



Review

The Common Approaches of Nitrogen Removal in Bioretention System

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Abstract: Bioretention is considered one of the best management practices (BMPS) for managing stormwater quality and quantity. The bioretention system has proven good performance in removing total suspended solids, oil, and heavy metals. The nitrogen (N) removal efficiency of the bioretention system is insufficient, however, due to the complex forms of nitrogen. Therefore, this paper aims to review recent enhancement approaches to nitrogen (N) removal and to discuss the factors influencing bioretention efficiency. To improve bioretention efficiency, several factors should be considered when designing bioretention systems, including nitrogen concentration, climate factors, and hydrological factors. Further, soil and plant selection should be appropriate for environmental conditions. Three design improvement approaches have been reviewed. The first is the inclusion of a saturated zone (SZ), which has been used widely. The SZ is shown to have the best performance in nitrogen removal. The second approach (which is less popular) is the usage of additives in the form of a mixture with soil media or as a separated layer. This concept is intended to be applied in tropical regions with wet soil conditions and a short dry period. The third approach combines the previous two approaches (enhanced filter media and applying a SZ). This approach is more efficient and has recently attracted more attention. This study suggests that further studies on the third approach should be carried out. Applying amendment material through filter media and integrating it with SZ provides appropriate conditions to complete the nitrogen cycle. This approach is considered a promising method to enhance nitrogen removal. In general, the bioretention system offers a promising tool for improving stormwater quality.



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1. Introduction

Urbanization and population growth are rapidly increasing with 7.2 billion people in the world, and more people are living in cities rather than in rural areas [1]. The expansion of impervious areas causes an increase in flood events and negatively affects stormwater quality. The issue of stormwater quality has received considerable attention and is known as the primary source of ecological contamination. To make matters worse, impervious areas, including streets, rooftops, car park areas, and buildings, affect stormwater quality by impeding the natural process of filtration through ground layers. Figure 1 shows stormwater precipitation (rainfall and snowmelt), whereby in a natural situation, a small amount of rainfall flows as surface runoff. In the case of an urban situation, a large amount of rainfall is converted to surface runoff [1]. Rain runoff passing over impervious surfaces carries pollutants from human activities before eventually reaching the groundwater by infiltration and settling in rivers, wetlands, lakes, etc. Runoff flow on impervious surfaces containing accumulated pollutants leads to nonpoint source pollution [2]. Therefore, nonpoint source pollutants caused by stormwater runoff are one of the main challenges of stormwater management [3].

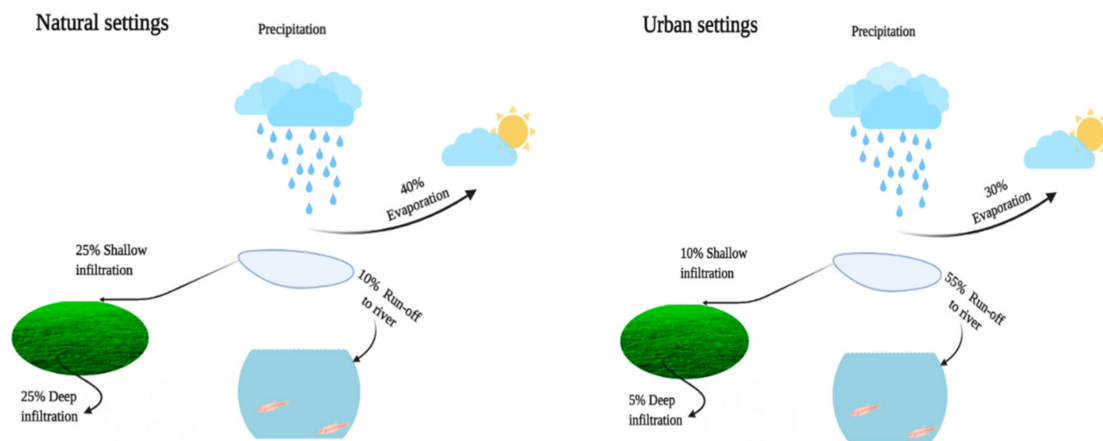


Figure 1. A comparison between the surface runoff of natural and urban surfaces.

