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Review

Airport Runoff Water: State-of-the-Art and Future Perspectives

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Abstract: The increase in the quantity and variety of contaminants generated during routine airport infrastructure maintenance operations leads to a wider range of pollutants entering soil and surface waters through runoff, causing soil erosion and groundwater pollution. A significant developmental challenge is ensuring that airport infrastructure meets high-quality environmental management standards. It is crucial to have effective tools for monitoring and managing the volume and quality of stormwater produced within airports and nearby coastal areas. It is necessary to develop methodologies for determining a wide range of contaminants in airport stormwater samples and assessing their toxicity to improve the accuracy of environmental status assessments. This manuscript aims to showcase the latest advancements (2010–2024 update) in developing methodologies, including green analytical techniques, for detecting a wide range of pollutants in airport runoff waters and directly assessing the toxicity levels of airport stormwater effluent. An integrated chemical and ecotoxicological approach to assessing environmental pollution in airport areas can lead to precise environmental risk assessments and well-informed management decisions for sustainable airport operations. Furthermore, this critical review highlights the latest innovations in remediation techniques and various strategies to minimize airport waste. It shifts the paradigm of soil and water pollution management towards nature-based solutions, aligning with the sustainable development goals of the 2030 Agenda.

Keywords: airport runoff water; water pollution; soil degradation; stormwater toxicity; best management practices (BMPs); sustainable development; environmental quality management

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1. Introduction

Urban regions consist of a mix of impermeable and permeable surfaces, resulting in intricate patterns of rainfall and runoff over both space and time [1–3]. The prevalence of paved surfaces reduces water infiltration and increases runoff after precipitation events, potentially exerting a significant influence on streamflow patterns and flood risk [4–9]. As urbanization accelerates and climate change progresses, extreme weather events are becoming more frequent than in the past, leading to significant challenges for urban areas, such as increased instances of urban waterlogging [10]. Urbanization has changed land use patterns and the hydrological regime of urban areas, resulting in most rainfall becoming runoff [10,11]. Urban runoff, also known as urban stormwater, urban run-off, surface, or rainwater runoff encompasses the runoff, resulting primarily from precipitation on impermeable surfaces within urban environments, such as rooftops, pavements, roadways, and parking areas [12–14]. Furthermore, in regions experiencing seasonal snowfall, urban runoff also includes snowmelt [4–6]. This runoff carries large quantities of sediments and pollutants that have accumulated on urban surfaces into nearby water bodies, leading to the degradation of water quality when they mix with groundwater [5,7]. Urban runoff also exacerbates soil erosion, particularly given the often deteriorated state of urban soils [7–9,14,15].

A distinct type of urban stormwater is runoff from airports, which represents a very specific type of sample that is increasingly being subjected to analysis [16,17]. Recently, air transport has become one of the most important and fastest-growing sectors of the global economy. Although the industry was severely impacted by the COVID-19 pandemic, with dramatic declines in service rates and passenger numbers, there are clear signs that the industry is beginning to recover [18]. According to the International Air Transport Association (IATA), the total number of passengers in 2021 was 47% of the 2019 level. The numbers increased to 83% in 2022 and 94% in 2023, with further growth projected to reach 103% in 2024 and 111% in 2025 [18,19]. Despite the numerous benefits of the rapid growth in the air transport sector, all activities associated with airport operations result in environmental pollution [10,20]. The extensive use of hardened pavement in airport construction results in a high proportion of impervious surfaces, disrupting the natural hydrological cycle [10]. One of the major issues associated with airport operations is runoff water, which is generated when precipitation or atmospheric deposition washes over the surfaces of the airport apron during its use. Runoff water from airport areas can contain a wide spectrum of contaminants at varying concentration levels [21–27].

On an international scale, environmental protection, including the reduction of the negative impacts of airports on the environment, is a priority in sustainable development policy, in line with the goals and objectives of the 2030 Agenda for Sustainable Development [28]. The management of airport stormwater has emerged as a matter of national and international concern recently, with significant attention being paid to the effects of de-icing/anti-icing activities on the quality of runoff. Literature data emphasize that airport runoff should be regarded as a distinct pollutant stream, necessitating specialized treatment before being discharged into surface waters. To effectively address airport effluent quality within the framework of environmental safety, it is imperative to adopt a comprehensive and integrated management approach [29,30]. Efforts to mitigate the impacts of airport runoff water through the development and implementation of best management practices (BMPs) are hindered by an incomplete understanding of the composition of airport runoff water samples. The current literature indicates a relatively narrow range of research focused on the analysis of airport stormwater samples. These studies are limited to determining the content of basic summary parameters such as COD, BOD_5, total nitrogen, TOC [31–33], and organic compounds, especially from the groups of glycols, benzotriazoles, and PAHs [34–44]. The analysis of literature data leads to the conclusion that it is necessary to develop appropriate methodologies for determining a wide range of contaminants in airport stormwater samples. Furthermore, the fate, transport, and toxicity of pollutants in airport runoff are not yet fully understood [45]. There are clear gaps in the study results concerning the composition of airport runoff water samples and the whole effluent toxicity of runoff water from airports. The absence of standardized methods for measuring contaminants and evaluating toxicity in airport stormwater samples poses a significant barrier to the design of BMPs and generates uncertainty in the regulatory context [45].

The scientific community is currently concentrating on developing best management practices at airports to maximize the reduction of the negative impact associated with polluted runoff, particularly concerning water pollution, soil erosion, and soil degradation. This manuscript presents recent advancements in analytical methodologies, including green techniques, for determining a wide range of pollutants in airport runoff and assessing the overall toxicity of airport stormwater effluent. Such chemical-toxicological methodologies act as tools to identify the types and quantities of contaminants present in airport runoff. This leads to precise environmental risk assessments and well-informed management decisions for sustainable airport operations. Additionally, this review highlights the latest innovations in remediation techniques and various strategies to minimize airport waste, shifting the paradigm of soil and water pollution management towards nature-based solutions that promote the concept of Low-Impact Development (LID). Actions to protect the environment must be integrated and should encompass three dimensions: social, economic, and environmental. This approach will ensure the quality of life expected by society for current and future generations.

2. Basic Airport Stormwater Characterization

Urban runoff originates from various types of urban surfaces, each characterized by different levels of permeability and water retention capacity. The main categories of these surfaces include impervious surfaces (such as streets, roads, sidewalks, parking lots, and building roofs), semi-pervious surfaces (such as cobblestones, paving slabs, and permeable pavements), and pervious surfaces (such as lawns, green spaces, fences, and gravel paths). As previously mentioned, a specific type of stormwater runoff forms in urbanized areas, known as airport runoff. Airport runoff is generated from the diverse range of surfaces present within the airport grounds. Designated and properly prepared areas within an airport include surfaces where aircraft movement occurs, as well as zones intended for the parking of aircraft and technical service vehicles. These areas encompass runways, taxiways, and apron pavements, as well as pavements situated around buildings designated for terminals and aircraft parking. This type of surface includes hardstands, uncovered assembly areas, and roads designated for aircraft movement. Additionally, airport surfaces encompass those located within hangar and assembly halls. Airport surfaces also include natural surfaces, such as soil-based, grass, and turf surfaces. Based on the available data from various airports, Table 1 presents the averaged percentages of different types of airport surfaces along with their characteristics [26,30,46,47]. The proportional distributions may exhibit slight variations depending on the specific airport, its scale, the nature of operations conducted, and the configuration of its infrastructure.

