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Developing a Comprehensive Framework for Assessing Airports' Environmental Sustainability

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Abstract: The background of this research is environmental sustainability assessments in the aviation ecosystem, particularly concerning airports, which are getting significant attention from industry representatives, regulators, and researchers. A standardized and comprehensive approach is essential to uniformly address the global impact of these assessments across the industry. The main objective of this study is to propose a framework that encompasses the requirements of aviation regulators, as well as industry and academic metrics, aiming for a standardized approach to environmental sustainability assessments at airports. The methodology employs the Sum of Rankings Method to rank each airport across various environmental indicators. This approach was applied to five globally distributed airports, offering a diverse testing ground for assessing the applicability and effectiveness of the proposed metrics and validating the ranking framework. The results show that applying the framework across varied airport environments demonstrated its ranking viability and effectiveness, indicating that it can be successfully applied to different airport realities. The conclusion shows that the developed framework can be successfully applied, suggesting that it is a valid method for adoption in environmental airport sustainability rankings.

Keywords: airport; performance; environment; aviation; sustainability

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1. Introduction

The importance of developing an assertive and comprehensive environmental sustainability framework for the aviation ecosystem is on the agenda, and all stakeholders must contribute to this end. This study is associated with airport management, focusing on the interaction between airport performance and environmental sustainability. The research highlights the growing approach to sustainability and the need to evaluate airports' environmental performance in the face of technological development and growing environmental concerns. Therefore, this study focuses on evaluating the environmental sustainability performance of airports with an emphasis on noise pollution, water waste and contamination, air pollution, and energy management [1].

The literature has already highlighted several environmental issues linked to airport operations, namely the impact of noise pollution on the local population in regions close to the airport, concerns about water scarcity and contamination, air pollution from emissions from aircraft and land vehicles, and the high energy consumption of airport facilities. The authors of [2–4] emphasized the importance of implementing measures to mitigate these environmental impacts, such as the development of noise management plans, water conservation strategies, and the use of sustainable energy sources.

Thus, a quantitative approach was implemented to evaluate the performance of airports in the environmental area by developing a framework that incorporates key performance indicators (KPIs) obtained through literature reviews and sustainability reports. By assessing airport performance across multiple environmental dimensions, the developed framework seeks to provide insights into the effectiveness of current sustainability initiatives and identify areas for improvement [2,5,6].

As global air travel continues to expand, the environmental sustainability of airports has emerged as a critical concern for the aviation industry and policymakers. Airports are pivotal hubs of economic activity, and they are significant sources of environmental impact, including greenhouse gas emissions, noise pollution, and resource consumption. Recent studies have emphasized the urgency of implementing sustainable practices to mitigate these impacts and ensure the long-term viability of the aviation sector.

The recent literature highlights several key areas in which airports can enhance environmental sustainability. The authors of [7] underscored the necessity of adopting comprehensive sustainability evaluation methodologies encompassing economic, social, and environmental dimensions. Their review revealed that holistic approaches are essential for airports to balance operational efficiency with environmental stewardship. The optimization of logistics and operations within airports is another area of focus. In [8], the authors demonstrated that reforming cargo handling operations could significantly reduce energy consumption and emissions. Their study of Indian air cargo terminals suggests that greener technologies and optimizing logistics can substantially benefit environmental sustainability.

Other important factors are energy efficiency and renewable energy adoption, as these are critical strategies for reducing the carbon footprint of airports. The authors of [9] provided a comprehensive overview of sustainability practices within the airport ecosystem. The authors identified energy management, waste reduction, and renewable energy sources as pivotal strategies for improving environmental performance. Furthermore, advancements in air traffic management and sustainable aviation fuels were highlighted as priorities for future research. The authors of [10] discussed the current challenges and opportunities in air transport management, emphasizing the need for innovative solutions to enhance the environmental sustainability of airports. This research points to the potential of sustainable aviation fuels and eco-friendly infrastructure to reduce the environmental impact of air travel.

Integrating sustainable practices into airport operations is crucial for mitigating environmental impacts and promoting long-term sustainability. The aviation industry must continue to innovate and adopt comprehensive strategies to address its environmental challenges. By leveraging recent research and advancements, airports can play a significant role in the global efforts to achieve environmental sustainability.

The specific research problem addressed in this study is the need to rank airports' environmental performance using performance indicators, considering noise pollution, water management, atmospheric emissions, and energy consumption. In doing so, this research simultaneously answers questions such as the following: How can standardized indicators improve the comparison and improvement of airport environmental performance? And also, how are airports transparent in their environmental sustainability practices?

The novelty of the proposed framework is substantiated using the same methodology for the airport environmental sustainability assessment of the main KPIs identified by several authors, organizations, and airports. The developed framework concatenates all the major KPIs for a unified and comprehensive evaluation upon the same foundation. This makes it possible to identify the best practices and areas of improvement in various environmental domains.

The article is organized as follows: Section 2 consists of a theoretical assessment focusing on four environmental areas: noise pollution, water waste and contamination, air pollution, and energy management, as well as the theoretical framework development. Section 3 presents the results, and Section 4 discusses the results of applying the framework to five airports. Finally, Section 5 offers conclusions and recommendations for future research and practices for airports' environmental sustainability.

2. Materials and Methods

2.1. Theoretical Assessment

According to the authors of [11], the topics of "water conservation and water quality", "air quality", and "energy management" are integral to airports' environmental sustainability. In addition to these areas, airports such as those of Athens, Hong Kong, Sofia, Sydney, and Toronto also included noise pollution in their environmental performance reports from 2021 to 2022, highlighting the comprehensive approach needed for effective environmental management.