Pollutants in stormwater runoff are classified into gross pollutants and dissolved pollutants [4]. Gross pollutants comprise agricultural and industrial wastes such as paper, bottles, plastic bags, leaves, and others [5]. Dissolved pollutants, on the other hand, contain nutrients, heavy metals, and hydrocarbons [6–8]. The dissolved form accounts for half of the pollutants in stormwater [7]. Existing pollutants in stormwater runoff such as nitrogen (N) have a harmful impact on the ecosystem, which leads to a decline in aquatic species, eutrophication, and harmful algal blooms [9]. Therefore, it is essential to decrease these nutrients in the stormwater runoff for environmental quality and water reuse [10].

Nevertheless, removing nitrogen (N) from stormwater poses a great challenge [11]. The removal of N would cost billions of dollars [12]. Thus, it is important to find cost-effective and environmentally sustainable solutions to mitigate the nitrogen threat to the ecological system. The stormwater management system is used worldwide to control stormwater quality and quantity. The main aim of stormwater management is the elimination of pollutants and runoff quantity [13]. Stormwater pollution can be reduced by applying advanced approaches such as Low-Impact Development (LID) and Best Management Practices (BMPs). In recent decades, these practices have attracted urban planners and city managers [14,15]. Some of these practices have been used to increase pervious surfaces and enhance rainfall infiltration. In the United Kingdom (UK), such a practice is employed in the Sustainable Urban Drainage System (SUDS). The Sustainable Urban Drainage System (SUDS) is divided into twelve types, namely (1) grassed swales, (2) infiltration trenches, (3) permeable pavements, (4) wet ponds, (5) bioretention zones, (6) tree boxes, (7) sand filters, (8) constructed wetlands, (9) soak ways, (10) infiltration basins, (11) extended dry detention basins, and (12) rain barrels and cisterns [16]. These devices must be maintained from time to time to achieve the best results. A similar concept is used in the US and Australia, namely Low Impact Development (LID) and Water Sensitive Urban Design (WSUD), respectively. Studies revealed that the effectiveness of most devices of LID will decrease over time if maintenance is neglected [17,18]. Lindsey et al. [17] tested the efficiency of different kinds of practices (infiltration trenches, infiltration basins, vegetated swales, dry wells, and porous pavement), and their study revealed that infiltration basins and porous pavement were shown to be less effective and needed more maintenance compared to dry wells and trenches. Moreover, maintenance is essential in tropical and subtropical countries to avoid diseases [19]. In Malaysia, the Department of Irrigation and Drainage (DID) has introduced the Urban Stormwater Management Manual (Manual Saliran Mesra Alam) 2012 [20]. The Manual was designed based on three primary pollutants characterizing runoff water, which are gross pollutants, total suspended solids (TSS), and nutrients, and particularly, total nitrogen (TN).

The bioretention system is one of the most favorable and frequently used in SUDS. It plays a key role in the degradation of stormwater pollutants, including suspended solids, heavy metals (zinc, lead, etc.), phosphorus, nitrogen, and oil [21–23]. The bioretention

system is considered a favourable technology in terms of cost and effectiveness in removing pollutants. Additionally, this technology provides an aesthetic view. A field test comprising a combination of bioretention and swale was conducted in Hubai, China [24]. The results indicated that the stormwater peak flow reduction of a bioretention cell was more significant than the swale. The bioretention system is considered a promising tool to enhance stormwater quality [16,25].

Nevertheless, previous studies have demonstrated that a traditional bioretention system has not achieved good nitrogen removal, especially for nitrate (NO_3) [26,27]. Understanding the complexity of a bioretention system is paramount for developing bioretention guidelines [28]. Although the performance of bioretention systems has been surveyed in many review articles [4,28,29], the popular approaches of nitrogen removal are yet to be adequately covered. Thus, this study was introduced to provide a clear view for researchers about the enhancement methods for nitrogen removal in bioretention system.