Table 1. Percentage distribution of main airport operational areas along with surface characteristics.

Main Operational Areas of Airport Infrastructure		Proportion of the Airport's Total Operational Area [%]	Characteristics
(1)	Runways	50–60	high-strength concrete/asphalt, durable for takeoffs and landings;
(2)	Taxiways	20–30	concrete/asphalt, designed for smooth aircraft movement;
(3)	Aircraft Parking Areas	15–25	reinforced concrete/asphalt, supports stationary aircraft during operations;
(4)	Aprons	15–20	reinforced concrete, withstands heavy equipment use;
(5)	Passenger Terminal Areas	10–20	asphalt/concrete, durable for high foot and vehicle traffic;
(6)	Cargo Areas	10–15	durable concrete, supports cargo vehicles and equipment;
(7)	Maintenance Areas	5–10	reinforced concrete, withstands heavy equipment use;
(8)	De-icing zones	2–5	reinforced concrete, resistant to de-icing chemicals.

Airport pollutants emitted into the atmosphere undergo dispersion or transformation during atmospheric transport. However, most pollutants present in the air, soil, and water return to the Earth's surface through wet or dry deposition or by being absorbed by aerosol particles. This includes gaseous pollutants, which can be transferred through surface waters or soil [6,48–50]. A significant portion of pollutant transfer from the atmosphere to the Earth's surface occurs through wet deposition, specifically precipitation and atmospheric deposition [6,48,51]. Precipitation, atmospheric sediment and the resulting runoff flush the airport's surfaces during everyday operations [5,47,52]. Airports employ various chemical substances that may be introduced into stormwater pathways. This runoff, containing organic and inorganic contaminants, infiltrates the soil, surface waters, and groundwater, potentially affecting sources of drinking water [6,53,54]. Furthermore, during heavy precipitation events, this stormwater can lead to microbiological contamination of source water for public drinking supplies [55,56]. Intense rainfall leading to runoff water, particularly from areas near airports, has been associated with a high risk of acute gastrointestinal illness (AGI), notably in highly developed countries like France, the United Kingdom, Canada, the United States, and Australia [45,56].

The drainage design of the airport operational area is similar to that of urban areas, primarily utilizing buried pipes to discharge rainwater. The drainage system in the airfield area primarily includes covered ditches, open ditches, blind ditches, box culverts, V-ditches, and detention ponds [10]. Runoff water is conveyed away from airport areas through sewer systems to prevent localized flooding, as the majority of airports, regardless of traffic intensity and size, do not have their wastewater treatment plants [57]. Most airports do not even have their preliminary wastewater treatment facilities. Consequently, the generated stormwater, along with its contaminants, is directed into drainage ditches, significantly increasing the load and burden on the wastewater system [20,54,58,59]. In the absence of a treatment plant or if a treatment plant is functioning improperly, various contaminants may enter the air, soil, and surface waters along with runoff water [28,45,60,61].

3. Contaminants in Airport Runoff Waters

Various forms of anthropogenic pressure associated with the operation of any airport lead to the dispersal of pollutants in the environment where they undergo chemical, biochemical, and photochemical transformations [62,63]. Airport runoff water samples may contain a wide array of hazardous substances, including polycyclic aromatic hydrocarbons (PAHs), glycols, benzotriazoles (BTs or BTR), polychlorinated biphenyls (PCBs), per- and polyfluoroalkyl substances (PFAS), pesticides, biocides, detergents, potassium acetate, potassium formate, sodium formate, sodium acetate, phenols, formaldehyde, heavy metal ions, and cyanides [24–26]. The aforementioned pollutants come from de-icing/anti-icing operations, fuel spills, aircraft and installation cleaning, and, in short, all human activities related to passenger transport and the maintenance and operation of installations at airports. The main sources of pollution at airports are presented in Figure 1 [22–24,64–66].

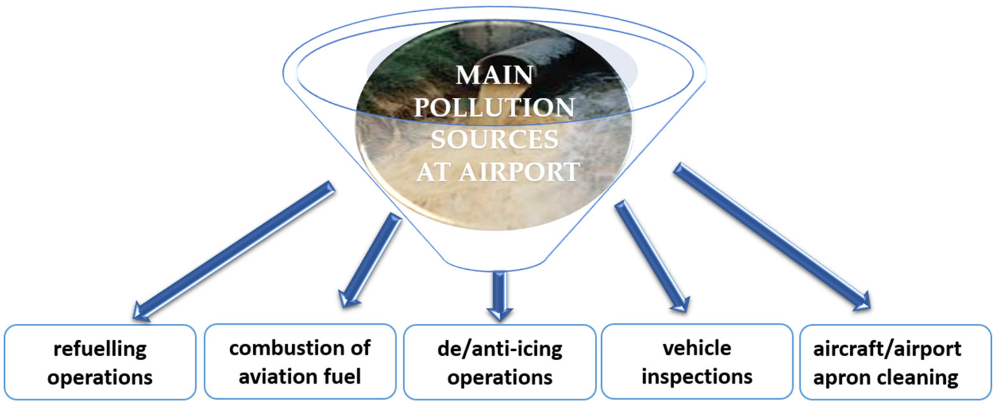

Figure 1. The most important sources of pollution at airports.

Our previous literature reviews on the analysis of xenobiotics in airport runoff water covered studies up to the year 2010 [24,25]. In this paper, an update is proposed, incorporating the latest data and research findings. Table 2 summarizes the studies published in the last years regarding the analysis of xenobiotics and determination of toxicity in airport runoff water samples. The target analytes, sampling site, along with the range of concentration and details about the bioassays and methodologies used for sample preparation and analyte determination, have been documented.

Based on data from global literature on the detection of xenobiotics in runoff water samples, it can be concluded that the most commonly analyzed inorganic analytes are cations, anions, total nitrogen, total phosphorus, and metals (Figure 2a). The most frequently detected organic compounds in runoff waters belong to the groups of PAHs, PCBs, PFCs, BTs, and glycols (Figure 2b). The data presented in Figure 2 indicate that different countries prioritize specific analytes in their airport runoff water testing. In Poland, the analysis of cations, anions, and total phosphorus among inorganic xenobiotics is a primary focus, while in Norway and the USA, there is a greater emphasis on the analysis of metals and total nitrogen. In terms of organic analytes, Poland leads in the detection of PAHs and PCBs, while the USA and China exhibit higher testing frequencies for glycols and PFCs.