Noise is present in all industries, and airports are no exception. However, when in excess or at high levels, it can become dangerous for the well-being of populations in the vicinity of airports. According to [12], noise pollution is any unwanted and disturbing sound that is higher than the comfort level of the human ear and that negatively affects people and society. At airports, the main sources of noise pollution are as follows [13–15]:

- Reverse thrust: According to [13], this mechanism is used primarily in landings and rejected takeoffs (RTOs). This helps decelerate the aircraft more effectively by redirecting the thrust forward. Despite enhancing the braking process and increasing overall safety during this critical flight phase, the noise produced also increases.
- Energy sources such as an auxiliary power unit (APU) and a ground power unit (GPU) are both generators. The first is incorporated into an aircraft, whereas the second is an external generator that is independent of the aircraft. The APU generates an average noise of 82.5 dBA, and it can reach about 100 dBA [14].
- The use of aircraft engines during taxi procedures and takeoff: During the taxi procedure, the engines operate mostly at idle power. During takeoff, the engines are the largest source of noise [15].

According to [16], in the European Union (EU) alone, more than 4 million people are exposed to dangerous levels of aircraft noise. Noise exposure has health consequences such as sleep deficits, hypertension, cardiovascular diseases, psychological disorders, and the deterioration of cognitive systems. There is no evident method for reducing airport noise pollution; therefore, according to [17], a balanced approach must be adopted. This has been increasingly used in airports, and it focuses on four main points:

- Decreasing noise at the source.
- Land use planning and management.
- Operational procedures for noise reduction.
- Operational restrictions on air traffic.

The first approach focuses on the development of the main sources of noise, such as aircraft engines. These are constantly developing, and aircraft manufacturers, such as Airbus and Boeing, systematically seek to develop more environmentally sustainable and less noisy engines. According to the authors of [18], Airbus developed a New Engine Option (NEO), which is approximately 50% less noisy than the Current Engine Option (CEO). Simultaneously, Boeing introduced MAX engines, which, among other new features, also presented similar noise reduction compared with Next-Gen (NG) aircraft [19].

The second is an efficient way to ensure that activities carried out around airports are aviation-compatible. The main objective is to reduce the number of people affected by aircraft noise. According to [20], some of the main land use and planning standards are as follows:

- Locate new airports away from noise-sensitive areas.
- Define zones around an airport with different noise levels, considering the population level and demographic forecasts, and establishing written criteria regarding the use of these zones per the ICAO standard.

- Ensure that written information about aircraft activities and their environmental impacts is available to communities near airports.

The third category includes several measures implemented to reduce noise during flights and on the ground. Some examples of noise abatement procedures (NAPs) in flights include the following: noise abatement departure procedures (NADPs), the continuous descent approach (CDA), and reverse-thrust limitations. Some examples of NAPs on the ground include limitations to APU use, engine testing restrictions, and the use of single-engine taxi procedures [20].

The last point concerns how air traffic controllers and airports manage their operations. According to [21], some examples are noise-preferred runways, arrivals, and airport curfews.

Water waste and contamination in airport construction and operation are topics that deserve some attention because airports are places with a large movement of passengers, employees, and aircraft, which causes challenges concerning the responsible use of water and its contamination. Airports use large amounts of water for activities such as flushing toilets, preparing food, heating, ventilation, heat–ventilation and air conditioning (HVAC) systems, soil irrigation, and aircraft cleaning [11]. It is important to highlight that many of these activities do not require the use of drinking water; however, they are still usually carried out in many airports.

Several common daily activities at airports can contaminate water reserves, reduce the water quality in regions close to airports, and have toxic effects on marine life. Substances such as aircraft fuel, ethylene glycol, and ammonia used in airports, even in extremely small quantities, are carcinogenic and can be lethal to fauna and flora, consequently causing ecosystem disturbances [22]. The use of de-icing and anti-icing fluids without adequate discharge control results in them being washed into rainwater drainage systems, which, in turn, can result in a reduction in water quality and a decrease in the amount of dissolved oxygen, making it impossible for some marine living beings to survive and presenting potential risks to human health [23].

When water demand exceeds supply, water stress occurs, which can compromise the entire region around an airport [2]. This situation is common at airports in the Middle East, where most of the water comes from expensive desalination processes, and at airports in large cities such as Denver, Los Angeles, Madrid, Santiago, and New Delhi, where the water stress is greater than 80% [2]. Therefore, it is important to implement measures to reduce water use. These measures can be as simple as implementing low-flush toilets or more complex processes, such as rainwater collection systems [3].

It is also important that airports can predict natural phenomena, such as floods, erosion, drainage problems, and the design of contingency plans, as well as implementing systems that allow the drainage and use of water before transporting contaminants present in the airport soil to other beds of water near an airport. The water used is normally classified as wastewater, which can be divided into graywater or blackwater [24]. The treatment and reuse of water used before it leaves airports is very important because it can contaminate the entire region in which it is located. Some airports reuse graywater for activities such as soil irrigation to reduce waste, as is the case at Hong Kong Airport [25].

The air pollution gernerated at airportscan be divided into the following [4]:

(a) Pollution produced directly at airports;
(b) Pollution produced on the outskirts of airports.

According to the authors of [26,27], the pollution produced directly at airports is due to normal aircraft operations (takeoffs, landings, taxi procedures, etc.), the diesel engines of airports' handling vehicles, and fuel emissions during aircraft refueling. The main pollutants are polycyclic aromatic hydrocarbons ($PAHs$), sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds ($VOCs$), carbon dioxide (CO_2) and carbon monoxide (CO) [28,29]. The pollution produced on the outskirts of airports is mainly due to road vehicles moving to and from airports, which, according to the authors of [26,30], represents the most non-aircraft-related airport pollution.