2. Overview of Bioretention System

Biofilters, which are also known as rain gardens or bioretention systems, are commonly adopted best-management practices (BMPs) [30]. In recent years, they have elicited more attention not only due to their stormwater quality and quantity management ability [31–33] but also because of the benefits they have for human health and the ability to mitigate the heat island effect [34,35]. Biofilters provide a cooling climate by means of evapotranspiration. A bioretention cell includes several items from bottom to top: gravel, sand, soil, and mulch, as well as plant species [13,31,36]. Stormwater is treated via a bioretention system through several processes. These include physical infiltration and retention; chemical adsorption and sedimentation; and biological plant uptake and microbial activity [37]. Figure 2 illustrates the various components of a traditional bioretention system.

The bioretention approach is a sustainable solution which may be applied to either individual or regional systems [38]. However, conventional bioretention systems are insufficient for removing nitrogen [39]. A lacking denitrification process results in nitrogen removal being unstable and widely variable in the bioretention system, particularly for nitrate (NO_3). Nitrogen removal is considered the main challenge encountered by bioretention designers [39–41]. Davis et al. [30] conducted a laboratory study on the performance of traditional bioretention systems on nutrient removal. The results showed the reduction of total Kjeldahl nitrogen (TKN) and ammonium (NH_4) to be 60% to 80%, while export nitrate (NO_3) was observed in some cases. The results of the field study undertaken by L. Li and Davis demonstrated that particulate organic nitrogen (PON), ammonia (NH_3), and nitrite (NO_2) were effectively removed, while leaching in dissolved organic nitrogen (DON) and nitrate (NO_3) was observed [42]. Recently, different enhancement methods have been applied to achieve good nitrogen removal [11,43,44]. For example, it has been observed that the conventional system was less efficient than the modified media system with TN removal 56.6% and 61.3%, respectively [7]. Inclusion of a saturated zone in bioretention system provides a better environment for the nitrogen cycle, thereby reducing effluent TN, while the leaching of nitrate still exists due to the ammonification of organic nitrogen which produces nitrate [11]. The efficiency of the conventional bioretention system in mitigating nitrogen depends on design factors, including the ratio of the bioretention surface area to the drainage area (SA/DA), filter media compositions, pollutant concentration, vegetation, and environmental factors [7,31]. Table 1 provides an overview of several studies on the conventional bioretention system, the efficiency of the bioretention system, and the disadvantages of each survey.

Table 1. The literature on the conventional bioretention system.

Plant	Soil Description	Cell Depth (mm)	Study Type	Study Description	Disadvantage	Results	Site Location	Ref.
Creeping juniper plants	Sandy loam	610 910	box prototypes Small (1070 × 760) Big (3050 × 1520) mm	Indicate which soil layer is more nutrient removal by port soil sampling	Data nitrate removal of small box not available due to the experiment problem.	Increasing TKN removal with soil depth and high removal in the lower layer, Export NO ₃ in the upper layer and poor NO ₃ removal in lower soil depth.	USA	[30]
No	Fine sand, sandy loam	1000	Column (1050 × 100) mm	Testing pollutant concentration in soil depth	Clogging in fine media due to absence of vegetation and the need to maintain the top layer of media.	Significant N removal in top 200 mm soil depth and leaching in lower layers due to native soil wash.	Australia	[45]
Banksia (<i>Banksia integrifolia</i>), Bottlebrush (<i>Callistemon pachyphyllus</i>), Pigface (<i>Carpobrotus glaucesens</i>), Flax Lily (<i>Dianella brevipedunculata</i>), Swamp Foxtail Grass (<i>Pennisetum alopecuroides</i>)	Three soil configurations: Gravel, sand, sandy loam	1000	Mesocosm (1000 × 500 × 500) mm	Test ability of different soil media to remove nutrient	Planted sand and planted sandy loam are the best in nitrogen removal than other types.	Planted sand and planted sandy loam are the best N removal without adding a carbon source	Australia	[46]
Foxtail Grass (<i>Pennisetum alopecuroides</i>), Flax Lily (<i>Dianella brevipedunculata</i>), Banksia (<i>Banksia integrifolia</i>), Bottle-brush (<i>Callistemon pachyphyllus</i>)	Sandy loam, loamy sand and pea gravel and 200 mm loamy sand	990	Mesocosm	Determine which media type has good nutrient removal and interaction it with vegetated and non-vegetated condition	TN retention in vegetated systems exceeded plant uptake. This happened with other processes which are have not mentioned in this study.	NOx removal can happen despite the absence of anox condition and soil microbial activity can do nitrification. Planted loam system is the best TN removal.	Australia	[37]

