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Review

Evaluating the Effectiveness of Bioretention Cells for Urban Stormwater Management: A Systematic Review

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Abstract: Bioretention cells (BRCs) are a promising low-impact development (LID) practice that are commonly used in urban settings to improve the water quality and mitigate the hydrological effects of stormwater runoff. BRCs have been the subject of extensive research in order to better comprehend their function and improve their effectiveness. However, BRC performance differs greatly among regions in terms of hydrologic performance and quality enhancement. Due to this variance in BRC effectiveness, the current study conducted a comprehensive systematic review to answer the question, "Are BRCs an effective LID method for urban catchment stormwater management?". This review study analyzed the effectiveness of BRCs in mitigating hydrologic impacts and enhancing the quality of stormwater runoff in urban catchments. A review of 114 field, laboratory, and modeling studies on BRCs found that the promising BRCs may be one of the most successful approaches to restore urban hydrology cycle and improve stormwater water quality. With further development of BRCs, their performance in terms of quantity and quality will become more reliable, helping to develop long-term solutions to stormwater urban drainage issues. At the end of this review, the knowledge gaps and future prospects for BRC research are presented. In addition to providing a foundational grasp of BRC, this review study outlines the key design recommendations for BRC implementation in order to address the issues raised by certain BRC design errors.

Keywords: bioretention; urban stormwater; low impact development; runoff; quality; field study; laboratory study; modeling study; systematic review

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1. Introduction

1.1. Background

The increase in global population in recent decades is unprecedented. According to UN projections, the global population might reach 11 billion by 2100 [1]. Furthermore, it is estimated that more than two-thirds of the global population will dwell in urban areas by 2050, with the rate of urbanization growth higher in developing countries than in developed ones [2]. The most significant effects of the rapid urbanization are the dramatic changes in land use, rising imperviousness, and increase in pollutant load build up on urban surfaces [3]. The transformation of natural permeable surfaces to impermeable surfaces has a concerning impact on the hydrology response of a catchment. As a result, runoff (both in terms of volume and peak flow rate) has increased, while infiltration and evapotranspiration have decreased, thus increasing the occurrence of flash floods and decreasing the recharge of groundwater supplies, as well as increasing nonpoint source contaminants [4–7].

At the same time, climate change exacerbates the aforementioned negative consequences. The quantity and quality of urban stormwater may be impacted by climate change-related alterations such as changes in the distribution of rainfall events on an annual basis, which will make dry regions drier and wet regions wetter, as well as increasing the frequency of intense rainfall events [8,9].

Historically, urban drainage systems have been designed to collect and convey stormwater and eventually its mixture with sewage (combined or separate approach) directly to the receiving water bodies [10,11]. In Europe, the standard conventional approach (known as gray infrastructure) to control stormwater runoff and limit the occurrence of floods in urban areas includes (other than the drainage of stormwater runoff as fast as possible through a network of channels and pipes) the construction of detention storage volume as well as structural defenses to protect exposed locations [12]. In response to the above mentioned effects of urbanization and climate change, the European Union (EU) focused its attention on both surface and groundwater bodies in 2000 by introducing the Water Framework Directive (WFD) to improve their quality and protect aquatic environments [13]. Consequently, the conveyance approach has been gradually replaced by source control approaches that emphasize aesthetic value, recreational value, ecological preservation, and other beneficial values over quantity and quality control [10,14]. Indeed, conventional drainage systems are unable to effectively manage the continuous and significant increase in stormwater runoff due to the effects of urbanization and/or climate change; additionally, there is a clear need to promote environmental protection policies and practices to minimize the impact of stormwater runoff discharges on aquatic ecosystems.

In this framework, low-impact development (LID) has been widely considered to deal with these issues. LID is an ecological engineering practice that aims to not only maintain or recreate natural hydrologic conditions in a developed area, but also to enhance the quality of runoff, promote evapotranspiration (ET), and provide a variety of other benefits [15,16]. The concept rests on four key activities: (1) minimizing impervious areas, (2) implementing on-site stormwater management systems, (3) routing stormwater through the watershed to mimic pre-development concentrations, and (4) educating the public on pollution prevention and on the maintenance of stormwater management systems [17,18]. It is noteworthy to mention that several similar concepts have also emerged in other developed countries, such as sustainable urban drainage systems (SUDS), green infrastructures (GI), blue-green infrastructures, best management practices (BMPs), and water sensitive urban design (WSUD) [19]. There are various well-known LID practices, such as bioretention cells (BRCs), rainwater harvesting systems, vegetated open channels, downspout disconnection, permeable pavements, and green roofs [20–23]. This review study focuses on BRCs, a kind of structural, vegetated LID that has attracted significant interest in recent years.

Bioretention systems (also known as bioinfiltration, raingardens, swales, or bioswales) are one of the source control LID practices that were first introduced in Prince George's County, Maryland, in the 1990s [24]. Since then, they have grown to be one of the most promising among LIDs [25]. The promising BRCs rely on the ecological functions of a terrestrial system (upland-based as opposed to wetland-based) of soil, plants, and microbes to retain and treat stormwater. Bioretention systems consist of a small areas which are excavated and backfilled with a mixture of high-permeability soil and organic matter designed to maximize infiltration and vegetative growth, and are covered with native terrestrial vegetation [26]. A schematic representation of a BRC is illustrated in Figure 1. Some of the unique benefits of bioretention are as follows: runoff quality is improved [27], runoff volume and peak flow are reduced [28], it can be adaptively integrated into urban landscapes [29], biodiversity and esthetics are enhanced [30], and the negative impacts of urban heat islands (UHI) are mitigated [31].

Extensive research has been conducted on BRCs in an effort to comprehend their functions, improve their performance, and extend their lifespan [32], but the real data on the performance of these system components over an extended period of operation in the field are insufficient and most of the studies have been conducted in the laboratory, using prototypes, synthetic inflow, and numerical studies [33]. As a consequence of this knowledge gap, bioretention designers and city planners are often unfamiliar with the different bioretention design options, such as the selection of vegetation to be utilized at a given site and the selection of substrates to be considered for certain goals of a BRC, such as the removal of inorganic or organic contaminants [34]. Although some developed countries have established regional guidelines to address this problem, these regulations tend to apply exclusively to specific regions [26]. In retrospect, it is possible to attribute some of BRCs' failures to the fact that these guidelines were adopted without giving adequate consideration to local infrastructure and climate conditions [35].

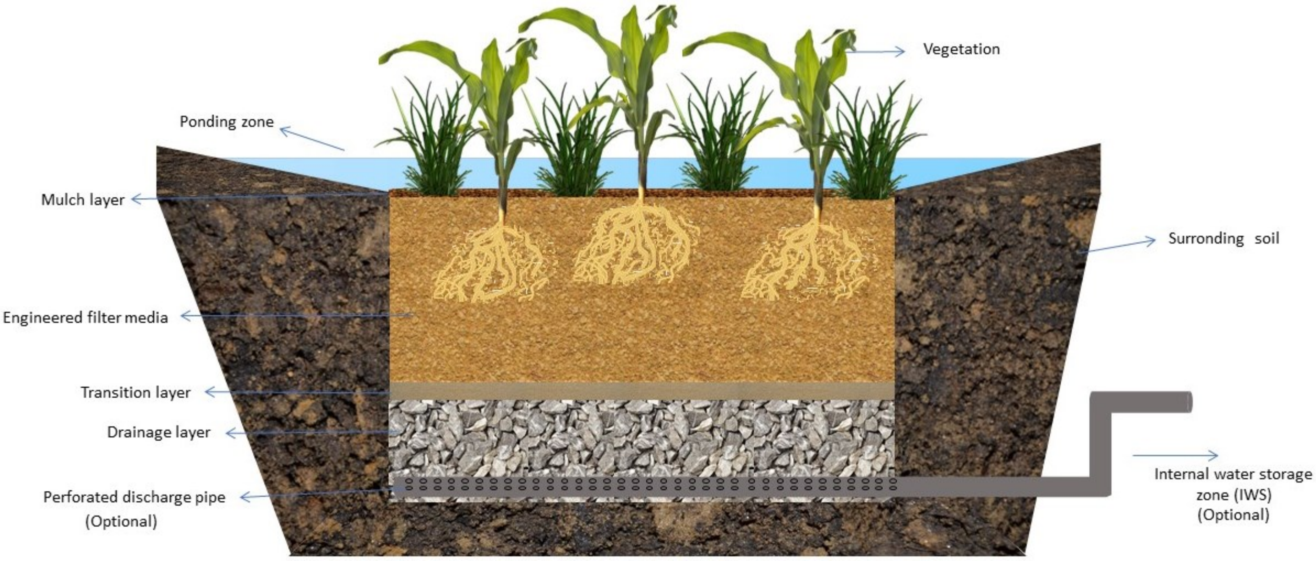

Figure 1. Schematic representation of a bioretention cell.

1.2. Previous Literature Reviews

Over the last five years, various review papers on bioretention systems have been published [36–40]. The effects of vegetation on the hydrologic and pollution mitigation performance of BRCs are underlined in [36]. Plants improve water infiltration, decrease media clogging, and allow water to evapotranspirate while reducing BRC surface erosion. The effect of plants on the removal of total suspended solids (TSS), phosphate, hydrocarbons, and pathogens is modest, but their effect on nitrogen removal is substantial. This is especially true when the broad range of nitrogen removal capacity among plant species is considered. Ref. [33] provides an overview of the relevance of vegetation in BRCs in terms of pollution removal and other advantages such as better esthetics, provision of urban micro-habitats, higher resilience to climate change, and the possibilities of enhancing air quality, biomass generation, and/or food production. Moreover, this research emphasizes the dearth of long-term field and continuous modeling investigations. Ref. [38]'s critical review study evaluates the efficiency of BRCs based on biochar for the removal of chemical and microbiological contaminants found in urban stormwater runoff. To enhance the long-term effectiveness of BRCs, ref. [39] emphasizes the need for comprehending the media–vegetation interactions and maximizing these synergistic interactions. Additionally, ref. [40] highlights the cutting-edge innovations in bioretention systems and provides a summary of research on nitrogen removal for urban stormwater runoff. However, previous review studies on BRCs in urban catchments were almost all narrative reviews that lacked a comprehensive and detailed analysis of the effectiveness of bioretention systems. The latest scoping review [37] was thoroughly prepared, and it investigated the methodology and metrics for the performance of BRCs in field studies. However, the efficacy of BRCs was not reviewed and laboratory investigations were not included in this review study [37].

The purpose of this systematic review article is to examine the effectiveness of BRCs in mitigating the alteration of the natural hydrological cycle and improving the quality of storm water runoff in urban catchments. The present review study concentrates on recently published publications encompassing field, laboratory, and numerical modeling research, and evaluates a number of factors that contribute to the performance of BRCs.

This systematic review study aims to answer the principal research question of whether or not BRCs are an effective practice for controlling stormwater runoff in urban catchments in terms of both quantity and quality issues. Additionally, the present review study made an effort to compile the most recent knowledge on the use and design of BRCs in a variety of climatic conditions, applications, and local infrastructures in order to assist researchers, operators, and regulators in avoiding specific design errors. Finally, this systematic review paper tries to identify knowledge gaps and future prospects for BRC research and present the key design recommendations for BRC implementation.

2. Materials and Methods

The research articles used in this study were from Scopus, one of the most prominent and comprehensive bibliographic abstract and citation databases currently accessible [41]. The time frame spans from the database records in 2017 through to the end of September 2022. The selection of this time period is based on the fact that, according to Scopus data, BRCs have recently gained increasing global attention in urban catchments for stormwater management, regarding both quantity and quality. In recent years, the number of countries contributing to BRC research has increased, bringing with it a greater variety of environmental and architectural aspects to evaluate. The present review study aimed to assess the most recent developments and studies conducted regarding BRCs in urban catchments for the management of stormwater from a quantity and quality perspective, which is another reason for choosing this time frame.

The approach for this systematic review was based on the framework established by Arksey and O'Malley [42]. An outline of the five stages of this research paradigm is provided below.

- Phase 1: Choosing the research questions. What are the research question(s) and what domain must be investigated?
- Phase 2: Identification. Finding relevant studies.
- Phase 3: Selection. Choosing studies that are pertinent to the question(s) using set inclusion/exclusion criteria.
- Phase 4: Data extraction. Arranging the data from the relevant selected studies.
- Phase 5: Collating. Reporting and summarizing the findings.

