushing airports and airlines to adopt cleaner technologies, integrate sustainable aviation fuels and modernize infrastructures in ways that reduce environmental footprints without compromising operational efficiency. Hence, airports can play a strategic role in this transition, acting as enablers of sustainable mobility and innovation hubs for green practices.

Consequently, many airports are exploring and adopting environmental initiatives, such as pursuing Airport Carbon Accreditation (ACA) programs and aligning their development plans with long-term net-zero emissions targets. Initiatives such as the Net Zero 2050 resolution by Airports Council International (ACI) Europe call on airports to achieve net-zero carbon emissions by the middle of the 21st century, urging coordinated action across operations, construction, energy sourcing and stakeholder engagement [5]. Additionally, the integration of renewable energy sources, the implementation of green building standards and the deployment of digital technologies for operational efficiency are now seen as essential levers in promoting airport sustainability. Hence, airports are not only merely adapting to sustainability frameworks, they are also becoming key agents in shaping the future of sustainable air transport.

On the other hand, focusing more on the scientific community, the research work of Raimundo, Baltazar, and Cruz (2023) [6] (who carried out a systematic literature review focused on sustainability in the airports ecosystem) evidenced that this topic remains on the current agenda and that its interest is still growing, with much research still needed in this area. According to the conclusions of the authors of this study, when addressing airport sustainability issues, airport managers should more often link environmental impacts to their on-site ecosystem effects, which would help the aviation and airports industry address key challenges worldwide [6]. These conclusions stem from the fact that most studies and publications on airport sustainability focus mainly on the environmental pillar, sometimes disregarding its interconnection with the other two pillars of sustainability.

In order to delve deeper into this essential topic of airport sustainability and to be able to properly understand and present the context of its current development, a systematic literature review on this topic was carried out. As mentioned above, Raimundo, Baltazar, and Cruz (2023) [6] have already carried out a systematic literature review that is deeply related to the topic of sustainability in airports, so a course of action that differs from the work of these authors was sought.

2. Materials and Methods

Raimundo, Baltazar, and Cruz (2023) [6] developed their work based on Web of Science (WoS) and Scopus, which are two bibliographic databases that have been the foundation for research in this kind of bibliometric analysis [7]. Hence, in order to develop an investigation that could be complementary, we decided to use the OpenAlex bibliographic database.

OpenAlex, whose name is inspired by the Library of Alexandria, is a new bibliographic database that aims to centralize all research information in one place and that indexes a miscellaneous type of research output (including articles, books, datasets, and dissertations) across all different areas of academic activity, even including academic fields that may be underrepresented in other databases [8]. OpenAlex was launched as a replacement for Microsoft Academic Graph, which was discontinued in the beginning of 2022, and offers much better literature coverage than other databases, as shown below in Figure 1.

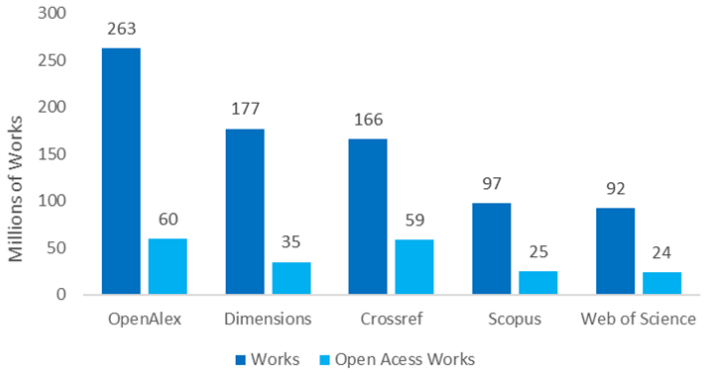


Figure 1. Number of works covered and available in different bibliographic databases.

According to the research of Maddi, Maisonobe, and Boukacem-Zeghmouri (2024) [9], OpenAlex indexes significantly more journals compared to Scopus and WoS and, geographically, while WoS and Scopus favor journals from Europe, North America, and Oceania, OpenAlex offers a much more balanced worldwide coverage. Despite being relatively new, OpenAlex has been widely studied and used in scientific research; moreover, it has already been scrutinized by authors such as Ortega and Delgado-Quirós (2024) [10] who studied the indexation of retracted literature in seven principal scholarly databases; additionally, Culbert et al. (2024) [11] analyzed the reference coverage of OpenAlex compared to WoS and Scopus.

Since OpenAlex is quite new and a fully open source of scholarly metadata, it does of course still have some limitations and a latent potential to improve the transparency of research evaluation, navigation, representation, and discovery [12]. However, it is worth highlighting the work developed by Alperin et al. (2024) [7], who focused on the suitability of OpenAlex for bibliometric analyses and concluded that OpenAlex is indeed useful for bibliometric analyses and can already be used as a replacement for traditional bibliographic databases for a limited set of analysis. In other words, the authors approved of OpenAlex as a valid literature review database; nonetheless, they supplied some warnings regarding some limitations and the need for complementing research with other data sources for more accurate results.

Bearing in mind that this systematic literature review was carried out as a complement to the research work developed by Raimundo, Baltazar, and Cruz (2023) [6], and given the usefulness of different databases according to previous authors, OpenAlex appeared to be a viable option; this is the reasoning behind this choice. The methodology chosen for the literature review approach was the same one employed by the aforementioned authors: PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses).

The PRISMA statement, which was first introduced in 2009, was developed to assist researchers in systematically reporting the purpose, methodology, and findings of their reviews [13] (see Supplementary Materials). Due to improvements in systematic review techniques and terminology, an updated version named PRISMA 2020 was introduced to enhance reporting practices [13]. PRISMA 2020 incorporates improved methods for study identification, selection, evaluation, and synthesis while restructuring the guidelines for easier application [13]. This updated statement includes a 27-item checklist, an extended version with detailed reporting recommendations, an abstract checklist, and revised flow diagrams for both original and updated reviews [13].

Consequently, the systematic literature review started with the search string "airport sustainability", being present in the full texts of scientific publications available through OpenAlex. This resulted in a wide variety of works (136,700 works) across very different types of scientific fields. As a result, the final search string was duly complemented to provide more up-to-date and precise results: "airport sustainability" being present in the full text, combined with the Boolean term "AND" and the years from "2010 to 2023", combined with the Boolean term "AND" and "airport sustainability" being present in the title of the scientific publications. It is important to mention that the year 2024 was purposely left out, as this research work began during that same year and it was decided to limit the work to full years in order to ensure the clear definition of the period of analysis.

To be clear, it is important to emphasize that the search string that was used also made the work carried out here very different from the research developed by Raimundo, Baltazar, and Cruz (2023) [6], while the latter authors focused more on the topic of "Airport Entrepreneurship", which eventually led to a sustainability component; in this scientific article, the present authors put their full focus on airport sustainability. In addition, it should be noted that it was necessary to somehow define a scope for this work that was compatible with the resources to be allocated; it was also important to be precisely focused to avoid becoming lost in analyzing topics and scientific articles that were irrelevant to the main subject. Hence, as this paper's title includes 'Sustainable Airport Development' (and considering other derivatives, such as like 'Airport Sustainability'), this was exactly the criteria included in the search string. Consequently, all the articles included in this literature review are relevant to the topic of airport sustainability and should be the core of scientific publications on this topic.

As presented in Figure 2, the search string aforementioned resulted in a total of 399 publications in one database (OpenAlex). From these 399 potentially relevant contributions that were identified, the screening process was developed as follows:

- An automation tool was employed to automatically retrieve all relevant bibliographic information from the publications, namely the title, the authors, the DOI, and the journal of publication. In 100 of the cases, there was relevant information missing, so these publications were marked as ineligible.
- Of the 299 potentially relevant contributions that remained, 192 were removed during the screening process due to other reasons: 163 were not publicly accessible and 29 were not published by any scientific journal. These reasons resulted in the elimination of these 192 publications.
- The steps mentioned above resulted in 107 relevant contributions that were identified and manually screened. From these 107 publications, 4 of them were excluded for not being written in English. The remaining 103 publications were sought for retrieval.
- During the retrieval process from OpenAlex, 37 publications were impossible to retrieve, despite being identified as "publicly accessible". Henceforth, the initial screening process was concluded with 66 reports assessed for eligibility.

- The actual number of studies included in this systematic literature review was the aforementioned 66; further analysis of these publications did not result in any subsequent eliminations, as shown in Figure 2.

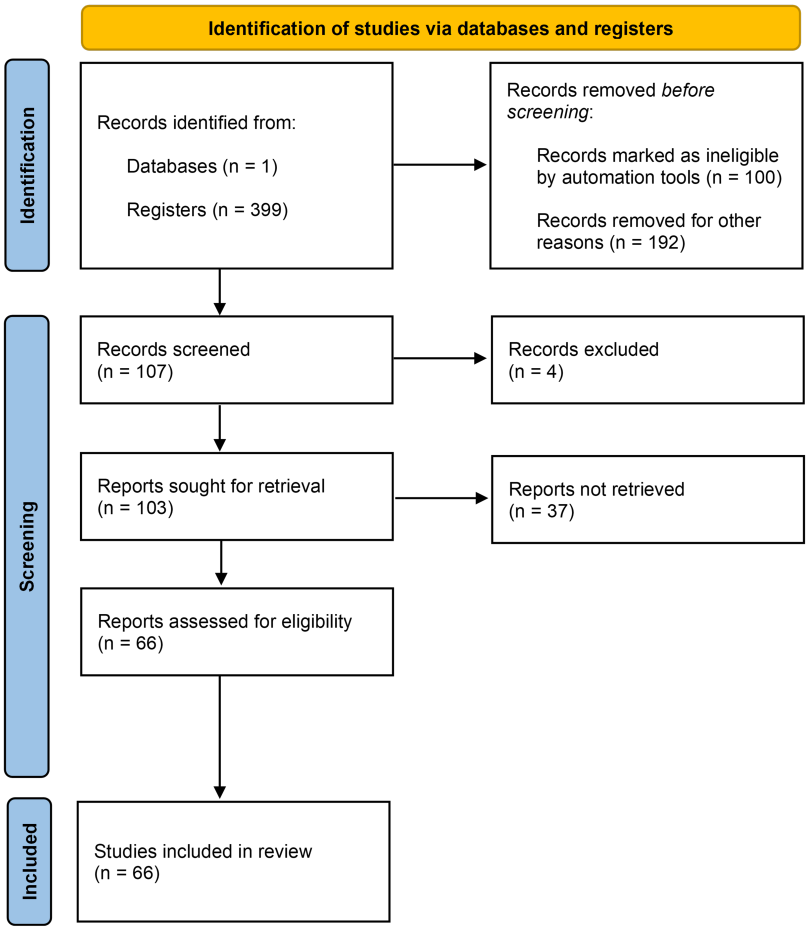


Figure 2. PRISMA 2020 flow diagram (source: own based on [13]).