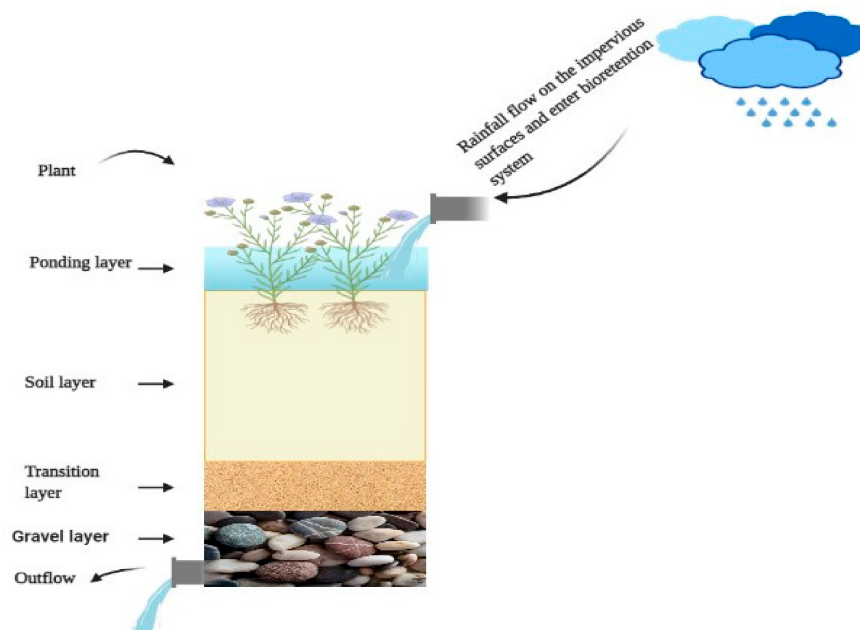


Figure 2. Traditional bioretention system.

2.1. Nitrogen Removal Process in Bioretention System

Total nitrogen (TN) includes dissolved organic nitrogen (DON), Ammonium (NH_4), Nitrate (NO_3), Nitrite (NO_2), and particulate organic nitrogen (PON) [47]. The main transformation processes of nitrogen in bioretention system occur through assimilation, adsorption, ammonification (mineralization), nitrification, and denitrification [4,25]. In the assimilation process, inorganic nitrogen forms (NH_4 , NO_2 , NO_3) are converted into an organic form in the plant biomass through plant uptake [48]. The adsorption process removes the NH_4 form through soil media. Nitrification (aerobic condition) is the biological oxidation of ammonium to nitrite and nitrate. The converted NO_3 from nitrification and runoff is transformed into nitrous oxide (N_2O), nitric oxide (NO), and dinitrogen gas (N_2) via the denitrification process (anoxic condition) [49]. Microorganisms play a vital role in nitrification and denitrification reactions. Many environmental conditions are required to achieve the denitrification process through soil media. These conditions include available N, organic carbon, sub-toxic or anoxic conditions, and available denitrifiers [50]. The denitrification process removes about 33.5% of dissolved nitrogen [51]. The stormwater should flow through the aerobic and anaerobic zones with adequate retention time to complete each process [29]. The incomplete denitrification process is the reason for the leaching and instability of N removal [23]. Figure 3 shows the nitrogen removal process in the bioretention system.

