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Review

Bibliometric Analysis and Comprehensive Review of Stormwater Treatment Wetlands: Global Research Trends and Existing Knowledge Gaps

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Abstract: Stormwater treatment wetlands are widely recognized as efficient and cost-effective solutions to growing stormwater problems. This study presented a new approach to evaluating the current status and trends in stormwater treatment wetlands research. The annual scientific productivity of different states was identified using a bibliometric analysis approach. The number of publications related to stormwater treatment wetlands has exhibited an increasing trend since the earliest record of publication. USA and China were among the states that had the most number of stormwater treatment wetlands-related publications and international collaborations. In terms of the population-to-publication ratio, Australia, Canada, and South Korea were found to have a higher level of scientific productivity. Analysis of frequently used keywords and terms in scientific publications revealed that the efficiency of stormwater treatment wetlands and the processes involved in the removal of nutrients and trace elements were adequately investigated; however, inquiries on the removal of organic micropollutants and emerging pollutants, such as pharmaceuticals and personal care products, microplastics, and industrial compounds, among others, are still lacking. Through the comprehensive review of related scientific works, the design, components, and primary factors affecting the performance of stormwater treatment wetlands were also identified. Future works that address the aforementioned knowledge gaps are recommended to optimize the benefits of stormwater treatment wetlands.

Keywords: bibliometrics; constructed wetland; nature-based solution; stormwater management

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Citation: Reyes, N.J.D.G.; Geronimo, F.K.F.; Guerra, H.B.; Kim, L.-H. Bibliometric Analysis and Comprehensive Review of Stormwater Treatment Wetlands: Global Research Trends and Existing Knowledge Gaps. *Sustainability* **2023**, *15*, 2332. https://doi.org/10.3390/su15032332

Academic Editors: Panayiotis Dimitrakopoulos, Mario A. Pagnotta, Miklas Scholz and Arshiya Noorani

Received: 6 December 2022
Revised: 20 January 2023
Accepted: 24 January 2023
Published: 27 January 2023

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1. Introduction

Stormwater management is an essential component of land-use planning and development. Over the past decades, stormwater-related disasters have continued to aggravate due to the conversion of natural land cover into impermeable areas and other forms of land-use changes [1]. Flooding is a natural disaster that affects the largest number of people. In the year 2014, it was estimated that approximately 16 billion USD and 1500 casualties were recorded due to flooding incidents [2]. Despite being a natural phenomenon, flood risks may also be influenced by land use and land-use changes. Urban areas experience higher flood risks since urban areas are characterized by a high percentage of impervious land cover or built-up zones that facilitate increased rainfall-to-runoff conversion and greater overland flow. Moreover, deforestation and the loss of vegetative cover stimulate runoff formation in headwater locations [3].

Stormwater is also an imminent threat to the environment and human health. Stormwater runoff contains a complex mixture of pollutants from natural and anthropogenic sources. A number of studies have indicated that stormwater runoff serves as a major source of water pollution and toxicity. Heavy metals are among the most toxic compounds that can be found in stormwater. Ma et al. (2016) developed a hazard index to identify the heavy metal species present in stormwater that can pose the highest risk to human health. The results indicated that chromium (Cr), manganese (Mn), and lead (Pb) were among the most toxic heavy metals that pose adverse effects to human health despite their relatively low concentrations in stormwater [4]. Apart from heavy metals, xenobiotic organic carbons, including pesticides and polycyclic aromatic hydrocarbons (PAHs), may also have detrimental effects on the environment [5]. Pesticides are associated with aquatic toxicity and biodiversity loss, whereas PAHs are known to possess human health and environmental toxicity [6,7].

The characteristics and amounts of pollutants in stormwater greatly depend on the land use and potential sources of pollution within the catchment. In the study conducted by Yang and Toor (2018), non-point phosphorus pollution in urban catchments originated from stormwater runoff [8]. Lee et al. (2020) reported the presence of pathogenic bacteria, protists, and fungi in stormwater that can potentially trigger an increase in water-borne disease outbreaks [9]. In urban areas, high vehicular traffic and anthropogenic activities may increase the pollutant concentrations in stormwater. Variable concentrations of toxic compounds (i.e., heavy metals, PAHs, pesticides, etc.) were observed by Zgheib et al. (2012) in the stormwater samples collected from densely populated urban areas [10]. In a more recent study, Pramanik et al. (2020) identified different emerging pollutants, such as per- and polyfluorinated substances and microplastics, in urban runoff [11]. The stormwater from agricultural areas also contains a considerable amount of pollutants that can potentially degrade the quality of receiving water bodies. Specifically, agrichemicals and organic materials that are incorporated in stormwater can be the primary drivers of water quality degradation. Generally, insufficient or inappropriate stormwater management schemes can lead to severe economic, environmental, and human health consequences.

Constructed wetlands (CWs) are increasingly utilized as efficient and effective stormwater treatment technologies. These engineered systems were designed as nature-based facilities that utilize biological and physico-chemical mechanisms to improve water quality. Additionally, CWs also provide provisioning, cultural, supporting, and other ecosystem services that benefit humans and the environment [12]. The effectiveness of CWs in treating stormwater runoff was widely reported in different scientific publications. Stefanakis (2019) highlighted the importance of CWs in urban stormwater and wastewater management [13]. The performance of CWs as stormwater runoff intervention facilities in the upstream regions of a watershed was investigated by Kabenge et al. (2018). It was found that vegetated microcosm wetlands effectively reduced pollutant concentrations in the stormwater by up to 76% [14]. Alihan et al. (2017) recommended the use of CWs for treating urban stormwater runoff. The CWs, which treat runoff from impervious roads and parking lots, effectively reduced the total runoff volume and pollutant concentrations by up to 37% and 81%, respectively [15]. Studies regarding the applicability of CWs in agricultural runoff treatment were also conducted by several authors. The horizontal subsurface flow CW evaluated by Grinberga and Lagzdins (2017) exhibited a considerably reduced concentration of nutrients in the stormwater runoff from an agricultural farmyard [16]. Apart from nutrients, McMaine et al. (2019) reported that constructed wetlands were capable of reducing the concentration of pesticides in plant nursery runoff by more than 79% [17]. The valuable contribution of constructed wetlands as sediment traps was highlighted in the study conducted by Ockenden et al. (2014). It was estimated that small CWs can intercept up to 70 tons of sediment from agricultural runoff over the period of three years, thus significantly reducing the sediment loads to waterways [18].

Review papers also provided considerable information regarding treatment efficiency, design, and other factors that affect the performance of constructed wetlands in managing stormwater. The removal pathways of heavy metals in constructed wetlands were reviewed by Headley and Tanner (2006), whereas Sharma et al. (2021) summarized the constructed wetland mechanisms involved in the effective removal of heavy metals and nutrients in stormwater [19,20]. Ingrao et al. (2020) compiled different studies related to the environmental and operational issues of constructed wetlands [21]. In the synthesis conducted by Li et al. (2018), several scientific publications regarding the performance of constructed wetlands in treating non-point source (NPS) pollution were highlighted [22]. Despite a large number of studies and review papers, there are currently no bibliometric analyses conducted to determine the current status of publication about the application of constructed wetlands in stormwater management. Therefore, this study was conducted to establish the trends of scientific publications focused on constructed wetlands used for stormwater management through a bibliometric analysis approach. The data from the extensive collection of published research works were used to determine the scientific productivity of various authors, institutions, and states in terms of the number of publications and citations. A comprehensive review was also conducted to create a detailed summary of the facility and catchment area characteristics, pollutant concentrations, the effectiveness of stormwater treatment wetlands in improving water quality, and other pertinent information contained in relevant scientific publications. Ultimately, the major research hotspots, knowledge gaps, and future research directions were also identified in this review.

2. Materials and Methods

2.1. Data Collection and Bibliometric Analysis

The Web of Science (WoS) platform is one of the most reliable and comprehensive scientific databases that is commonly used for bibliometric analysis [23]. A standard document search was conducted in the Science Citation Index Expanded (SCI-Expanded) and Emerging Sources Citation Index (ESCI) collections of the WoS platform. The terms (“constructed wetland*” OR “treatment wetland*” OR “engineered wetland*” OR “artificial wetland*”) AND (“stormwater*” or “storm water*”) were used to retrieve all documents related to the search term. In the analysis field, all documents containing the search terms in the title, abstract, keywords, keywords plus, and publications from the earliest records available in WoS (1 January 1990) up to 31 December 2021 were considered. The bibliographic information exported from the database includes authors, titles, sources, abstracts, author keywords, affiliations, and cited references. Initial query results returned a total of 452 documents. Among the list, 414 documents were classified as articles, 34 were review papers, seven were proceedings papers, and seven documents were classified as editorial materials, corrections, and news items. The list was further downsized to articles written in English, thus resulting in a total of 413 documents used in the analysis. The detailed process of data collection and the processes associated with the bibliometric analysis were illustrated in Figure 1.