2.1. Research Question

In terms of the quality and quantity of urban stormwater management, BRC research continues to be active despite its widespread implementation and development. It should be highlighted, however, that the performance of BRCs in terms of hydrologic effects and quality improvement varies considerably from one region to another. This discrepancy in results is attributable to several factors, such as design flaws in BRCs or the disregard of regional climate and site-specific hydrologic responses and runoff quality characteristics. As a result of this discrepancy in BRC performance, the purpose of this review study is to investigate the reliability of BRCs in urban catchments for urban stormwater management in terms of quantity and quality. Therefore, the fundamental research question of this systematic review study is "Are BRCs an effective LID practice for urban catchment stormwater management?". This fundamental research question is broken down into two more specific questions, which are as follows:

- Are BRCs an effective practice for implementation in urban catchments with the objective of restoring the natural hydrological processes?
- Are BRCs an effective practice for implementation in urban catchment areas with the purpose of improving the quality of stormwater?

In this study, the authors describe a systematic review as a sort of research synthesis that maps the literature on a certain topic or research area and allows for the identification of key concepts, research gaps, and evidence types that may be used to inform practice and future studies [43]. In order to comprehend the effectiveness of BRCs in terms of water quality and quantity management for urban stormwater, an assessment of several BRC research studies was conducted using a large database of field, laboratory, and numerical modeling investigations.

2.2. Identification and Selection of Relevant Studies

This section outlines the second and third phases of the research paradigm. The PRISMA (Preferred Reporting Items for Systematic and Meta-Analysis) 2020 flow diagram [44] visually summarizes the screening process. It first shows how many publications with a specific set of keywords are available in Scopus, and then it streamlines the selection process by outlining the decisions made throughout the systematic review. Figure 2 shows a sequence of steps beginning with the identification of relevant studies and concluding with their ultimate inclusion.

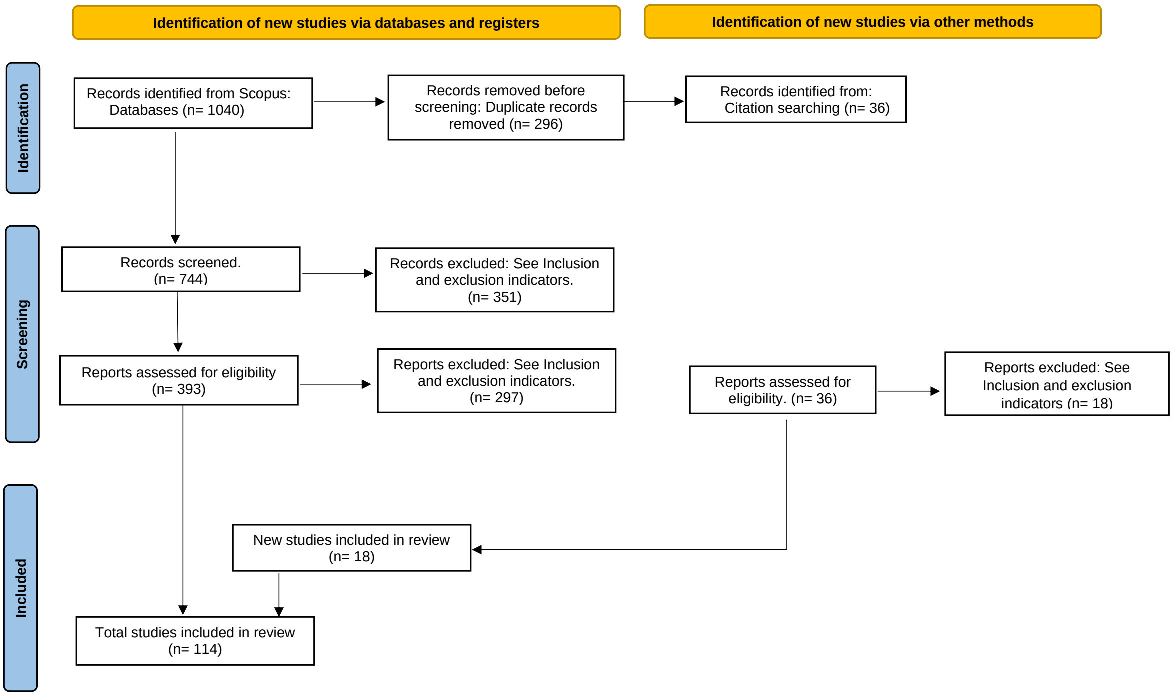

Figure 2. PRISMA 2020 diagram of study selection procedure.

Scopus was used as the bibliometric database to extract the peer-reviewed literature, book chapters, and proceedings of indexed conferences. The studies in this systematic review range in chronological order from 2017 to the end of September 2022. The following is a list of the key terms and their various combinations that were used in our review study: "bioretention", "biofiltration", "raingarden", "urban catchment", and "stormwater".

In the primary search, 1040 citations were downloaded from the Scopus database for various combinations of the keywords. After running them through Endnote's deduplication tool [45], 296 were dropped. Then, a set of inclusion and exclusion indicators reported in Table 1 was provided, based on a modified version of [37], to verify that the study selection process was conducted correctly and that all studies contribute to answering the two sub-questions. The studies were chosen based on the complete design and description of the BRC (see Figure 1 and Section 3.1.1 for more details). Studies in which a BRC was combined with other stormwater management practices were included. Another significant indicator is inflow type. Studies must investigate stormwater runoff in urban catchments and the properties of urban stormwater runoff in terms of quantity and quality impacts, whereas other types of inflows (i.e., wastewater) are not included in this review. In addition, the enhancement in social and environmental values by BRCs, life cycle analysis (LCA) analyses, economic background, and only maintenance recommendations for bioretention systems are not included.

Table 1. Inclusion and exclusion indicators adopted to select relevant studies.

Indicator	Inclusion	Exclusion
Definition of BRC	Definition of a BRC as it is mentioned (see Section 3.1.1).	Any stormwater management approach without full BRC defining elements and proprieties
Type of inflow in BRC	The runoff entered into BRCs must be generated by stormwater in urban catchments or the properties of the urban runoff must be included	Any type of wastewater other than urban stormwater runoff
Type of study	Studies that evaluate the quantity and quality effectiveness of BRCs in field, laboratory, and numerical modeling settings	Studies that evaluated economic, LCA, or other indicators but did not include quality and hydrology metrics
Type of publication	Peer reviews, conference proceedings, and book chapters	Review articles and theses
Language	English	Other languages
Chronological order	Studies between 2017 and September 2022	Other studies outside of 2017–September 2022

Selecting the appropriate studies requires careful consideration; hence, two stages of screening (based on the indicators in Table 1) were performed when the duplicates were excluded. In the first stage of screening, the titles and abstracts (in some cases, the complete text was reviewed to find unrelated studies) of the studies were evaluated for eligibility. In this stage, 351 studies, including 45 reviews, were discarded. In the second stage, the full texts of the studies that had been identified in the first screening were re-evaluated using the indicators reported in Table 1. This resulted in the elimination of 297 studies from the remaining 393. The overall number of remaining relevant papers was 96; however, to increase the comprehensiveness of the review study, other articles were included through the investigation of remaining study references. With this aim, the referenced papers of these 96 articles were considered. Consequently, an additional 36 papers were considered in our screening pool, from which 18 were selected for inclusion. Finally, 114 articles were reviewed that seemed sufficient for reaching an adequate conclusion.

2.3. Data Extraction/Chart

Following the identification and selection of relevant studies, the full texts of all relevant studies were analyzed to obtain the required data. General and specific data were collected based on the following criteria:

- General information: author(s), publication year, and country of origin.
- Watershed features: location, land use category, contribution drainage area (CDA), and percentage of imperviousness.
- Bioretention technical design characteristics: media composition, media depth, ponding zone depth, $\frac{BRC}{CDA}$ area, and internal water storage (IWS) depth.
- Results from BRC quantity and quality performance.
- Type of modeling, simulation type, hydrology and quality metrics for modeling, and calibration status.

Each Excel spreadsheet contained a different combination of the above items in order to reduce the possibility of bias and provide more reliable data from which conclusions and choices may be derived.

Although every effort was made to follow the same procedure to extract the essential information from each of the 114 papers included in this review, this was not always possible due to the absence of key details in certain studies. Data are not always presented in the most user-friendly way, as has been noted by [46].

2.4. Collating

Following the extraction of data from the 114 studies, the purpose was to provide an overview of all data analyzed and, as a result, address questions regarding the quality and quantity of BRC effectiveness in urban catchments. There are two distinct ways to show the results. To begin, an initial mapping was performed, including the main components of BRC and the possible mechanisms that occur in BRCs, such as physical, biochemical/chemical, and biological mechanisms (see Figure 3 for more details), as well as the geographical distribution of the research studies, the number of studies conducted over the time period covered by the review study, and the number of studies classified into each of the three categories (field, laboratory, and numerical modeling studies).

The performance of BRCs in terms of quantity was classified into three categories: volume reduction, peakflow reduction, and capture of runoff. Additionally, the effectiveness of BRCs for reducing certain contaminants that are found in excessive amounts in urban stormwater runoff can be classified into the following five groups: total suspended solids (TSS), nutrients (N species and P species), heavy metals (Zn, Cu, and Pb), pathogen microorganisms and COD/BOD_5, and microplastics (MP). The category of model studies included data on the models employed, temporal scale analysis, calibration and validation settings, and quantity and/or quality metrics.

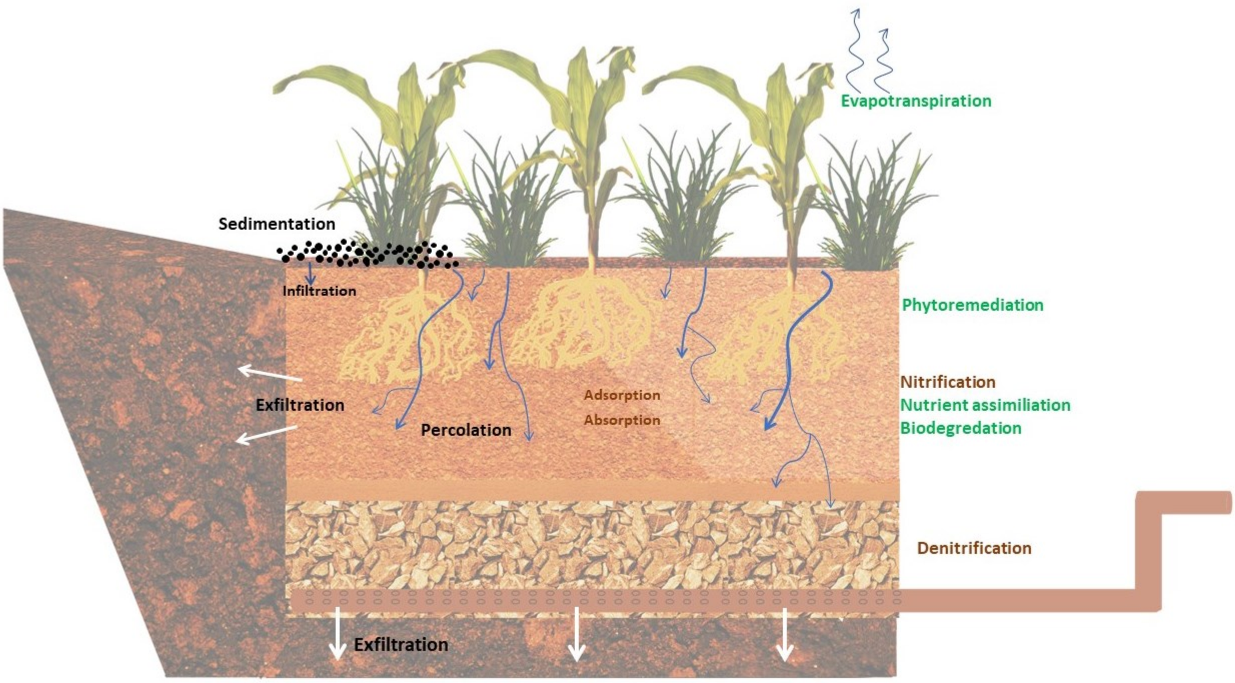

Figure 3. Fundamental physical (black label), biochemical/chemical (brown label), and biological (green label) mechanisms that occur in BRCs. Infiltration/percolation (blue arrows) and exfiltration (white arrows) are illustrated.