Subsequently, the process followed the steps defined in the methodology presented by Marzi et al. (2024) [14] for carrying out bibliometric–systematic literature reviews (B-SLRs), which is composed of 10 steps, as presented in Table 1. Hence, after obtaining a refined dataset, a bibliometric approach with a respective analysis of clusters regarding trending topics was developed; this was followed by a final sample selection that was the basis for the holistic analysis that materialized in the actual systematic literature review.

Table 1. Methodology used in the systematic literature review (source: own based on [14]).

Step	Task	Main Outcome
Step 1	Research question	Inclusion criteria
Step 2	Search definition	Search string
Step 3	Database selection	Selected database
Step 4	Data screening	Raw dataset
Step 5	Data cleaning and export	Refined dataset
Step 6	Bibliometric approach	Preliminary bibliometric analysis
Step 7	Analysis of clusters	Graphical representation
Step 8	Sample selection	Ordered dataset
Step 9	Systematic literature review	Holistic analysis
Step 10	Theoretical contribution	Research agenda

3. Literature Analysis: Trending Topics

Before moving on to the more in-depth analysis that was carried out on the 66 publications from the screening process, VOSviewer scientific software was used to visualize the relationship between co-occurrence of keywords across all publications. VOSviewer (version 1.6.20) is a software tool designed for creating and visualizing bibliometric networks, which can include journals, researchers, or publications. These networks are built using relationships such as citation links, bibliographic coupling, co-citation, or co-authorship; additionally, the software features text-mining capabilities that allow for the extraction and visualization of the presently used co-occurrence networks of key terms from the scientific literature [15].

Hence, a bibliometric study was conducted to analyze and uncover key indicators of scientific information dynamics and evolution. By utilizing VOSviewer software, this research work focused on identifying the most relevant keywords in studies related to airport sustainability, with the main goal of understanding the main areas of expertise involved. In order to limit the number of clusters formed by the analysis in VOSviewer and to enable a more precise analysis, a condition of the co-occurrence of five keywords was used, which resulted in the formation of four main clusters.

As expected given the greater scope of OpenAlex compared to other scientific databases, the clusters formed in VOSviewer turned out to be more diverse in areas of expertise than those analyzed by Raimundo, Baltazar, and Cruz (2023) [6], who were much more focused on the aviation industry, as presented in Figure 3 (despite using more clusters and different inputs both for VOSviewer and for the string search to the systematic literature review).

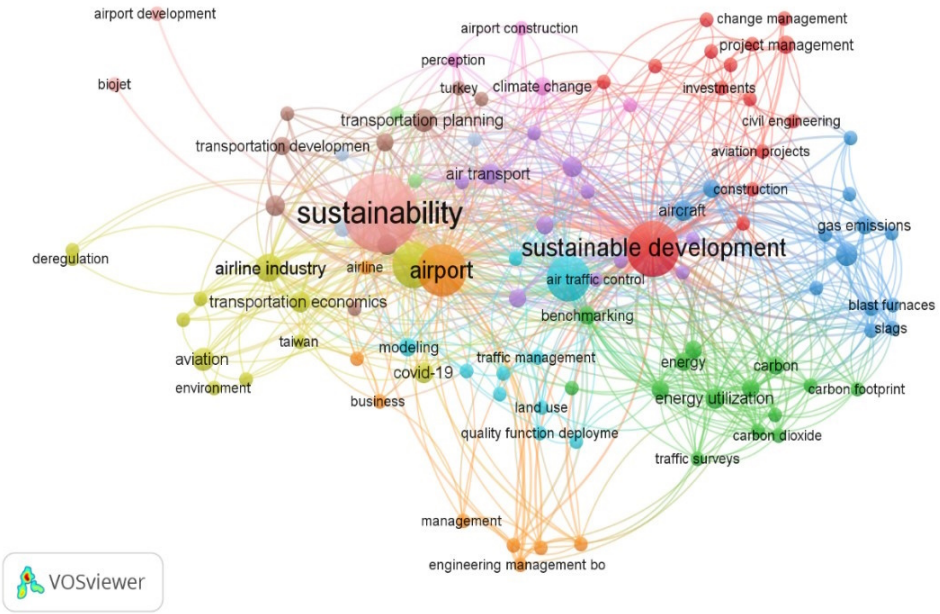


Figure 3. Network of all keywords from Raimundo, Baltazar, and Cruz (2023) [6].

Nevertheless, our analysis of the clusters formed in the present bibliometric study confirms the conclusions of the study performed by Raimundo, Baltazar, and Cruz (2023) [6]; this partially motivated the present research work. As can be observed in Figure 4 below, there is a great focus on the environmental pillar of sustainability, while the other two pillars (social and economic) are not well represented in the clusters.

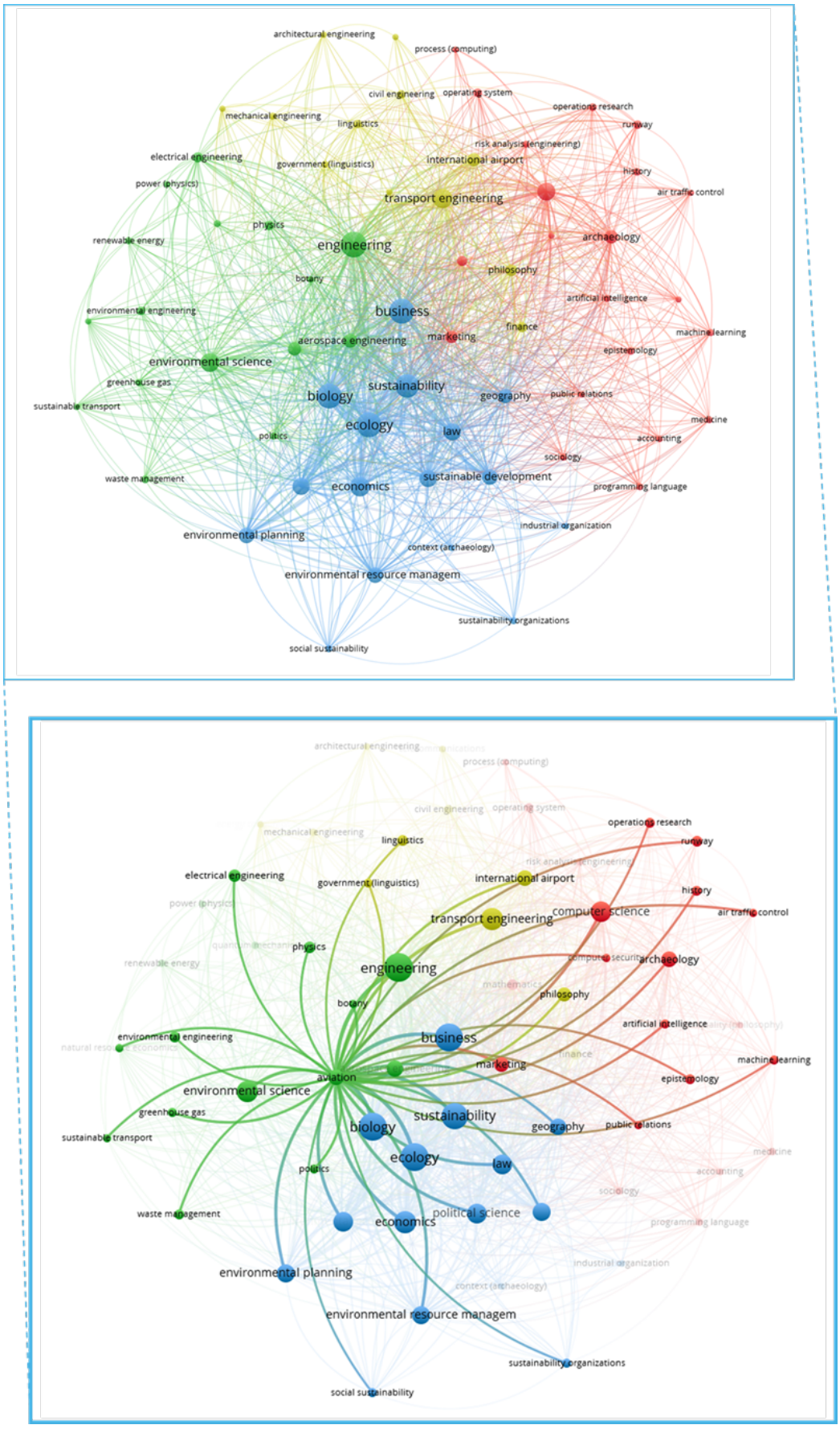


Figure 4. Network of co-occurrence of keywords (source: own elaboration via VOSviewer).

For a more focused analysis of the aviation sector, Figure 4 also highlights the relationship between the term "aviation" and other keywords. Once again, this analysis confirms that the environmental component ends up being the most recurrent in these airport sustainability publications, namely through the relationship between "aviation" and the following terms:

- Environmental science;
- Environmental planning;
- Environmental resource management;
- Environmental engineering;
- Greenhouse gas;
- Waste management.

However, it is also worth mentioning that the analysis in Figure 4 shows some co-occurrences of keywords related to other pillars of sustainability (although these are less frequent): "social sustainability", "economics", and other operational terms such as "operations research", "runway", and "air traffic control". This analysis already provides a slightly different and broader view than what was presented in the work of Raimundo, Baltazar, and Cruz (2023) [6], probably due to the influence of the search string that was used (more focused on sustainability while the authors focused on entrepreneurship) and due to the influence of using OpenAlex.