Reducing air pollution is a complex challenge. However, developing strategies that enable green transport and sustainable airport operations is becoming increasingly crucial as environmental concerns grow. According to [4], there are several ways to reduce air pollution at airports. These include the use of electric and hybrid ground vehicles and, ideally, an electric fleet of public transport that serves the airport, as is the case in Brisbane [26].

The use of single-engine taxi procedures in congested airports with long travel times between stands and runways can reduce air pollution. According to the authors of [31], single-engine taxi operations lasting more than 15 min resulted in reductions of 46%, 45%, 43%, and 44% in CO/NOx/SOx/HC emissions.

In addition to these two measures, it is important to use sustainable aviation fuel (SAF), which will represent 65% of the contributions to achieving "NET Zero Carbon in 2050". This reduces CO_2 emissions by 80% [32].

Regarding energy management, airport terminals are some of the largest structures in the transport sector, and most operate 24 h a day, meaning they have extremely high energy consumption. In some cases, these terminals use fossil fuels and electricity to meet various operational requirements, such as regulating the temperature of facilities, lighting runways and buildings, and fueling airport support vehicles and ground support equipment (GSE) [32].

According to [33], energy use in terminals represents more than 50% of all airport energy consumption, as terminals differ from that of other public buildings in terms of architecture, equipment, and use. Terminals are typically large buildings with several floors of retail stores and other forms of entertainment for passengers, which is why they require a large amount of energy to meet the comfort needs of their users in terms of temperature, humidity, and air quality. According to the authors of [34], HVAC systems account for the largest amount of energy used at airports. According to [6], a study of several Greek airports concluded that there is, in many cases, an inefficient use of these systems, where, for example, in summer, they cool the terminals too much. In winter, the opposite is true when energy is used unnecessarily.

Many communities rely on natural gas, coal, and oil as energy sources. In addition to being responsible for greenhouse gas emissions, these are resources that our planet cannot produce at the rate that the population consumes, which leads to a gradual increase in their price or the overexploitation of resources, which is not sustainable and which irreversibly affects the planet. Therefore, it is necessary to explore viable alternatives. The first is the use of renewable energy sources [6,34].

Another possible measure is the optimization of HVAC systems. As mentioned in [6], many airports do not use these systems efficiently and must review their HVAC operation policies. Therefore, thermal satisfaction surveys could be conducted among terminal users, and the systems could be adjusted according to the preferences of most users, which would result in lower energy expenditures at these airports.

Comparing airports' environmental performance using a set of standardized indicators helps airport managers and stakeholders evaluate airport performance at a comparative level and by airport [35]. According to the authors of [36], environmental indicators related to airports' operational activities must consider relevance, comparability, verifiability, clarity, and understandability. According to the same authors, the methodology for evaluating airport performance in environmental areas comprises several steps:

(i) Data collection;
(ii) Data analysis and conversion;
(iii) Evaluation of information;
(iv) The preparation of reports and communication.

A review of environmental and sustainability issues demonstrates that not only does the previous literature indicate, but also the aviation industry itself adopted, four areas of environmental sustainability and their indicators as sustainability metrics: noise pollution, waste and water contamination, air pollution, and energy management, as evidenced in their annual reports [28,37–45].

Given the lack of a universally accepted environmental sustainability evaluation framework endorsed by regulatory bodies and policymakers, the primary objective of developing the proposed framework was to ensure universal applicability. To achieve it's universality, the KPIs from Table 1 were designed to be sufficiently flexible so that they could be implemented at any given airport worldwide while maintaining a high degree of accuracy in assessing a comparative environmental impact analysis. This universality is crucial because it allows for consistent environmental assessments across diverse geographical and operational contexts, thereby facilitating comparative and benchmarking studies. Furthermore, the framework incorporates a set of KPIs widely accepted in both academic research and industry best practices, ensuring that it captures a comprehensive range of environmental impacts.

The intercorrelation between the proposed indicators is also important to assess, which is essential for understanding how the various areas of environmental sustainability are interconnected. For example, by imposing noise reduction measures such as single-engine taxi procedures, airports simultaneously reduce air pollution. Noise can be reduced using specific arrival procedures, which also reduce air pollution. Using electric ground vehicles not only improves air quality but also highlights the importance of renewable energy while simultaneously emitting less noise.

Table 1. Framework indicators and KPIs.

Environmental Area	References	KPI	KPI Number
Noise pollution	[37,38,41]	Existence of a noise management plan	1
	[38,41,45]	The use of reverse thrust	2
	[37,44]	Engine run-up areas	3
	[38,46]	Airport curfew	4
	[37,41,45]	Specific arrival procedures for noise mitigation	5
	[37,42]	Number of noise complaints	6
	[37,38,41]	Number of noise complaints compared to the previous year	7
	[37,45]	Number of people affected by prolonged sound levels above 70 dBA	8
	[37,44]	Noise-preferred runways; nightly and aircraft model fees	9
	[37]	Importance given by the airport operator to noise pollution on a scale of 1 to 5	10
	[37]	Importance given by airport stakeholders to noise pollution on a scale of 1 to 5	11
Water waste and contamination	[37,45]	Importance given by the airport operator to water management on a scale of 1 to 5	12
	[37,45]	Importance given by airport stakeholders to water management on a scale of 1 to 5	13
	[41,44]	Water consumption per movement compared to the previous year	14
	[41,44]	Water consumption per passenger compared to the previous year	15
	[37,45,47]	Water stress from main water sources used at the airport	16
	[44]	Passenger awareness programs	17
	[38,41,44]	% of wastewater treated as a function of the total water used	18
	[38,41,45]	Water quality control on the surface of the airport	19
	[38,41,45]	Quality control of the airport's groundwater	20