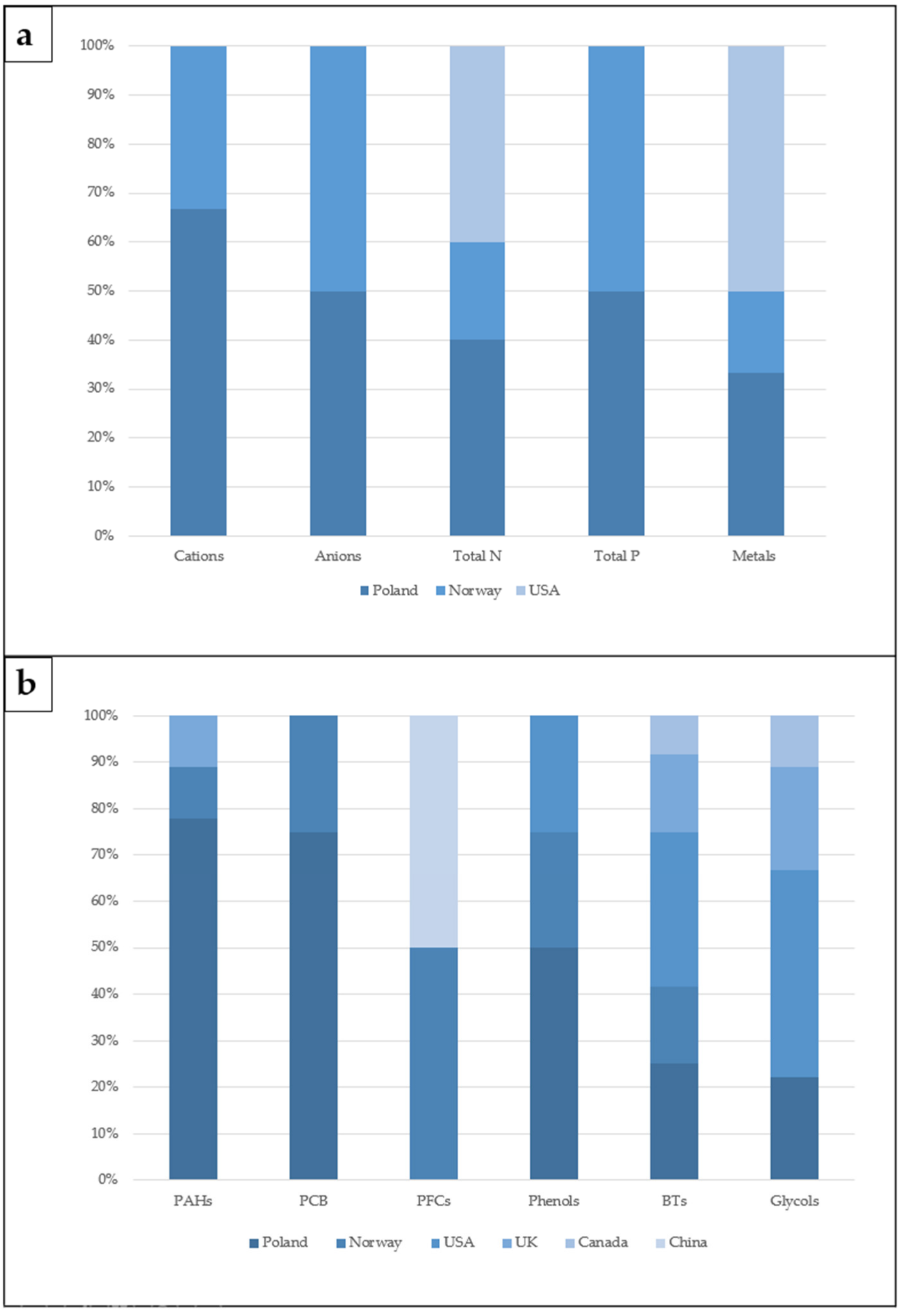

Figure 2. Percentage distribution of the most commonly analyzed inorganic (**a**) and organic (**b**) analytes in runoff water samples from airports across various countries.

The percentage distribution of toxicity tests conducted on airport runoff water samples across various countries is presented in Figure 3. In summary, based on the available literature, the Microtox® test and the Thamnotoxkit F™ are the most commonly used methods for assessing the toxicity of airport runoff water. The most extensive research on the toxicity of these water samples has been conducted in the USA and Poland.

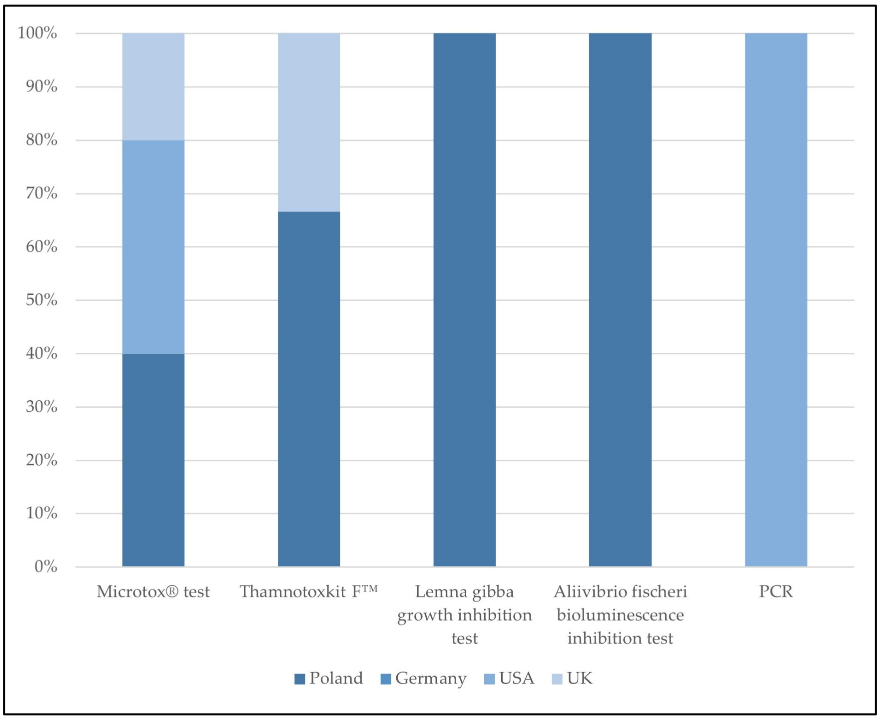

Figure 3. Percentage distribution of the conducted toxicity tests on airport runoff water samples in various countries.

National and international focus have intensified on the impact of de-icing/anti-icing activities on runoff quality [27,67,68]. De-icing/anti-icing of aircraft and airport platforms are fundamental operations to ensure safety at airports and during flights [69]. De-icing/anti-icing agents are routinely applied year-round at airports, across a wide range of temperatures [70]. Aircraft de-icing/anti-icing processes generally involve spraying the aircraft with de-icing and antifreeze fluids (ADAFs) that contain environmentally harmful and toxic chemical agents [65]. Chemical pollutants from the groups of glycols and benzotriazoles, primarily generated during de-icing/anti-icing operations on airport surfaces and aircraft, pose a significant threat to all elements of the environment due to their estrogenic potential, high toxicity, mutagenicity, and carcinogenicity [36,62,63,66,68,71–80]. Furthermore, recent studies indicate that exposure to benzotriazoles during pregnancy may elevate the risk of developing gestational diabetes mellitus (GDM) [62,81]. Due to their widespread use and poor degradability, these pollutants are commonly found in surface waters and wastewater treatment plant (WWTP) effluents globally.