3. Results

3.1. Initial Mapping

This section will outline an overview of BRCs, including their fundamental components, the various BRC designs, and the underlying natural mechanisms involved in BRCs. A chronological and geographical analysis of BRC research studies throughout the review period will also be included in this section.

3.1.1. BRC Overview

The selection of bioretention components is significantly impacted by the local climatic variables (such as precipitation intensity, evaporation rates, and antecedent moisture conditions), the hydrologic and hydraulic characteristics of the site, the characteristics of the pollutant load associated with runoff, the required water quality standards of effluents, and the local availability of BRC components such as vegetation, soil media, and substrates. It is important to note that, for instance, in temperate countries, BRCs are designed to capture the first flush of runoff. In tropical climates, however, where rainfall is often heavy and frequent, the impact of the first flush may not be as significant as in temperate climates [35]. Furthermore, a comprehensive review of 40 years' worth of data for more than 60 cities throughout the world revealed that urban runoff and nutrient content in tropical regions differ from those in temperate regions [47]. Additionally, countries in the temperate zone, such as Australia, the United Kingdom, and the United States, receive around 800 mm of precipitation annually, whereas those in the tropics, such as Singapore and Malaysia, receive around 2500 mm [48]. These tropical nations frequently experience short, intense thunderstorms, which are less frequent in temperate countries. Hence, it is crucial to account for the rainfall characteristics in designing BRCs to avoid under-sizing of the system, thus leading to runoff bypassing the system [35].

BRCs employ excavated areas to form depressed planting beds to collect and treat stormwater runoff. As illustrated in Figure 1, bioretention generally includes the following layers, starting from the top: a surface ponding area, plants, a layer of mulch, an engineered filter medium, a transition layer, and an underlying drainage layer. The system optionally includes an underdrain that links to the main urban drainage system (eventually with reuse purposes) and the outlet section may be raised to determine the internal water storage (IWS) [49,50]. The latter is typically constructed by adding a 90 degree elbow to the underdrains in the BRC. It is important to mention that the presence of an underdrain depends on the implementation goal of the BRC as well as the characteristics of the soil surrounding the BRC, such as the rate of infiltration and pollutant concentration.

The effectiveness of each design varies greatly because different BRC designs lead to different hydrological and quality responses, especially when it comes to nutrient contaminants [51,52]. The BRCs may be constructed without an underdrain for complete exfiltration, with an underdrain (most preferred) for partial exfiltration, or with an impermeable liner and underdrain for no exfiltration. Typically, based on the discharge configuration, BRCs may be divided into two categories: BRCs with a conventional drainage design and BRCs with an internal water storage zone (IWS). BRCs mainly act as a source of aerobic substrates, organic material, and microorganisms for the nitrification of produced ammonium and mineralization of incoming organic nitrogen. Raising the underdrain outlet to create an IWS zone will result in anaerobic conditions [53–56]. As result of incorporating IWS into BRCs, the system has improved nitrogen removal due to the comparatively higher denitrification because of the anaerobic environment in the submerged zone. In addition to the advantage of nitrogen removal, an IWS zone may have a considerable hydrologic influence on runoff reduction [54,57,58]. Another classification of BRC designs is related to the overflow design. BRCs can be designed to be offline and online. In contrast to offline bioretention, which only permits the amount of storm runoff storage determined by design to enter the BRC, online bioretention captures all flow from the drainage area and conveys large event flows to an overflow outlet.

Stormwater runoff can be managed in terms of quantity and quality near to where it originates by implementing BRCs into a site's structure. The majority of possible natural mechanisms that can occur in BRCs are illustrated in Figure 3. These mechanisms are divided into three categories: physical/hydrological, biochemical/chemical, and biological [19,56,59]. The physical processes consist of exfiltration, infiltration, percolation, and sedimentation. In BRCs, chemical and biological classifications are challenging processes. Absorption and adsorption are chemical processes that commonly occur in soil and plant components. Nitrification and denitrification processes, occur mostly in the soil profile, plant roots, and IWS zone. Figure 3 shows that biodegradation, nutrient assimilation, phytoremediation, and ET are all biological processes that occur in BRCs. The mechanisms involved in BRCs, as well as how they affect the quantity and effectiveness of treatment, will be examined in further detail.

One key feature of BRCs is their adaptability in practice [60]. BRCs can be implemented in parking lot landscaping, alongside highways, and in open spaces close to impermeable surfaces.

3.1.2. Chronological and Geographical Analysis of BRC

Numerous studies have been conducted to enhance BRC effectiveness and to construct cost-effective BRC designs under various climatic conditions since the advent of bioretention in the 1990s [61]. As shown in Figure 4, in recent years, an increasing number of researchers from all over the world have been drawn to the utilization and effectiveness of BRCs in urban stormwater management. There were 744 publications found in this review research, with an annual average of 124 articles regarding BRCs in the field of urban stormwater management. Although there was a decline in publication trends in 2020—about 24% less than in 2019—the long-term average has increased by about 16% annually. The growing amount of the literature on urban stormwater management from 2017 highlights the significance of BRCs.

It is worth noting that throughout the time frame covered by this review study, laboratory research accounted for 44% of the total number of studies, while field and numerical modeling studies accounted for 24% and 31%, respectively. The fact that laboratory studies are so prevalent may be explained by the fact that they are preferred for obtaining essential information because of their ability to simplify full-scale systems and focus on improving specific qualities. Furthermore, by conducting laboratory investigations, the high expenses as well as the variety of constraints connected to field-scale research may be minimized.

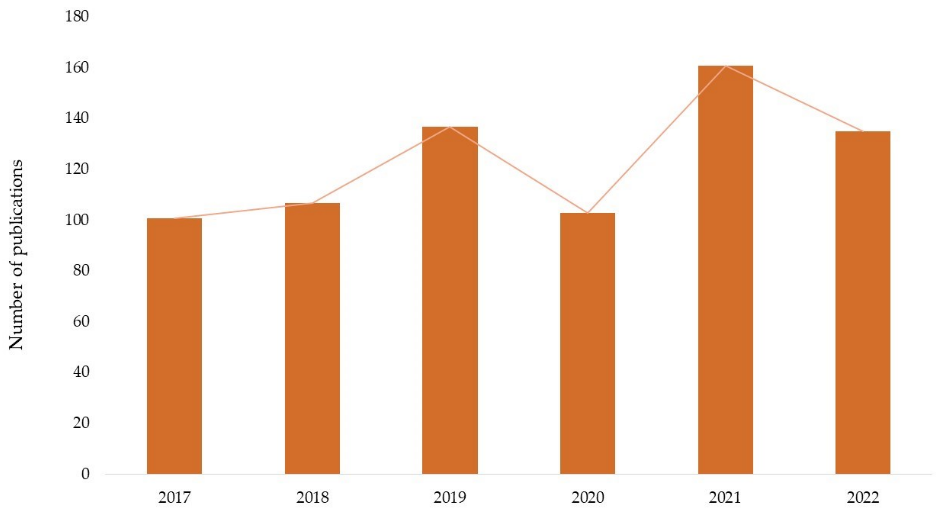

Figure 4. Trend in the annual number of studies published, 2017–2022.

Figure 5 illustrates that over the last five years, the United States and China have contributed the most publications on BRCs for urban stormwater control, with 269 and

242 articles, respectively. Other noteworthy contributors besides those mentioned above were Australia (58), Canada (41), Hong Kong (18), Brazil (16), and Sweden (15).

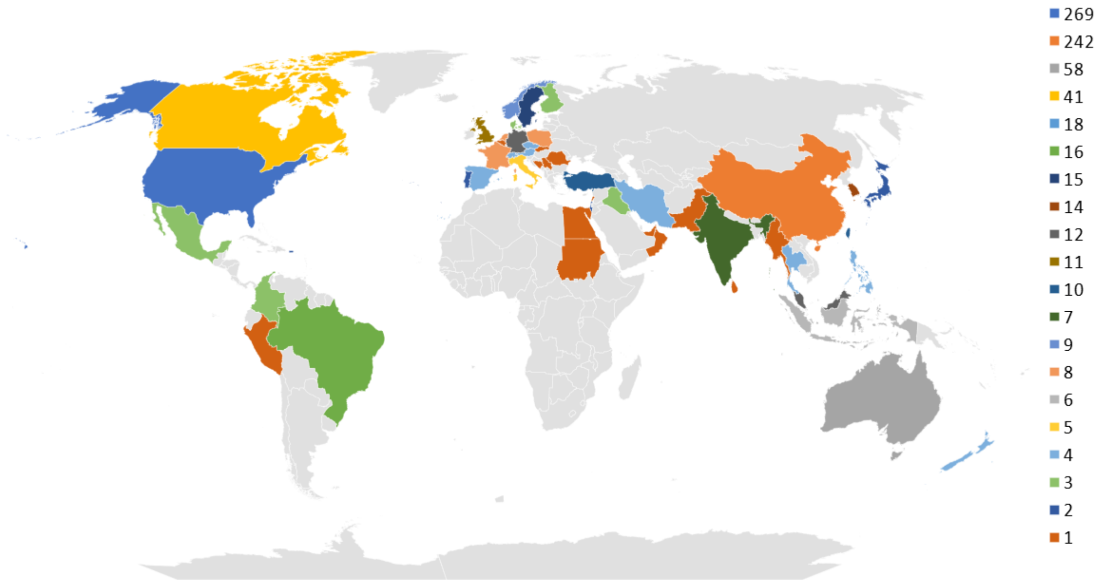

Figure 5. Country-wise analysis of studies published on BRCs, 2017–2022.

As previously stated, laboratory studies constitute the vast majority of research, with China accounting for around 45% of all studies. On the other hand, the United States conducted 35% of all field studies, making it the top in this area. Figure 6 shows the percentages of studies that belong into each of these three categories based on the countries that contributed the most.

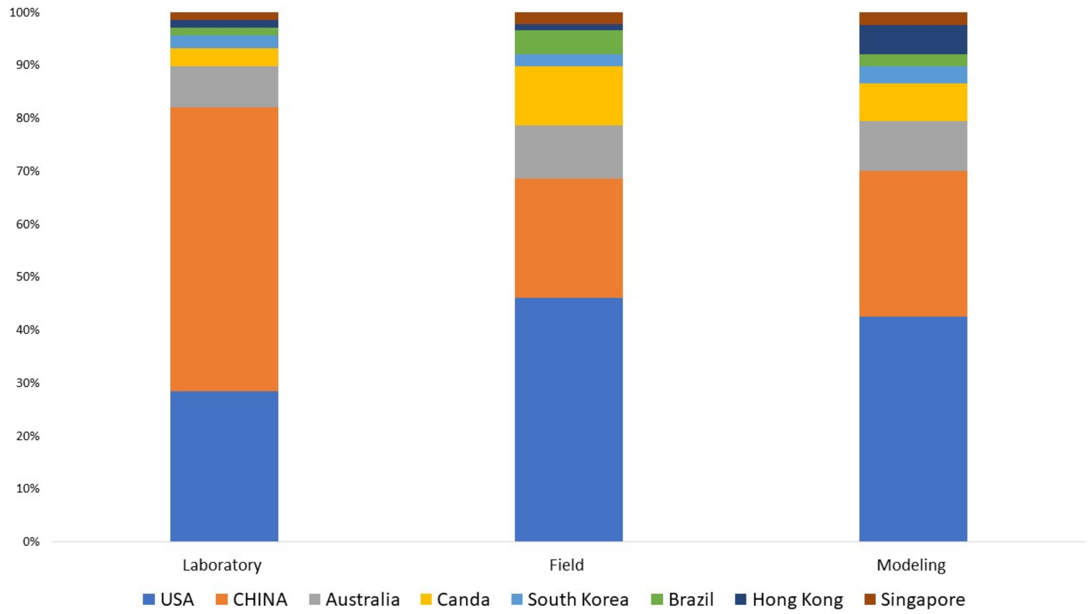

Figure 6. Leading countries in laboratory, field, and modeling studies on urban stormwater management by BRC, published 2017–2022.

This bibliometric analysis demonstrates that only a small number of nations have undertaken novel research on BRCs, while others have not yet initiated such comprehensive research. Given the current concern about global climate change, increasing urbanization, and the vast network of impervious road surfaces, it is necessary to do more research in a diverse range of geographical regions with varying precipitation regimes and local soil conditions. As a result, additional research can provide a more solid foundation for evaluating the effectiveness of BRCs.