Table 1. *Cont.*

Environmental Area	References	KPI	KPI Number
Atmospheric pollution	[37,45]	Importance given by the airport operator to air pollution on a scale of 1 to 5	21
	[37,45]	Importance given by airport stakeholders to air pollution on a scale of 1 to 5	22
	[41,42,44]	Ground vehicles' fuel type	23
	[38,41,43]	Use of SAF	24
	[37,45]	Emission of greenhouse gases	25
	[28,37,45]	Emission of other polluting gases	26
	[41,42]	APU usage restrictions	27
	[37,42]	CO_2 emissions (Kg/PAX) compared to the previous year	28
	[37,42]	CO_2 emissions (Kg/Mov) compared to the previous year	29
	[42]	Implementation of single-engine taxi procedures	30
Energy consumption	[37,45,48]	Importance given by the airport operator to energy management on a scale of 1 to 5	31
	[37,45,48]	Importance given by airport stakeholders to energy management on a scale of 1 to 5	32
	[37,38,41,48]	Energy reduction plan	33
	[42,44,48]	Use of renewable energies	34
	[42,45,48]	LED lighting systems	35
	[37,38,41,48]	Energy used per passenger compared to the previous year	36
	[37,38,48]	Energy used per movement compared to the previous year	37

2.2. Theoretical Framework Development

The Sum of Rankings Method (SRM) is a decision-making tool that works on a simple principle: ranking numerous parameters and summing the ranks to establish the most favorable alternative [49,50]. The SRM is used in various fields for classification and ranking; for example, in biology [49] an SRM variant was used to compare the performance of different analytical methods. The authors of [50] stated that the SRM can be used in almost every field and is an excellent tool since it does not have biased results or opinions. Ref. [51] uses the SRM for sensor fault detection and estimation in aircraft avionics, providing a comprehensive methodology for troubleshooting. More recently, with the rise of generative artificial intelligence (AI), large language models (LLMs) need to have a framework for ranking the probabilities for natural language processing (NLP). The authors' approach in [52] used the SRM to rank the NLP probabilities that can be used, for example, with AI chatbots.

Regarding the application of the SRM, the performance of each airport for each KPI is scored, and the scores are summed to yield an overall composite score. Using the SRM may provide important insights into the environmental sustainability of airport operations.

From a complexity perspective, the SRM is very simple to implement because of its clear implementation methodology. This simplicity is crucial in data management and analysis, which require a large amount of data to provide the right and necessary reports regarding airports' environmental performance.

Furthermore, the SRM can simultaneously host many sustainability indicators at the same time. The environmental impacts of airports are multifaceted, indicating that an inquiry into only one parameter will not yield satisfactory results in the field. The SRM allows every indicator to be examined and ranked for ultimate assessment. This ensures a more realistic view of airports' environmental sustainability performance. Most importantly, the ranking order adopted by the SRM allows variability that cannot be averted in the operations, size, and location of airports, which may impact the environment. Other methods could be biased towards airports with similar characteristics. Nevertheless, the SRM provides a framework in which all airports have the same chance to perform well in environmental sustainability, irrespective of their inherent factors. Moreover, this implies that the indicators and their weighting can be amended over time and that these changes can reflect the changing nature of environmental issues and their scientific understanding. This ensures that the SRM remains relevant and fits the purpose of dynamic environmental challenges. Finally, SRM is a very flexible tool because it can be easily adapted to new indicators.

The first step in implementing the SRM framework is to ensure that the data are in a suitable format, following Equation (1), where X is the indicator, w_i is the weight of the i-th indicator, and x_{ij} is the score of the j-th airport for the i-th environmental indicator.

$$X = \{w_i \cdot x_{ij}\} \tag{1}$$

Equation (2) introduces the weighing behavior. The weight of each indicator provides an opportunity for airports to perceive the most important and relevant ones. The crucial aspect of this framework is that, to have a universal metric to accomplish this, the same rules must be applied for all airports, which means that the weight of each indicator must be defined by policymakers or regulators and should be the same in all airports.

$$w_i \geq 0, \quad \sum_{i=1}^{n} w_i = 1 \tag{2}$$

Therefore, for each environmental indicator, each airport is ranked based on its performance score given via Equation (3):

$$R_{ij} = \text{rank}\{w_i \cdot x_{ij}; \text{desc}\} \tag{3}$$

where R_{ij} denotes the rank of the j-th airport for the i-th indicator. The function $rank\left(x_{ij}; desc\right)$ assigns the highest score to rank 1, the second highest to rank 2, and so on, with higher scores being considered better. These ties are assigned the same rank.

The summation of the ranks for each airport across all indicators gives a composite score, reflecting an overall performance assessment according to Equation (4).

$$S_j = \sum_{i=1}^{n} \cdot R_{ij} \tag{4}$$

where S_j is the sum of the ranks for the j-th airport, and n is the number of indicators.

The global ranking encompassing all indicators across all environmental areas was obtained by ordering the composite scores S_j from the lowest to the highest. Lower scores indicate better overall performance owing to the ranking system design, for which the best performance in each category received the lowest rank number.