Another persistent and unresolved issue is the generation of pollution associated with the combustion and spillage of aviation fuel. In this context, a group of compounds that require particular attention are polycyclic aromatic hydrocarbons. Compounds from the PAH group are primarily emitted during the combustion and spillage of aviation fuel, including fuel transport, refueling, and aircraft repairs [82]. Polycyclic aromatic hydrocarbons are recognized for their carcinogenic, teratogenic, and mutagenic properties, contributing to various health issues such as cancer, infertility, oxidative stress, and atherosclerosis [36,63,68,73–77,82]. PAHs present substantial health risks, and their elimination from the environment continues to be a worldwide priority [83].

Table 2. Recent literature data on the analysis of airport runoff water samples.

Sampling Site	Target Analytes/Summary Parameters	Analytical Methodology (Sample Preparation, Determination)/Bioassays	Range of Concentration	Reference
		XENOBIOTICS ANALYSIS		
Luleå Airport, Sweden	cations (Ca, Fe, K, Mg, Na, Al, Cu, As, Cd, Co, Cr, Mn, Ni, Pb, Zn), anions (Cl^-, SO_4^{2-}, NO^{3-}, NO^{2-});	-inductively coupled plasma atomic emission spectroscopy (ICP-AES); -inductively coupled plasma sector field mass spectrometry (ICP-SFMS);	<0.2–61.5 mg/L	[65]
	total phosphorus (total P)	colorimetric method	0.01–0.5 mg/L	
	total nitrogen (total N) NH_4^+-N, NO_3^-N, NO_2^--N	chemiluminescence method, nesslerization method, phenate method, Griess–Ilosvay method,	<MDL [2]–5.8 mg/L	
	benzene, toluene, ethylbenzene, and xylenes(BTEX), methyl tertiary butyl ether (MTBE), polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCB), aliphatics, chlorinated aliphatics, chlorinated pesticides, chlorinated benzenes, chlorophenols;	gas chromatography (GC), gas chromatography-mass spectrometry (GC-MS);	<MDL [2]–48 μg/L	
	perfluorinated compounds (PFCs) -perfluorooctane sulfonate (PFOS), -perfluorooctanoic acid (PFOA);	high-performance liquid chromatography (HPLC);	<0.01–0.23 μg/L	
International airport, Poland (high capacity) [1]	phenols; formaldehyde;	spectrophotometric method	0.052–163 mg/L	[17,52,84,85]
	PCBs	solid phase extraction (SPE) coupled with gas chromatography-mass spectrometry (GC-MS);	0.350–116 μg/L	
	16 PAHs [naphthalene (Naph), acenaphthylene (Acy), acenaphthene (Ace), fluorene (Flu), phenanthrene (Ph), anthracene (An), fluoranthene (Flt), pyrene (Py), chrysene (Chry), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), benzo(a)pyrene (BaP), benzo(a)anthracene (BaA), indeno(1,2,3-cd)pyrene (InPy), dibenz(a,h)anthracene (DBahA), benzo(g,h,i)perylene (BghiP)];	-SPE-GC-MS; -headspace solid-phase microextraction (HS-SPME) coupled with comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry (GC × GC-TOF-MS);	2.25–187 μg/L	[52,86]
	benzotriazoles (BTs):1H-benzotriazole (1H-BT) 4-methylbenzotriazole (4-MeBT), 5-methylbenzotriazole (5-MeBT), 5,6-dimethyl-1H-benzotriazole (5,6-diMe-1H-BT),	SPE-GC–MS; HS-SPME-GC × GC-TOF-MS;	0.079–467,000 μg/L	[17,52]
	glycols: ethylene glycol (EG), propylene glycol (PG), diethylene glycol (DEG),	SPE-GC–MS, HS-SPME-GC–MS,	1.84–19,166 mg/L	[52,87]

Table 2. *Cont.*

Sampling Site	Target Analytes/Summary Parameters	Analytical Methodology (Sample Preparation, Determination)/Bioassays	Range of Concentration	Reference
		XENOBIOTICS ANALYSIS		
International airport, Poland (medium capacity) [1]	phenols, formaldehyde,	spectrophotometric method,	0.012–3.98 mg/L	[88]
	PCBs,	SPE-GC-MS,	0.325–1.39 µg/L	
	16 PAHs,	liquid–liquid extraction (LLE-GC–MS),	3.71–141 µg/L	
	EG, PG, DEG,	SPE-GC–MS, HS-SPME-GC–MS,	25.6–1184 mg/L	
	1H-BT, 4-MeBT, 5-MeBT, 5,6-diMe-1H-BT,	SPE-GC–MS, HS-SPME-GC × GC-TOF-MS,	0.402–156 µg/L	
International airport, Poland (low capacity) [1]	phenols, formaldehyde,	spectrophotometric method,	0.021–3.72 mg/L	[17,84]
	PCBs,	SPE-GC-MS,	0.424–1.71 mg/L	
	16 PAHs,	LLE-GC–MS, SPE-GC–MS, HS-SPME-GC × GC-TOF-MS,	2.3–190 µg/L	
	EG, PG, DEG,	SPE-GC–MS, HS-SPME-GC–MS,	1.9–19,166 mg/L	
	1H-BT, 4-MeBT, 5-MeBT, 5,6-diMe-1H-BT,	SPE-GC–MS, HS-SPME-GC × GC-TOF-MS,	0.079–467,000 µg/L	
International airport, United Kingdom (high capacity) [1]	16 PAHs,	SPE-GC–MS, HS-SPME-GC × GC-TOF-MS,	1.9–43 µg/L	[17,52]
	EG, PG, DEG,	SPE-GC–MS, HS-SPME-GC–MS,	3.97–270 mg/L	
	1H-BT, 4-MeBT, 5-MeBT, 5,6-diMe-1H-BT,	SPE-GC–MS, HS-SPME-GC × GC-TOF-MS,	0.083–7.67 µg/L	
Stuttgart airport, Germany	TOC	coulometric method,	300–1500 mg/L	[31]
Pearson Airport, Buttonville Airport, Canada	BTs: 1H-BT and its derivatives, UV stabilizers (BZT-UVs),	Solid phase extraction (SPE)-liquid chromatography-electrospray ionization-tandem mass spectrometry (HPLC-MS/MS)	8–3800 ng/L	[89]
Snohomish County Airport, Washington, USA	Zn (zinc),	-Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), -Scanning Electron Microscopy with an Energy Dispersive X-Ray (SEM & EDX)	1.25–25.0 µg/L	[90]
Białystok Airport, Poland	4-MeBT, 5-MeBT, 2-(3-tert-butyl-2-hydroxy-5-methylphenyl)−5-chloro-2H-benzotriazole (UV-326), 2-(2HBenzotriazol-2-yl)-4-(1,1,3,3-tetramethylbutyl)phenol (UV-329),	microextraction by ultrasound-assisted emulsification (USAEME)-GC–MS,	<MDL [2]–5.31 µg/L	[75]