3.2. Evaluation of BRC Effectiveness

The total effectiveness of BRCs in lessening the negative effects of urbanization is significantly influenced by their hydrologic performance [54,62–64]. As a result of this, the present review begins with an assessment of BRCs' hydrological effectiveness. Subsequently, the quality performance of BRCs will be examined.

3.2.1. Quantity Effectiveness of BRC

According to a quantity point of view, the primary function of a BRC is to reduce the volume of stormwater runoff and to slow the peak flow rate. The quantity effectiveness in lowering runoff volume and peakflow has been the topic of various research works in recent years, and efforts have been made to enhance the overall performance of BRCs.

There are several assessment indicators that can be used to assess the quantity effectiveness of BRCs that are collectively referred to as the hydrologic performance of BRCs. Common indicators include lag time, volume and peakflow reduction, runoff coefficient, and capture. The time elapsed from the start of a rainfall event until the start of bioretention system discharge is referred to as the lag time. The runoff coefficient represents the system's effectiveness at infiltrating precipitation into the soil and minimizing the quantity of runoff generated.

In this systematic review, the hydrologic performance of BRCs is analyzed based on three indicators: volume reduction, peakflow reduction, and capture. Volume reduction, in the context of BRC effectiveness, is evaluated as the absolute percentage difference between the outlet (evaluated as the sum of the outflow and overflow volumes) and inlet volumes. Peak flow reduction is similarly evaluated as the absolute percentage difference between the overflow peak and inlet flow peak rates. The capture is evaluated as the percentage of the number of events for which the inlet is completely captured. Note that the captured volume by a BRC refers to the volume of runoff that is retained without any overflow, underdrain flow, and exfiltration.

Tables 2–4 report the volume reduction, peakflow reduction, and capture for the selected literature studies, respectively, in USA, Canada, and other countries (China, Brazil, Australia, Korea, and Czech Republic). For each study, the site characteristics, including contribution drainage area (CDA), imperviousness rate (Imp.Rate), and land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas (BRC/CDA), and the internal water storage (IWS). In BRCs, the volume of runoff can be reduced by a range of mechanisms. These mechanisms include infiltration, storage in the pores of the media compositions, percolation and lateral flow to surrounding soils, shallow interflow, evaporation or evapotranspiration to the atmosphere, and assimilation by plant roots. It should be noted that the treated water from BRCs (with underdrain) can be reused for irrigation and other non-potable purposes, such as toilet flushing [58]. Peakflow reduction implies smoothing of the runoff hydrograph, which reduces erosion, scour, and sediment transportation into receiving water bodies. More specifically, bioretention acts as a buffer to runoff peak flow by producing ponds on the surface, keeping runoff within the media and slowly releasing it [60]. BRCs may continue to gradually release water downstream through the underdrain for several days after precipitation events [55,60,65]. Concerning the capture, the term "Bioretention Abstraction Volume" (BAV) was developed in [63] to represent the volume captured by BRCs. This reduced or captured volume of runoff is supposed to be lost or retained (the term "retain" to indicate reducing surface runoff is gaining acceptability in the stormwater sector, even if rainwater that is evapo-transpired, captured, utilised, or infiltrated is not truly, retained; instead, it is prevented from running off).

In accordance with all advancements in the most recent studies analyzed in this review study, the findings show that BRC performance in terms of volume and peakflow reduction is appropriate for stating that BRCs can effectively contribute to mitigating the risk of floods, mimic pre-development conditions, and address the impacts of hydromodification on urban areas. In Tables 2–4, the volume reduction rates are in the range of 50–98% for the field experimental studies, with the exception of the site located at Grove (OK, USA), where an interaction with the groundwater table significantly limits the performance [66]. For laboratory experiments, the volume reduction rates are lower with respect to the field studies (in the range of 11–71%) since the generated rainfall intensity reaches the 5-years return period. Similarly, the peak reduction rates are in the range of 65–100% for the field sites and are reduced in the range of 10–98% for the laboratory experiments. As for the capture, it ranges from 19% to 84%, depending mainly on the rainfall characteristics of the site and on the age of the systems (see, e.g., [50,62,67]). Specifically for the age of the system, ref. [50] analyzed the BRC capture performance throughout two time intervals (2013–2014 and 2017–2018). The rainfall depth and intensity, as well as antecedent dry weather period (ADWP), were comparable across the two periods. In this study, the BRC was able to catch 84% rainfall events in 2013–2014 and 51% in 2017–2018. Other long-term research undertaken in [68] (from November 2018 to January 2020 with 124 rainfall events) indicated that the BRC performance in terms of capturing the rainfall was about 56%. It should be mentioned that, in these two investigations, the BRC was able to capture rainfall events that were less than or equal to 15 mm.

In an effort to improve the hydrologic performance of the BRC, recent research has focused on a variety of BRC-related elements, such as the general design, selection of the media composition, and vegetation type [69]. Notwithstanding, the BRC's fundamental elements, the local conditions linked to climate characteristics, and surrounding soil conditions (such as soil permeability, groundwater table, etc.) also affect the BRC's hydrologic efficiency, as mentioned in the previous section.

As for climate-related conditions, there are several indicators influencing BRC hydrologic performance, such as rainfall intensity, precipitation depth, seasonality, and ADWP [49,58,62,68]. In [62], eight BRCs were monitored under a variety of conditions including different rainfall intensities and a variety of plant types. The results were 75% for volume reduction, 91% for smoothing the peakflow, and 31% for capturing. In addition, the significant sensitivity of peakflow reduction to peak inflow was discovered, whereas volume reduction was contingent on inflow volume, peak inflow, and precipitation depth. Seasonality is another factor that should be considered significant for the BRC's performance. In the study of [68], considering the high variability between individual events within each season, it was observed that a variation in the mean volume reduction efficiency of the summer (85%) compared to other seasons is considerable (the mean volume reduction of other seasons is approximately 70%). The precipitation amount and intensity, as well as the antecedent moisture conditions, may explain this phenomenon [63,68]. The relative importance of the various performance indicators varies depending on the time of year. For example, during dry weather periods, the antecedent soil moisture conditions and the rainfall intensity were found to be more important than the total precipitation depth; whereas, during the wet period, the hydrologic performance of BRCs was primarily influenced by the total rainfall depth and the maximum rainfall intensity [49,58]. Additionally, this variation may be partially explained by a reduced water holding capacity and ET rate during the winter months compared to the summer months. Considering that 19% [70] of volume reduction in BRCs relies on ET (plants transpiration and abiotic evaporation), low ET rates impact not just the BRC's internal water level, but also the surrounding high-water table. In the colder months, BRCs retain the water that would have evaporated in the warmer months. As a result of the lower ET throughout the winter, the local water table was higher. In consequence, the increased water table around the cell reduced the quantity of exfiltration [71].

Numerous BRC design characteristics influence the hydrologic performance of a BRC such as the composition and the depth of the filter media, the outflow configuration, the types of vegetation, and the construction and maintenance of the system [50,54,55,58,62,67]. Most research studies suggest that the total potential advantages of BRCs are heavily reliant on the optimal selection of media substrates. The particle-size distribution (PSD), porosity, pore-size distribution, and saturated hydraulic conductivity (Ks) have a significant impact on the rate of infiltration, as well as an impact on the soil stability and compaction. All of these effects are dependent on choosing the right combination of media composition. This helps to partially explain why [67] concluded that the initial moist deficit (IMD) is crucial for BRCs to catch inflow runoff. In general, the ability to collect and store runoff increases as the IMD increases. In this study, BRCs with pumice sand compositions outperformed those with sand-based compositions, with 28% and 10% better capturing outcomes, respectively, because pumice has the potential to hold water inside its aggregate structure. Furthermore, ref. [55] evaluated the effectiveness of various media compositions in cold climates with severe climatic conditions and found that media composition has a substantial impact on BRCs. In terms of peak flow reduction, sandy loam media performed better than sand-based media. This study's outcome might be explained by the water-holding capacity of the media composition, indeed, sandy loam has more micropores compared to sandy soil, allowing it to hold more water.

The performance of filter media has recently been the focus of several research efforts studying the effect of altering their constituent parts. Adding a certain amount of suitable admixtures to the BRC filter material might provide a solution. However, the admixtures must be affordable, conveniently accessible, beneficial to plant growth, long-lasting, and, most importantly, efficient in removing pollutants [72–75]. On the whole, several changes may be made to filter media to affect their water-holding, adsorption, and infiltration capacities, and these can all be considered when evaluating BRC hydrologic performance. It was found that both organic and inorganic supplements may increase the hydrologic performance of BRCs [58,74,76]. According to [76]'s assessment of the effectiveness of a water treatment residual (WTR) and biochar substrates in the columns with regards to quantity management, BRCs with biochar were more stable than BRCs with WTR with regard to the water volume control effect, and both were superior to bioretention soil media (BSM). Regarding peak flow reduction, the effect of BRCs with biochar was very steady throughout a range of inflow circumstances, all of which were greater than 74%. In order to illustrate how biochar addition might alter the performance of filter media, the effect of biochar on the bulk density of the filter media could well be considered. In particular, the addition of biochar decreases the soil's bulk density, and increases the soil's overall porosity and the capillary force of the filter media. Furthermore, biochar's larger surface area and its micropores could explain its consistent efficacy in reducing peakflow. It should be noted that the high carbon content and biological origins of biochar make it a suitable substrate for microbial colonization; in turn, these microorganisms can contribute to additional runoff reduction [75]. The hydrologic performance of field-scale biochar-amended BRCs was examined with four rainfall recurrence intervals under varied biochar distributions in [74]. When layered and uniform mixing of biochar distributions were compared, it was discovered that uniform mixing of biochar distributions may more effectively improve the soil water holding capacity, which in turn enhances the ability to regulate runoff. It is possible that uniform mixing distributes the biochar evenly throughout the soil, allowing for a more consistent improvement in the soil water holding capacity. This increased capacity can lead reduced runoff compared to layering, where the biochar may be concentrated in specific areas, leading to more variable results. It is crucial to highlight, however, that this is only one possible explanation; the performance of BRCs under various amended distributions should be explored further.

Recently, researchers have attempted to apply the internal water storage zone (IWS) in BRCs for a variety of purposes, including hydrologic performance [54,55,58,74]. The IWS is a subsurface part of the filter media that contributes to BRC storage capacity. The effects of the IWS on volume reduction have been examined in several studies such as [58], which that found that the IWS has the most significant importance for volume reduction after the infiltration rate of the media. In addition, in [74], the effects of varying the IWS depth were studied. Comparing the impacts of three different IWS heights, it was discovered that the volume reduction pattern increased with increasing IWS depth, from the range of 11.4–16.2% with no IWS to 38.4–59.8% with a 40 cm IWS. The volume reduction achieved by a 20 cm IWS was 16.3–29.6%. This was because the increase in the IWS zone height led to an increase in the internal storage water capacity and a decrease in outflow [77].

One of the most essential design variables is the size of the BRC, which should be selected based on the loading and target performance, as well as on local regulations and spatial and economic constraints. Local regulations generally define both runoff volume and water quality discharge limits that need to be addressed. Based on results examined in the present review, a BRC-to-contribution drainage area ratio between 8 and 25% is recommended [50,54,61,78,79]. The specific size may vary depending on land use (i.e., imperviousness), rainfall patterns, targeted volume management, and pollution treatment effectiveness. Another vital point is to keep an appropriate distance between the bottom of the BRC and the seasonal high groundwater table. Various bioretention manual guidelines recommend a distance of between 30 and 60 cm for this [80]. For instance, ref. [66] observed that two BRCs had groundwater seepage which had a detrimental effect on their ability to reduce volume. In this study, the volume reduction performances of the two BRCs were substantially negative. In this investigation, as shown in Table 2, the underdrain flow of one BRC was 200% more than the influent flow.