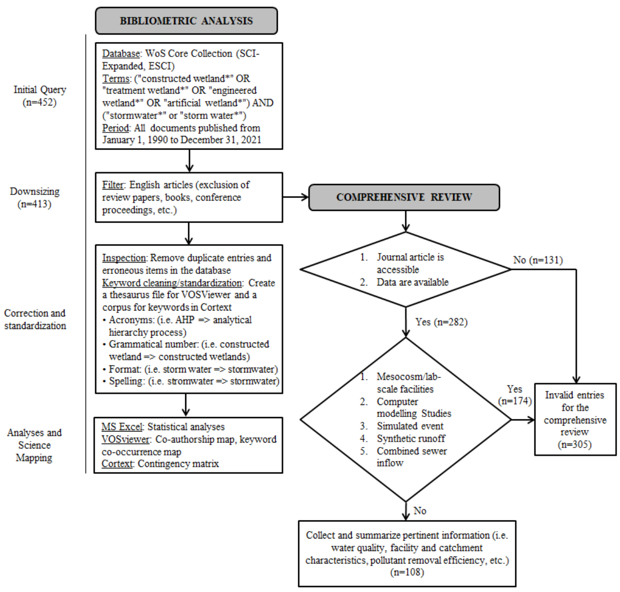


Figure 1. Data collection and analysis flowchart.

2.2. Data Visualization and Science Mapping

Aside from determining the trends and status of research, the bibliometric analysis approach also provides an overview of the interrelationships among the terms, authors, and other pertinent information that can be obtained from large volumes of bibliographic information [24]. Science mapping tools were utilized to generate accurate visualizations of bibliographic information. Co-authorship networks and keyword co-occurrence maps were created using the VOSviewer software, whereas contingency matrices were generated in the Cortext platform (www.cortext.net). VOSviewer is commonly used as a tool for generating maps or networks from an extensive collection of bibliographic information from different scientific databases. This software can be used to create visualizations of co-authorships, keyword co-occurrences, and co-citations, among others, in order to analyze the relationships or interrelationships among different variables. Cortext is an online platform that provides tools for textual analysis, text mining, and science mapping. It can also be used to generate diagrams that effectively show the frequency, correlation, and evolution of terms used in different scientific publications.

Prior to mapping, bibliographic entries were inspected to remove duplicates and erroneous items. Manual inspection and correction were also conducted to standardize the terms used in the analysis. The network map generated through VOSviewer provides information regarding the frequency, relatedness, and co-occurrence of keywords. Larger circles and labels indicate that the terms were used more frequently in different publications. The distance between the terms and the curved lines that connect the keywords indicate their relatedness based on co-occurrences. Terms are also grouped into clusters, as represented by the color groups, to signify a relatively higher degree of relations. The Cortext platform enables users to generate contingency matrices that show interrelationships among the different variables contained in a bibliographic dataset. A contingency matrix expresses the degree of correlations and anti-correlations between two selected parameters. Cells that are highlighted in red describe a positive relationship or a high degree of co-occurrence between the two parameters. On the other hand, blue-colored cells indicate anti-correlations or lower co-occurrences as compared to the expected number of co-occurrences. The white cells represent items that do not show any correlation. The Chi^2 score expresses the ratio between the square of the difference between the number of co-occurrences between A(i) and B(j) and its expected number of observations and the expected number of observations [25,26]. The data inputs and methods of analysis employed in the science mapping software were summarized in Table 1.

Table 1. Data inputs and methods of analyses used in VOSviewer and Cortext.

Software	Parameter	Inputs/Method of Analysis
VOSviewer (Network map)	Bibliographic database file	WoS plaintext file
	Type of analysis	Co-occurrence
	Unit of analysis	Author keywords
	Counting method	Full counting (terms have the same weight)
	Minimum number of co-occurrences	5
Cortext (Contingency matrix)	Bibliographic database file	WOS plaintext file
	Field values	Author keywords—Country/State Author keywords—Year of publication
	Contingency analysis measure	Chi^2 score
	Number of nodes	10 (Default software value)

2.3. Comprehensive Review

A comprehensive review was performed to summarize important information provided in relevant scientific publications. From the downsized list of 413 research articles, only 282 documents were accessible or contained pertinent data. In order to limit the review to real-world application scenarios, studies that utilize computer models or simulate runoff events were excluded from the review. Inquiries that investigated combined sewer inflows or utilized mesocosms, lab-scale facilities, or synthetic stormwater runoff were also excluded to reflect the actual performance of stormwater treatment wetlands in reducing runoff pollutant concentrations. A total of 108 scientific publications were considered for the comprehensive review. Essential information, such as the size and characteristics of study areas, the types and components (i.e., filter media and plants) of stormwater treatment wetlands, and the investigated water quality parameters, were compiled from each of the valid documents.

3. Results and Discussion

3.1. Bibliometric Analysis and Science Mapping

3.1.1. Trend of Scientific Productivity and Characteristics of Published Literature

The annual scientific productivity or number of published documents related to stormwater treatment wetlands was exhibited in Figure 2. Based on the records of the WoS database, papers that focused on constructed wetlands used for stormwater management were first published in the year 2012. The annual scientific productivity exhibited an increasing trend until the year 2017, when the maximum number of articles was reached (57 articles). Despite the relatively lower number of publications from the year 2018 to 2021, the number of documents published within this period was 10% to 55% higher than the number of publications in the year 2012. In terms of the number of citations, a continuously increasing trend was observed from 2012 to 2021. The initial number of citations in the year 2012 only amounted to 11, whereas the maximum number of citations, amounting to 1268, was observed in 2021. The number of citations proportionally increased alongside the surge in the number of publications since the network of researchers specializing in constructed wetlands and stormwater management also expanded over the years. Generally, the observed growth in the number of scientific publications and citations indicated that constructed wetlands have become an important component of stormwater management strategies.

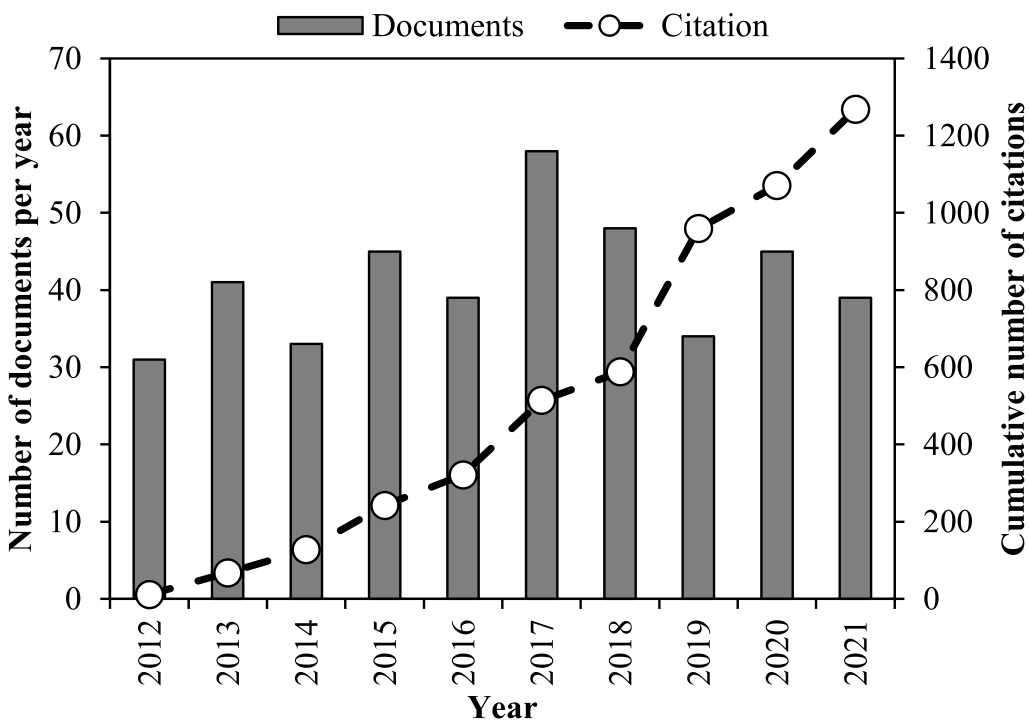
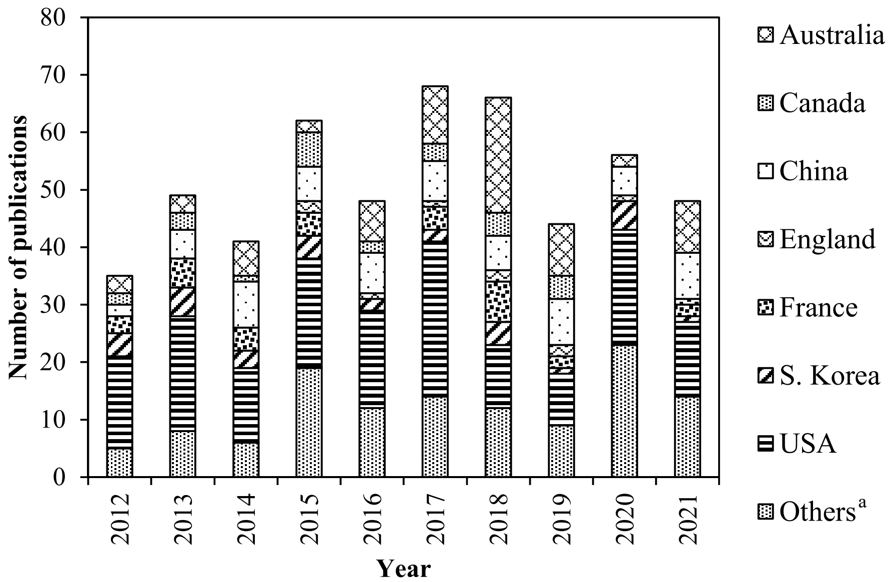