Table 2. *Cont.*

Sampling Site	Target Analytes/Summary Parameters	Analytical Methodology (Sample Preparation, Determination)/Bioassays	Range of Concentration	Reference
		XENOBIOTICS ANALYSIS		
Białystok Airport, Poland	heavy metals (HMs): Cd, Pb, Ni, Cr, Cu, Zn,	filtration and mineralization, flame atomic absorption spectrometry (FAAS),	<1.00–213.6 μg/L	[91]
Beijing Capital International Airport (BC), Shanghai Pudong International Airport (SP) and Guangzhou Baiyun International Airport (GB), China	perfluoroalkyl and polyfluoroalkyl substances (PFAS),	SPE and ultra-high performance liquid chromatography coupled with triple quadrupole tandem mass spectrometry,	19.0–342 ng/L	[92]
General Mitchell International Airport, USA	1H-BT, 4-MeBT, 5-MeBT,	-SPE-GC-FID (before year 2007), -filtration (hydrophilic polytetrafluoroethylene (PTFE) syringe filters and HPLC-MS/MS (2007 and later),	<0.25–6600 μg/L	[68]
		TOXICOLOGICAL ANALYSIS		
International airport, Poland (high capacity) [1]	Microtox® test, Thamnotoxkit F™,		36.4% [3] 93.9% [4]	[93]
International airport, Poland (medium capacity) [1]	Microtox® test, Thamnotoxkit F™,		9.6% 79%	
International airport, Poland (low capacity) [1]	Microtox® test, Thamnotoxkit F™,		11.8% 97%	
International airport, United Kingdom(high capacity) [1]	Microtox® test, Thamnotoxkit F™,		NT [5] 20%	
Stuttgart airport, Germany	Lemna gibba growth inhibition test, Aliivibrio fischeri bioluminescence inhibition test,		31% 29%	[31]
Milwaukee Mitchell International Airport in Milwaukee, USA	Polymerase Chain Reaction (PCR): characterize relative *Sphaerotilus* abundance, determination of *sthA* sequence,		-	[94]

[1] Generic airport names are derived from cooperation agreements; [2] MDL—method detection limit; [3] The number of samples identified as toxic (relative to the total number of samples analyzed within the airport) using the Microtox® test; [4] The number of samples identified as toxic (relative to the total number of samples analyzed within the airport) using the Thamnotoxkit F™ test; [5] NT—non-toxic.

Runoff originating from airport surfaces can adversely affect the quality of soil and downstream water bodies, thereby disrupting the ecological integrity of aquatic, benthic, and terrestrial ecosystems [45,95]. A wide range of pollutants can accumulate in different components of the abiotic environment. Subsequently, a broad spectrum of pollutants can enter plants and, through the food chain, make their way into animal organisms and ultimately into human organisms. Chemicals emitted into the environment as a result of airport operations can cause numerous adverse effects immediately after exposure and later on, leading to delayed toxic response, mutagenic effects, and carcinogenic effects. The most effective way to reduce the environmental impact of pollutants emitted from airport operations is to prevent their generation [96]. For this reason, one of the primary tasks in airport infrastructure management is to continuously monitor and control the levels of pollutants emitted into the environment, along with measuring their toxicity [16,31,59,97–99].

4. Challenges in Studying Runoff Water from Airport Zones

In the field of pollutant analysis related to airport operations, new challenges continually arise. These challenges primarily involve the need to detect a wide range of analytes in samples with very complex and often variable matrix compositions. Special attention must be given to compounds from the groups of glycols, benzotriazoles, and PAHs, which pose a particular threat to all elements of the environment due to their toxicity and carcinogenicity.

Regardless of the location and scope of runoff water sample studies, conducting these analyses presents a substantial analytical challenge. One of the main challenges to tackle is the very low concentration levels of many contaminants in runoff water samples. Additionally, there is high variability in the levels of specific contaminants across different airports and at various times of the year. Furthermore, there is the possibility that the tested samples contain components with very similar physicochemical properties but significantly different toxicity towards the abiotic parts of the environment and the biota. Besides, the lack of standard techniques and equipment for sampling runoff water can significantly impact the reliability of measurement data. Another challenge is the difficulty in standardizing the measured results due to the geographical location of airports, varying intensity of air traffic, and changing meteorological conditions. There is also a lack of, or very limited access to, appropriate standard solutions. An important limitation is the shortage of reference materials with various metrological characteristics necessary for the calibration of control and measurement instruments, as well as the validation of analytical methods.

As previously mentioned, the literature indicates a relatively narrow scope of studies on airport stormwater samples [31–33]. A visualization of the number of research studies conducted on the determination of xenobiotics in airport stormwater around the world to date is shown in Figure 4. Although the first reports on the results of airport runoff water sample analyses, including our research, have appeared in the literature, this issue is still far from being fully understood and recognized [31,68]. However, it can be stated with full confidence that such material objects are gaining increasing interest as a source of information about the potential negative impact of airport activities on environmental conditions [14,17,68,100].

The literature review (Table 2) highlights the need for developing methodologies to detect a wide range of contaminants in airport stormwater and assess their toxicity, driven by ecotoxicological concerns and the goal of improving environmental assessments [30]. These methodologies must have such metrological parameters that enable the detection, identification, and quantification of a wide range of xenobiotics present in the samples at trace and even ultra-trace levels. This approach not only involves typical chemical methods and speciation analysis but also focuses on determining the toxic, mutagenic, and carcinogenic properties of collected samples. Such an integrated chemical-toxicological approach to assessing environmental pollution in airport areas allows for a comprehensive understanding of environmental quality [93,101–103]. In the context of the sustainable development agenda, it is crucial to have a comprehensive knowledge base and the necessary tools to effectively address a range of environmental and social issues.

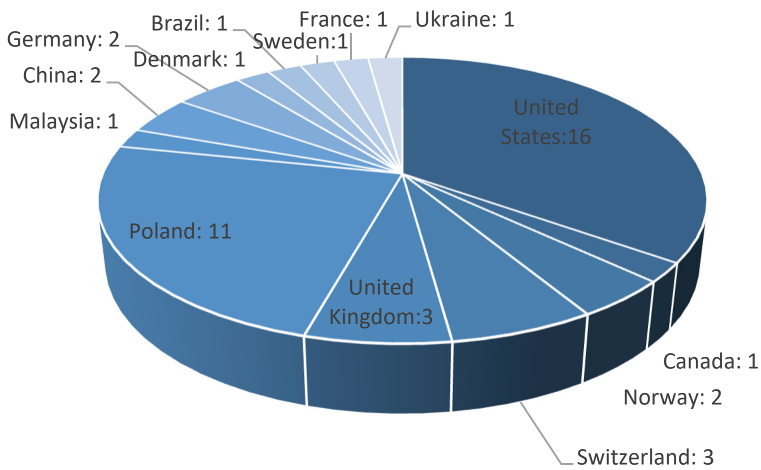

Figure 4. Pie chart of scientific publications on xenobiotic determination in airport runoff water samples, categorized by country and number of publications.