The vegetation or the plant zones are components differentiate BRCs from other LIDs. The ability of plants to intercept and hold runoff and to decrease water flow with stalks, stems, branches, and foliage is one of the better recognized functions of vegetation [81]. Vegetation maintains the soil, and media porosity allows for infiltration, temporary storage, and then exfiltration through the subsoil, all of which act to attenuate the peak flow [62]. Despite the fact that several manuals emphasize the role played by vegetation in achieving various hydraulic, hydrologic, and treatment goals, the topic of the beneficial contribution of plants in hydraulic or pollutant removal is not trivial, and yet the role of vegetation and roots in the context of bioretention has not been thoroughly researched. Ref. [62] examined the effectiveness of a high and low diversity (low-diversity treatment (VL) contains two species, and the high-diversity treatment (VH) contains seven species) of vegetation and found that VL effects on peak flow were not negligible. Moreover, appropriate plant species, for example, ones that reach maturity faster alongside occupying a greater soil area and accumulating a larger above-ground and below-ground biomass while tolerating changing environmental conditions, should be considered for bioretention in cold climate regions. In [82], the influence of media–vegetation interactions on ET was determined by observing 24 mesocosms containing various types of vegetation. The impacts of the vegetation, which became more prominent over time, were also observed. This study uncovered the impacts of vegetation and media on ET, which, in turn, impacted the performance of BRCs.

The ponding depth is another important design feature to consider. Ponding depth allows for the temporary storage of rainwater prior to filtering it through the BRC, the storage of excess runoff, and the settling of particles and evaporation of surplus water. This design feature is critical for estimating the hydraulic loading of treatable surface runoff [61,83]. The ponding zone is typically determined by local guidelines; however, ref. [84] suggests that the ponding depth should be more than the product of the infiltration rate and 24 h. In addition, to provide for the appropriate drainage and to avoid stagnant water, a slope of 1% is often suggested. Therefore, the maximum ponding depth is determined by the fact that standing water drains in less than twenty-four hours, which is less than the time required for one mosquito breeding cycle.

Table 2. The hydrologic performance, volume reduction, peakflow reduction, and capture of the BRC literature studies in the USA. For each study, the site characteristics, including the contribution drainage area (CDA), the imperviousness rate (Imp.Rate), and the land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas (BRC/CDA), and the internal water storage (IWS).

Reference	Location	CDA (ha)	Imp .Rate (%)	Land Use Category	Media Depth (cm)	Media Compositions	Ponding Zone (cm)	$\frac{BRC}{CDA}$ (%)	IWS (cm)	Volume Reduction (%)	Peak Flow Reduction (%)	Capture (%)
[66]	Grove (OK)	0.26	90	Residential	60	95% sand , 5% fly-ash	30	5.7	**	13	-	-
		0.76	36	Parking lot				2.2		−200	-	-
		0.25	100	Parking lot				2.5		73	-	-
[54] [1]	Blacksburg (VA)	0.16	N/A	Parking lot	60	88% sand, 8% silty clay, 4% leaf compost	10	2	30	98	91	-
										84	82	-
[62] [2]	Burlington (VT)	0.003–0.012	N/A	Roadway	61	60% sand, 40% compost	15.2	7.7	**	75	91	31 [3]
[85]	Weslaco (TX)	0.16	N/A	Parking lot	76	Sandy	15	3	**	82	-	-
[67]	Hoboken (NJ)	0.0142	100	Roof	55.9	88% pumice-sand, 12% compost	42.3	5	**	-	-	19
		0.0109						6		-	-	45
		0.0054						12		-	-	56
		0.0098						7		-	-	24

Note: "-" is not evaluated, "**" is not included, and "N/A" is not available in the study. [1] This study is an evaluation of the maturation of the BRC's effectiveness (2007–2008 (first row) and 2013–2014 (second row)). [2] The study site consists of eight bioretention cells, the results are the average across all. [3] The value refers to the number of events that are completely captured with respect to the overall monitored event.

Table 3. The hydrologic performance, volume reduction, peak flow reduction, and capture of the BRC literature studies in Canada. For each study, the site characteristics, including location, contribution drainage area (CDA), imperviousness rate (Imp. Rate), and land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas (BRC/CDA) and the internal water storage (IWS).

Reference	Location	CDA (ha)	Imp.Rate (%)	Land Use Category	Media Depth (cm)	Media Compositions	Ponding Zone (cm)	$\frac{BRC}{CDA}$ (%)	IWS (cm)	Volume Reduction (%)	Peak Flow Reduction (%)	Capture (%)
[50] [1]	Vaughan	0.02	N/A	Parking lot	40	3–99% sand, 1–7% silt, 0–1% clay	N/A	12	**	98 93	- 95	84 51
[68]	London, Ontario	0.13	55	Roadway	100	91% sand, 9% fine soil, 3% organic matter	N/A	4	**	73	-	56
[55] [2]	Edmonton	N/A	N/A	Lab. Exp.	86 84.9 85.8 86.4	51% sand, 29% silt, 20% clay 67% sand, 20% silt, 13% clay 48% sand, 28% silt, 19% clay, 0.5% steel-wool, 5% woodchips 64% sand, 19% silt, 12% clay, 0.5% steel-wool, 5% woodchips	11.5	N/A	0 0 20 20	-	80 39 82 67.5	-

Note: "-" is not evaluated, "**" is not included, and "N/A" is not available in the study. [1] This study is an evaluation of the maturation of the BRC's effectiveness (2013–2014 (first row) and 2017–2018 (second row)). [2] The results of peakflow reduction are the average.

Table 4. The hydrologic performance, volume reduction, peakflow reduction, and capture of the BRC literature studies in China, Brazil, Australia, South Korea, and Czech Republic. For each study, the site characteristics, including the contribution drainage area (CDA), imperviousness rate (Imp.Rate), and land use category, are reported together with the system characteristics, including media depth and composition, ponding zone, fraction between the BRC and contribution drainage areas(BRC/CDA), and the internal water storage (IWS).

Reference	Location	CDA (ha)	Imp. Rate (%)	Land Use Category	Media Depth (cm)	Media Compositions	Ponding Zone (cm)	$\frac{BRC}{CDA}$ (%)	IWS (cm)	Volume Reduction (%)	Peak Flow Reduction (%)	Capture (%)
[86]	Xi'an Xianyang China	0.028	N/A	Residential	50	80% silt, 11.3% sand, 9% clay	20	8	**	54.08	-	-
[87]	São Carlos	2.3	N/A	Roadway sidewalk	320	sandy	N/A	0.3	**	100	100	-
	(SP) Brazil	N/A	N/A	Lab. Exp.	100	sandy	N/A	N/A		99.9	-	-
[73]	Cheonan City S. Korea	0.047	100	Parkinglot sidewalk	80	soil, sand, and ash	N/A	1.05	**	88	-	-
[88]	Gold Coast City Australia	6.58	32	Residential area	80	N/A	10	0.4	**	49.5	94.2	-
[74] [1]	Guangzhou China	0.01	N/A	Lab. Exp	55	BSM and different biochar distribution	20	8	0	11.4–16.2	7.4–49.4	-
									20	16.3–29.6	8.6–44.6	-
									40	38.4–59.8	10–50.6	-
[76] [2]	Shaanxi China	0.025	N/A	Lab. Exp	70	BSM	30	5	**	12.6–33.9	20–88.4	-
						BSM, 5% biochar				29.05–70.54	74.6–97.1	-
						BSM, 5% WTR				32.4–61.69	46–87.46	-
[89] [3]	Buštěhrad Czech Republic	0.0038	100	Roof	30	50% sand, 30% compost, 20% topsoil	30	25	**	13	75–97	-
		0.0038	N/A	Lab.Exp				N/A		14	13-34	-

Note: "-" is not evaluated, "**" is not included, and "N/A" is not available in the study. WTR: water treatment residue, BSM: bioretention soil media.[1] The hydrologic performance was assessed for an artificial rainfall event, the performance was assessed for rainfall intensities in the 2-year to 0.2-year return period. [2] The hydrologic performance was assessed for an artificial rainfall event, the performance was assessed for rainfall intensities in the 3-year- to 0.5- year return period for two rainfall durations of 2 and 6 h. [3] The results of the first row refer to natural rainfall while those in the second row refer to a ponding experiment with an influx corresponding to a 5-year return period.

3.2.2. Quality Effectiveness of BRC

The potential of BRCs to reduce pollutant concentrations and/or loads provides a measure of their effectiveness in improving urban stormwater quality. The quality of BRC outflow is highly reliant on all the parameters that influence BRC hydrologic performance. Furthermore, the concentration of contaminants in the inflow is another factor that can affect the BRC's quality efficiency [50,62,90]. The previous section of this review study provided in-depth information concerning BRC hydrological performance and the criteria that influence that effectiveness. Hence, the mechanism and efficiency of BRC performance in reducing the contaminants in urban runoff will be discussed in the following sections. In order to address the second research question, BRC water quality performance will be divided into five subgroups: total suspended solids (TSS), nutrients (N and P species), total heavy metals (Zn, Cu, and Pb), oxygen-demanding substances (COD and BOD_5), and microplastics (MP). The selected pollutant constituents represent the pollutants typically associated with urban stormwater runoff.

Each section aims to outline information on the pollutant sources, the BRC mechanisms involved in treating the pollutant, and the effectiveness of pollutant removal.

The water quality performances of BRCs, as shown in Table S1 included as supplementary material, demonstrate that they have the potential to be one of the most effective LIDs for pollutant removal from urban runoff. It should be mentioned that the water quality data are presented as relative values (i.e., the percentage of reduction rate) and not as absolute values (i.e., the concentration/mass values), considering the differences both in the monitoring programme adopted to collect water quality data, as well as the analytical methods used to detect the pollutant constituents.

Solids

Total suspended solids (TSS) include a wide range of organic and inorganic materials, such as silt, decomposing organic matter, fallen leaves, and debris. The removal of TSS by BRCs is accomplished by the mechanisms of physical filtration of the particulates and colloids during percolation through the soil profile [60,62,91,92].

BRCs are consistently effective in TSS removal, with the removal rate generally exceeding 78% on average. TSS removal is more effective in mature BRCs [50,93]. In this review study, a BRC is assumed to be a mature system when it has been operating for several years. [93] monitored a rectangular BRC for three years from 2012 to 2017 to assess the efficiency of the mature BRC; the average TSS reduction varied from 79% in 2012 to 97% in 2017. Settling and compaction occur naturally during system maturity; therefore, this may explain why TSS removal rates tend to rise with time [93,94]. Similarly, ref. [50] acknowledged that the settling of the soil media and the development of the plants after two years of construction provided a reasonable performance evaluation of the BRC. It is critical to recognize that the TSS may cause a clogging problem, which in turn impairs the BRC hydrologic performance. Ref. [95] investigated TSS removal by examining four bioretention mesocosms with varying media filter compositions and temperatures (ranging from -20 to +20). According to this study, the efficiency of loam and sandy loam to remove TSS was comparable. Notably, although the results of TSS removal in [95] between two types of filter media were equivalent, the media composition in BRCs plays a vital role in TSS removal. Several factors, including porosity and compaction, can explain the influence of the media's composition on TSS removal. In addition, contrary to expectations, [95] showed that the freeze–thaw cycle did not inhibit TSS removal, since TSS removal is primarily a physical treatment mechanism.

BRCs are highly reliable at removing TSS regardless of rainfall depth, ADWP, and influent load quantities according to [62]. Similarly, ref. [91] stated that the intensity of rainfall has a negligible effect on the TSS removal by BRCs. An increase in rainfall intensity causes a higher runoff rate conveyed towards BRCs, resulting in a shorter hydraulic detention time, whereas TSS removal is based on physical mechanisms, such as filtering and sedimentation, which are not significantly influenced by a change in hydraulic detention time. It is essential to note that outflow configurations can impact TSS reduction. In [96], IWS improved TSS removal with a mean removal rate of 98%, while TSS was effectively retained in the BRC without IWS, with a mean removal rate of 90%. It has been found that the reduction in TSS was increased by roughly 8% when IWS was used. There are several causes for this, including decreased macropore development in BRCs with IWS and decreased fine re-suspension, which results in fewer preferred flow paths allowing particles to pass through the filter [96,97].

Nutrients

Nutrients are of great concern in urban stormwater [98]. Stormwater management focuses primarily on reducing nitrogen (N) and phosphorus (P), since excessive concentration of both are linked to ecological consequences such as eutrophication, hazardous algae blooms, and aquatic casualties [60,99].

Nutrients in urban stormwater runoff primarily originate from the wash off impervious surfaces, as well as the atmospheric wet and dry deposition. On the whole, natural (e.g., atmospheric deposition), anthropogenic, and biogenic (e.g., leaf litter and grass clippings) components all contribute to the N and P concentrations in urban settings [66,100].