Figure 2. Annual number of published documents and cumulative number of citations.

The contribution of various states to the total number of publications was illustrated in Figure 3. Researchers from 51 different states contributed to the total number of indexed publications. Authors from the USA had the largest contribution to scientific publication with a total of 165 articles and an average annual scientific productivity of 17 articles. The second-most productive state in terms of the number of publications was Australia, with a total of 71 documents. China (62 articles) and South Korea (31 articles) were the leading Asian states in stormwater treatment wetlands research, whereas France was found to be the most active European state in terms of the number of published papers in this particular field of research (31 articles) in this area of study. The scientific productivity of different states was also evaluated in terms of the population-to-publication ratio. This ratio is indicative of the state's contribution to a specific research field in relation to its total population. Australia, Canada, and South Korea were found to have the highest level of scientific productivity, with corresponding population-to-publication ratios of 36,000:1, 1,530,000:1, and 1,669,000:1. Despite having the largest number of scientific publications in the Asian Region, China had the lowest population-to-publication ratio, with approximately 23,000,000 people per article in the WoS database.



[a] States with less than ten publications

Figure 3. Annual scientific productivity of different states.

3.1.2. Journal Publications and Related Subject Areas

The research on constructed wetlands used for stormwater management covers a wide range of subject areas and specializations. The major subject areas related to stormwater treatment wetlands research was listed in Table 2. A total of 32 subject areas were identified among the list of publications. This indicated that studies on constructed wetlands and stormwater management are multi-faceted and established through complex collaborations among professionals and researchers from various fields of expertise. Among the 32 subject areas identified, approximately 81% of the published literature was directly relevant to "Environmental Sciences Ecology." Constructed wetlands are widely-used technologies for environmental preservation and restoration, and thus, most of the analyzed published literature is related to "Environmental Sciences Ecology." Publications that fall under "Engineering" (49%) and "Water Resources" (35%) were also found to be abundant. Despite being considered nature-based facilities, constructed wetlands are built systems that integrate advanced engineering techniques and natural processes to achieve water quality goals, mitigate flooding conditions, and support water resource conservation efforts.

Generally, it was observed that individual documents can be classified into multiple subject areas, implying that most scientific publications are multi-disciplinary in nature.

Table 2. Major subject areas relevant to constructed wetlands and stormwater management research.

Subject Area	Number of Documents	% of Total
Environmental Sciences Ecology	334	81%
Engineering	204	49%
Water Resources	146	35%
Geology	19	5%
Marine Freshwater Biology	19	5%
Science Technology Other Topics	16	4%
Meteorology Atmospheric Sciences	11	3%
Others [a]	68	16%

[a] Subject areas with less than 10 documents.

The journals having the most publications related to stormwater treatment wetlands were summarized in Table 3. The 413 articles retrieved in the query were published in 116 journals. The Ecological Engineering journal contains the largest number of publications, amounting to 83, followed by Science of the Total Environment with 26 and Water with 22 articles. Journal impact factors are commonly used to evaluate the quality of journals or the research articles published in a specific journal. Despite the opposition from several researchers and institutions, this metric is still widely used for journal rankings due to the lack of alternatives and ease of use [27,28]. Four of the most productive journals in stormwater treatment wetlands research have impact factors greater than three. Moreover, three of the journals on the list belong to Q1 (top 25%) in the ranking of Environmental Engineering journals.

Table 3. List of most productive journals in terms of the number of publications.

Journal	Impact Factor (as of 2020)	Number of Documents	% of Total
Ecological Engineering [a]	4.035	83	20%
Science of the Total Environment [a]	7.963	26	6%
Water	3.103	22	5%
Water Science and Technology	1.915	21	5%
Desalination and Water Treatment	1.254	17	4%
Water Research [a]	11.24	14	3%
Journal of Environmental Engineering	1.746	11	3%
Others [b]	-	219	53%

[a] Q1 journals in the field of Environmental Engineering. [b] Journals with less than 10 publications.

3.1.3. Frequently Cited Research Works on Constructed Wetlands

Four out of the five most-cited articles presented results on the effectiveness of constructed wetlands in treating nutrients and heavy metals in stormwater. As listed in Table 4, the study conducted by Xu et al. (2017) received the highest number of citations. This study explored the mechanisms involved in the removal of nitrogen and phosphorus in stormwater. Specifically, the nutrient uptake capabilities of two wetland macrophytes (i.e., *Iris pseudacorus* and *Thalia dealbata*) were evaluated to determine their contribution to the nutrient removal process. A systematic plant harvesting strategy was also recommended to optimize the performance of the constructed wetland [29]. The second-highest number of citations was noted in the paper by Winston et al. (2013) about the conversion of stormwater ponds into floating treatment wetlands. While there were no significant statistical differences in pollutant removal observed after retrofitting the ponds, results suggested that the addition of plants to the system contributed to beneficial treatment mechanisms [30]. The article published by White and Cousins (2013) received a total of 80 citations within a period of eight years. This inquiry focused on the evaluation of the season-long nutrient removal efficiency of a floating treatment wetland. The nutrient assimilation rates of two macrophytes (i.e., *Canna flaccida* and *Juncus effuses*) and the changes in physico-chemical characteristics of the wetland effluent were also documented in this study [31]. The papers published by Borne et al. (2013) and Payne et al. (2014) were also among the most cited literature related to constructed wetlands and stormwater. Borne et al. (2013) explored the heavy metal treatment performance of floating treatment wetlands, whereas Payne (2014) highlighted the fate and dominant processes involved in the removal of nitrogen from stormwater [32,33].

Table 4. List of highly cited publications.

Title	Author/s	Journal (Year)	Number of Citations
Improving Urban Stormwater Runoff Quality by Nutrient Removal through Floating Treatment Wetlands and Vegetation Harvest [29]	Xu, Bing, Xue Wang, Jia Liu, Jiaqiang Wu, Yongjun Zhao, and Weixing Cao	Scientific Reports (2017)	101
Evaluation of floating treatment wetlands as retrofits to existing stormwater retention ponds [30]	Winston, R. J., Hunt, W. F., Kennedy, S. G., Merriman, L. S., Chandler, J., & Brown, D.	Ecological Engineering (2013)	97
Floating treatment wetland aided remediation of nitrogen and phosphorus from simulated stormwater runoff [31]	White, S. A., & Cousins, M. M.	Ecological Engineering (2013)	80
Floating treatment wetland retrofit to improve stormwater pond performance for suspended solids, copper and zinc [32]	Borne, K. E., Fassman, E. A., & Tanner, C. C.	Ecological Engineering (2013)	77
Temporary Storage or Permanent Removal? The Division of Nitrogen between Biotic Assimilation and Denitrification in Stormwater Biofiltration Systems [33]	Payne, G., Fletcher, T., Russel, D., Grace, M., Cavagnaro, T., Evrard, V., Deletic, A., Hatt, B., & Cook, P.	PloS ONE (2014)	67

3.1.4. Co-Occurrence of Keywords and International Research Collaborations

Keywords are one of the most essential pieces of bibliographic information since they represent the important contents of a scientific publication [34]. Overall, 1120 unique keywords were identified from the 413 articles considered in this study. Keywords that were used at least two times in different documents only amounted to 268. Increasing the minimum number of keyword occurrences to three further limited the list to 127 unique terms. The considerable decrease in the number of unique keywords as the minimum number of occurrences increased implied that most studies were focused on a specific topic. In order to extract the terms most relevant to stormwater treatment wetlands, the minimum number of occurrences of a unique keyword should be increased. The network map shown in Figure 4a represents the most frequently used terms in publications related to stormwater treatment wetlands. The keywords exhibited in the figure were derived by setting the minimum number of occurrences to five. Among the initial 1120 unique keywords, only 67 terms met the threshold.