5. Integrated Chemical and Ecotoxicological Approach to Assessing Environmental Pollution in Airport Areas

The increase in the quantity and diversity of pollutants generated during daily airport infrastructure maintenance operations contributes to a broad spectrum of contaminants entering soil and surface waters through runoff. A significant developmental challenge is to ensure that airport infrastructure meets high-quality standards. In this regard, it is essential to have appropriate tools for monitoring and controlling the quantity and quality of water generated within airports and surrounding coastal areas. To determine the extent of environmental contamination resulting from airport operations, identify the emitted pollutants, and assess their toxicity levels, an integrated approach to the analysis of runoff water samples is necessary. The integrated (chemical and ecotoxicological) approach to assessing environmental pollution in airport areas will provide a detailed understanding of environmental quality. This will improve the management of environmental factors and mitigate the impact of various pollutants on the environment.

5.1. New Determination Methodologies for Monitoring the Airport Runoff Waters

A comprehensive analysis must be considered to obtain detailed qualitative and quantitative information about the pollutants in airport stormwater samples. Additionally, it is crucial to track the environmental fate of these pollutants. This includes monitoring the processes of transport, and the chemical, photochemical, and biological transformations of various compound groups that enter runoff waters due to specific activities and operations associated with airport functioning. Considering the available literature, the problems, and challenges associated with runoff water analysis indicate that, so far, there are a limited number of procedures for monitoring and controlling the quality of this new type of environmental sample. Additionally, these procedures typically have limited applications and are often time- and labor-intensive.

To obtain reliable information about the analyte content in airport stormwater samples with a complex matrix composition, high toxicity to living organisms, and many interfering compounds, it is essential to develop appropriate isolation and enrichment techniques. Additionally, the choice of the proper determination method is also crucial, with chromatography techniques playing an increasingly important role in this field. The use of different extraction and determination techniques for detecting xenobiotics in airport runoff water can lead to significantly different outcomes. A comparative analysis of the efficiency of various analytical protocols can be conducted in studies of these material objects. An additional significant aspect is that, optimizing the extraction and determination process conditions. This helps to effectively remove interfering components, enhance detectability, facilitate the separation of analytes during chromatographic analysis, and reduce the operational time of control and measurement equipment during the sample extract testing phase [104].

Based on a review of the available literature, it can be concluded that procedures primarily based on liquid-liquid extraction (LLE) and solid-phase extraction (SPE) have been successfully applied to determine xenobiotics in airport water. Standard analytical techniques used to detect and quantify xenobiotics in airport runoff water samples include gas chromatography-mass spectrometry (GC-MS), gas chromatography-flame ionization detection (GC-FID), and high-performance liquid chromatography (HPLC). These techniques, often employed after isolation or derivatization steps, also encompass high-performance liquid chromatography-mass spectrometry (HPLC-MS), high-performance liquid chromatography with ultraviolet detection (HPLC-UV), and high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS). Additionally, other methods, such as gel permeation chromatography (GPC), thin-layer chromatography (TLC), atomic absorption spectroscopy (AAS), and inductively coupled plasma mass spectrometry (ICP-MS), are also employed [24,25].

The growing interest of researchers in developing and optimizing modern, reliable, green, and powerful analytical procedures for the determination of xenobiotics in airport runoff water led to intensive research in this field (Table 2). This manuscript provides an update on green sample treatment methodologies applied recently for the extraction of xenobiotics from airport runoff water samples. Solid-phase microextraction (SPME) is a modern alternative to traditional extraction methods that have been used for isolating analytes from runoff water samples. SPME is a simple, convenient, and solvent-free extraction technique that combines extraction, concentration, and sample introduction into a single step. The experimental data demonstrate that the HS-SPME technique is an effective method for extracting de-icing/anti-icing compounds (glycols) from airport stormwater samples without the need for analyte derivatization. The newly developed methodology, based on SPME and GC–MS, described in this study facilitated the sensitive, accurate, precise, relatively rapid, and cost-effective identification and quantification of propylene glycol, ethylene glycol, and diethylene glycol in airport stormwater samples [87]. Another example is the development of a reliable and accurate analytical procedure based on HS-SPME coupled with comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry (GC $\times$ GC-TOF-MS) for the simultaneous determination of polycyclic aromatic hydrocarbons in airport stormwater samples. In this case, it is particularly important to highlight the usefulness of the GC $\times$ GC-TOF-MS technique for determining analytes in the extracts. Gas chromatography is a commonly used technique for separating and identifying organic compounds. Despite the high resolution offered by capillary columns, GC is often inadequate for separating the wide spectrum of interfering substances commonly found in environmental samples. The peak capacity of GC $\times$ GC is significantly higher compared to one-dimensional GC [105,106]. The use of comprehensive two-dimensional gas chromatography greatly enhances analyte separation. Furthermore, it is feasible to separate analytes from interfering components in stormwater, including, for example, petroleum-derived substances, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls. Another example of a newly developed modern analytical procedure for determining analytes in stormwater runoff is the HS-SPME-GC $\times$ GC-TOF-MS-based method for identifying anti-corrosive compounds, including 1H-BT, 4-MeBT, 5-MeBT, and 5,6-diMe-1H-BT, in airport stormwater from various European airports [17]. Yet another innovation in the effective determination of analytes in airport runoff water samples is the use of a microextraction by ultrasound-assisted emulsification, combined with gas chromatography–mass spectrometry. This is used for the determination of low-molecule benzotriazoles such as 1H-BT, 4Me-BT, 5Me-BT, 5Cl-BT, and benzotriazole UV stabilizers (UV-326, UV-329) [78].

Despite some progress in green analytical methods for detecting xenobiotics in airport stormwater, the issue remains insufficiently recognized, necessitating ongoing development and enhancement of existing procedures. It is essential to conduct extensive, continuous monitoring and systematic control of the impact of runoff water on various environmental components, and indirectly on living organisms. Airports urgently require robust and economical solutions to tackle the challenges posed by the pollution of stormwater [26].

5.2. Assessment of the Toxic Potential of Airport Runoff Water

Biomonitoring of runoff water samples from airports must also be considered, as it allows for the analysis of the impact of pollutants on metabolic and physiological processes, mortality and survival rates, development, reproduction, and bioaccumulation capacity (resulting from bioconcentration and biomagnification) in living organisms. Additionally, it facilitates the observation of changes in flora and fauna in the monitored airport areas. Biomonitoring of runoff water samples from airports can be performed using various biotests, including toxicity tests (e.g., *Pseudokirchneriella subcapitata*, *Daphnia magna*), embryotoxicity tests (e.g., *Danio rerio*), enzymatic tests (e.g., EROD, *Vibrio fischeri*), the comet assay for cytogenetic analysis, carcinogenicity tests (e.g., SOS chromotest), and mutagenicity tests (e.g., Salmonella/Ames test).