The studies analyzed for this review study show that the ability of BRCs to remove N and P species differs significantly. Recent advancements in BRC design, on the other hand, have served to lessen this uncertainty. Based on these findings, this review study can infer that the efficiency of BRCs in reducing nutrients has improved, albeit that more study is still needed.

The primary P removal mechanisms within the BRC are precipitation, adsorption, filtration, and plant uptake. P ions can be readily absorbed by several types of soil via ion exchange or ligand substitution [50,96,101]. Filtration allows particulate P to be retained in BRC media [26]. For plant uptake, soluble PO_4 is the most easily accessible P species [102]. The rate of phosphorus uptake by plants is a function of several interrelated factors, including the age of the plant and its root system, the prevailing soil temperature and acidity, and the composition of the filtration media [103].

Based on the above considerations, it emerges that the main factors affecting P removal include the filter media composition and the plant characteristics. Concerning the media composition, ref. [62] demonstrates that BRCs with granules of Fe and Al oxide has a significantly enhanced P adsorption ability. According to [104], pyrite was more effective than zeolite at removing TP by 81.6% compared to 47.5%; furthermore, the stability of pyrite was confirmed after 8 months of monitoring. According to [105], the highest treatment performance for TP (93.7%) was found in iron-coated biochar-amended media, according to the evaluation of various BRC filter media. In the research conducted by [66], 5% of fly ash amendment in BRC filter media resulted in a TP removal rate ranging between 64% and 75% after seven years of construction.

Concerning plants, vegetation plays a key role in determining preferential flow pathways, indeed, [106] showed that the preferential flow patterns observed during the laboratory phase implied a wide range of variation in TP removal efficiency (4–99%). Considering that TSS removal implies particle bound P, BRCs equipped with IWS have a consequent impact on TP removal. This is evident in [74], where study of IWS depths equal to 40, 20, and 0 cm showed TSS removal rates of 93.9%, 81.1%, and 70%, respectively. Correspondingly, the TP removal was equal to 59.5%, 46.6%, and 40.2%. Additionally, because TSS removal and TP removal are closely related, an increase in rainfall intensity does not significantly impact TP removal either [91,92].

In order to treat nitrogen (N) species, several mechanisms within BRCs, such as ammonification, volatilization, nitrification, denitrification, and plant assimilation, usually occur. Ammonification is the transformation of organic N molecules into ammonium (NH_4). The loss of nitrogen from ammonium to ammonia gas is referred to as volatilization. It must be noted that ammonium can be converted to ammonia gas at an alkaline pH (basic);

however, the majority of BRC filter media are characterized by pH values below 7.5 or 8 [56]. Nitrification is a microbiological process in which reduced N molecules (mostly NH_4) are oxidized to NO_2 and NO_3 in a sequential manner [71]. Autotrophic bacteria regulate nitrification, which requires a pH range between 6 and 8 ([107]) and a dissolved oxygen concentration ranging between 0.5 and 5 mg/L ([108]). Nitrification occurs in moist soils, particularly in the oxygenated region around plant roots [54,109] and in other aerobic zones. Under anaerobic conditions, bacteria convert NO_3 to N_2 gas by a mechanism known as denitrification. The root systems of plants are responsible for taking up NH_4 and NO_3 from the soil and using them in the plant's physiological processes.

Similarly to P removal, N removal is greatly influenced by various factors such as filter media and plant features.

Concerning BRC media, amendments such as zeolites, coal slag, vermiculite, and perlite reduce the ammonium concentration by adsorbing NH_4^+ through ion exchange processes. Zeolites have a negative framework that attracts positive ammonium ions. Coal slag and vermiculite bond with ammonium ions chemically, and perlite has a large surface area for physical adsorption of ammonium ions. For instance, zeolite, coal slag, vermiculite, and perlite showed a reliable performance with rate of reduction of 83% of NH_4 [91]. In another study ([62]), boosting the BRC media with the addition of granular Fe and Al significantly increased the performance of the BRC for NO_x reduction [62]. Indeed, Fe and Al can act as adsorbents for nitrogen oxides. Furthermore, carbon source additions such as newspapers, woodchips, compost, biochar, and coconut husk have been widely used to promote N reduction [35,48,92,95]. Soil media qualities, absorption, infiltration, retention, and maintaining a proper plant development all contribute to N removal, which may be accomplished by using carbon amendments [110]. Another important note to mention is that these amendments to media can form tiny anoxic zones for additional nitrification [48].

The denitrification process, important for additional nitrate removal, requires a prolonged retention period. With this aim, BRCs equipped with IWS increase retention time, consequently impacting TN removal [50,54,56,92,111]. For instance, according to [56,95], a deeper IWS has the potential to greatly enhance the removal rates of NO_3, while the removal rate of NH_4 did not increase significantly, since NH_4 removal occurs primarily under aerobic conditions and through soil adsorption processes [71]. The long-term effects of IWS and a conventional outflow configuration has been evaluated in [111], where the NO_x removal was 81% in BRCs with IWS, while in conventional BRCs, the removal rate was only 29%. The presence of organic matter, which serves as a source of energy for the bacteria, and a low-oxygen environment promotes the removal of nitrates from the water and a prolonged retention time, which is present in the IWS zone of bioretention systems. By providing a deeper internal water storage zone, bioretention systems can lengthen the retention time time for denitrification to take place, resulting in an increase in nitrate removal. In this framework, it may be beneficial to add carbon sources as a source of organic matter to promote bacterial growth in the IWS zone and improve plant growth, thus reducing the leaching of N. It is important to note that the amount of carbon sources in the IWS zone should be limited to avoid any clogging effects in BRC media; some research has suggested incorporating between 1% and 5% biochar by volume into the IWS layer [56], and in [56], 5% carbon source (newspaper) was included at the bottom of the BRC in the IWS zone. The impact of hydrologic and hydraulic variables led to the denitrification of NO_3 and the mineralization of organic N during ADWPs, and this contributed to the removal of TN in the form of stored runoff. During a rain event, BRC media are able to absorb NH_4, which is then quickly nitrified or digested by microorganisms during the following dry period. As a result, there is almost no net NH_4 leaching in the BRC. Ref. [62]'s results demonstrated that rainfall depth and peak flow rates are the most important hydrologic factors affecting poor nutrient removal efficiencies by BRCs. This is due to the fact that nutrients, especially if the media is mostly sand [50], can readily bypass the adsorption capacity of the media filter layer and leak out of the soil. The concentration of N in the influent is one of the factors that determines N removal rate; at influent concentrations between 6.15

and 9.61 mg/L, ref. [112] determined that the NO_3 removal efficiency was limited (20.5%). Similarly, ref. [91] showed that influent concentration values between 10.23 mg/L and 14.11 mg/L implied a limited TN removal rate (15%). The input concentration load has a positive effect on adsorption processes because it increases the adsorption capacity of fillers for such pollutants until the fillers are saturated. On the other hand, the denitrification efficiency decreases with increasing input concentration [62,91].

Several studies have shown that the presence of vegetation improves nitrogen removal [54,62,113]. It is worth mentioning that some plant species may accelerate the rate of N species decomposition. For instance, the variability of plants in nutrient removal was studied in [62]. Plant absorption of dissolved N (NH_4 and NO_3) can contribute to pollutant removal to varying degrees depending on the species involved. Recent studies conducted in BRC mesocosms showed that high-biomass plant species, in particular those with deep root systems, may be capable of reducing a significant amount of N from stormwater runoff [54,113].

The maturity of a BRC can affect the removal of N-containing species. Over time, the BRC filter medium is likely to accumulate carbon from plant growth, death, and decay; this carbon acts as a catalyst for denitrification [54,114]. In addition, it is a reasonable point to make that mature vegetation will have a larger root mass than when it was first planted, which may lead to an increase in N removal owing to a larger surface area for nutrient uptake and microbial communities [115]. Seasonal cycling of decaying plant matter into the soil media also provides an optimal environment for nitrogen-fixing microbes [62,104], on the other hand, it contributes to enriching the media in nutrients.

Metals

Heavy metals can be found in large amounts in urban stormwater runoff. Most of these metals come from traffic-related sources such as worn tires, brake linings, engine and vehicle body wear (sources of copper and zinc), atmospheric deposition (sources of copper, cadmium, and lead), and building claddings (sources of copper, zinc, lead, and cadmium) [60,116]. Although low concentrations of some heavy metals such as copper (Cu) and zinc (Zn) are essential to plants, humans, and animals, high heavy metal concentrations are toxic [117]. In contrast, even low concentrations of lead (Pb) may have detrimental consequences [118].

Metals in stormwater may be found in dissolved or particle-bound forms [119], and their partitioning and average concentration values vary greatly from one location to another [120]. However, a variety of factors, including the pH, temperature, and urban paved surface type may influence their partitioning and speciation [121].

Heavy metal removal mechanisms in BRCs include sedimentation, filtration, adsorption, and vegetation assimilation [91,122,123]. Sedimentation and filtration are effective methods for removing heavy metals in their particle forms. In addition, heavy metals in a dissolved form are removed through sorption onto clay and filter media amendments.

In this research, Cu, Pb, and Zn were examined to assess the effectiveness of heavy metal removal by BRCs.

Using a variety of filter media and amendments, six sand-based BRCs with different amendments in [92] were able to remove Cu, Pb, and Zn, with more than 90% removal rates. Likewise, ref. [124] showed that biochar amendment capacity for heavy metals (Cu, Pb, and Zn) is reliable. Although both sand and biochar additives in filter media effectively reduced heavy metal content, biochar impacts should be specifically highlighted. As the concentration of heavy metals in the inflow increased, filter media with biochar performed noticeably better. The reason may be biochar's ability to elevate the pH of the solution, thereby lowering the solubility of metals and increasing their precipitation rate. In addition, biochar's numerous anions, such as carbonate, phosphate, and hydroxide, may promote the adsorption of metals by ion exchange, chemical precipitation, and the complexation of negatively charged functional groups on its surface. This is particularly true for the chemical precipitation of cationic metals.

BRCs are more successful in removing heavy metals from the top filler layer (10–20cm), according to several research works [92,123,124]. This is a result of the quick absorption of heavy metals by the filler and the considerable quantity of TSS retained in the filler's top layer. It is worth noting that the elimination of TSS has a clear correlation with the elimination of heavy metals in BRCs [124].

The removal efficiency of heavy metals in BRCs may also be affected by the presence of vegetation. The effectiveness of bioretention in removing heavy metals depends on factors such as the plant species used, the soil's composition and properties, and other environmental conditions (e.g., climate). The water-holding capacity and nutrient availability of the soil have a significant impact on the qualities of plant roots; hence, it is reasonable to assert that plants frequently play a secondary role in heavy metal removal [73,124,125]. However, further study and analysis are required to identify the role of vegetation (including root structure) in the removal of heavy metals in the context of BRCs. According to [124], increasing the amount of biochar adsorption prevented heavy metals from penetrating further into the filter medium, suggesting that suitable additions to the filter media can enhance the potential of BRCs to impede the transport of heavy metals into the effluent.

Oxygen Demanding Contaminants

Two common water quality criteria may be used to quantify the amounts of organic compounds in stormwater runoff: chemical oxygen demand (COD) and biological oxygen demand (BOD_5). In most cases, the depletion of dissolved oxygen (DO) in streams that should have sufficient DO under ideal conditions may be related to anthropogenic sources of organic matter that increase oxygen demand. Leaf and other yard wastes, pet and animal wastes, fertilizer, sediment containing organic matter (such as topsoil), and hydrocarbons (e.g., oil) are examples of organic matter sources in urban stormwater runoff [60,126].

The four most common mechanisms for removing the COD in BRCs are adsorption, filtration, microbial degradation, and plant uptake [85,92]. In particular, the adsorption mechanism is crucial because it acts as a fast capture mechanism and short-term storage reservoir, paving the way for longer-lasting processes such as biodegradation and plant uptake [127].

BRCs show potential for treating various oxygen-demanding pollutants. After 13 months of field monitoring, the BRC removal rate of BOD_5 was 51% in [85]. Similar outcomes were found in [128], in which the author also kept tabs on three sets of BRCs, two of which had vegetation and one of which did not. The BOD_5 removal rates for the sets with plants were 88% and 87%, whereas the BOD_5 removal rate for the set without plants was 79%. This research demonstrated the importance of plant absorption. However, it is important to note that since plant uptake and biodegradation are slow processes, COD removal rates are highly dependent on the adsorption rate of the filter media [85,92]. According to the outcomes of the study in [92], vermiculite and coal slag were shown to have higher and fairly constant COD removal rates compared to zeolite, volcanic rock, and perlite. This might be attributed to the static adsorption capabilities of particles such as vermiculite and coal slag. The effects of appropriate additives (WTR, vermiculite, and zeolite) were also seen in [88] throughout 9 months of field monitoring, achieving 78% COD removal.