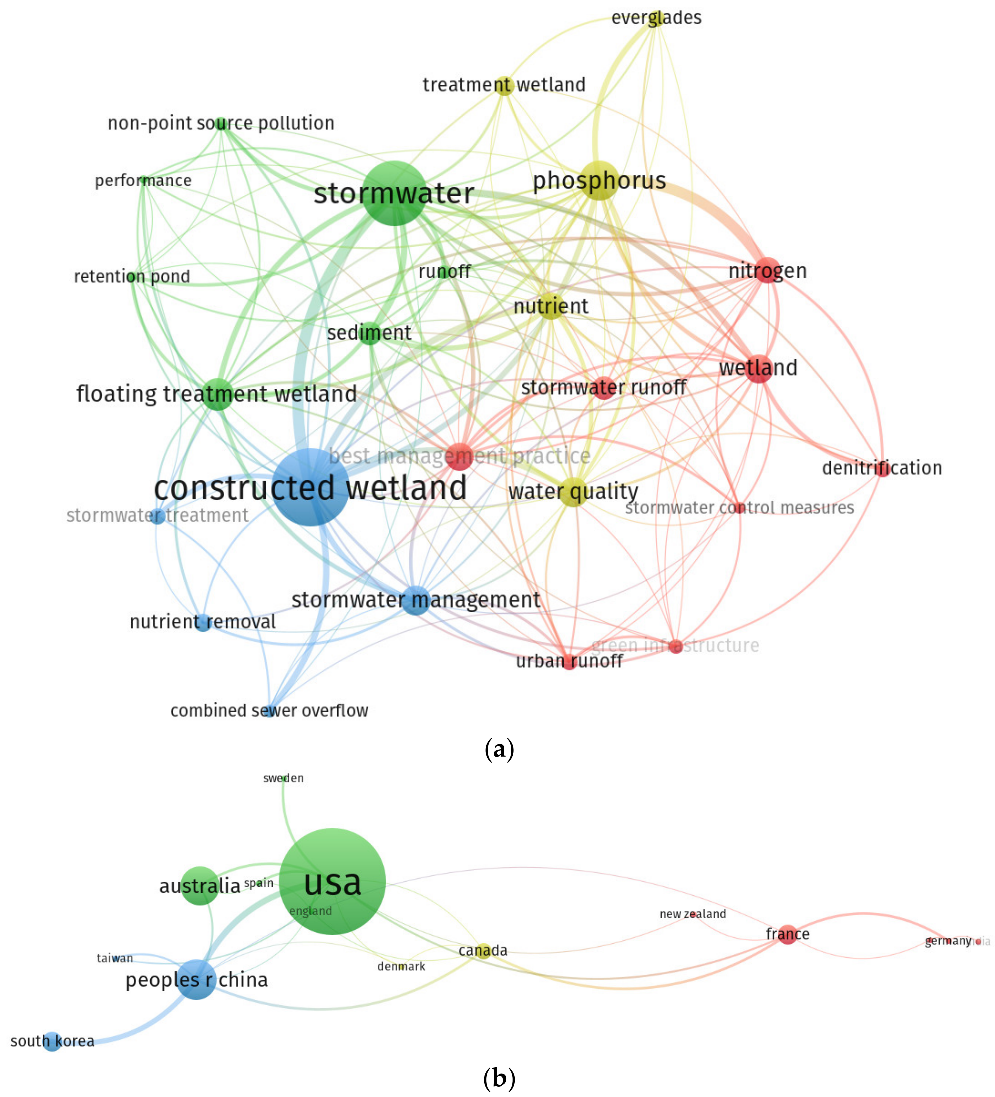


Figure 4. (**a**) Network map of keyword co-occurrence; (**b**) collaboration network among different states.

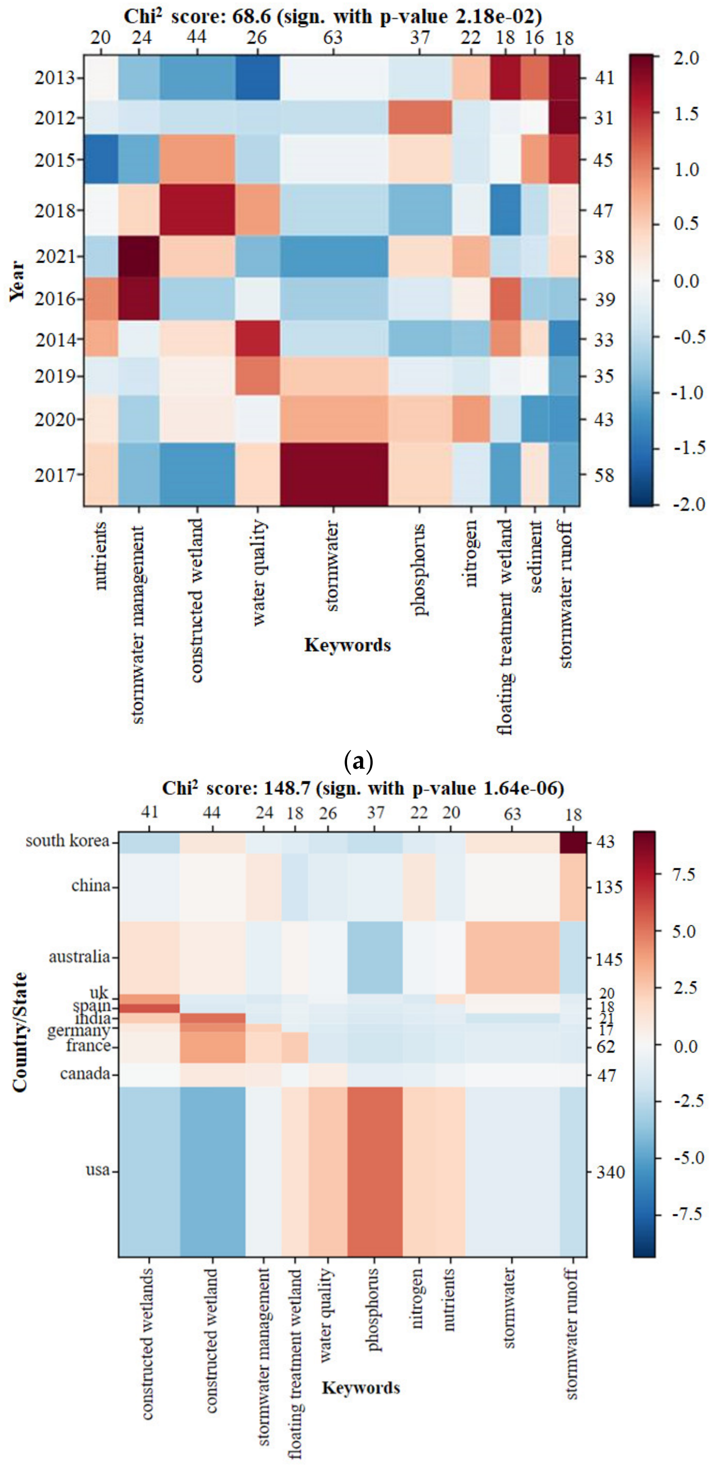
Excluding the terms used in the query, the most frequently used keywords in related documents were phosphorus (n = 37), water quality (n = 26), best management practice (n = 24), nutrient (n = 23), and nitrogen (n = 22). The frequently used keywords reflected the primary role of constructed wetlands in water quality improvement. Specifically, the ability of constructed wetlands to treat nutrients (i.e., nitrogen and phosphorus) incorporated in stormwater runoff was extensively studied. The application of constructed wetlands as a valuable stormwater best management practice can also be deduced from the map. In terms of co-occurrence, constructed wetlands had high relations with best management practices and stormwater management, whereas water quality exhibited considerable relations with stormwater control measures and nutrients. Phosphorus and nitrogen also had strong links, indicating that the two nutrient compounds are commonly studied jointly in scientific publications. There were seven clusters identified based on the relatedness of terms. The clusters represent the main topics associated with the research on stormwater treatment wetlands. Moreover, these groups also suggest topics that have been extensively investigated by past inquiries or publications.

Aside from the co-occurrence of keywords, the status of international collaboration can also be visualized through a network map. As illustrated in Figure 4b, the USA had the highest number of networks or co-authorships with other states. Aside from being the top publishing state, the USA established international collaboration networks that resulted in high scientific productivity. The highest link strength was observed between the USA and China, indicating that the two states had the most co-authored publications. The number of co-authored papers among European states, including France and Germany, was also relatively high; however, the collaboration among European and Asian states was found to be limited.