Nonetheless, at a first glance, the same recommendation would be maintained as suggested by these authors. This bibliometric analysis also points out to a growing need for more studies covering other pillars of sustainability and their respective relationships between each other.

4. Discussion: Theoretical Perspectives

As already mentioned above, the final dataset included 66 articles representative of the topic of airport sustainability in several areas of the aviation and airports industry, with a wide variety of case studies all across the globe. These publications were thoroughly examined and grouped by their area of expertise, resulting in the following split across 13 main topics:

- Seven publications on air pollution;
- Seven publications on airport building (two of those also cover energy management);
- One publication on airport noise;
- Nine publications on airport operations;
- Six publications on airport strategic management;
- Nine publications on assessing sustainability (one that also covers runway maintenance);
- Three publications on balancing growth and sustainability;
- Three publications on best practices/literature review;
- Seven publications on energy management (two that also cover airport building and one that also covers water management);
- Four publications on runway maintenance (1 that also covers assessing sustainability);
- Six publications on terminal management;
- Four publications on waste management;
- Five publications on water management (one that also covers energy management).

It is important to reiterate that, according to the topics covered above, there are some scientific publications that cover more than one area of expertise and, consequently, can be included in more than one of the thirteen aforementioned main topics. Therefore, in these cases, publications will be repeatedly referenced and duly analyzed on both topics

(e.g., two publications that cover airport building also cover energy management and, for that reason, these two publications will appear in both the airport building and the energy management sections).

The published articles in question also covered a lot of different geographies all around the world and resorted to a multitude of methodologies to delve into each of the research topics. To summarize all this information regarding the articles analyzed, Tables 2–14 are presented. These tables show the case studies, the main methods that were used, and the sustainability pillars that were clearly addressed (when possible, by priority order) in each one of the thirteen aforementioned expertise areas.

4.1. Air Pollution

In the field of airport sustainability, numerous studies have focused on mitigating air pollution through innovative solutions. As an example, Baxter (2020) [16] investigated the use of sustainable aviation biofuels at Oslo Airport Gardermoen, the first airport globally to offer biofuels to all airlines. In their study, the author revealed that the adoption of biofuels resulted in a 10–15% reduction in greenhouse gas emissions, highlighting the environmental benefits of this approach. Similarly, Sharma et al. (2021) [17] examined the potential of sustainable aviation fuel (SAF) production at Memphis International Airport and showed that supplying 136 million gallons of SAF annually could reduce greenhouse gas emissions by 62.5% compared to conventional jet fuel. Expanding on alternative energy solutions, Ochoa Robles et al. (2019) [18] explored a hydrogen airport ecosystem in Hautes-Pyrénées, France, using a multi-objective optimization model to design a hydrogen infrastructure. According to their study, this solution meets the airport's energy needs sustainably and the authors emphasized the adaptability of this model for other hydrogen ecosystems aiming to reduce environmental impacts.

Table 2. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on air pollution (source: compiled by the authors).

Case Study	Main Methods	Pillars
Oslo (Norway)	Instrumental qualitative case study research design through document analysis [16]	Environmental
Memphis (USA)	Stackelberg leader–follower model that accounts for economic interaction between SAF processor and feedstock producers [17]	Environmental and economic
Hautes-Pyrenees (France)	Model based on a multi-objective optimization framework to consider four levels: energy sources, hydrogen production, transport, and storage [18]	Economic and environmental
Italy	Simulation of the benefits, both environmental and monetary, obtained by using the TaxiBot system [19]	Environmental and economic
Purdue (USA)	Evaluation of impacts of automated mowing [20]	Economic
Manchester (UK)	Evaluation of three technological innovations that will enable sustainable transport solutions for surface access and of the role of behavioral changes from a theoretical perspective, using empirical data [21]	Environmental and social
Canada	Statistical analysis of 10-year data of PM2.5 and selected emitted co-pollutants (CO, NOx, and O_3) [22]	Environmental

On the operational side, technological innovations have shown promise in reducing emissions, such as the work developed by Postorino, Mantecchini, and Gualandi (2017) [19].

The authors assessed the environmental and financial benefits of using semi-robotic TaxiBots for aircraft taxiing at a medium-sized airport, proving that integrating TaxiBots not only reduced local emissions but also provided cost savings for airlines (but not for airports specifically). Similarly, Hubbard, Baxmeyer, and Hubbard (2021) [20] examined automated mowing at Purdue Airport, which employs electric-powered mowers to reduce emissions. This study demonstrated that this innovation, particularly if enhanced with solar-powered mowers, presents a sustainable alternative to traditional mowing, though its applicability depends on site-specific conditions such as terrain and power availability. Hence, the main focus in this study ends up being the economic benefit and not the environmental component. Additionally, it is also worth mentioning the work by Ryley et al. (2013) [21], which focused on surface access emissions at Manchester Airport. In their study, these authors emphasized the need for enhanced data collection and long-term policy measures to reduce carbon emissions from airport-related travel; also, they briefly consider the economic context of implementing such measures.

Lastly, and shifting focus to local air pollution, Rangel-Alvarado, Pal, and Ariya (2022) [22] conducted a decadal analysis of PM2.5 and co-pollutants near major Canadian airports. On the one hand, this study revealed that colder climates exacerbate pollutant accumulation during fall and winter. In contrast, the authors also concluded that airports in milder climates do not experience such disproportionate pollutant build-up, therefore underscoring the role of environmental factors in influencing the effectiveness of air quality management strategies at airports. Together with the articles aforementioned, all these studies illustrate a broad spectrum of approaches to mitigate air pollution at airports, from sustainable fuels and energy solutions to technological and operational innovations, all contributing to the overarching goal of airport sustainability.

4.2. Airport Building

In the field of sustainable airport building, a variety of innovative approaches have been explored to improve energy efficiency, material use, and overall environmental impact. Dalkiran (2023) [23], in a case study on airports in Turkey, emphasized the importance of using sustainable materials throughout airport construction and maintenance. This research highlighted that materials like plastic, paper, and those used in airport projects significantly affect sustainability, reinforcing the need for a broader approach to resource conservation. This work also aligns with the review by Bak (2018) [24], which assessed sustainable development solutions, including green walls, renewable energy, and water-saving devices, for their applicability at passenger airports. In this case, findings suggested that simple and cost-effective investments can substantially improve environmental outcomes, emphasizing the importance of proper operation and ongoing maintenance to ensure sustainability goals are met. It is important to mention that this last author briefly touched other sustainability pillars, mainly the economic one, despite the major focus being the environmental component of the solutions analyzed.

Similarly, the work of Kareem, Abd, and Zehawi (2021) [25] on Baghdad Airport used Building Information Modeling (BIM) technology to identify optimal construction materials and energy-efficient systems. The authors found that elements like building orientation, window-to-wall ratios, and shading can influence energy consumption and highlighted the significance of energy-efficient lighting systems and HVAC systems (the largest energy consumers). Moreover, this study also demonstrated that the use of photovoltaic panels was showed to significantly reduce energy intensity, supporting the overall sustainability of airport buildings. On the other hand, from a different perspective, the research work of de la Fuente et al. (2017) [26] on the rail extension to Barcelona's El Prat Airport used the MIVES method to assess sustainability in tunnel lining. The authors tried to integrate economic,

environmental, and social factors to demonstrate how multi-criteria decision making can optimize airport sustainability. However, despite mentions to other sustainability pillars, their clear focus of analysis was economic.

Table 3. Case studies, main methods used, and sustainability pillars clearly addressed in publications on airport building (source: compiled by the authors).

Case Study	Main Methods	Pillars
Turkyie	Airport benchmarking [23]	Environmental
Not applicable	Critical review of the feasibility of selected sustainable development goals through solutions in the field of environmental engineering. Then, an analysis of their application at airports was carried out [24]	Environmental and economic
Baghdad (Iraq)	Building Information Modeling (BIM) technology and the associated programs (such as Autodesk Revit 2021 and Autodesk Insight 360) in order to determine optimal strategies [25]	Environmental
Barcelona (Spain)	Sustainable analysis of different concrete and reinforcement configurations for segmental linings of TBM tunnels via MIVES method (a multi-criteria decision-making approach to assess sustainability) [26]	Economic
Not identified	Analyzed and assessed thermal–cooling loads within an airport building using Panasonic software [27]	Social and environmental
Istanbul (Turkyie)	Building Information Modeling (BIM) for energy analysis. A heuristic optimization incentivizes transforming BIM to Building Energy Modeling (BEM) for decision-making processes of retrofitting [28]	Economic and environmental
Xuancheng (China)	Designed and adopted the LCA (Life Cycle Assessment)–Emergy–ANN (Artificial Neural Network) framework to assess and analyze an airport building system for sustainability [29]	Environmental and economic

One other example is the research work developed by Yulia et al. (2023) [27], which focused on the thermal–cooling loads within airport buildings. This study showed that managing peak cooling demands (particularly during afternoon hours) can reduce energy consumption. Thus, the authors contributed to sustainable building practices by advising in the design of HVAC systems, which is crucial for improving energy efficiency and ensuring thermal comfort for passengers and staff. In addition, it is also worth mentioning the research work of Keskin and Salman (2018) [28] on the Istanbul Grand Airport Project, which explored how BIM tools can streamline energy analysis and optimize energy efficiency in retrofitting airport buildings. The authors' findings showed that integrating BIM with Building Energy Modeling (BEM) allows for significant cost and time savings in energy analysis, further emphasizing the role of advanced technologies in sustainable building practices.

Finally, the study developed by Xie et al. (2023) [29] in Xuancheng, China, used a combination of Life Cycle Assessment (LCA), Emergy, and Artificial Neural Networks (ANN) to assess the sustainability of an airport building system. The authors concluded that material and operational stage Emergy were the primary contributors to the building's environmental impact, thus proposing an optimization strategy to improve long-term sustainability. This comprehensive approach to sustainability emphasizes the importance of evaluating not just energy use, but also broader lifecycle impacts in building systems.

Once again, together with the articles mentioned above, these studies demonstrate a range of innovative strategies that contribute to the development of more sustainable and environmentally friendly airport infrastructure.