The COD removal rate is adversely affected by a high COD concentration in the inflow. In [91], when the concentration of COD in the input increased from 125 mg/L to 500 mg/L, the removal rate dropped below 20%. These results are comparable to those of an earlier work [86], according to which the adsorption of the filter media was the main mechanism responsible for the short-term removal of COD, despite its limited adsorption capacity. This suggests that on raising the COD influent concentration values, the COD removal rate decreases, exceeding the fillers' maximum adsorption capacity for COD [86,92]. In contrast, the rainfall intensity has a limited impact on the COD reduction rate; increasing the precipitation intensity varied the COD removal rate by just 9% [86]. Mature BRCs are more effective than newly constructed BRCs, for example, [73] found that after 5 years, the studied BRC consistently removed 91% of COD in 23 monitored events.

Due to the pervasiveness of microorganisms in the environment, urban stormwater runoff comprises a vast diversity of them. Fecal indicator bacteria (FIB), with E. coli and enterococci making up the majority of these bacteria, are commonly used to evaluate the possibility of microbial contamination of urban stormwater [129]. Ref. [130] found that urban stormwater had the highest concentrations of fecal contaminants among rural, mixed land use, and urban catchments. The presence of fecal bacteria in urban stormwater runoff poses a concern to human health and is a substantial obstacle to stormwater reuse. Pathogen microorganisms enter runoff from a variety of sources, including sewage leaks, animal waste, and human waste. It is generally known that the amount of fecal indicators and total bacterial cells in urban stormwater runoff is affected by land use and the seasons [131,132].

The two fundamental processes in BRCs to remove pathogen microorganisms from urban stormwater are physical straining and adsorption [54,85]. Given that the cell diameter of these organisms is less than 5% of the sand particle diameter, straining would be ineffective. In [85], the evaluation of the BRC's effectiveness in removing E. coli showed an average reduction rate of 49%.

Microplastics

Microplastics (MPs) negatively affect the environment and human health owing to their chemical properties, prolonged existence, toxicological effects, and bio-accumulation characteristics [133,134]. MPs are defined as plastic particles of 100 nm to 5 mm in diameter and include intentionally produced MP beads (primary MPs) or fragments from degraded plastic products (secondary MPs) [134]. It has been determined that urban stormwater runoff, with MP concentrations ranging from 0.4 to 191 p/L (particles per liter), is the principal route for MP entry points into waterbodies [93,135,136]. The principal sources of MPs in urban stormwater runoff include tire particles (in high numbers [137]), artificial turf, air deposition, industrial paved surfaces, and litter [134]. Moreover, face masks are also a significant source of MPs following their widespread use after the outbreak of COVID-19 [138,139]. There is heterogeneity in MP concentrations because the sources of MP are not uniform across land uses.

After highlighting the significance of considering MPs in urban stormwater, the BRC mechanisms for reducing MPs will be outlined. Physical filtration and soil–media interactions both contribute to the reduction of MPs by BRCs [93,135,136]. Notably, filtering has been identified as the principal process for reducing MPs [135].

The effectiveness of BRCs in reducing MPs has not been thoroughly investigated; nevertheless, initial studies have given positive results. The lack of sufficient MP studies precludes the comprehensive assessment of the BRC performance in removing MPs.

According to [135]'s investigation carried out during a two-year monitoring phase, the studied BRC achieved a concentration-based decrease in MPs of 84% and a load reduction of >92%. Ref. [136] found that MP particles in the range of 100 to 300 µm could be effectively removed by a BRC, the average particle concentration was reduced from 12 to 1.4 p/L.

Keeping in mind that BRCs are better able to retain bigger particles of MPs, although based on solely three monitored storm events, [93] found an efficiency of 100% for MPs with size fractions of >500 µm, 81% for particles between 355 and 500 µm, and 55% for particles between 125 and 355µm.

In the framework of the present review, only one work was found that evaluated the MP removal efficiency of BRCs in the range of 20 to 100 µm [140]; MP particles between 20 and 100 µm in size were not significantly reduced by the sand filter. In contrast, rubber and bitumen particles in the 100 to 300 µm size fraction were efficiently removed by the BRC.

3.3. Numerical Modeling of BRC

Numerous field and laboratory studies (see Sections 3.1 and 3.2 for references) have demonstrated that bioretention cells (BRCs) improve the hydrologic performance and water quality of urban stormwater; consequently, BRCs have gained widespread acceptance among practitioners, researchers, and communities. Despite BRCs' apparent promise, their modeling has received remarkably little attention. The present review study will explore only a few of the numerous compelling reasons that highlight the importance of BRC modeling in the investigation, design, implementation, and evolution of BRCs.

- Before implementing BRCs, it is essential to model them in order to predict their hydrologic and quality performance under various situations. The use of models makes it possible to simulate BRC performance by varying local conditions such as climate variables (e.g., temperatures and precipitation), vegetation, and other territorial specifics. Researchers employ models on the site scale to overcome the limitations in doing fieldwork and to explore more problems than they could assess by monitoring. In particular, when BRC performance is evaluated in a controlled environment, such as a laboratory, those results can be transferred to the field scale using models.
- To date, almost all studies of BRC efficacy have been undertaken on the site scale (including laboratory experiments), while the impacts of BRCs on the catchment scale have received relatively less attention. Indeed, the effects of implementing several BRCs in a catchment, as well as the optimum placements for these BRCs, can be determined with the use of BRC modeling.
- Modeling allows researchers to comprehend the complex internal dynamic mechanisms associated with the movement of water and the fate, transport, and retention of pollutants within a BRC [141].

Based on such considerations, both the quantity and quality modeling of BRCs are required for substantiated findings, even if in such modeling studies, the hydrologic and hydraulic aspects of BRCs have been emphasized over the quality behavior. In Tables 5 and 6, the most relevant quantity studies are reported, focusing on the analysis at the site scale and at the catchment scale, respectively, while the quality studies are reported in Table 7.

Tables 5–7 report the site characteristics, including the location and spatial scale; the modeling features, including the program type and calibration phase; the simulation conditions; and the simulated variables for each study. By analyzing the program type, it emerges that the US EPA's Storm Water Management Model (SWMM), which was utilized in 38% of all the studies analyzed in this review study (35% of all the ones listed in the tables), was the most widely used model for modeling studies; followed by HYDRUS-1D or HYDRUS 2D/3D with 8% (11% of all the ones listed in the tables) and RECARGA with 4% of all the studies analyzed in this review study. Other models such as the source load assessment and management model for Windows (WinSLAMM), the model for conceptualizing urban stormwater improvement (MUSIC), the green infrastructure flexible model (GIFMod), DRAINMOD (by the NC STATE University), MIKE URBAN (by DHI), and other specifically developed algorithms were used.

Concerning the quantity, modeling tools generally involve the following hydrologic variables: inflow, outflow, and drainage. For specific applications, the simulations also concern soil moisture, lateral flow, ponding depth, and water table. Concerning the quality, models reproduce the mass and effluent concentration of the following pollutants: TSS, TP, and TN. A more detailed modeling analysis allows to predict the nitrogen speciation (NO_3-N and NH_3-N), the dissolved fractions (DRP and DOC), TOC, and metals (Cu, Zn, and Cd).

When taking into account the temporal scale of the modeling, a high-resolution discretization (1-minute intervals) is required to suitably predict the evolution with time (hydrograph) of the hydrologic variables [142], rather than simply simulating the cumulative values (volumes) on the daily, event, monthly, or annual scales [143]. Indeed, with low-resolution time steps, the modeling loses part of the temporal dynamics of the BRC system during storm events and becomes incoherent with the concentration times of urban catchments. Therefore, a high-resolution discretization is essential for investigating the event-based performance of BRCs, including, at the catchment scale, the assessment of the urban flood mitigation [144,145]. Parallelly, continuous long-term simulations at various time steps can provide insight into the hydrologic variables, such as the flow duration curve [144], improve the understanding of BRC biogeochemical reactions and physical processes [146], and are essential in defining operation and maintenance conditions [147].

Quantity modeling studies on the site scale acknowledged that the SWMM can be used to simulate BRCs [148–150]; however, the SWMM calibration optimizes one single variable and the IWS representation should be improved [150]. Specific developed algorithms and/or other programs, such as HYDRUS, HM-RWB, and RECHARGE, can provide more accurate estimates of the involved hydrologic processes [86,151,152], especially when the calibration involves more variables [153] or includes the drainage flow [150]. Modeling results on the site scale supports the definition of configurations that improve the BRC hydrologic performance [154], defining optimal media characteristics and IWS and ponding depths, including a cost analysis [86], and taking into account the groundwater dynamics that occur at the site [152].

Quantity modeling studies at the catchment scale, eventually calibrated at the site scale for a single BRC installation [144], can support the selection of the optimum extent (aerial coverage) of BRCs based on a single objective or multiple objectives including a cost analysis [145]. It is crucial to highlight that different modeling studies on the catchment scale are focused on determining how combined LIDs [144,155] may contribute to improving the management of stormwater runoff rather than on concentrating solely on BRC implementation.

Quality modeling encompasses a huge number of parameters with various degrees of uncertainty. For instance, several pollutants, both soluble and particulate, may interact with or be modified by microbial degradation mechanisms in BRCs; therefore, models should reproduce nonlinear biogeochemical reactions and associated physical processes affecting them. However, numerical tools on this are still limited. Consequently, quality modeling has its own difficulties, and existing models predict stormwater quality with less reliability than stormwater quantity [141,156], even if several studies (e.g., [149,157]) have highlighted the importance of accurate hydrologic modeling in making reliable predictions of BRC quality performance. In the modeling study of [157], the calibration and validation of TSS reduction by BRCs has been performed, in addition to the hydrograph inflow and outflow. In this study, a developed SWMM add-in tool was implemented to predict the BRC performance in TSS reduction and bench-marked against the TSS removal predicted by WinSLAMM. In the investigation conducted in [158], HYDRUS-1D was used to model BRC performance using calibration and validation data for contaminants including COD, NO_3-N, NH_3-N, TN, TP, Cu, Zn, and Cd with fairly good performance. For instance, the average NSE for COD calibration was 0.57, while the NSEs for NO_3-N, NH_3-N, and Zn were 0.60, 0.66, and 0.65, respectively. However, in [146], a 95% confidence interval of the reproduced water quality metrics was wider than the findings for quantity modeling due to the greater uncertainty in the parameters and the lower number of observed data points in comparison to the number of model parameters.

Modeling results for both quantity and quality variables support the optimization of BRCs by pointing out design characteristics that mostly affect the system behavior and efficiency. [146] found that the effectiveness of BRCs may be affected by the IWS height, the filter media depth, and the size of the contributing drainage area, while [153] performed a sensitivity study to determine the effects of changing the saturated hydraulic conductivity on BRC performance. Ref. [146] revealed that the effect of IWS on N load reduction was between 10 and 20%, and considering the minimal cost of implementing IWS, indicated that it was a desirable practice. Due to the higher HRT and duration of anoxic conditions in engineered soil media and aggregate layers, IWS was found to have a more apparent influence on water quality component load during moderate and small occurrences, but not during large events. Increasing the media layer's thickness had comparable consequences to increasing the IWS's height. Additionally, it was also shown that doubling the contributing catchment area considerably decreased the volume reduction efficacy of the bioretention system.

Table 5. Modeling studies of the hydrologic processes in BRCs on the site scale. For each study, the site characteristics, including the location and spatial scale, are reported together with the modeling features, including calibration phase, simulation conditions, and modeled variables.