3.1.5. Shifts in Research Interest and State-Specific Research Trends

Research trends change over time due to the changes in the policy of a specific state, the degree of saturation or number of current studies for a certain topic, and the advancements in analysis procedures that can significantly affect data acquisition, among others. It is also important to note the shifts in research interests to determine the existing knowledge gaps or potential research directions. The contingency matrix exhibited in Figure 5a shows the annual trend of keyword use. In the early year of research on stormwater treatment wetlands (2012), "stormwater runoff" and "phosphorus" were the most dominant keywords used in scientific publications. The terms "stormwater" and "floating treatment wetlands" emerged as the most commonly used keywords in the succeeding years, alongside the growth in the number of publications from different states. "Constructed wetland" and "water quality" became the most relevant terms in the years 2018 and 2019. Except for the year 2016, it was observed that there was a shift from using the term "floating treatment wetland" to a more general term, "constructed wetland." This also highlighted the developments in the design of engineered systems used for stormwater management. Aside from free-water surface wetlands, other variants of engineered wetlands (i.e., subsurface flow constructed wetlands and hybrid constructed wetlands) became available, thereby resulting in changes in the frequency of keywords used in publications. More recent studies published in the years 2020 and 2021 utilized the terms "nitrogen" and "stormwater management" more frequently. Generally, shifts or changes in the pattern of keyword use created a general idea of the current status of research in a particular subject area.

State-specific use of terms also provides significant information that can be useful for the development of policies and environmental management strategies. The contingency matrix of the most relevant keywords used by the researchers from the top publishing states is shown in Figure 5b. The term "phosphorus" had the highest correlation with the USA, implying that stormwater treatment wetlands in the USA were primarily used for treating phosphorus in stormwater. "Stormwater" and "stormwater runoff" were the dominant terms used in the publications from South Korea, China, Spain, and Australia. This suggested that constructed wetlands were extensively used as a tool for stormwater management in the aforementioned states. Publications from Canada and France have increased usage of the term "sediment", whereas Germany and India frequently used the keyword "constructed wetland." The term "nutrient" was highly associated with publications from the United Kingdom (UK), indicating that the function of stormwater treatment wetlands as nutrient sinks was of particular interest in the state.



(**a**)

(**b**)

Figure 5. Contingency matrix of (**a**) keywords and year of publication and (**b**) keywords and state.

3.2. Data Synthesis and Comprehensive Review

3.2.1. Land Use Types and Catchment Area Characteristics

Land use and catchment area characteristics are among the primary factors that affect the quality of stormwater runoff. The extent of anthropogenic activities and the intensity of development may also exhibit direct and indirect relationships with the distribution of pollutants within the catchment area. The list of typical land use types frequently investigated in different studies is summarized in Table 5. Most scientific inquiries focused on the application of stormwater wetlands to treating runoff from urban catchments. Constructed wetlands emerged as cost-effective and socially acceptable stormwater treatment technologies due to their multiple benefits fit for an urban setting [35]. Wetlands designed for agricultural pollution mitigation were also extensively investigated. Treatment wetlands are commonly used as low-energy and low-cost alternatives for abating polluted agricultural runoff. Specific wetland components, such as plants and microorganisms, also contribute to efficient nutrient cycling to prevent the excessive deposition of pollutants in natural waterways [36]. The review of published literature also suggested that wetlands are extensively utilized to treat stormwater runoff from residential areas, parking lots, highways, and mixed land use catchments.

Table 5. Drainage areas (in ha) of dominant land use types in reviewed scientific publications.

Land Use Type	Agricultural	Highway	Mixed	Parking lot	Residential	Urban	Others [a]
Frequency, n	41	10	25	7	12	54	5
Minimum	0.81	0.13	3.60	2.31	2.00	0.04	0.09
Maximum	86000	13.07	3139	2.37	572	2060	2.30
Median	42.70	1.70	320	2.37	5.40	95	0.45
Average	7876.51	3.01	781.30	2.35	76.51	271.86	0.82
Standard Deviation	24704.92	4.14	1059.91	0.03	176.99	465.53	0.90

[a] Land use types with a frequency of less than five (i.e., suburban, grassland, municipal, etc.).

The size of catchment areas investigated in previous studies varied greatly. As exhibited in Table 5, treatment wetlands were applied to site-specific or catchment-scale treatment of stormwater runoff. Parking lots, highways, and residential areas constituted relatively small catchment areas, with mean values ranging from 3.01 ha, 2.35 ha, and 76.61 ha, respectively. One major factor limiting the application of CWs is spatial constraints; however, recent developments have allowed the installation of CWs despite the limited space availability. The concept of "pocket wetlands" can be applied to small drainage basins to provide additional stormwater treatment or achieve water quality goals. The size of pocket wetlands is more restricted as compared to their catchment-scale counterparts, and thus, these systems are often used for stormwater runoff polishing [37,38]. Among the identified land uses where stormwater treatment wetlands were applied, the highest drainage area was recorded in an agricultural catchment (86,000 ha) located in a section of the Everglades agricultural area, South Florida, United States. With an approximate treatment area exceeding 27,000 ha, the Everglades Stormwater Treatment Areas (STAs) are considered the world's largest and most complex constructed wetlands. The construction of STAs was implemented through the Everglades Forever Act, which aims to reduce the TP loads discharged from predominantly agricultural areas upstream of the Everglades Protection Area [39–41].

3.2.2. Types and Sizes of Stormwater Treatment Wetlands

The choice of design and components of stormwater treatment wetlands can be influenced by the climate, availability of materials, influent pollutant concentrations and water quality targets, public perception, and existing environmental regulations, among others [42–45]. Based on the reviewed literature, free water surfaces (FWS) (n = 40) and floating treatment wetlands (FTW) (n = 26) were commonly employed for stormwater treatment. FWS wetlands are commonly used as stormwater management facilities due to their high volume capacities. Apart from the intrinsic capability of FWS wetlands to attenuate flooding, these systems can also provide efficient treatment of stormwater due to the prolonged retention time in the system [46,47]. FTW systems were also extensively studied due to their potential for increasing the ecosystem benefits of existing stormwater infrastructure. Unlike other types of treatment wetlands with considerable space requirements for field-scale applications, FTW systems can be incorporated into existing stormwater ponds to improve their general function. In the study conducted by

Borne et al. (2013), retrofitted stormwater ponds with FTWs showed higher treatment efficiencies as compared to conventional detention ponds [32]. Winston et al. (2013) and Tirpak et al. (2022) also reported improvements in the pollutant removal performance of stormwater ponds retrofitted with FTWs; however, the treatment contributions provided by FTWs were found to be limited or highly influenced by the pond design [30,48]. Studies regarding other wetland designs, including hybrid, horizontal subsurface flow (HSSF), and vertical subsurface flow (VSSF) stormwater treatment wetlands, were relatively scarce, with reporting frequencies of five, four, and seven times, respectively.

The size of stormwater treatment wetlands from the compiled data ranged from 7 m^2 to more than 270 km^2. Small facilities were specifically designed to treat runoff from site-specific sources, whereas treatment wetlands with relatively large surface areas were designated for catchment-scale runoff management. The surface area-to-catchment area (SA/CA) ratios of stormwater treatment wetlands applied in various land use types were illustrated in Figure 6. The typical SA/CA ratios of FWS and hybrid treatment wetlands were approximately 0.5% to 3%, whereas HSSF treatment wetlands exhibited higher SA/CA ratios ranging from 1.65% to 12.78%. It can be noted that FTWs had low SA/CA ratios (0.07% to 0.38%), since these are compact and modular facilities that are used as additional features to a stormwater detention pond. Nature-based facilities, including stormwater treatment wetlands, usually have small surface areas relative to the drainage area. In the study conducted by Hong et al. (2016), low-impact development facilities with SA/CA ratios of 1% to 5% were capable of reducing runoff volume by more than 40% [49]. Choi et al. (2018) also indicated green stormwater infrastructures with SA/CA ratios of 1% to 2% can provide adequate pollutant removal from stormwater [50].

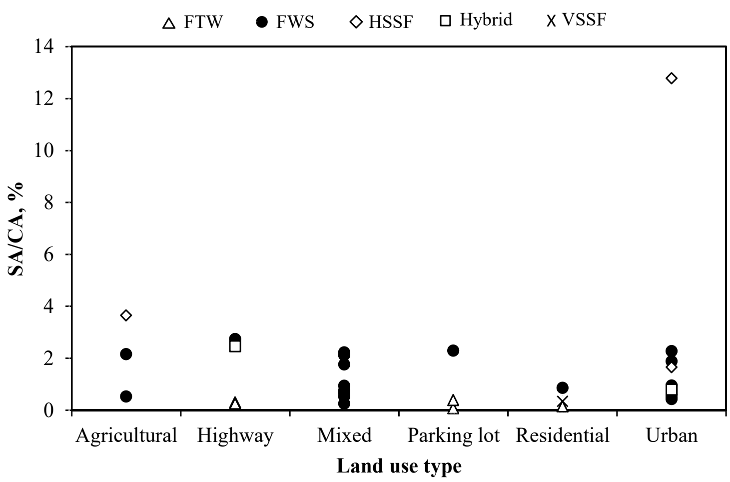


Figure 6. SA/CA ratio of stormwater treatment wetlands in different land uses.