4.3. Airport Noise

The management of airport noise has become a critical aspect of sustainable aviation, especially in densely populated areas near airports. In this context, Iemma and Centracchio (2022) [30] focused on a community-oriented approach to optimizing takeoff and landing procedures for commercial aircraft, aiming to minimize both the SEL exceeding 60 dBA around the airport and the amount of fuel burned. It is important to recall here that the SEL metric is crucial as it quantifies the noise impact on surrounding communities, while fuel consumption is directly linked to environmental emissions. Hence, this multi-objective optimization not only addressed noise reduction but also contributed to reducing the chemical emissions associated with aviation operations.

Table 4. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on airport noise (source: compiled by the authors).

Case Study	Main Methods	Pillars
Not applicable	Community-oriented approach to the multi-objective optimization of sustainable takeoff and landing for commercial aircraft. The objective functions are defined as the measure of area surrounding the airport where the Sound Exposure Level (SEL) is higher than 60 dBA, and the amount of fuel burned during the procedure [30]	Social and environmental

This research work highlighted the need for innovative approaches in managing airport operations, suggesting a shift toward more sustainable procedures. By employing a global and deterministic optimization method, the study also provided numerical results for different aircraft types, offering valuable insights into balancing operational efficiency and noise reduction. These findings indicate that optimizing takeoff and landing procedures can significantly reduce the environmental footprint of airports while also mitigating the noise pollution affecting nearby residents. Nonetheless, as previously mentioned, this study on airport noise focuses a lot on the environmental and social pillars of sustainability, but does not account for the economic pillar; this demonstrates the gap in the literature that motivated the present work.

4.4. Airport Operations

In the field of airport operations, a variety of innovative solutions have been explored to improve efficiency, mitigate risks, and ensure sustainability in day-to-day operations. González, López, and Martínez (2016) [31] focused on the case study of the Spanish dual-use airport in San Javier (Murcia), combining both civilian and military flights. These authors highlighted the application of falconry as a wildlife control technique to manage bird strikes, which is a major safety concern for airports. The findings by these authors demonstrated the effectiveness of falconry, a natural approach, in maintaining safety without harming the environment. In a different approach, Carpitella et al. (2023) [32] worked on enhancing risk management within airport operations, but focused on Occupational Stress Risks (OSRs) among airport staff. By using a recommendation system implemented through Python, that also employed Fuzzy Cognitive Maps (FCMs) to assess OSRs, the authors provided prioritized recommendations for mitigating risks. This system proved highly reliable and

adaptable, offering significant improvements in the airport's ability to manage staff stress, thereby contributing to overall airport efficiency and personnel well-being.

Table 5. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on airport operations (source: compiled by the authors).

Case Study	Main Methods	Pillars
Murcia (Spain)	Raptor's "Right Hunger" Characterization [31]	Environmental
Italy	Recommendation system to enhance sustainable risk management in airport operations, with a special focus on Occupational Stress Risks (OSRs), via Python code and Fuzzy Cognitive Maps (FCMs) [32]	Social
Doha (Qatar)	Multi-objective integrated optimization problem incorporating the newly proposed Active Routing concept. A holistic economic optimization framework is also included from a Pareto front [33]	Economic and environmental
Graz (Austria)	Transform spatial complexity in the airport environment into a sustainably integrated spatial development for city, region and neighboring communities into SmartAIRea [34]	Social and environmental
Not identified	A calculation tool in Excel was implemented to assess the capacity and dimension of the facilities for each functional subsystem of an airport terminal [35]	Social
USA	Calculation model to assess runway capacity, calibrated with outputs from different airport configurations with the circular of the Federal Aviation Administration Airport Capacity and Delay [36]	Economic
Spain	Methodology to calculate the technical efficiency level of airports based on non-parametric DEA (Data Envelopment Analysis) models [37]	Economic
Slovakia	Educational information model and software for an airport network and information systems risk assessment. The solution is based on the application of the fuzzy logic method [38]	Social
Campinas (Brazil)	Development of a concept with design guidelines to balance between the logistics activities and the environmental constraints on business viability [39]	Environmental and social

On the other hand, in another area of airport operations, Weiszer, Chen, and Locatelli (2015) [33] introduced a multi-objective optimization model in Doha (Qatar), aiming to optimize various airport functions (including aircraft routing, runway scheduling, and airport bus coordination). By integrating these factors into a unified framework, these authors' study showed that operational efficiency could be improved while minimizing fuel consumption and environmental impact. Additionally, this approach also effectively allowed airports to make informed decisions that balance economic, environmental and, operational goals. In a similar tone, Forster and Pansinger (2018) [34] explored the spatial development of airport areas, particularly at Graz Airport in Austria, through the concept of SmartAIRea. This case study demonstrated that this innovative approach could not only enhance the airport's operational efficiency but also contribute to regional development, turning the airport environment into a resilient and interconnected area. It is noteworthy

that both studies underscore the importance of integrated models that account for multiple operational factors to improve efficiency and sustainability at the same time.

On a more operational side, Di Mascio, Moretti, and Piacitelli (2020) [35] analyzed the design and level of service (LoS) of terminal areas in an international airport, specifically in the context of the challenges posed by the COVID-19 pandemic. This study is particularly interesting because it used IATA's Airport Development Reference Manual (ADRM) as a basis, which helped finding out that many terminal subsystems were over-designed to accommodate social distancing measures. These findings emphasized that a flexible terminal infrastructure is essential for adapting to future operational needs, particularly in light of public health concerns. Moreover, this theme of adaptability was also explored in a study by Di Mascio, Rappoli, and Moretti (2020) [36] in the USA, which focused on runway capacity. In this research work, the authors developed a calculation model to assess runway system efficiency, concluding that using simulation software could provide valuable insights into runway optimization.

Further, on airport operations, the work by Ripoll-Zarraga (2015) [37] that explored the technical efficiency of Spanish airports through non-parametric models like DEA (Data Envelopment Analysis) is noteworthy. This author's case study revealed that larger airports showed significant improvements in gross margin over time, but this was largely attributed to centralized management decisions rather than being a true reflection of operational performance. In addition, the study also highlighted that medium-sized airports experienced greater efficiency improvements when competing with similarly sized airports, suggesting that competition drives operational efficiency. It is important to state that this research had a second phase planned where the environmental component would also be explored. In a similar context, the findings of Kelemen et al. (2020) [38] also worth mentioning; these researchers developed an educational model for airport network and information systems risk assessment in Slovakia. Through a fuzzy-logic-based approach, the authors aimed to improve airport information security and risk management, emphasizing the importance of continuous education and adaptation to improve overall efficiency and safety in airport operations.

Lastly, in the context of logistics and sustainability, Lima et al. (2010) [39] studied the logistics platforms in Campinas (Brazil), focusing on balancing logistics activities with environmental constraints; while sustainability was not always the central goal, their research demonstrated that implementing energy-efficient building practices and water conservation measures can still lead to significant social and environmental benefits. These authors' findings contributed to a broader understanding of how airport operations can integrate sustainability into logistics and infrastructure management. It is noteworthy that this last publication slightly touches a third sustainability pillar, but does not properly address it.

4.5. Airport Strategic Management

In the field of airport strategic management, several studies explore various aspects of airport operations, competitiveness, sustainability, and corporate governance. Piedade, Marques, and O'Neill (2023) [40], in their study of Lisbon Airport, investigated how sustainable business practices can be embedded into daily operations. By surveying employees and performing quantitative analysis, the authors found that a clear motivation for sustainable practices exists among staff, but a more comprehensive action plan is needed to engage employees further and ensure widespread adoption of sustainable measures. In a similar scope, the findings of Pishdar et al. (2019) [41], who focused on Iranian airports, revealed that airport resilience plays a critical role in enhancing sustainability and reputation. This study showed that sustainability positively affects airport reputation,

which in turn influences passenger behavior and encourages self-promotion, leading to both financial and non-financial benefits. Both these studies highlight the growing importance of sustainability and corporate reputation in strategic airport management.

Table 6. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on airport strategic management (source: compiled by the authors).

Case Study	Main Methods	Pillars
Lisbon (Portugal)	Questionnaire surveys to airport employees, with a quantitative analysis and testing the efficiency of the proposed measures to improve sustainability practices in business management and daily routines [40]	Social and environmental
Iran	Partial Least Squares Structural Equation Modeling (PLS-SEM) is used for analyzing data and testing hypotheses [41]	Social
Poland	An innovative extension of the Data Envelopment Analysis (DEA) method using methods from spatial econometrics and artificial intelligence [42]	Economic and environmental
China	Explores the competition in a multi-airport region based on route level and its impact on passenger airport choice using three liner models [43]	Economic and social
Indonesia	Analyzes the correlation between airport sustainability and local government budget in Indonesia. The method used is mixed method research [44]	Economic
Not identified	Defines the role of retail, before considering the carbon consequences of business models. Analysis of products that increase aircraft weight and fuel burn, being sources of emissions for duty-free retailers [45]	Environmental and economic

On the other hand, the study by Szaruga and Załoga (2022) [42] on 12 Polish airports used advanced spatial econometrics to analyze energy consumption, passenger movement, and airport competition. These two authors identified inefficiencies in airport operations and demonstrated that airports tend to compete with each other rather than cooperate. This conclusion also aligns with the research work of Liao, Cao, and Li (2019) [43] on the competition between airports in China's Greater Bay Area (GBA); they concluded that, while domestic routes in this China Multi-Airport System (MAS) are mature, international markets remain underdeveloped. Additionally, this study emphasized the importance of understanding airport competition in MASs, not just focusing on single airports or airlines and how this competition impacts passenger choice. The conclusions of both these studies contributed to a broader understanding of how airport strategy should account for both internal efficiencies and external competitive dynamics.

On a different note, the case study on Indonesian airports by Setiawan et al. (2018) [44] explored the relationship between local government budgets and airport sustainability. The authors found that cooperation agreements between local governments and airport management can benefit both parties: airport managers improve services, while local governments gain financial contributions, emphasizing the importance of strategic partnerships in achieving mutual goals. In some way, this also reflects the findings of Heyes et al. (2020) [45], who highlighted the challenges faced by airport retailers in adopting sustainable business models. This study pointed out that the current logistical and political constraints make it difficult for retailers to implement sustainable practices, although there is significant potential for reducing carbon emissions by reevaluating product offerings and business operations.