2.3. Framework Application

An environmental impact assessment framework was developed by combining measurable and quantitative indicators with equal weights, since the reports were not uniform and were used in the academic literature, among aviation organizations, and in the aviation industry to carry out a more specific and independent assessment in various areas of airport sustainability analysis. The framework combines the 37 indicators listed in Table 1, and it is evaluated with the evaluation scale given in Table A1 in Appendix A.

The 37 indicators were divided into four areas that raised the greatest environmental concern for airports:

(i) Noise pollution (11 indicators);

(ii) Water waste and contamination (9 indicators);
(iii) Atmospheric pollution (10 indicators);
(iv) Energy management (7 indicators).

To evaluate the performance of airports, a 5-level Likert scale (1 to 5) was used, and each indicator was given a score based on its performance, with one being very poor performance, two poor performance, three average performance, four good performance, and five very good performance. If there was no available information in the airport report for one or more indicators, it was considered 0.

After the classification of each airport for each KPI, the airports were ranked using the SRM. This method ranks airports according to the classification of each KPI by assigning a numerical rank based on each airport's performance relative to others in the same KPI. Specifically, the SRM assigns the best-performing airport in each KPI the lowest rank (e.g., 1 for the best performance) and the worst-performing airport the highest rank, which are then summed across all KPIs for each airport, resulting in a composite score. The lower the composite score, the higher the overall performance of the airport across all the considered KPIs.

For instance, let us consider three airports evaluated using three different KPIs—noise management, energy efficiency, and water conservation. Suppose Airport A ranks the best in noise management (Rank 1), second in energy efficiency (Rank 2), and the worst in water conservation (Rank 3). Conversely, Airport B ranks second in noise management (Rank 2), the best in energy efficiency (Rank 1), and second in water conservation (Rank 2). Airport C, which performs the worst in noise management and the best in water conservation, receives rank 3 in noise and 1 in water, with a middle rank of 2 in energy. The composite scores are calculated as follows:

- Airport A: 1 (Noise) + 2 (Energy) + 3 (Water) = 6
- Airport B: 2 (Noise) + 1 (Energy) + 2 (Water) = 5
- Airport C: 3 (Noise) + 2 (Energy) + 1 (Water) = 6

In this example, Airport B, which has the lowest composite score of 5, ranks the highest overall, indicating that it has the most balanced performance across the evaluated KPIs.

For comparison, 5 airports were included in the study based on several factors that make the framework as complete as possible. First of all was geographic distribution. The chosen airports were from different continents: Toronto Airport (Toronto Pearson International Airport, ICAO Code: CYYZ), Hong Kong Airport (Hong Kong International Airport, ICAO Code: VHHH), Sofia Airport (Sofia International Airport, ICAO Code: LBSF), and Sydney Airport (Sydney Kingsford Smith Airport, ICAO Code: YSSY). Additionally, Athens Airport (Eleftherios Venizelos International Airport, ICAO Code: LGAV) was included to allow for the assessment of two airports from the same geographical region (Europe), providing insights into regional performance variations within the sustainability framework. The chosen airports allow a global perspective on environmental performance levels. Second, airports were chosen based on data availability from 2021 and 2022 to provide the most reliable, relevant, and comprehensive data. Finally, the airports were hubs of the respective regions with different numbers of passengers, flights, and destinations, as shown in Table 2, to verify the impact of the environmental framework.

Table 2. Studied airports' analytical movement data.

Airport	Sofia	Athens	Sydney	Hong Kong	Toronto
N° of Pax [Million] (2022)	6	22.7	29.1	12.4	35.6
N° of Movements (2022)	53,000	213,000	277,000	161,000	337,000
N° of Destinations (2022)	85	143	95	150	152

3. Results

After the SRM method was applied to the KPI's from Table 1, and the evaluation scale given in Table A1 in Appendix A was used, the studied airports were classified per Table 3.

Table 3. Detailed airport performance under the framework for each KPI.

Environmental Area	KPI Number	Value of Performance at Different Airports				
		LBSF	LGAV	YSSY	VHHH	CYYZ
Noise Pollution	1	5	5	5	5	5
	2	2	3	5	1	3
	3	5	3	3	5	3
	4	1	1	5	1	1
	5	5	5	4	5	5
	6	4	3	5	5	1
	7	5	5	1	5	0
	8	5	0	0	0	1
	9	5	3	3	4	3
	10	3	0	0	0	0
	11	2	0	0	0	0
Water Waste and Contamination	12	1	0	0	0	2
	13	1	0	0	0	2
	14	5	5	5	5	5
	15	5	5	5	5	5
	16	2	1	2	4	4
	17	1	1	1	3	1
	18	1	3	3	5	1
	19	1	5	5	5	5
	20	1	5	5	5	5
Atmospheric Pollution	21	3	0	0	0	3
	22	3	0	0	0	3
	23	3	4	3	5	3
	24	4	5	5	5	2
	25	5	5	5	5	5
	26	5	5	5	5	5
	27	2	5	3	3	3
	28	5	5	5	5	5
	29	5	5	5	5	5
	30	1	1	1	1	1
Energy Management	31	3	0	0	0	3
	32	2	0	0	0	4
	33	2	5	5	5	5
	34	2	4	4	4	2
	35	2	3	4	4	5
	36	5	5	5	5	5
	37	4	5	5	4	5

When analyzing Table 3, it can also be seen that, concerning the noise pollution environmental area, for a total of 11 indicators evaluated at the five airports, 23 of the 55 performance values (41.8%) presented a good rating (value 4) or a very good rating (value

5), 10 (18.2%) showed average performance (value 3), and another 10 (18.2%) showed below-average performance. It should be noted that the remaining 12 values (21.8%) correspond to indicators not reported at the airports. Considering the five studied airports, the indicators with the best performance were the "Existence of a Noise Management Plan" (KPI 1) and "Specific Arrival Procedures for Noise Mitigation" (KPI 5) because all the airports had a plan for the constant monitoring of noise and actions to control and reduce it and because most large airports have continuous descent approaches (CDAs) with attention to noise caused in residential areas. The indicators with the worst performance (among those applicable to all) were "Airport Curfew" (KPI 4) and "The Use of Reverse Thrust" (KPI 2) because, in general, airports do not have restrictions on the use of reverse thrust, and only Sydney airport limited aircraft movements at night hours.