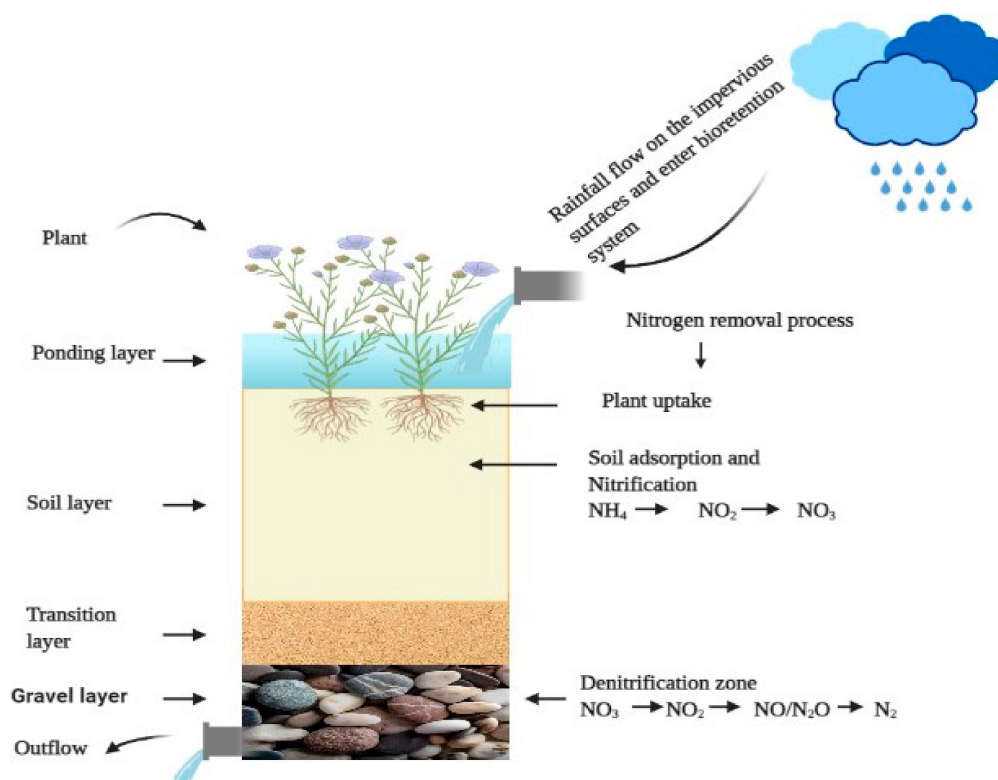


Figure 3. The nitrogen removal process in the bioretention system.

2.2. Performance of Bioretention System

One of the main issues of stormwater is non-point source pollutants caused by stormwater runoff passing over impermeable surfaces (parks, buildings, roads). The concentration of non-point source pollutants is one of the main factors affecting the performance of bioretention. The common pollutants that characterize stormwater include total suspended solids (TSS), total nitrogen (TN), ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), and total phosphorus (TP). These pollutants are significantly affected by geographical features of the location along with meteorological (rainfall intensity, rainfall duration, and runoff volume), land use (commercial, industrial, and agricultural), and geological (soil type and bedrock geology) factors [1,10,52–54]. Considering the types of impervious surfaces is not sufficient for indicating stormwater quality. Beck et al. [55] revealed that the links between the impervious surface, the type of green land cover, and the type of buildings in these areas are accurate indicators of stormwater quality. However, the amount of nutrients is also influenced by the catchment area, the percentage of natural surfaces, surrounding land use, and rainfall depth [56]. The highest pollutant concentration of a specific location should be considered when designing a bioretention system [57]. Design features such as climate factors (including rainfall intensity, temperature, dry and wet periods, rainfall duration, and first-flush raining) and hydrologic conditions (including runoff volume, hydraulic conductivity, flowrate, bioretention surface area, and catchment area) are also important factors that should be considered to achieve the best efficiency.