Together with all the publications mentioned above, these studies illustrate the multi-faceted nature of airport strategic management, emphasizing the need for sustainability initiatives, strategic collaborations, and an understanding of competitive dynamics in multi-airport regions to optimize airport performance and reputation. From improving internal operations to navigating external challenges, strategic management in airports requires a holistic approach that accounts for both operational efficiency and long-term sustainability goals. In other words, a holistic approach that accounts for all pillars of sustainability at the same is needed, instead of focusing on just one or two of them like usually observed.

4.6. Assessing Sustainability

In the topic of airport sustainability assessment, a wide range of approaches have been proposed to evaluate and improve environmental and operational performance. One good example is the work of Wan et al. (2020) [46], which used a synthetic evaluation index model to assess sustainability over a 10-year period, identifying key factors that influence airport sustainability. This study highlighted that the method could be applied to other airports, offering a standardized approach to evaluate sustainability in diverse locations. On the same topic, Jia, Macário, and Buyle (2023) [47] reviewed 33 academic papers on airport sustainability, categorizing methodologies like Data Envelopment Analysis (DEA), Multiple-Criteria Decision Making (MCDM), and composite index-based assessments. The authors ended up suggesting a shift towards a more holistic sustainability modeling, integrating systems thinking to address complex interactions within sustainability systems.

A complementary approach to sustainability is found in the work of Eid et al. (2022) [48], who systematically examined the relationship between airport sustainability knowledge, attitudes, and behaviors. This research underscored the need for further exploration of sustainability awareness in airports to improve behaviors and align practices with sustainable development goals. Meanwhile, Kucukvar et al. (2021) [49] presented an optimization-based approach that utilized an eco-efficiency analysis in 30 major international airports. This study highlighted the discrepancy in sustainability data reporting across airports and concluded that consistent and real-time data could enable better comparison of sustainability performance. These studies also align with the work of Dimitriou and Karagkouni (2022) [50], which emphasized the role of sustainability in strategic management, demonstrating that environmental awareness in airport operations directly influences business resilience and competitiveness.

Further on this topic, Janic (2010) [51] explored the development of an indicator system to assess airport sustainability, incorporating economic, environmental, and social dimensions. This methodology was tested through a practical application, proposing it as a valuable tool for ongoing sustainability assessments. Additionally, it is also worth mentioning another study by Dimitriou and Karagkouni (2022) [52], which complemented this idea by demonstrating that strategic management plays a critical role in overcoming barriers to sustainability, particularly in a competitive and economically sensitive climate. These authors' results underscored the challenges airports face in aligning sustainability with business performance, a point that is further reinforced by the same authors, Karagkouni and Dimitriou (2022) [53], in their case study in the Mediterranean Islands.

Additionally, in this theme, Uzule (2023) [54] investigated the use of integrated reporting (IR) at Northeastern European airports. The author found that these airports are not yet fully adopting IR, though a shift towards this approach could enhance sustainability reporting practices. This finding also aligns with the emerging trend of combining financial and non-financial information to evaluate long-term sustainability targets, as demonstrated in another similar research study by Dimitriou and Karagkouni (2022) [50].

Finally, another work that is worth mentioning is the one by Babashamsi et al. (2016) [55], which provided an important contribution by assessing the sustainability aspect specifically for runway pavement management. This study examined various sustainability assessment tools, such as lifecycle cost analysis and multi-criteria decision-making, and their relevance to pavement management projects. In conclusion, this study highlighted the need to integrate sustainability factors into the standard assessment process, as traditional evaluations often overlook environmental impacts. It is noteworthy that all these studies illustrate the breadth of methodologies that are contributing to the evolving understanding and management of airport sustainability, highlighting a growing recognition of the need for standardized frameworks to improve airport sustainability practices.

Table 7. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on assessing sustainability (source: compiled by the authors).

Case Study	Main Methods	Pillars
Baiyun (China)	Synthetic evaluation index model of airport sustainability (AS) constructed based on the benefit of the doubt (BoD) model [46]	Economic, environmental, and social
Not applicable	Comprehensive review of 33 academic articles on airport sustainability, to delve into an analysis of 16 papers that implement specific methodologies [47]	Not applicable
Not applicable	Investigation of Airport Sustainability Awareness (ASA) through knowledge, attitudes, and behavior of airport sustainability practices, based on a systematic literature review and bibliometric analysis [48]	Environmental, social and economic
Multiple	Combining the optimization-based frontier approach with the Global Report Initiative's comprehensive sustainability database. Eco-efficiency analysis carried out with four input-oriented models [49]	Economic, environmental and social
Europe	Assessment tool for strategic plans and environmental reports, addressing how to promote sustainability. Methodology based on a comparative analysis between airports and regulatory authorities [50]	Environmental
Europe	System of indicators and their measures reflecting the airport operational, economic, social, and environmental dimension of performances [51]	Environmental, social, and economic
Worldwide	Assessment tool for airport strategic plans based on a comparative analysis between airports and regulatory authorities. Sustainability in the airport ecosystem depicted with a systemic approach [52]	Environmental and social
Mediterranean Islands	In-depth assessment of the environmental sustainability performance of airports based on the identification of evidence about key management performance aspects in environmental reports [53]	Environmental
Europe	The aim was to determine if airports apply the integrated reporting IR framework to their annual sustainability communications with stakeholders [54]	Economic, environmental, and social
Not applicable	General depiction of the major sustainability appraisal tools, namely cost–benefit analysis, lifecycle cost analysis, lifecycle assessment, multi-criteria decision making, environmental impact assessment, and social lifecycle assessment [55]	Environmental, economic, and social

4.7. Balancing Growth and Sustainability

Balancing growth and sustainability in airport management is one of the key motivations of the present research. This balancing presents complex challenges for the aviation sector, especially in Europe, where the intersection of environmental sustainability and economic growth is a central issue. On this topic, the work developed by Regan (2014) [56] is noteworthy; it explored how Europe grapples with reconciling air transport liberalization with its environmental obligations, emphasizing the conflict between the economic and social benefits from a competitive aviation market while ensuring environmental sustainability. The author's findings suggested that the capacity constraints imposed by environmental concerns will increasingly shape the development of air transport in Europe, as economic growth must align with sustainability goals.

Table 8. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on balancing growth and sustainability (source: compiled by the authors).

Case Study	Main Methods	Pillars
Europe	"How to reconcile the conflicting objectives of air transport liberalisation and environmental sustainability?"—assessment of the the current strategy in light of recent capacity status of airports [56]	Economic, social, and environmental
Amsterdam (The Netherlands)	Conceptual framework building on complexity theory to shed light on the balance between growth and sustainability. Application of the framework to recommend ways forward to broaden the debate about the sustainable development of airports [57]	Economic, environmental, and social
Italy	DEA (Data Envelopment Analysis) method to investigate how a number of factors impact on the efficiency and economic sustainability of regional airports [58]	Economic and environmental

In a similar topic, the case study of Schiphol Airport by Boons, Van Buuren and Teisman (2010) [57] examined how airports can shift from narrow, growth-focused perspectives to broader, more sustainable approaches. By using a conceptual framework grounded in complexity theory, the study highlighted the need for a more dynamic system of knowledge production, where government, stakeholders, and experts collaboratively explore alternatives to traditional growth models. In addition, this study also advocates for a paradigm shift that integrates economic viability with social and ecological considerations, recommending that interdisciplinary research breaks free from the dichotomy of growth versus environmental impact.

In Italy, Carlucci, Cirà, and Coccorese (2018) [58] applied the DEA method to assess the efficiency and sustainability of 34 airports between 2006 and 2016, particularly focusing on the role of airport size, privatization, and low-cost carriers. These authors concluded that privatization and deregulation could enhance the efficiency and economic sustainability of regional airports, underscoring the positive impact of market mechanisms on sustainability in the aviation industry. It is noteworthy that all these findings are particularly relevant to the present research topic, as they highlight various approaches and strategies to align growth objectives with sustainable practices within a holistic framework.

4.8. Best Practices and Literature Review

The examination of best practices in airport sustainability highlights numerous initiatives from different airports, offering valuable insights for future improvements. For instance, Naples International Airport stands out for its pioneering efforts in addressing

aircraft noise in a study developed by Miedico (2018) [59]. Since it was the first airport in Italy to install a noise monitoring system in 2005, this study demonstrated that Naples significantly reduced its noise footprint by more than 26% and minimized the population exposed to noise by 52%. Furthermore, this airport has adopted smart mitigation actions, such as the delocalization of general aviation traffic, thereby promoting sustainable growth.

Table 9. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on best practices and literature review (source: compiled by the authors).

Case Study	Main Methods	Pillars
Naples (Italy)	Identification of best practices for airport sustainable growth [59]	Environmental and social
Not applicable	Summarizes the current state of airport environmental sustainability practices through a systematic literature review using PRISMA [6]	Environmental, economic, and social
United Kingdom	Drawing on specific examples, examines the ways in which airports have responded to the challenge of reducing the environmental impacts of operations for which they are directly responsible [60]	Economic, social, and environmental

Furthermore, the already-mentioned systematic literature review conducted by Raimundo, Baltazar, and Cruz (2023) [6] is another study that synthesizes current environmental sustainability practices in airports worldwide. This review consolidates knowledge on key sustainability areas, including greenhouse gas emissions, energy management, water conservation, and waste management. This study emphasizes the growing importance of sustainability in airport operations and underscores the need for further research to deepen understanding and enhance sustainability efforts across airports.

There are also good examples from the United Kingdom (UK), where airports have responded to environmental challenges with a variety of green and sustainable practices aimed at reducing their direct operational impacts, as demonstrated by the research work of Budd, Budd, and Ison (2015) [60]. As an example, the adoption of green energy solutions and sustainable working practices has led to immediate environmental and economic benefits. The diversity of initiatives observed across UK airports indicates a promising trend that could be replicated globally and, as more airports implement such measures, there will be an increased potential for knowledge sharing and continuous improvement in sustainable practices.