3.2.3. Choice of Filter Media and Substrates

Treatment wetlands that contain subsurface structures are equipped with filter media that help enhance the facilities' filtration and pollutant retention functions. In the case of FTWs, the platforms or modules where the treatment units are mounted also contain substrates that support the growth of plants. The summary of the usage rates of various filter media and substrates reported in relevant scientific publications is shown in Figure 7. Sand and gravel were the most common filter media used for HSSF, hybrid, and VSSF stormwater treatment wetlands. The high usage rate of sand (18% to 36%) and gravel (27% to 50%) can be attributed to their relative abundance as construction materials and effective pollutant removal performance [51,52]. Marine-grade foam (48%) and recycled plastic fibers (31%) were the most common compositions of FTWs. These materials provide buoyancy and bond the platform carrying the substrates and plants [19,53]. Other types of filter media, such as laterite, rubber mulch, pebbles, woodchips, volcanic rock, and bioceramic, were also utilized as filter media for stormwater treatment wetlands. The treatment wetland presented in the study conducted by Adyel et al. (2016) utilized laterite aggregates to enhance phosphorus removal in stormwater. It was found that laterite acted as an important phosphorus sink due to the ligand exchange reaction that prompted effective phosphorus adsorption [54]. Packed rubber mulch and pebbles were primarily used to enhance the physico-chemical and biological processes in the filter bed. Han and Tao (2014) attributed the enhanced industrial runoff treatment to the effective biosorption and adsorption of pollutants in the packed rubber mulch and pebbles [55]. The tradeoff of using woodchip filter materials for treating stormwater was reported by Niu et al. (2018) [56]. Zhang et al. (2020) cited high adsorption capacity, porous properties, and resistance to degradation as the major advantages of using volcanic rock and bioceramics as filter media [57]. Woodchips serve as additional carbon sources for enhancing the denitrification process in a filtration system but may also lead to elevated chemical oxygen demand (COD) concentrations in the effluent. Based on the information presented in the reviewed articles, the choice of filter media or substrates was found to be influenced by the availability and properties of the materials.

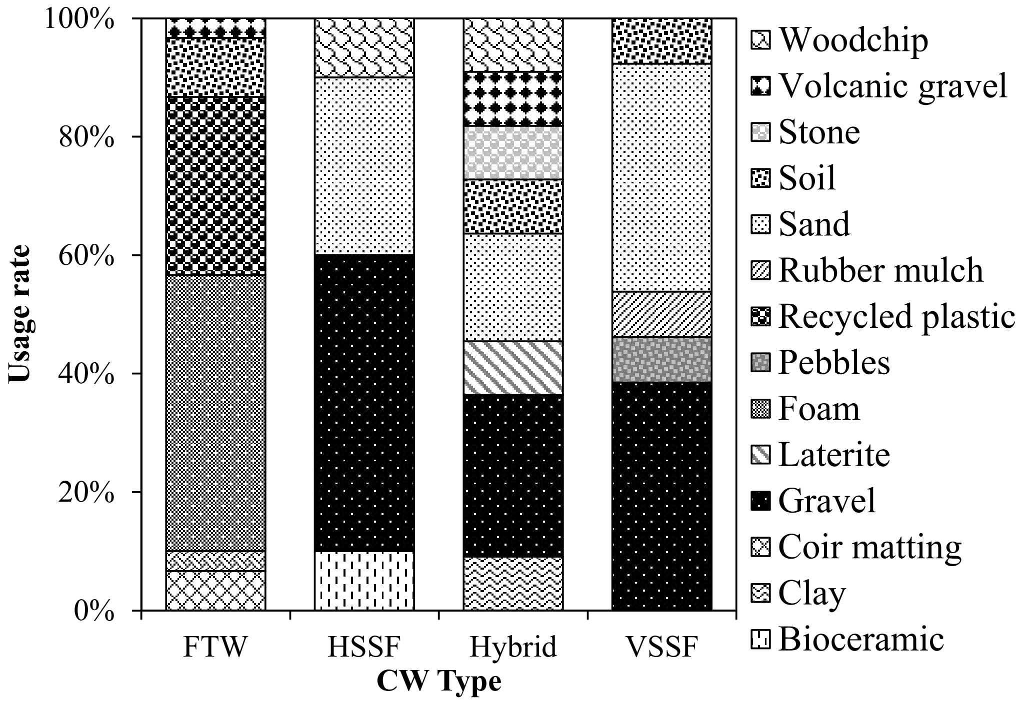


Figure 7. Usage rate of filter media and substrates used in stormwater treatment wetlands.

3.2.4. Plants in Stormwater Treatment Wetlands

Plants are considered essential components of stormwater treatment wetlands. The vegetative components of wetlands directly contribute to the efficient management of nutrients, the removal of toxic pollutants through plant uptake and assimilation, and the carbon storage functions of the system [58–60]. Plants can also enhance the treatment properties of wetlands by prompting efficient sedimentation of particulates in the wetland bed, providing favorable conditions for the growth of microorganisms, and preventing internal algal blooms through shading. A total of 94 genera and 160 species of wetland plants were identified from the reviewed articles (see Table S1). As exhibited in Figure 8, the five most common plant genera used in stormwater treatment wetlands include *Typha*, *Juncus*, *Carex*, *Phragmites*, and *Schoenoplectus*, with reporting frequencies of 45, 38, 29, 18, and 16 times, respectively.

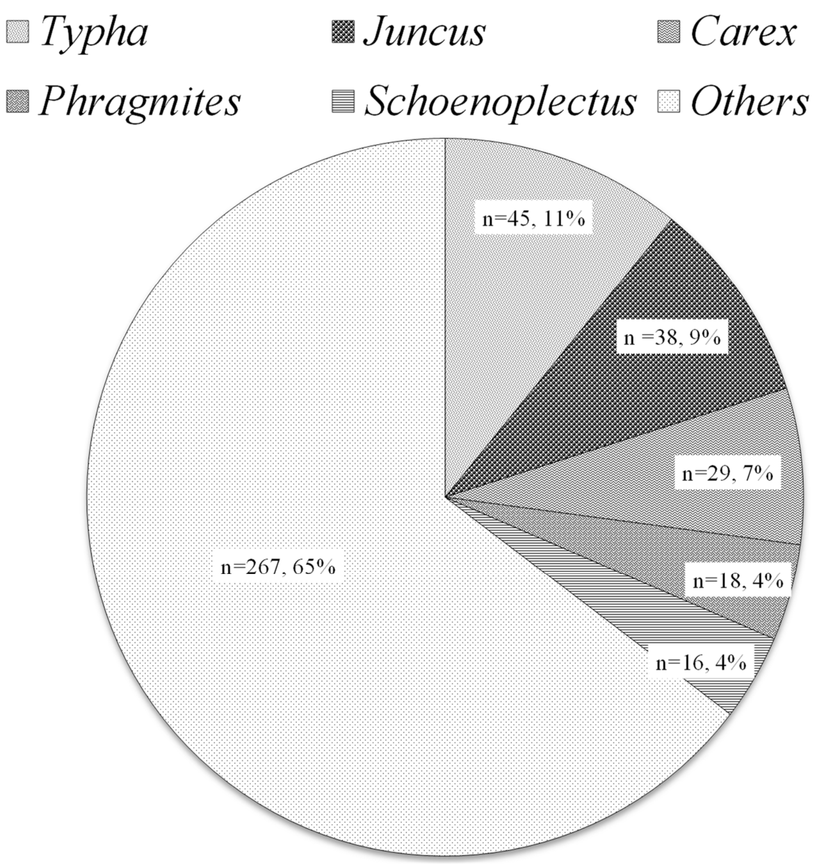


Figure 8. Distribution of the most commonly used plants in stormwater treatment wetlands.