Regarding the environmental area of water waste and contamination, and for the total of 9 indicators evaluated at the 5 airports, 21 of the 45 performance values (46.7%) presented above-average performance, 3 (6.7%) had average performance, and 15 (33.3%) had poor or very poor performance. Considering the five studied airports, the indicators with the best performance were "Water Consumption per Movement Compared to the Previous Year" (KPI 14) and "Water Consumption per Passenger Compared to the Previous Year" (KPI 15) because all the airports substantially reduced the consumption of water by 2022. The worst indicators (among those for which all data were available) were "Passenger Awareness" (KPI 17), "Water Stress of the Main Water Sources Used at the Airport" (KPI 16), and "% of Wastewater Treated as a Function of the Total Water Used" (KPI 18); this is because the only airport that carried out some passenger awareness campaigns to reduce the wasting of water resources was VHHH. Most of the airports are located in areas of high water stress and treat less than 60% of the water used. LBSF and CYYZ were used at concentrations of less than 20%.

Regarding the environmental area atmospheric pollution, and 10 indicators evaluated at the five airports, 27 of the 50 performance values (54.0%) had above-average performance, 10 (20%) corresponded to average performance, and 7 (14%) had weak or very weak performance. The remaining 6 (12%) corresponded to indicators not reported at the respective airports. Considering the five studied airports, there were four indicators for which all the airports achieved the maximum performance (KPIs 25, 26, 28, and 29) because they all control the emission of greenhouse gases and other polluting gases and plan to reduce emissions in the long term. Furthermore, compared to 2021, all the airports reduced CO_2 emissions per passenger and movement. The indicators with the worst performance were the "Implementation of Single-Engine Taxi Procedures" (KPI 30) and the "APU Usage Restrictions" (KPI 27) because no airport suggested the use of just one engine before takeoff or after landing. In addition, on the overall basis of the five airports studied, there are few recommendations and restrictions regarding APU usage.

For the last environmental area, energy management, and the 7 indicators evaluated, 21 of the 35 performance values (60%) were good (value 4) or very good (value 5), three (8.6%) average performance levels were achieved, and five (14.3%) weak (value 2) or very weak (value 1) performance levels were recorded. The remaining six (17.1%) corresponded to indicators not reported at the studied airports. Considering the five studied airports, the two indicators with the best performance were the "Energy Used per Passenger in KwH Compared to the Previous Year" (KPI 36) and the "Energy Used per Movement in KwH Compared to the Previous Year" (KPI 37) because all the airports managed to reduce energy consumption per passenger and movement significantly. The two indicators with the worst performance were the "Use of Renewable Energy" (KPI 34) and the "Use of LED Lighting Systems" (KPI 35).

The indicators that measure the importance given by the airport operators and stakeholders to the different areas of environmental performance allow for a better understanding of the obtained results because it would be expected that an airport that scored 5 in these indicators would have worse general results than those of an airport that obtained a score of 1. This, in turn, would also help airports perform a self-evaluation and understand which areas required greater engagement to enhance environmental sustainability performance. On the other hand, an airport that does not have available data to measure these KPIs could exhibit a lack of focus on that specific environmental area or a lack of transparency by not providing data that would disclose unfavorable information and create a negative public perspective about the airport's commitment to the environment; therefore these are valuable KPIs for a complete evaluation of airport sustainability.

The overall airport performance, considering all 37 indicators from the proposed framework, is shown in Table 4, which indicates the results of the airports studied across all four environmental areas. Based on these results, the following points can be assessed:

- Noise pollution: LBSF has the best performance in noise pollution environmental area management, showing the lowest score, and hence, it ranked the best in this category. Both CYYZ and YSSY, having the highest and second highest scores, respectively, indicate potential areas for significant improvement in noise pollution management at these two airports.
- Water waste and contamination: VHHH and CYYZ perform best in managing the water waste and contamination environmental area, as evidenced by their lowest scores. With the highest score, LBSF had the greatest room for improvement in this category.
- Atmospheric pollution: LGAV and VHHH tied for the best performance in the atmospheric pollution environmental area, as shown in their lowest scores. Although with only a slightly higher score, LBSF has the most room for improvement in this category.
- Energy consumption: CYYZ has the best performance in the energy consumption environmental area, with only 10 points. On the other hand, LBSF has a much higher score than all the other airports, which means it lags well behind in energy management.

Table 4. Overall airport performance under the framework.

Environmental Area	LBSF	LGAV	YSSY	VHHH	CYYZ
Noise Pollution	17	24	26	21	28
Water Waste and Contamination	25	19	17	13	13
Atmospheric Pollution	19	15	17	15	17
Energy Consumption	22	14	12	15	10
Overall Score	83	72	72	64	68

The global scores provide a summary metric derived from aggregating the ranked results across all environmental areas. The difference in global scores (from 64 to 83) suggests that airports have different environmental performance levels. VHHH is slightly ahead, showing a small but potentially significant edge in environmental sustainability practices. LBSF still has room for improvement in environmental performance. When comparing the two European airports, it is possible to verify good competition with a difference of 11 in the framework score.