Based on the analysis of available literature, it can be concluded that there are significant gaps in the research devoted to estimating the overall environmental impact of airport runoff water. Most studies report on the potential toxicological effects of aircraft de-icing/anti-icing solutions on various aquatic organisms, including *Pimephales promelas*, *Daphnia magna, Daphnia pulex*, *Ceriodaphnia dubia*, *Photobacterium phosphoreum*, *Lemna gibba*, and *Aliivibrio fischeri*. The results of the conducted research are mostly limited to the analysis of a single airport, where sample collection campaigns were not systematically organized. Globally, only a limited number of studies have been conducted to estimate the toxicity of airport runoff water (Table 2). To summarize, studies conducted to estimate the overall environmental impact of runoff water around airports involved assessing the toxic potential of runoff waters from five European international airports with varying capacities. Procedures based on the use of *Aliivibrio fischeri*, *Lemna gibba*, *Vibrio fischeri*, and *Thamnocephalus platyurus* bioassays were employed as tools for monitoring and controlling the quality of airport runoff water [31,84,93]. The results of the conducted studies indicate that runoff water samples from the monitored airports were often characterized by high or very high toxicity, according to the toxicity classification by G. Persoone et al. [107]. Recommended management actions were presented for all monitored locations at the airports. Based on the data obtained, it was determined that immediate corrective actions are necessary to improve the effectiveness and efficiency of environmental management systems, particularly in aircraft de-icing zones, airport aprons, runways, passenger terminal areas, and parking zones [93].

Furthermore, adopting an additional method to evaluate the environmental risk of xenobiotics in airport stormwater samples can help identify and understand the sources, pathways, and impacts of these environmental stressors. Accordingly, results from lab-scale toxicological studies are incorporated into this process [9,78]. However, there is a lack of comprehensive knowledge regarding the toxicological data of various xenobiotics. Based on the available literature, it can be concluded that there is a very limited scope of research focused on estimating the environmental risk associated with airport stormwater runoff. Attempts were made to estimate the environmental risk of low molecular weight benzotriazoles and benzotriazole UV stabilizers exclusively [17,78]. This approach can contribute to the development of effective strategies to prevent or mitigate the impacts of pollutants on soil erosion and degradation, as well as on surface water and groundwater resources.

Determining the toxicity levels of airport runoff waters and estimating the environmental risk of different pollutants generated within airports' activities is crucial for effective management. However, the available literature does not provide the data required for a comparative analysis of the toxicity of runoff water generated at airports of different sizes in different geographical regions and with varying levels of throughput. This area of research is not yet well understood and requires further analysis and numerous research tasks to be conducted [31,93].

6. Sustainable Stormwater Management at Airports

Numerous stakeholders have expressed their commitment to mitigate the risks that the airport's stormwater contamination may pose to the environment with potential economic, social, health, and public safety consequences [69,99]. Considering the increasing pressure to mitigate adverse effects and conserve soil and water resources, airports must manage their activities and operations to reduce water consumption and limit pollutants emitted in runoff during routine maintenance activities. Airports are responsible for safeguarding soil, surface water, and groundwater resources [108]. In light of reports presented by the U.S. Federal Aviation Administration (FAA), the International Civil Aviation Organization (ICAO), and the European Union Aviation Safety Agency (EASA), managing the quantity and quality of runoff water poses a particularly challenging task for airports [96,109,110]. It is important that effectively manage stormwater in a manner that does not compromise aircraft safety while simultaneously adhering to a multitude of federal, state, and local regulations aimed at safeguarding soil and water resources [111].

Stormwater Best Management Practices are measures, techniques, or structural controls designed to manage the quantity and improve the quality of stormwater in a cost-effective manner. To ensure compliance with relevant water management regulations, BMPs at or near airports must be carefully designed, considering site-specific physical conditions, watershed dimensions, runoff dynamics, peak flow rates, and targeted water quality objectives [112–114]. A key aspect in designing BMPs is the consideration of the characteristics of the underlying surface composition across the airport's various functional areas. Figure 5 presents a hypothetical airport layout with the main operational areas of airport infrastructure highlighted, as numbered in Table 1, which are typically found at airports. Considering the characteristics of the underlying surface composition across the airport's various functional areas in BMP planning can significantly contribute to preventing, reducing, and controlling erosion, sediment, and pollutant runoff from different operational zones of the airport.

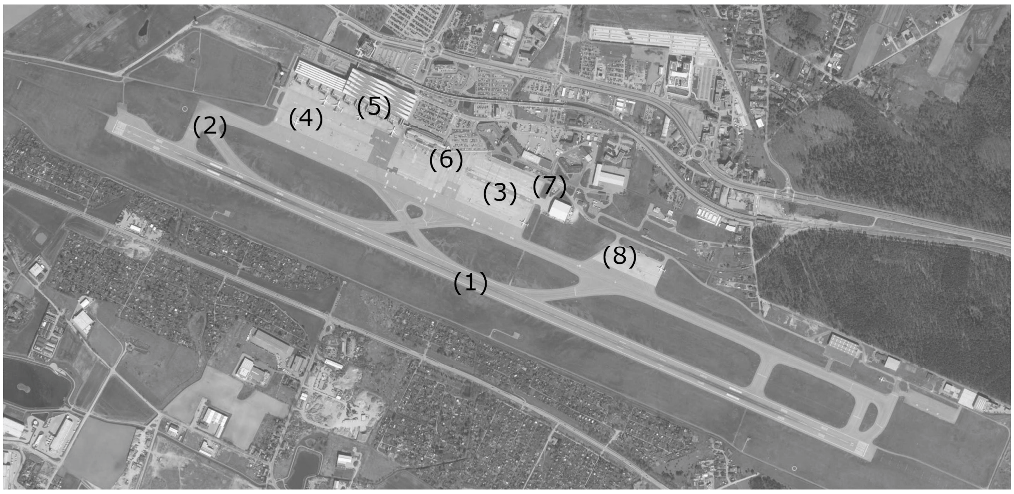

Figure 5. Hypothetical airport layout illustrating the main operational areas of airport infrastructure, numbered (1)–(8) according to the descriptions in Table 1.

Developed progressively since the late 1990s, the concept of Low-Impact Development focuses on managing stormwater and pollution through decentralized, small-scale source control measures (evapotranspiration, detention, retention, infiltration, drainage, and exfiltration of runoff water) [115]. The goal is to mimic the natural hydrological cycle as closely as possible within the development area [10]. LID can manage runoff, control soil erosion, and improve water quality. Selecting appropriate LIDs and evaluating their potential environmental impacts before implementation is critically important. Hydrology and soil erosion models have been extensively used to predict how hydrology and water quality respond to BMPs, including LIDs, in urban systems [115]. The traditional approach to airport rainwater management focused on rapid discharge through pipelines, canals, and pumps. Nowadays, airports are adopting strategies such as expanding green spaces, constructing large-capacity water storage facilities, installing green roofs, and prioritizing the treatment and reuse of rainwater resources [10,116,117]. Table 3 summarizes recent studies on technological solutions for treating and recycling airport runoff waters, as well as innovative approaches to ensure the environmental sustainability of airport development. Our previous literature review on remediation technologies, including forced hot air de-icing, the appropriate use of less glycol, recycling, and infrared de-icing, covered studies up to the year 2010 [24]. This literature review proposes an update that includes the latest data and newly developed solutions for managing airport runoff.