Typha is widely used in treatment wetlands due to its high pollutant uptake capabilities and extremely resilient properties. *Typha* is known to be an important nutrient sink, making it suitable for managing eutrophication [61]. Chandra and Yadav (2011) emphasized that *Typha* can be used for heavy metal phytoremediation since these plants can accumulate Cd, Cr, Cu, Fe, Ni, and Pb in their roots [62]. These plants also have a high phytotoxic tolerance, making them suitable components of wetlands receiving highly contaminated runoff [63]. *Juncus* is also a typical wetland plant known for its high ecosystem value. It was previously reported that different *Juncus* species have promising phytoremediation potential and high biomass yield [64–66]. Plants of the genus *Carex* are commonly applied on FTWs due to their adaptability, ability to uptake heavy metals, and ease of harvesting [20,67]. *Phragmites* are wetland plants known for being potent hyperaccumulators of trace elements [68–70]. *Phragmites* species are often planted in treatment wetlands to increase pollutant remediation; however, these plants are also considered ubiquitous, highly invasive, and phytotoxic due to the production of allelochemicals detrimental to the growth of other plant species [71]. Wetland plants belonging to the genus *Schoenoplectus* are leafless species with large underwater surface areas. These plants are commonly utilized in treatment wetlands due to their remarkable tolerance to physicochemical changes in water quality (i.e., pH, temperature, and salinity) and high nutrient-regulating properties [72,73].

3.2.5. Runoff Water Quality and Treatment Performance of Stormwater Wetlands

A complex mixture of chemicals and compounds can be incorporated into stormwater as a factor of land use, geomorphological characteristics, and the patterns of pollutant deposition in the catchment area. Stormwater treatment wetlands are usually employed in different catchments due to their versatility in treating a wide range of pollutant compounds with substantially varying concentrations. A total of 91 unique water quality parameters and constituents were identified from the collection of reviewed articles concerning stormwater treatment wetlands. As shown in Figure 9, total phosphorus (TP) and total nitrogen (TN) were the most commonly investigated runoff constituents. Various nitrogen forms, including total Kjeldahl nitrogen (TKN) and nitrate-nitrogen (NO_3-N), were also typically included in inquiries related to stormwater treatment wetlands. Nutrients are primary stormwater pollutants that can trigger eutrophication and algal blooms. Treatment wetlands are associated with the treatment of nutrients in stormwater runoff since these systems perform mechanisms that effectively remove different nitrogen and phosphorus forms in stormwater. Wetlands remove nitrogen from stormwater through the combination of physico-chemical and biological processes (i.e., adsorption, plant uptake, ammonification, etc.) involved in the transformation of nitrogen compounds. The removal of phosphorus in CWs can also be influenced by biological processes, such as biodegradation and plant uptake, but sedimentation and soil retention are considered the main pathways for long-term phosphorus removal in treatment wetlands [74]. Suspended solids (SS) concentration is also a well-represented water quality parameter in the reviewed articles since stormwater is a major transport route of sediments and particulates to waterways. The high reporting frequencies of SS in published literature can also be attributed to the relative simplicity of experimental methods for quantifying sediments or particulates in stormwater [75,76]. Heavy metals, such as calcium (Ca), copper (Cu), and zinc (Zn), and dissolved organic carbon (DOC) were also widely investigated, with reporting frequencies of more than 10. The presence of emerging stormwater pollutants, including pesticides, polycyclic aromatic hydrocarbons, and microplastics, was also documented in some studies, but the reporting frequencies of these compounds were relatively low [77–79].

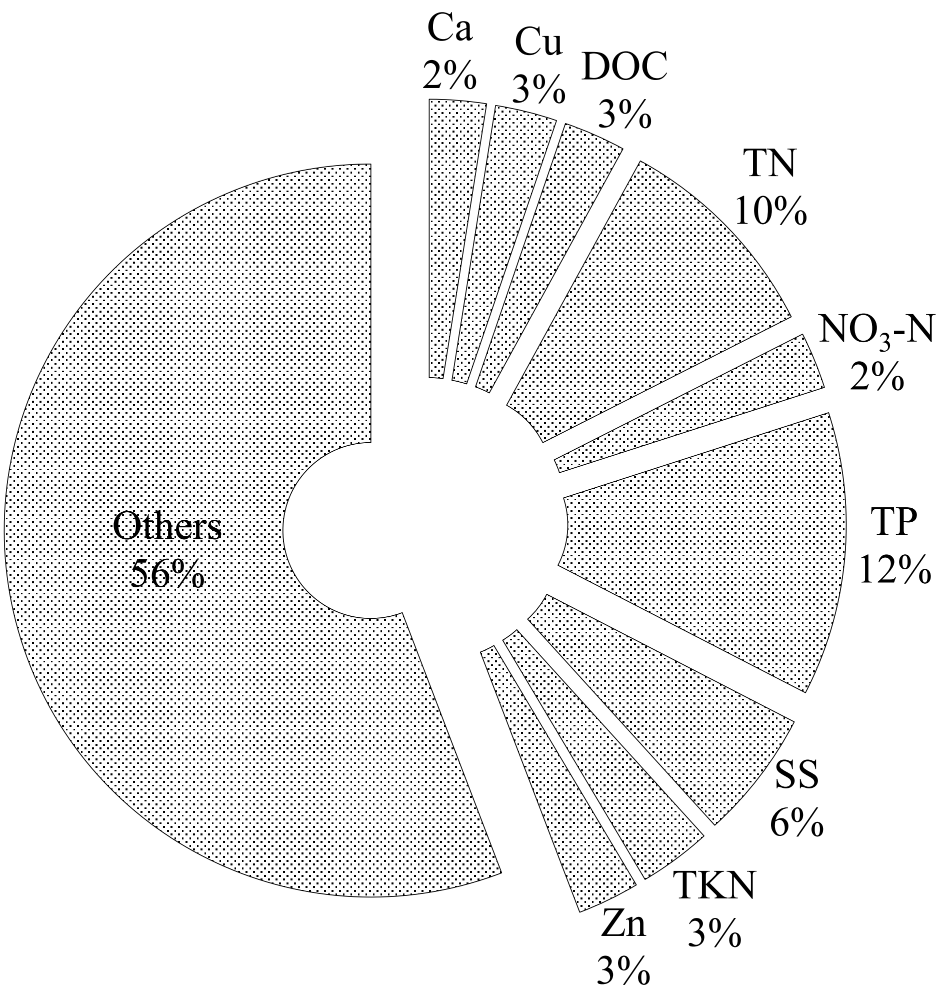


Figure 9. Typical water quality parameters investigated in stormwater treatment wetlands research.

The concentrations of the three most frequently reported water quality parameters were summarized in Figure 10. The highest concentration of TP, amounting to 700 mg/L, was reported in the runoff from an agricultural catchment, whereas maximum TN (54 mg/L) and SS (1953 mg/L) concentrations were observed from a predominantly urban catchment. Phosphorus loads may originate from various natural or anthropogenic-related processes; however, agricultural activities are known as the principal sources of excessive phosphorus loads in water bodies [80]. In urban areas, SS and TN concentrations are mostly influenced by the disturbance of natural features and the accumulation of pollutants on impermeable surfaces. Elevated SS concentrations in urban areas usually originate from construction activities, road and highway maintenance, traffic-related activities, and wet and dry atmospheric deposition [81,82]. High nitrogen concentrations in urban runoff were also reported, considering its diverse sources. The dominant sources of nitrogen in urban runoff include fertilizers applied to lawns, wastewater, atmospheric deposition, and combustion [83]. Among the different land use types identified in the review, parking lot and highway runoff had the lowest mean TP (0.17 mg/L), TN (1.64 mg/L), and SS (42 mg/L) concentrations. Highways and parking lots are usually maintained through sweeping or the removal of accumulated detritus. Since various pollutants are bound to particles, reducing the sediment build-up also resulted in a significant decrease in stormwater pollutant concentrations [84,85].

Stormwater treatment wetlands are capable of reducing pollutant concentrations to a certain extent. As seen in Figure 9, effluent pollutant concentrations were considerably lower than the observed concentrations in the inflow. The treatment wetland investigated by Byeon and Nam (2020) exhibited a pollutant removal performance of up to 99%, indicating that the facility is fit for mitigating the negative impacts of NPS pollution [86]. Li et al. (2020) also reported removal efficiencies exceeding 90%, citing the contribution of effective microorganisms in improving the overall performance of wetlands in treating nutrients in runoff [87]. The stormwater treatment wetlands monitored by Grinberga et al. (2021) showed relatively lower mean pollutant removal efficiencies, ranging from 17% to 80%. It was highlighted that the poor pollutant removal performance of the system can be attributed to the low influent pollutant concentrations caused by stormwater dilution [88]. Some studies also reported negative removal efficiencies or higher outflow concentrations after receiving treatment from stormwater treatment wetlands. Walaszek et al. (2018) recorded a negative removal of PAHs and heavy metals in a stormwater treatment wetland due to the resuspension of solids containing particulate heavy metal fractions in the system [78]. Howitt et al. (2014) emphasized the effect of external factors, including wind mixing, fine sediment resuspension, and external pollutant loading, on the performance of treatment wetlands [89]. The information compiled from the reviewed scientific literature clearly indicated that stormwater runoff management is essential in mitigating environmental degradation. Studies also suggested that treatment wetlands are effective green stormwater infrastructures, but the design of facilities should also be adapted to the stormwater characteristics and catchment area conditions.