Reference	Location	Spatial Scale	Program	Calibration	Simulation	Hydrologic Variables	Highlights
[149,150]	Cleveland (OH, USA)	Site scale (3600 m^2)	DRAINMOD-Urban SWMM	Y	Individual events (1-min time step)	Outflow, overflow, drainage	DRAINMOD-Urban calibration improves both volumes and hydrographs; the percolation is predicted with a physically based equation considering the unsaturated flow. The SWMM calibration optimizes one single variable. The IWS representation should be improved.
[159]	Melborne (Australia)	Site scale (1800 m^2)	R Algorithm	Y	Individual events (6-min time step)	Outflow, overflow, infiltration, drainage, water level	The model is based on storage in series, accounting for the water balances in storage and water fluxes exchanges between storage. The model is not able to reproduce empty initial conditions.
[160]	Singapore	Site scale (280 m^2)	RECHARGE	Y	Individual events (1-min time step) Continuous (0.5-year long)	Surface and subsurface outlets, soil moisture, ponding depth	Simulation results support the definition of configurations that improve performance efficiency.
[85]	McAllen (TX, USA)	Site scale (1618 m^2)	WinSLAMM	Y	Individual events	Runoff	The calibrated model suitably reproduces the outflow runoff volume. A cost analysis is available.
[148]	Istanbul (Turkey)	Laboratory scale (40 m^2)	HM-RWB	Y	Individual events	Runoff, infiltration, drainage	The model accuracy is better with respect to SWMM simulations, the accuracy is also evaluated for drainage flow.
[153]	Cleveland (OH, USA)	Laboratory scale (48 m^2)	HYDRUS 2D/3D	Y	Continuous (500 days long)	Drainage, ponding depth, water table depth, soil water content	The model is able to describe the ground water dynamics that occurred at the site. The model sensitivity to key parameters, including the saturated hydraulic conductivity for soil layers within and around the BRC, is examined.

Note: Y/N in the calibration column refers to whether the calibration phase was performed/not performed.

Table 6. Modeling studies of the hydrologic processes in BRCs on the subcatchment scale, eventually including model calibration at the site scale for a single BRC installation. For each study, the site characteristics, including the location and spatial scale, are reported together with the modeling features, including the calibration phase, simulation conditions, and modeled variables.

Reference	Location	Spatial Scale	Program	Calibration	Simulation	Hydrologic Variables	Highlights
[142]	Oslo (Norway)	Site scale (100 m^2) Sub-catchment scale (50 ha)	MIKE Urban (MU)	Y N	Individual events (1-min time step) Continuous (1-year long)	Outflow FDC [1]	A sensitivity analysis of RG parameters was carried out. The simulations for FDC do not account for evapotranspiration. The model predicts the efficiency of different degrees of implementation of NBS (seven scenarios).
[161]	Guangzhou (China)	Sub-catchment scale (5000 m^2)	SWMM	N	Individual events	Outflow	Model results, including a cost analysis support, the definition of the optimum extent (aerial coverage) of BRCs in the catchment based on a single objective (i.e., outflow volume or peak flow reduction) or multiple objectives.
[162]	Beijing (China)	Catchment scale (651 km^2)	SWMM	N [2]	Individual events	Runoff, flood volume	Model results have been paired with an LCA cost analysis to evaluate an integrated LID strategy to mitigate urban flooding.

Note: Y/N in the calibration column refers to whether the calibration phase was performed/not performed. [1] FDC: flow duration curve. [2] The model calibration involved the runoff at the outlet section of the catchment, no calibration has been carried for the BRCs.

Table 7. Modeling studies of BRCs including quality processes at the subcatchment scale, eventually including model calibration at the site scale for a single BRC installation. For each study, the site characteristics, including the location and spatial scale, are reported together with the modeling features, including the calibration phase, simulation conditions, and modeled variables.

Reference	Location	Spatial Scale	Program	Calibration	Simulation	Hydrologic Variables	Quality Variables	Highlights
[151]	Punggol (Singapore)	Site scale (480 m^2)	MUSIC	Y	Individual events (5-min time step)	Outflow rate and volume	TSS, TN, TP	The quantity module was not able to predict different inflow in dry/wet conditions. The treatment modules were able to simulate outflows and effluent pollutant concentrations.
[146,147]	Cincinnati (USA)	Site scale	GIFMod	Y	Continuous (3 years long)	Inflow, outflow, drainage	TP, DRP [1], TN, NO_3^-, NH_3, TOC, DOC, TSS, VSS	GIFmod allows for the incorporation of nonlinear biogeochemical reactions and the associated physical processes affecting them.
[158]	Xi'an (China)	Site scale	HYDRUS-1D	Y	Individual events (15-min time step)	Inflow, outflow, drainage, soil moisture	COD, NO_3-N, NH_3-N, TN, TP, Cu, Zn, Cd	The model can simulate 1D vertical water and solute transport ignoring lateral transport. Model results support the optimization of BRC facilities.
[157]	Woodbridge, (ON, Canada)	Site scale (297 m^2)	SWMM	Y	Continuous (4 months long)	Inflow, outflow	TSS	The SWMM add-in tool is able to suitably predict the TSS reduction.
[28]	Hong Kong (China)	Site scale (5000 m^2)	SWMM	N	Continuous (9 years long)	Inflow, outflow	First flush	Model results define an optimization problem (single and multi objective).
[144]	Cul-de-sac (Sint Maarten, Caribbean)	Sub-catchment scale (2.4 km^2)	SWMM	N	Individual events Continuous (20 days long)	Outflow	TSS, TN, TP	Different combinations of NBS are modeled. Continuous simulation is essential to define operation conditions.

Note: Y/N in the calibration column refers the performed/not performed calibration phase; [1] DRP is Dissolved Reactive Phosphorus.

4. Research Needs

Even if BRC performance has recently improved, further research is still required, especially in system optimization, including design recommendation, long-term performance assessment, emerging pollutant treatment efficiency, and model validation.

Concerning the system optimization, future research should be addressed to the optimal media composition. The properties of the media influence both the quantity and the quality of BRC urban stormwater management performance. Therefore, significant care must be taken while selecting a BRC medium with appropriate long-term permeability, suitable hydraulic characteristics, and the ability to support plant growth. It is suggested that appropriate additives should be used to make the BRC media more effective in pollutant abatement. Moreover, additives that can be made from a variety of waste products and that support eco-friendly waste management are strongly recommended. However, further study is required before additives can be used effectively. This includes determining the best sort of admixture, how to best distribute it throughout the filter media, and how long it will last. Conventionally built BRCs have a significant water infiltration rate, leading to a short retention duration. This provides limited possibilities for dissolved pollutants, including trace organic contaminants, to undergo transformation during a runoff event. Adding an appropriate additive will improve the elimination of organic pollutants because their characteristics, such as large surface area and porosity, could combat the problem of short retention time. In addition, the configuration of the underdrain can be modified through the installation of IWS in order to address this issue; however, further research is required on the IWS design, including its depth, and the addition of an appropriate quantity of carbon source to the BRC bottom (in the IWS zone). On the other hand, more research is needed to determine how existing BRC systems might be altered to increase treatment efficiency while still providing sufficient hydrologic performance.

Particular attention should be paid to the design of the outlet section; in particular, the automated control of the system is an emerging area of research. The reduced flow outlet valve, which prolongs the time that water stays in the filter medium, provides outstanding hydrologic and quality performance. This encourages water to leave the filter medium from the sidewalls and the bottom of the cell, creating a more suitable environment for treating contaminants such as N species. More research is necessary to determine how the presence of a valve, as well as variations in valve design and placement, affect the underdrain, which has the potential to provide versatile control of BRC hydrology and quality. In situations where BRCs can be inspected and maintained regularly, these valves can be operated manually. Alternatively, they can be automated and controlled remotely. Although automated control of stormwater BRCs is appealing, it has yet to be demonstrated to be feasible, cost-effective, and dependable in actual use.

There are comparatively few long-term research studies in the BRC field. Consequently, the real performance of BRC components during an extended period of field operation is unclear. Regarding the long-term effects, studies on the effectiveness and longevity of BRCs are scarce. There is a paucity of long-term modeling of BRCs under various climatic and design situations [141]. More research with bigger datasets (calibration and validation) must be undertaken to strengthen statistical results, particularly for quality modeling and overflow occurrences.

The efficacy of BRCs in treating MP concentrations has not been thoroughly investigated. To produce a more definitive performance assessment and to enable comparisons of different BRC performances, studies should be performed in various geographical regions with varying media composition and design. Furthermore, as nano-plastics are a growing concern, research on BRC's effectiveness for filtering particles smaller than 100 μm is required.

Although there are a number of BRC modeling programs available, validated models are required to assess hydrologic performance and nutrient removal. Requirements for future models include the integration of plant growth and root growth over time, the modeling of the temporal fluctuation in soil characteristics, the validity of soil parameter estimates, and the modification of drainage designs. Future model development should account for the fact that the performance of BRCs evolves over time in order to more accurately represent the long-term performance of BRCs.

5. Conclusions and Recommendation

BRCs are an effective solution for controlling urban stormwater, according to this systematic review. BRCs are one of the most successful LID approaches for limiting the hydrologic effects of fast urbanization and enhancing the water quality in urban settings. Several knowledge gaps impede the advancement of BRCs in the context of managing and treating vast quantities of urban stormwater with variable characteristics. The key design recommendations for BRC implementation that have been addressed in the selected studies are summarized and discussed below.

- The IWS design has several advantages; however, IWS installation requires careful consideration. First, the top of the IWS should not be closer than 30 cm to the medium's surface and should not be lower than 30 cm above the cell bottom [77,163]. In addition, for sandy sites, it is recommended that the IWS outlet be 30 cm from the surface of the medium, whereas for clay sites, this value might vary between 47 and 60 cm. The reason for the suggested distance could be the plants' ability to survive [155]. The plants in a BRC can be damaged by a long duration of saturated soil conditions. A vadose zone (free draining depth) of at least 30 cm is necessary at the top of the cell to enable appropriate root growth. Additionally, if the IWS takes up too much of the soil medium layer, there is a chance that organic matter or nutrients might leak out through the underdrain [77,155,163].
- The composition of the medium plays a crucial role in both hydrological and water quality effectiveness. The exact ratio of these components will vary depending on local conditions, but a typical mix may consist of 40–60% silty loam, 30–50% sand, and 10–30% organic matter. In some cases, other admixtures can be added to the mix to improve water holding capacity, increase retained moisture, and promote plant growth. In addition, adding suitable additives can enhance the water quality performance of BRCs. For instance, adding a carbon source can be an effective method for enhancing the performance of bioretention systems, but the source and amount of carbon added should be considered carefully.
- The filter medium depth is a critical design variable. According to studies, 20–50% of the runoff entering BRCs was lost owing to exfiltration and ET [77]. In a field study, researchers found that a deeper fill medium allowed for more exfiltration and less outflow [77]. The results of another study [50] suggest that dead volumes occurred because the entire BRC was not used for storage. To decrease dead volumes and increase interaction inside the BRC, increasing the medium depth is one strategy. A deeper medium, on the other hand, may increase excavation expenses and affect groundwater levels, causing a BRC to fail. Therefore, the medium depth should be carefully designed by considering factors such as the minimum distance between the bottom of the BRC and groundwater level, the project's cost-effectiveness, and the medium's composition.
- The issue of clogging, which is the limiting factor in BRC long-term performance, has to be considered. Clogging can be classified as either happening at the surface or within the medium. When stormwater runoff has a high concentration of fine and silt particles, surface infiltration can be hindered, which can have an adverse effect on the hydrologic performance of BRCs and cause them to be undersized. In addition, the physical, chemical, and biological processes inside the filter medium may be constrained, resulting in a decrease in the hydrologic and quality performance of the BRCs [77,152]. Using appropriate additives, clogging of the filter medium can be limited. To prevent clogging and deterioration of bioretention performance,

ref. [164] recommends replacing BRC media every 5 to 10 years, without taking into consideration the function of plant roots.

- Vegetation for BRCs is usually chosen for its resilience in the face of adversity, its esthetic appeal, and its local availability. In most cases, plants are not evaluated based on strict performance criteria for their ability to remove specific contaminants and deal with hydrological processes. In order to select the vegetation for a BRC, it is essential to consider the following criteria: the plant should be native, have a high phytoremediation ability, have significant above-ground biomass, have thick and widespread roots, require minimal care or fertilizer, be able to resist dry conditions, and offer a habitat for a variety of microorganisms.

Despite the fact that this promising practice may represent the greatest effort to restore the hydrology of urban areas and improve the water quality of stormwater, with additional advances in the development of BRCs, its performance in terms of quantity and quality will become more reliable, thereby contributing to the establishment of long-term solutions to stormwater urban drainage problems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15050913/s1, Table S1: This study is an evalutaion of the Maturation of the BRC's effectiveness ((2007–2008)(first bullet) (2013–2014) (second bullet)).

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