4. Discussion

The designed framework provides a dual-purpose tool for enhancing airport environmental sustainability ranking assessments. First, it establishes a standardized scoring metric that ranks environmental sustainability indicators across various airports. This method facilitates a consistent and objective evaluation and ranking of the four key environmental areas identified by academy, airport-industry, and aviation-ecosystem stakeholders. The environmental areas of noise pollution, water waste and contamination, atmospheric pollution, and energy management are crucial for evaluations with the same metric standards to obtain a comprehensive score.

Second, since the framework supports the creation of a comparative ranking system, it enables stakeholders to benchmark and identify leading airports in terms of environmental sustainability, fostering a competitive environment that encourages continuous improvements in sustainable practices. The integration of these elements within the framework not only aids in the holistic assessment of airport sustainability but also promotes transparency and accountability in the management of airport operations.

The absence of airport information in some KPIs indicates a lack of uniformity in sustainability performance reporting. Aviation regulators must not only enforce the practice at all airports with an annual sustainability report but also create a uniform framework of the required KPIs to be assessed and reported at airports. This lays the foundation for a more transparent and assertive evaluation of airport sustainability and performance metrics.

The findings align with and extend existing research assessing the environmental sustainability of airports. Notably, the results corroborate the findings of previous studies such as [12–18,20,21,35,46], which noted the significant impact of noise management and energy efficiency on overall airport sustainability. Similarly, our observations regarding water management practices reflect the concerns raised by [22–25,35] regarding the water scarcity and contamination challenges faced by global airports. Regarding atmospheric pollution, the assessment presented in this study also corroborates the results of previous studies [26,28–30,35]. The last-analyzed environmental area, energy management, and the presented insights are aligned with the findings of the authors of [34,35,48]. Furthermore, the study contributes new insights into the practical application of these KPIs across a varied set of airports, highlighting disparities and potential areas for improvement. This dual approach of validating and expanding on previous findings emphasizes the robustness of our methodology and the relevance of our results in contributing to the broader discourse on sustainable airport operations.

5. Conclusions

It was possible to develop a comprehensive and complete environmental impact assessment framework that combines measurable and quantitative indicators used in previous literature, at aviation organizations, and in the industry to carry out a more specific independent and complete assessment of various areas of environmental sustainability. The developed framework integrates indicators in four distinct areas of sustainability: noise pollution, water waste and contamination, atmospheric pollution, and energy management. This framework was validated through its application to the LGAV, VHHH, LBSF, YSSY, and CYYZ airports, showing that the developed framework can be applied to aviation industry standards. The framework application showed that there is competition between the airports, with some differences in performance, with VHHH showing the best performance but still with room for improvement and LBSF as the airport in need of better performance. Comparing airports in Europe revealed that the performance was only slightly different; LGAV had more environmentally sustainable performance than LBSF.

Although the SRM is comprehensive and straightforward to implement within an environmental sustainability framework, it has limitations. One of the primary challenges is its reliance on relative rankings, which can obscure the magnitude of the differences between data points. This means, for example, that if an airport is classified as second and another as third, despite their distance in the ranking being small, a huge difference can exist globally between them. Also, because some indicators are dimensionless, a better rank does not necessarily mean a greater decrease in absolute values. Additionally, the SRM can be sensitive to outliers, which may disproportionately influence the overall results; therefore, regarding the SRM method, it only makes sense to apply it with the same framework globally or regionally to a fairly large airport dataset.

Moreover, sustainability is a very important topic that has consequences if it is not addressed, including a decrease in public health, environmental degradation, and high economic costs for current and future generations. Therefore, it is recommended that the aviation ecosystem and airports continue to develop and implement strategies that improve environmental sustainability, such as controlling noise and pollutant emissions, the quality and management of airport water usage, and the use of renewable energy.

The global community is currently confronted with significant environmental and sustainability challenges. Among all sectors, the aviation industry is particularly tasked with addressing these issues. It is imperative that all stakeholders, including the academic community, actively engage in proposing and implementing novel technologies, methodologies, and frameworks to mitigate, manage, and eradicate environmental concerns effectively.

For future work, it is important to assess the framework at a larger scale, either at the regional level or at the global level. It is also important to add to the SRM methodology a qualitative scale; for example, red, yellow, and green can be used as qualitative indicators to visually reflect the overall environmental sustainability practices for any given airport.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
APU	Auxiliary power unit
CDA	Continuous descent approach
CEO	Current Engine Option
EU	European Union
GPU	Ground power unit
GSE	Ground support equipment
KPIs	Key performance indicators
HVAC	Heat–ventilation and air conditioning
LED	Light-emitting diode
LLM	Large language models
NADPs	Noise abatement departure procedures
NAPs	Noise abatement procedures
NEO	New Engine Option
NG	Next generation
NLP	Natural language processing
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
RTO	Rejected takeoff
SAF	Sustainable aviation fuel
SRM	Sum of Ranking Method
VOCs	Volatile organic compounds

Appendix A

Table A1. Sustainability framework evaluation metrics.