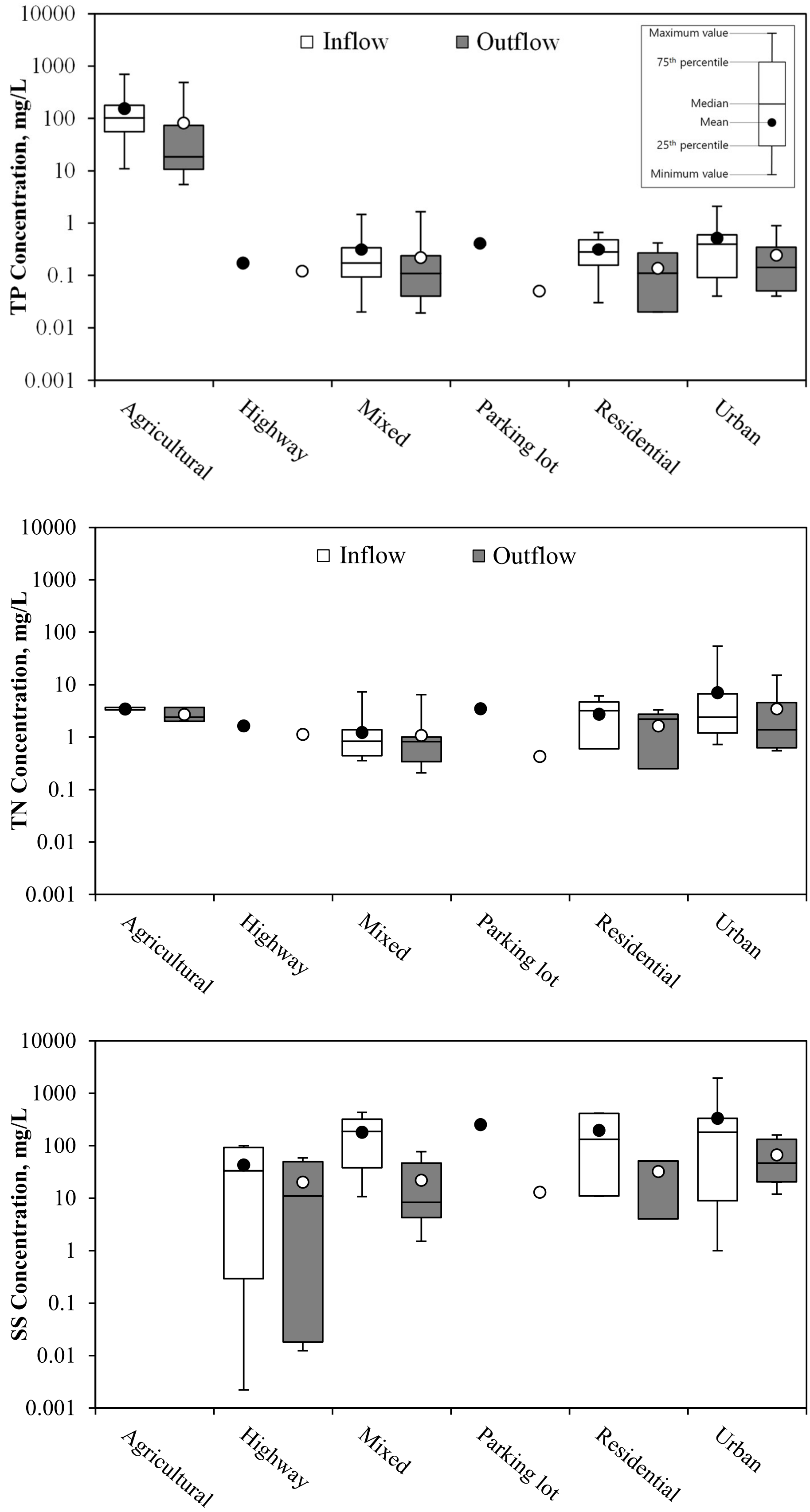


Figure 10. Synopsis of pollutant concentrations in the runoff and stormwater treatment wetlands effluent.

3.3. Knowledge Gaps and Future Research Directions

Stormwater contains various types of pollutants derived from natural and anthropogenic sources. The typical pollutants in stormwater include sediments, nutrients (nitrogen and phosphorus), organics, and heavy metals; however, the occurrence of micropollutants and other emerging pollutants in stormwater was also identified in recent inquiries. Piñon-Colin et al. (2020) detected the presence of plastic particles smaller than 5 mm, known as microplastics, in stormwater. Furthermore, it was found that stormwater is the primary mode of microplastic deposition in water bodies [90]. In the year-long survey conducted by Wicke et al. (2021), different organic micropollutants, such as plasticizers, flame retardants, and PAHs, were identified in stormwater. It was estimated that the stormwater collected from the catchment composed of different land uses contained 24 µg/L of an organic micropollutant mixture [91]. Recent advancements in analysis and instrumentation methods have also enabled the detection of compounds present in minute concentrations. The stormwater samples analyzed by Tran et al. (2019) were contaminated by compounds used in the synthesis of pharmaceuticals and personal care products [92]. Similarly, Fairbairn et al. (2018) reported the presence of 123 different compounds, classified as emerging pollutants, in stormwater. The analysis also revealed that emerging pollutant loads from stormwater may exceed the treated wastewater effluent loads to receiving water bodies [93]. The detection of emerging pollutants and other organic micropollutants in stormwater raised major environmental concerns; however, studies that explore the feasibility of using constructed wetlands as potential treatment systems for the new suites of pollutants are still limited. Based on the analysis of terms, most studies related to stormwater treatment wetlands only focused on the treatment of trace elements (i.e., heavy metals) and nutrients in stormwater. It is, therefore, necessary to conduct inquiries on the applicability of stormwater treatment wetlands in the treatment of emerging pollutants to maximize their water quality treatment benefits.

International collaborations open the platform for scientific productivity. The bibliographic information extracted from published literature revealed that only selected states (i.e., the USA and China) have a well-established network of authors that collaborate on scientific publications. Furthermore, European states were found to be more active in terms of publication as compared to states from other regions. It is recommended to promote knowledge sharing through international collaboration in order to increase scientific productivity and improve the functions, design, and benefits of stormwater treatment wetlands.

4. Conclusions

The number of publications related to stormwater treatment wetlands has considerably increased over the years, indicating that green stormwater infrastructures and NBS have become relevant approaches in stormwater management. USA and China were found to be the most productive states in terms of the number of scientific publications and research collaborations; however, further analyses revealed that Australia, Canada, and South Korea had the highest level of scientific productivity in terms of population-to-publication ratio. The typical design and components of stormwater treatment wetlands in different regions were identified through a comprehensive review of related scientific literature. FWS and FTW were the most common types of CWs used for stormwater treatment, and the size of facilities varied from 7 m^2 to more than 270 km^2. Sand and gravel were typically used as filter media for HSSF, VSSF, and hybrid treatment wetlands since these materials are abundant and have high pollutant removal performance. The most common plant genera used in CW systems include *Typha*, *Juncus*, *Carex*, *Phragmites*, and *Schoenoplectus*. These plants are considered hyperaccumulators of pollutants with high biomass yields and high resistance to toxic environments. Generally, studies on water quality parameters, including nutrients and heavy metals, were the most established field in stormwater treatment wetlands research; however, inquiries regarding the treatment of micropollutants and emerging pollutants by stormwater treatment wetlands are still lacking.

This study identified the need for future works that focus on addressing the aforementioned research gaps that are necessary to optimize the benefits of stormwater treatment wetlands. Strengthening the collaboration among different states can also promote greater scientific productivity and new paradigms for the utilization of nature-based systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15032332/s1, Table S1: List of plants used in stormwater treatment wetlands.

Author Contributions: Conceptualization, N.J.D.G.R., F.K.F.G., and H.B.G.; methodology, N.J.D.G.R.; software, N.J.D.G.R.; validation, N.J.D.G.R.; formal analysis, N.J.D.G.R.; investigation, N.J.D.G.R., F.K.F.G., and H.B.G.; resources, L.-H.K.; data curation, N.J.D.G.R.; writing—original draft preparation, N.J.D.G.R.; writing—review and editing, F.K.F.G., H.B.G., and L.-H.K.; visualization, N.J.D.G.R.; supervision, F.K.F.G., H.B.G., and L.-H.K.; project administration, L.-H.K.; funding acquisition, L.-H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National University Development Project by the Ministry of Education in 2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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