All these findings reflect a growing commitment across airports to implement best practices that align with sustainability goals, thereby contributing to the broader environmental objectives of the aviation sector. Such practices not only help mitigate negative environmental impacts but also provide long-term economic benefits, marking them as critical components for future airport development strategies. This topic is especially relevant to the research focus of the present work, as it directly addresses the integration of sustainability practices within the broader management of airports.

4.9. Energy Management

The management of energy consumption and the adoption of sustainable practices are crucial components of airport sustainability, with a particular focus on reducing environmental impact and improving energy efficiency. Several studies have addressed energy management strategies across different airports, shedding light on the importance of energy optimization and its contribution to sustainable airport operations, as presented in the next paragraphs.

As already analyzed in airport building publications, Yulia et al. (2023) [27] conducted a study analyzing thermal–cooling loads in an airport building, specifically focusing on enhancing energy efficiency and ensuring thermal comfort. This study highlighted the importance of energy management systems and how they contribute to the broader goal of sustainable airports. Similarly, the previously analyzed study by Keskin and Salman (2018) [28] showed that BIM can improve the retrofit planning process, offering time and cost savings while also enabling efficient selection of energy-saving measures. On this particular topic, this study underscores how advanced digital tools like BIM can significantly enhance energy efficiency in airport facilities, paving the way for more sustainable airport management practices.

Table 10. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on energy management (source: compiled by the authors).

Case Study	Main Methods	Pillars
Not identified	Analyzed and assessed thermal–cooling loads within an airport building using Panasonic software [27]	Social and environmental
Istanbul (Turkey)	Building Information Modeling (BIM) for energy analysis. A heuristic optimization incentivizes transforming BIM to Building Energy Modeling (BEM) for decision-making processes of retrofitting [28]	Economic and environmental
London (UK)	In-depth longitudinal research design [61]	Environmental and economic
Oslo (Norway)	In-depth longitudinal research design [62]	Environmental
Greece	Theoretical approach complemented with an analysis of the main environmental and energy achievements of different airports [63]	Environmental
Adriatic Region	Benchmarks where the most plausible predictive variables were selected according to literature. Stepwise linear regression method was used to select significant predictive variables [64]	Environmental and economic
Copenhagen (Denmark)	Exploratory qualitative and quantitative case study research approach to empirically examine sustainable airport energy management practices and energy-saving initiatives [65]	Environmental

On the other hand, Baxter (2021, 2023) [61,62] provides valuable insights into energy management practices at major international airports. This author's study of London Gatwick Airport identified electricity and natural gas as the primary energy sources, with various energy-saving measures being implemented over time [61], including energy-efficient lighting and heating systems. Similarly, this author's case study of Oslo Gardermoen Airport highlighted a variety of energy sources, including renewable options such as sustainable aviation fuels [62]. In this case, Oslo's success in mitigating environmental impact was attributed to the implementation of energy conservation measures and technological innovations, such as the introduction of biofuels and other sustainable aviation fuels, as mentioned in the topic of air pollution.

The focus on energy sustainability was further examined by Papagrigoriou, Palantzas, and Nalmpantis (2023) [63], who analyzed the environmental and energy achievements of airports, highlighting best practices in energy management. It is noteworthy that the integration of these practices could potentially accelerate global efforts toward sustainable

energy use in airport operations. Furthermore, Mancinelli et al. (2021) [64] evaluated the greenhouse gas savings and economic benefits associated with sustainable water and energy management at six small-to-medium airports. In their study, the authors identified positive sustainability measures, including the adoption of green electricity tariffs and the use of natural gas for heating. Notably, this research concluded by reinforcing the need for continued efforts to decarbonize transport fuels and improve energy efficiency in airports.

Finally, there is another study on Copenhagen Airport by Baxter, Srisaeng, and Wild (2018) [65], which examined energy management practices and energy-saving initiatives aimed at reducing CO2 emissions from both air-side and land-side operations. This research demonstrated that Copenhagen's use of technological solutions, process enhancements, and stakeholder collaboration led to notable energy savings while simultaneously mitigating environmental impact. In summary, all these studies demonstrate that airports are increasingly adopting innovative practices to optimize energy use and reduce environmental impact. This growing body of research provides a valuable framework for airports looking to enhance their sustainability efforts and contribute to understanding how airports can balance operational efficiency and sustainability goals.

4.10. Runway Maintenance

Runway maintenance is a crucial aspect to ensure both safety and sustainability of airport management. Hence, it is understandable that several studies have focused on innovative methods for runway maintenance, particularly in terms of assessing and modeling runway condition. As an example, Sever, Doler, and Kovačič (2021) [66] conducted an in-depth study at in Maribor airport focusing on the detection of runway evenness and compared five different approaches to modeling runway evenness. These authors' findings revealed that the TIN-based linear interpolation method yielded the most accurate results, making it highly useful for runway management systems, particularly in smaller airports. By offering precise geodetic measurements, it is important to note that this approach can help ensure both safety and operational efficiency of runway activities.

Table 11. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on runway maintenance (source: compiled by the authors).

Case Study	Main Methods	Pillars
Maribor (Slovenia)	Comparison between five different approaches to Modeling runway evenness: approximation with regression plane, inverse distance weighted interpolation (IWD), and interpolation based on a triangulated irregular network (TIN)—linear and cubic [66]	Economic
Maribor (Slovenia)	Geodetic survey and management information system prototype, which enables the evaluation of results and suggests runway maintenance measures [67]	Economic
Not applicable	General depiction of the major sustainability appraisal tools, namely cost–benefit analysis, lifecycle cost analysis, lifecycle assessment, multi-criteria decision making, environmental impact assessment, and social lifecycle assessment [55]	Environmental, economic, and social

In addition, Kovačič, Doler, and Sever (2021) [67] also further explored runway condition monitoring by developing an enhanced process for determining runway defectiveness. In this study, the authors integrated geodetic surveys with a management information system prototype to evaluate runway conditions and suggest appropriate maintenance

actions. It is noteworthy that this system enables the graphical and tabular display of runway irregularities, facilitating timely and informed decision making; consequently, this methodology can prevent unexpected runway closures by supporting the planning of maintenance works, thus reducing operational costs.

One last example that is worth mentioning on this topic is the aforementioned study by Babashamsi et al. (2016) [55], which provided an important contribution by exploring the sustainability aspect of runway pavement management. Together with the other two scientific publications, all these studies emphasize the importance of advanced modeling techniques, efficient maintenance planning systems, and sustainability considerations in the management of airport runways, contributing to both the operational resilience and environmental sustainability. By incorporating sustainability into runway maintenance practices, airports can reduce their environmental footprint while maintaining safe and efficient operations, alongside the much needed balance between growth and sustainability.

4.11. Terminal Management

In the terminal management context, there are several studies that explore a wide variety of factors, from passenger behavior to environmental considerations, all aiming to optimize efficiency and sustainability. One good example is the study developed by Tłoczyński, Szmelter-Jarosz, and Susmarski (2022) [68], who conducted a survey focusing on passengers' commuting choices and the factors influencing their decision to use more sustainable transportation. These authors' research highlighted the role of travel time in these decisions and found that passengers were more willing to accept longer travel times when they had no choice but to use less sustainable transport modes. Additionally, the study also mentions that factors such as the purpose of the trip, location, and job status influenced these choices too.

Table 12. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on terminal management (source: compiled by the authors).

Case Study	Main Methods	Pillars
Gdansk (Poland)	Passenger survey on travel choices regarding commuting to airport [68]	Social
Bologna (Italy)	A one-month monitoring was performed on Indoor air quality (IAQ). Four strategic areas were equipped with electronic monitoring platforms, with different contaminants and two micro-climatic sensors [69]	Environmental and economic
Chicago (USA)	Monte Carlo method to design the queuing network for sustainable development. A network diagram is used to determine the critical working point and design a functionally sustainable network [70]	Social
Korea	Survey data from 339 airport users with a support vector machine (SVM) model to classify resistance causes correctly and csQCA (crisp set Qualitative Comparative Analysis) to understand causes [71]	Social
Korea	Based on 327 survey responses, complemented with the use of Structural Equation Models (SEMs) to extract first- and second-order constructs [72]	Social

From a different perspective, Zanni et al. (2018) [69] explored the importance of indoor air quality (IAQ) in airport terminals, more specifically at Bologna Airport, in Italy. These authors studied monitored IAQ parameters, such as gaseous contaminants and micro-climatic comfort, thus concluding that the airport's current ventilation system

was adequate. Nevertheless, the study also suggested that an integrated real-time air management system could further improve sustainability and cost-effectiveness.

Shifting focus to the design and management of airport systems, Xu et al. (2018) [70] applied a Monte Carlo-based method to develop a sustainable queuing network model at an airport in the USA. The proposed model's main goal was to enhance throughput, reduce passenger waiting time variance, and maintain security standards. After its application through case studies, the authors suggested that sustainable queuing design could benefit both airport staff and passengers. Similarly, Kim, Costello, and Lee (2019) [71] explored the factors behind resistance to adopting sustainable technologies in Korean airports, through the examination of the perceived risks and benefits of innovations like biometric security. This study concluded that perceived risks and a lack of perceived benefits were the main barriers to technology adoption, thus providing valuable insights for airports looking into service quality while integrating sustainable technologies.

Further research by the same authors, Kim, Lee, and Costello (2020) [72], and also in Korea, delved into passenger intentions regarding the use of biometric security technology. Through survey data, their study found that both perceived benefits and risks had a significant impact on passengers' willingness to adopt biometric security measures. Additionally, the authors also emphasized the need for airport managers to address these perceptions to ensure the successful implementation of sustainable technologies while creating value for passengers. Consequently, together with all the aforementioned studies, these works highlight the need for integrated, user-focused approaches to sustainability in airport terminal management.