KPI Number	Performance/Classification Metric				
	1	**2**	**3**	**4**	**5**
1	There is no noise management plan	There is a noise management plan, and noise values are measured over periods longer than one year.	There is a noise management plan, which measures noise values over 6 months and one year	There is a noise management plan, and noise values are measured over 1 and 6 months	There is a noise management plan, and noise values are measured monthly
2	There are no mandatory limitations or recommendations	There is no mandatory limitation, but there are nighttime recommendations	There are no limitations, but there are recommendations for the whole day	There are limitations at night and recommendations during the day	There are limitations throughout the day
3	There is no specific zone for engine run-up	There is a specific zone for engine run-up without time restrictions	There is a specific zone for engine run-up with time restrictions	There is a specific area for engine run-up with a sound barrier, without time restrictions	There is a specific engine run-up zone with a noise barrier and with time restrictions
4	There is no airport curfew	Curfew < 2 h	2 h < curfew < 4 h	4 h < curfew < 5 h	5 h > curfew
5	The approximations do not take into account noise pollution, nor are there CDAs	The approximations do not take noise pollution into account but there are CDAs	The approaches do not take into account noise pollution, but at night, ATC provides radar vectors with distance to go into CDAs	The approximations are not CDAs but take noise pollution into account	The approximations take noise pollution into account and are CDAs
6	More than 100 complaints	50 < complaints < 100	25 < complaints < 50	0 < complaints < 25	0 complaints
7	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
8	More than 100 people affected	50 < people affected < 100	25 < affected people < 50	0 < affected people < 25	0 people affected
9	Noise does not influence the choice of lane in use, and there is no difference in rates depending on the time of day	Noise has no influence on the choice of lane in use, but there is a difference in rates, depending on the time of day	Noise has no influence on the choice of lane in use, but there is no difference in rates depending on the time of day	Noise influences the choice of lanes throughout the day, and there is a difference in rates, depending on the time of day	Noise influences the choice of runway throughout the day, and there are differences in rates, depending on the time of day and type of aircraft
10	1	2	3	4	5
11	1	2	3	4	5
12	1	2	3	4	5
13	1	2	3	4	5

Table A1. *Cont.*

KPI Number	Performance/Classification Metric				
	1	**2**	**3**	**4**	**5**
14	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
15	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
16	Extremely-high	High	Medium-high	Low-medium	Low
17	No passenger awareness campaign was carried out for passengers	1 passenger awareness campaign was carried out for passengers in the last year	2 passenger awareness campaigns were carried out in the last year	3 passenger awareness campaigns were carried out in the last year	More than 3 passenger awareness campaigns were carried out in the last year
18	Treated water < 20%	20 %< Treated water < 40%	40% < Treated water < 60%	60% < Treated water < 80%	80% or more Treated water
19	It was not reported, or there is no control	The last quality control was more than a year ago	Quality control is carried out annually	It is checked occasionally during the year	It is monitored regularly throughout the year
20	It was not reported, or there is no control	The last quality control was more than a year ago	Quality control is carried out annually	It is checked occasionally during the year	It is monitored regularly throughout the year
21	1	2	3	4	5
22	1	2	3	4	5
23	They are diesel-powered, and there is no plan to replace them	They are diesel-powered, and there is a plan to replace them in the future	They are powered by diesel, and there is a plan to replace them that is currently being implemented	The ground vehicle fleet is made up of hybrid and electric vehicles	The vehicles are electric
24	The airport does not have SAF or intends to start using it	The airport intends to start using SAF within more than 2 years	The airport intends to start using SAF within 1 to 2 years	The airport intends to start offering SAF within less than a year	The airport offers SAF
25	The airport does not account for greenhouse gas emissions	The airport counts direct greenhouse gas emissions but does not have a plan to reduce them	The airport counts direct and indirect greenhouse gas emissions but does not have a plan to reduce them	The airport counts direct and indirect greenhouse gas emissions and is developing a plan to reduce them	The airport counts direct and indirect greenhouse gas emissions and is implementing a plan to reduce them
26	The airport does not count the emission of other polluting gases	The airport does not count emissions of other polluting gases but intends to start doing so	The airport counts emissions of other polluting gases but does not have a plan to reduce them	The airport counts emissions of other polluting gases and is developing a plan to reduce them	The airport counts emissions of other polluting gases and is implementing a plan to reduce them
27	There are no restrictions, and no GPU is provided	There are no restrictions, but GPU is provided	There are no restrictions, but GPU and air conditioning are provided	There are restrictions; GPU is provided, but not air conditioning	There are restrictions, and GPU and air conditioning are provided
28	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%

Table A1. *Cont.*

KPI Number	Performance/Classification Metric				
	1	2	3	4	5
29	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
30	The airport does not encourage single-engine taxi procedures	The airport encourages single-engine taxi procedures only in taxi-in	The airport encourages single-engine taxi procedures only in the taxi-out	The airport encourages single-engine taxi procedures, taxi-in, and taxi-out when a long taxi time is expected	The airport encourages single-engine taxi procedures for taxi-in and taxi-out in all cases
31	1	2	3	4	5
32	1	2	3	4	5
33	The airport does not have an energy reduction plan	The airport has an energy reduction plan updated every 5 years or more	The airport has an energy reduction plan updated every (3–5) years	The airport has an energy reduction plan updated every (1–3) years	The airport has an energy reduction plan updated annually
34	The airport does not use renewable energy	The airport does not use renewable energy but plans to use it.	The airport uses at least one type of renewable energy, representing less than 10% of total energy	The airport uses at least one type of renewable energy, representing between 10 and 50% of total energy	The airport uses at least one type of renewable energy, representing more than 50% of total energy
35	The airport does not use nor has any plans to use LED lamps	The airport does not use LED lamps but has plans to do so in the future	Less than 50% of lamps are LED	More than 50% of lamps are LED	All airport lamps are LED
36	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%
37	Increased by more than 5%	Increased by up to 5%	Same as the previous year	Reduced up to 5%	Reduced more than 5%

For the KPI 16, the classification from Extremely-high to Low is giving in accordance with [47].

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