There are numerous techniques available for removing contaminants from stormwater, which can be categorized as gravity or coalescence separators, electrical separators, mechanical separators, and chemical separators [118,119]. Membranes have been considered a technology that can address this issue and mitigate global water shortages [117]. Another viable solution is the corrugated plate oil–water separation technology, which integrates gravity and coalescence separation methods. This technology has garnered significant attention from researchers and companies due to its feasibility, low operating costs, and high efficiency. When it comes to oil separators, Corrugated Plate Interceptors (CPI) are the most practical and cost-effective option, given their low initial and operating costs, as well as their ability to perform effectively under a wide range of operating conditions. In contrast, electrical and mechanical separators require additional power and chemical separation techniques demand a subsequent process to remove the chemicals used [119]. Numerous studies indicate that a drainage scheme integrating LID with pumping stations provides the most effective runoff management [115].

Various strategies have been proposed and implemented at the local, regional, and global levels with the aim of mitigating the negative effects of airport stormwater on the environment [109,110]. The summarized technological solutions for treating and recycling airport runoff waters, as well as the proposed innovative approaches, can enhance the environmental safety of airport operations. These proposals form the basis for developing strategies to ensure the environmental sustainability of airport development. However, there is still insufficient regulatory scope regarding the necessity of determining and removing a wide spectrum of toxic xenobiotics from runoff water generated during airport activities. In some cases, the implementation and enforcement of existing regulations and management actions are lacking. Poor international cooperation and insufficient participation of states in regional initiatives are also contributing factors [96]. The primary concern is the inclusion of compounds from the benzotriazole group, along with various other xenobiotics generated at airports, in the lists of substances particularly hazardous to the aquatic environment. These should be addressed in the regulations of the European Parliament and Council (EC), the Food and Agriculture Organization (FAO), and the International Civil Aviation Organization (ICAO).

A global data repository should be established to document the degree and type of pollution in water runoff from airports. This repository will enable comprehensive digital data analysis and management for existing and planned airports worldwide. Additionally, such a database will support the concept of Low-Impact Development and facilitate improved modeling and management of environmental quality. An exemplary instance of utilizing such a data source is the World Council on City Data (WCCD) database. This database has facilitated the creation of valuable and insightful studies on the quality of life in cities across Europe and globally, based on sustainable development indicators as defined by the ISO 37120 standard [120,121].

Table 3. Techniques and solutions for managing airport runoff.

Remediation/ Pollution Minimization Techniques/Solutions	Operating Principle	Materials/Equipment	Airport	Benefit	References
Vertical flow planted sand beds (VFPB)	organic load removal from glycol contaminated runoff water,	-addition of optimal quantity of nitrogen, phosphorus;	Orly Airport, France;	removal of high suspended matter content, high hydrocarbon loads;	[122]
Polyvinylidene fluoride membranes with tin (IV) dioxide (SnO_2) additives	water filtration using membrane technology with polyvinylidene fluoride (PVDF) polymer mixed with Tin (IV) Dioxide (SnO_2),	-Scanning Electron Microscopy (SEM); -Clean Water Permeability (CWP) tool;	Husein Sastranegara Airport, Indonesia;	increasing concentrations of PVDF and SnO_2;	[117]
Electrochemical treatment	electrolysis (3–4 V);	-Ti/PbO_2 electrode; -Electron microcopy; -XRD analysis;	model runoff water containing ethylene glycol;	electrochemical oxidation of ethylene glycol, reduces COD values;	[123]
Additional treatment (Coalescenting filter –Electrolyser deaerator –Sorption filter)	-coalescence-removes water insoluble pollutants; -cavitation; -electrochemical treatment (electrolyzer-deaerator and electrohydrocyclones); -photocatalytic ozonation; -sorption;	-coalescenting filter; -hypochlorite unit; -cavitation unit; -electrochemical treatment (electrolyzer-deaerator, electrohydrocyclones); -ozonator; -UV unit; -sorption filter;	International Airport Kharkiv, Ukraine;	-reduces: weighted substances, BOD, oil products, COD, phosphorus (total), iron; -nitrogen (total);	[20]
Corrugated Plate Interceptor (CPI)	-separating the oils from water;	-oil Water Separator; -inlet, outlet pipes; -sludge collectionsumps;	Malaysian airport;	the system separates and safely retains oils from water until removal;	[119,124]
A wastewater recycling centre	water recycling with a regular monitoring program for quality at the airport;		Osaka's Kansai International Airport, Japan;	increases the annual recycled water ratio (66.1%); -monitoring of COD, total nitrogen, total phosphates.	[108]

7. Conclusions and Future Trends

Given the increase in the amount and variety of pollutants produced during routine airport infrastructure maintenance operations, it is crucial to focus on the contaminants entering soil and surface waters through runoff. These pollutants contribute to soil erosion and significant water pollution. A major developmental challenge is ensuring that airport infrastructure complies with high-quality environmental management standards. In this context, it is essential to have suitable tools for monitoring and managing the volume and quality of wastewater produced within airports and adjacent coastal areas. The analysis of pollutants from airport operations presents new challenges, primarily involving the detection of diverse analytes in complex, variable matrices with a high level of accuracy, sensitivity, and selectivity.

An integrated chemical and ecotoxicological approach to assessing environmental pollution in airport areas enables the monitoring and control of airport runoff water quality, as well as the creation and updating of databases for international environmental information systems. This approach allows for rapid ecological risk assessment associated with airport wastewater streams and estimates the long-term effects of organism exposure to toxic substances present in airport runoff waters.

In sustainable stormwater management, various strategies have been implemented to mitigate the negative effects of airport stormwater on the environment. However, the regulatory framework remains insufficient regarding the need to detect or remove a wide spectrum of toxic xenobiotics from runoff water generated by airport activities. It is necessary to establish permissible levels for the presence of the aforementioned chemical compounds in water runoff from airports due to their toxicological impact on living organisms and the environment. The primary concern is the inclusion of compounds from the benzotriazole, glycol, and PAH groups, along with various other toxic xenobiotics generated at airports, in the lists of substances particularly hazardous to soil and aquatic environments. Furthermore, these substances should be subjected to rigorous monitoring and control within the context of operational airports and their surrounding areas. Comprehensive monitoring studies should consider the research schedule in relation to airports in different geographical regions with varying meteorological conditions, intensities of air traffic, and seasons for sampling campaigns and subsequent analysis. The article's content addresses the principles of Low-Impact Development and explores the quality of life paradigm, understood as the comprehensive interaction of environmental, social, and economic factors.

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