4.12. Waste Management

Waste management strategies at airports are vital in achieving sustainability and several airports have been recognized for their progressive approaches to minimizing their environmental impact through efficient waste handling systems. A prominent example is Kansai International Airport in Japan, which implemented world-class waste management practices from 2002 to 2015. This case is duly demonstrated through an in-depth case study, a quantitative analysis by Baxter, Srisaeng, and Wild (2018) [73], which revealed significant improvements in waste reduction per passenger and aircraft movement in this particular airport. Additionally, the airport also saw a marked increase in recycling rates, with all these results underscoring the transferability of Kansai's waste management approaches to other airports and suggesting a global potential for waste reduction.

Similarly, another study by Baxter, Srisaeng, and Wild (2018) [74] on Copenhagen Airport adopted a mix of qualitative and quantitative case study methods to assess its waste management systems from 1999 to 2016. In this case, the airport's waste generation primarily stemmed from aircraft operations and ground activities, with waste volume increasing in line with passenger and aircraft growth. Copenhagen Airport managed waste by sorting it into categories for recycling, incineration, or landfill disposal; notably, waste from passenger terminals and airport facilities was centrally processed and sorted to mitigate environmental impact. It is noteworthy that all these efforts comprise a key component in reducing the environmental footprint of airport operations.

In contrast, the research work by Dinu, Zaharia, and Pietreanu (2019) [75], in Romania, took a more targeted approach to specific waste streams by focusing on the de-icing process during the winter months. In this case, the airport analyzed the effectiveness of its waste management system to collect and treat de-icing fluids. These authors' study emphasized the creation of a specialized platform to manage the de-icing process more efficiently and without contaminating local water sources. It is important to note that this initiative not

only benefited the environment but also provided collateral benefits such as converting the resulting sludge into usable fertilizer for agriculture.

Table 13. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on waste management (source: compiled by the authors).

Case Study	Main Methods	Pillars
Kansai (Japan)	In-depth case study research design. The qualitative data gathered for the study were analyzed using document analysis. The quantitative data were analyzed using *t*-tests [73]	Environmental
Copenhagen (Denmark)	Qualitative and quantitative case study to examine waste management strategies and systems [74]	Environmental
Bucharest (Romania)	Analytical assessment of an airport flight schedule and a series of data from a handling company, presenting the ADF/AAF (aircraft de-icing fluids/aircraft anti-icing fluids) quantities resulting from different weather conditions [75]	Environmental
Hong Kong (China)	Lifecycle cost–benefit analysis (LC-CBA) framework, with integration of lifecycle assessment (LCA) and cost–benefit analysis (CBA), to guide decision making in sustainable waste management [76]	Environmental, economic, and social

Additionally, it is also worth mentioning the study by Lam et al. (2018) [76] on Hong Kong's airport, which took a lifecycle approach to food waste management by integrating lifecycle cost–benefit analysis (LC-CBA) with lifecycle assessment (LCA). This framework enabled the airport to evaluate various waste management scenarios, ultimately finding on-site incineration to be the most sustainable option. The authors concluded that on-site incineration resulted in significant economic and environmental savings, highlighting the broader applicability of such a model to other airports globally.

All these case studies collectively show that airports worldwide are adopting diverse strategies for waste management. These approaches range from enhanced recycling practices to specialized waste treatment systems, all duly contributing to their overall sustainability efforts. By employing both qualitative and quantitative approaches, researchers have demonstrated that airports have achieved significant reductions in waste generation and disposal, with the potential to transfer these best practices across the industry.

4.13. Water Management

Finally, the topic of water management has gained significant attention in the context of airport sustainability. It is noteworthy that several airports are implementing strategies to reduce water consumption, improve water quality, and manage water resources more efficiently. Hence, quite a few studies have explored the diverse approaches to water management, emphasizing both environmental benefits and operational efficiency.

One notable study by Baxter (2022) [77] is focused on Hong Kong Airport, highlighting its comprehensive water management system, which integrates municipal water, seawater, and treated wastewater. In this case, the airport's "triple water system" has been designed to optimize the use of these resources, ensuring the efficient handling of water for irrigation and other non-potable uses. This author's case study emphasize the importance of an integrated approach to water sourcing, with the clear goal of reducing the environmental impact of water consumption at airports.

Similarly, one other study by Baxter, Srisaeng, and Wild (2018) [78] shows that Kansai International Airport has made substantial progress in reducing water consumption, de-

spite increased passenger traffic. In this particular case, the airport has adopted sustainable water management practices, including water reclamation and regular quality testing. The authors' study showed that the airport's strategic focus on water conservation has not only led to a reduction in total water consumption but has also improved the ratio of reclaimed water over the years. Additionally, this study also demonstrated that the implementation of a dedicated wastewater processing center further contributed to the airport's sustainability goals.

Table 14. Case studies, main methods used, and sustainability pillars clearly addressed in the publications on water management (source: compiled by the authors).

Case Study	Main Methods	Pillars
Hong Kong (China)	In-depth longitudinal research design [77]	Environmental
Kansai (Japan)	Exploratory research to examine sustainable water management strategies and systems. Qualitative data from document analysis and quantitative used for regression analysis on a longitudinal study [78]	Economic and environmental
Copenhagen (Denmark)	Longitudinal qualitative research design to analyze annual water consumption at an airport [79]	Environmental and social
Adriatic Region	Benchmarks where the most plausible predictive variables were selected according to literature. Stepwise linear regression method was used to select significant predictive variables [64]	Environmental and economic
Mildura (Australia)	Determined the potential water harvesting capability of airports with processing of satellite imagery, combined with the image processing functionalities of Matlab, and some basic mathematics [80]	Economic and environmental

On the other hand, in Europe, the research work of Baxter, Srisaeng, and Wild (2019) [79] on Copenhagen Airport also focused on sustainable water management. Over a period of ten years, from 2006 to 2016, the airport's water consumption increased in line with passenger volume. However, the airport has implemented various initiatives to mitigate this increase, such as an aquifer thermal energy system and the use of separate sewer systems for handling surface and wastewater, thus ensuring the protection of local water quality. In addition, this study also demonstrated that Copenhagen Airport regularly monitored drinking, ground, and surface water quality, which is a key factor allowing the airport to mitigate environmental risks.

Moreover, it is important to recall the research on Adriatic region's small-to-medium airports by Mancinelli et al. (2021) [64]; these airports have also shown positive strides in water management. It is noteworthy that this study in the Adriatic region revealed that these facilities had incorporated sustainable water practices, such as using green electricity tariffs and focusing on natural gas for heating. Lastly, in the context of regional airports, a study by Somerville et al. (2015) [80] on Mildura Airport in Australia explored the potential for rainwater harvesting as part of a sustainable water management strategy. This study concluded that regional airports could significantly reduce their reliance on municipal water by capturing rainwater, which would be particularly valuable in some arid regions prone to drought.

Collectively, all these studies underscore the importance of comprehensive water management systems at airports, illustrating how airports can adopt innovative methods to reduce water consumption and mitigate environmental impacts. From advanced water

recycling systems to rainwater harvesting and energy-efficient water management practices, airports worldwide are moving toward more sustainable operations. Through these efforts, airports are not only enhancing their operational efficiency but also contributing to global sustainability goals.

4.14. Summary

First of all, sustainability in airports remains a prevailing global trend and stands out as a key focus area, as it can be observed from the geographical distribution of the case studies in this literature review (see Figure 5 below). Although there is a strong concentration of case studies on the European continent, there is a generalized distribution around the world, with many case studies also referring to Asia and North America. The least represented continents turned out to be South America and Oceania and, notably, no case studies have covered the African continent.

However, it is important to remember that this literature review was based on scientific publications in English, or at least in a language compatible with those of the authors (namely Portuguese or Spanish). This linguistic criteria may also have somewhat affected the geographical distribution of the case studies in this analysis, which is shown in Figure 5.

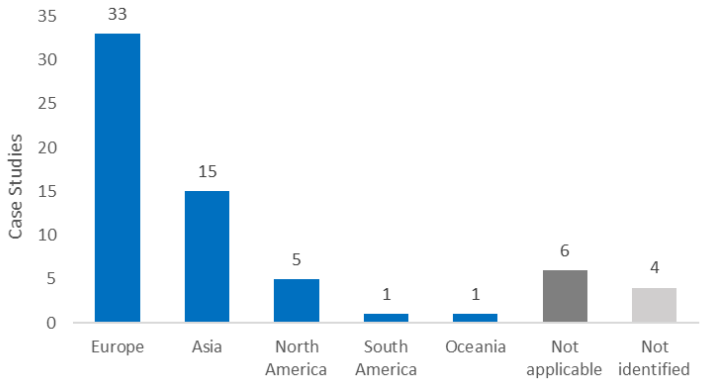


Figure 5. Geographic distribution of the case studies.

Secondly, it is worth emphasizing the significant value these studies bring to both the advancement of scientific knowledge and the practical development of the aviation and airport industry. Despite their varied thematic focuses, the analyzed articles contribute in a transversal manner to a broad range of operational and strategic domains. This is clearly reflected in the diversity of the 13 topics explored, ranging from practical aspects like construction materials, energy efficiency, terminal operations, and resource management to more theoretical themes such as best practices, tools to assess sustainability, and theories to balance growth with sustainable development. Thus, this literature review demonstrated how sustainability-related research in airports intersects with multiple areas of expertise and supports more holistic and informed decision making.

Finally, the main motivation behind this research must be addressed, i.e., the number of sustainability pillars clearly covered by the literature analyzed is important. Figure 6 presents an overall assessment of the number of pillars that were covered in the scientific publications; the pattern presented by Raimundo, Baltazar, and Cruz (2023) [6] seems to be partially confirmed. Analyzing Figure 6, it can be confirmed that the vast majority of the scientific literature focuses on just one or two of the sustainability pillars at a time. Nonetheless, 11 research works were identified that simultaneously covered the three pillars of sustainability in an interconnected way.

Before analyzing these data in more detail, it is also important to mention the following: some of the articles analyzed only covered up to two pillars of sustainability; however,

these often made mention of a third pillar, though they did not directly address it in the developed research. Some examples of this are Sharma et al. (2021) [17] on the topic of air pollution, Kareem, Abd, and Zehawi (2021) [25] on the topic of airport building, and Weiszer, Chen, and Locatelli (2015) [33] on the topic of airport operations. These authors end up mentioning a third pillar of sustainability, but do not analyze it directly in their methodologies, often referring to it only qualitatively or as an indirect benefit.

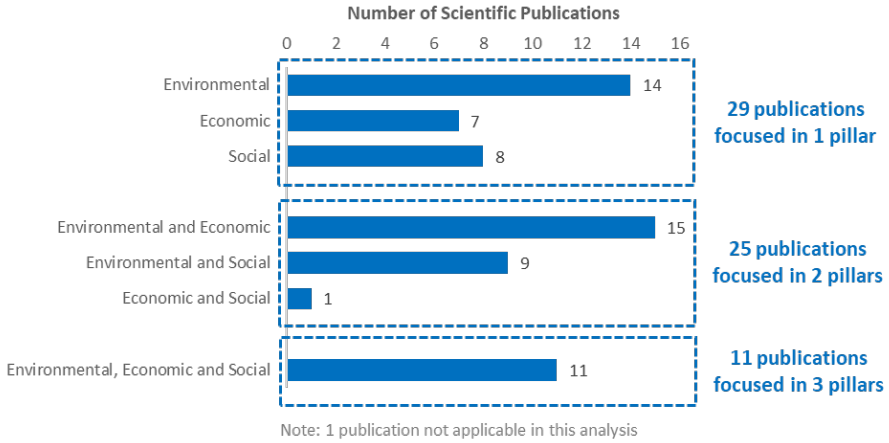


Figure 6. Sustainability pillars covered in the scientific publications.

In addition, it is important to remember that there is sometimes a silent interconnection between the sustainability pillars in some themes. For example, on the topic of terminal management, Zanni et al. (2018) [69] measured air quality at Bologna airport in a study predominantly focused on the environmental and economic aspects, trying to quantify direct benefits in these two pillars of sustainability. However, the benefits for the third pillar of sustainability (social) are inherent in this work, since air quality benefits passengers and airport workers and the reduction in environmental impact is also a benefit for the community. These third pillar benefits have not been directly addressed or quantified, but they are sometimes underlying in the work carried out.

It should be remembered that this literature review focused on scientific articles whose title directly refers to "Airport Sustainability". Bearing in mind that the theoretical definition of sustainability implies three pillars and that this is the main focus of the literature analyzed, there should be a greater prevalence of research directly addressing the three sustainability pillars. What Figure 6 does not show is that the only topics in which the three pillars have been addressed are those that are predominantly theoretical: assessing sustainability, balancing growth and sustainability, and best practices/literature reviews. As these are theoretical topics, it would be very atypical if they did not address the sustainability topic in a complete and coherent way, focusing the three pillars.

Hence, since the literature review of Raimundo, Baltazar, and Cruz (2023) [6] focused on "Airport Entrepreneurship", which has as much more practical component, it is understandable that their conclusions revolved around a lack of interconnection between all the sustainability pillars. Analyzing the literature with practical approaches, the present literature review also shows that all scientific studies covered one or two pillars of sustainability, thus neglecting or not clearly addressing the relation with a third pillar. Despite the disclaimers made above regarding some exceptions, a literature review that is focused on airport sustainability like this one should present a different standard.

This analysis is in no way intended to discredit the studies analyzed, not least because, in some cases, addressing a third pillar of sustainability would mean allocating far more resources to research and/or substantially increasing the scope of the work carried out. In

fact, it should be noted that many studies identify this third pillar of sustainability in their chapter on limitations and future work, demonstrating that it clearly did not fit within the scope of the research. However, there should not be a total absence of this type of practical study covering three pillars; consequently, it is concluded here that some practical studies should explore frameworks that duly consider the interaction between the three pillars of sustainability and the trade-offs between them.

5. Conclusions

This systematic review of airport sustainability literature reveals a notable pattern: although significant steps have been made in advancing sustainable practices, most studies focus only on two pillars of sustainability at a time, rather than integrating all three (environmental, economic, and social) into a cohesive framework. Specifically, it is noteworthy that some studies emphasize environmental and social sustainability, while others concentrate on environmental and economic aspects, but the vast majority of them did not address the three dimensions all at once.

For instance, the research works analyzed on terminal management and water management frequently examined environmental and social impacts, such as indoor air quality for passenger well-being or water conservation for community benefit; nonetheless, these studies often overlook the economic implications of implementing such sustainable practices. Alternatively, some other scientific publications analyzed tend to prioritize environmental and economic outcomes (e.g., assessing the cost-effectiveness of recycling programs or energy recovery solutions), often neglecting social factors like community engagement or worker welfare.

This systematic literature review also provided some examples of exceptions in a few studies that hint at interconnected impacts across all three pillars of sustainability, albeit not explicitly framing them in practical terms. It is clearly observed throughout the analysis that the only topics that address the three pillars are the more theoretical ones: assessing sustainability, balancing growth and sustainability, and best practices/literature review. Nevertheless, the remaining topics with more practical approaches often end up focusing on only one or two sustainability pillars at a time, as demonstrated in the previous chapter.

There are some remaining exceptions that come from the industry (industry is mentioned here as opposed to the scientific community that was analyzed in the present research), as large aviation and airports organizations have recently been demonstrating some advances in holistic approaches to sustainability. Two good industry examples are ACI (2021) [81] covering the three pillars of sustainability in a compatible way in its Sustainability Strategy for Airports Worldwide, and IATA (2022) [82], stating on its Airport Environmental Sustainability Policy that green investments should be properly complemented by assessing their respective impact on operations and considering all types of costs involved and eventual financial return through detailed cost–benefit analysis.

In conclusion, this fragmented approach reiterates the gap in the literature identified by Raimundo, Baltazar, and Cruz (2023) [6] that partially motivated the present research work; the complex interdependence between environmental stewardship, economic viability, and social responsibility are not fully explored, mainly when it comes to practical approaches. Hence, addressing this gap requires a more holistic perspective that simultaneously considers the environmental benefits, economic feasibility, and social impacts of airport sustainability initiatives, which could lead to more comprehensive strategies that better support the long-term sustainability of airports. Additionally, more scientific studies should focus on addressing the real-world problems experienced by the industry, that can be represented by case studies; the relationships between at least three essential aspects

of sustainable airport development, that duly represent the three pillars of sustainability, should be investigated.

5.1. Limitations and Future Work

In terms of limitations, it can be mentioned that the screening process could have adopted a broader approach, considering more publication years, fewer restrictions regarding the search string that was used, and more refined processes that could allow an increase in the final database size. However, given the scope and time constraints of the present research, it was not possible to conduct a more in-depth screening process. This limitation also arose due to the fact that this systematic literature review represents only one component of a broader research project being developed by the authors.

Therefore, a clear criteria had to be defined that would allow the authors to maintain a precise focus in this work, which resulted in the search string presented in the second chapter of this paper. Nevertheless, the search string could have considered "airport sustainability" only in the body of text of the papers, in the keywords, or in other ways that would have made it possible to broaden the scope of the analysis and gather a greater number of publications for the systematic literature review.

Additionally, other aspects such as considering articles only in English (or other languages understood by the authors, such as Portuguese and Spanish) or even the use of this new database for scientific publications (OpenAlex) may also have been a limitation; this prevented a global reach, which can induce some gaps when an extensive characterization of all the existing literature is sought. In this case, one of the motivations of this research work was also to test this new database and complement the results that Raimundo, Baltazar, and Cruz (2023) [6] obtained with Scopus and WoS. However, incorporating more than one scientific database would allow a broader scope and would enable us to collect a larger number of scientific publications.

Consequently, indications for future work that can deepen and complement this systematic literature review revolve around the following areas: using more than one scientific database; considering a wider time interval that include scientific publications before 2010 and after 2023; applying a search string that would broaden the scope and increase the final number of publications to be reviewed; and considering translation tools that allow the inclusion of other languages in the analysis besides English, Portuguese, and Spanish.

5.2. Recommendations

A first recommendation emerging from this review is that future scientific research should explicitly address a third pillar of sustainability when it is not yet considered; while many of the studies analyzed provide valuable contributions to one or two of these dimensions at a time, very few incorporate all three pillars in an integrated manner. It would be beneficial for researchers to adopt a broader analytical lens, and, even when a study is clearly focused on only one or two sustainability domains, they should at least reflect qualitatively on the potential implications, benefits, or trade-offs in relation to the missing sustainability pillar. By acknowledging the interdependencies between environmental, economic, and social impacts, academic research can offer more comprehensive and realistic insights into sustainable development in the airport sector.

A second recommendation is to promote the increased use of methodologies in the scientific literature that allow for the quantification of sustainability benefits, such as cost–benefit analyses (CBAs), while ensuring that all three sustainability pillars are explicitly considered in such assessments. Several of the CBAs and similar evaluations reviewed here were limited to economic and environmental aspects, overlooking relevant social factors.

So, in trying to present some other concrete examples with a missing pillar, we make the following recommendations:

- In studies where the social dimension is absent, future research should incorporate parameters such as levels of service, passenger fare impacts, satisfaction indicators, or well-being in surrounding communities, using approaches such as surveys or structured interviews.
- In studies lacking the economic component, researchers should integrate tools like CBAs or at least provide qualitative estimates regarding investment needs, operational costs, or revenue-generation potential.
- For studies lacking environmental analysis, it is essential to employ environmental sustainability assessment methods and consider ESG-related criteria, potential contributions to certifications like the Airport Carbon Accreditation (ACA), or a broader environmental footprint analysis of the initiatives under study.

Accordingly, studies related to sustainability should strive to eliminate any gray areas. Each sustainability pillar should be accounted for, either quantitatively or qualitatively, within a declared and justified scope.

It is noteworthy that these recommendations are not directed at policymakers or airport managers per se. In fact, as previously mentioned, the industry has already begun to demonstrate progress toward more holistic sustainability practices that take into account the three sustainability pillars. Instead, the recommendations are primarily aimed at the academic community. Researchers who present sustainability as a core focus, particularly when it is prominently stated in the article's title, have a responsibility to ensure that all three sustainability pillars are addressed in an explicit and deliberate manner. By doing so, scientific research works can contribute more effectively to the development of integrated knowledge that supports not only scientific advancement but also supports evidence-based practices in real-world airport sustainability efforts.

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