2.3. Influence of Filter Media

The filter media is an essential factor involved in the inadequacy of bioretention nutrient removal. The filter media provides microbial conditions and electron donors as well as the nutrient sorption medium [29]. Generally, the filter media is comprised of soil and sand with different portions depending on the design manuals. Some guidelines propose using net soil, while others recommend sand and loam sand. The sandy soil is considered to have low water content and high porosity. Furthermore, coarser media affects plant growth due to the lower moisture content and lesser water holding capacity [44].

Sand media and sandy loam are used in many countries with high annual precipitation to increase the filtration rate [20]. The sand portion increment creates voids in the media and facilitates the infiltration process. Using clay or loam soil causes a low infiltration rate, collaging pollutants, high water content, and the collapse of the bioretention system due to decreasing soil porosity [13]. Clay or loam soil is used in temperate countries such as the USA, Australia, and China [58–60]. These countries have annual precipitation lower than tropical countries [28]. The media composition depends on the climate conditions and precipitation of the region. Overall, sandy loam media is preferred to remove nitrogen (N) [61,62]. Sand and sandy loam are the most popular for enhancing N and nitrate (NO₃) removal [23,63]. Nitrate (NO₃) removal occurs in filter media via soil cation exchange [64]. Applying different particle sizes in filter media helps achieve the best consistency and good nutrient removal, as well as providing the best water holding capacity for the plant's survival. Furthermore, the nutrient concentration in filter media before raining affects the variance in the pollutant removal via the bioretention system [65].

On the other hand, the filter media's depth plays a significant role in pollutant removal. Deeper filter media achieves greater total nitrogen (TN) reduction [66]. More in-depth soil media requires greater excavation efforts and costs. The filter zone must range from 150 to 1200 mm, and this also depends on the contribution area [38]. Takaijudin et al. [66] found that the minimum depth of a bioretention system required to achieve good nutrient removal was 400 mm. Generally, filter media depth ranges from 400 mm to 1200 mm, and the depth also depends on the type of plant and pollutant concentration [67]. Table 2 shows the depth and composition of filter media in different manuals. It also demonstrates the difference in filter media depth, which is related to climate, the type of vegetation, and root depth.

Table 2. Filter media details and target nitrogen removal in different manuals.

Manual	Soil Description (%)	Soil Depth (mm)	TN Removal (%)	Ref.
Bioretention Technical Design Guidelines	100 Sand loam	500–1000	45	[68]
Urban Stormwater Management Manual, Malaysia	(20–25) Topsoil (50–60) Sand (12–20) Leaf compost	450–1000	50	[20]
Adoption Guidelines for Stormwater Biofiltration Systems, Australia	(10–30) Fine sand (40–60) Coarse sand (0–10) Coarse sand	>500	>50	[69]
Bioretention Manual, Maryland	(20–30) Topsoil (50–30) Sand (20–30) Leaf compost.	750–1200	33–66	[58]
New Jersey Stormwater BMP Manual, USA	(85–95) Sand (2–5) Silt clay (3–7) Organics	450–600	30	[70]
Pennsylvania stormwater best management practices manual, USA	(20–30) Compost (70–80) Soil bases	>450	30 for NO ₃	[59]
Guide of Sponge City Construction, China	Plant soil	250–1200	N\A	[60]
ABC waters design guidelines, Singapore	Sandy loam	400–600	45	[71]
North Carolina Stormwater Design Manual	(85–88) Sand (8–12) Fines (3–5) Organic	600–900	35–60	[72]

2.4. Influence of mulch Layer

The mulch layer is located on the top of the engineered soil, which is comprised of decaying leaves, bark, or compost. It provides organic matter for plant survival and prevents the surface layer from clogging due to fine particles in runoff [73]. The depth of the mulch layer is recommended in the range from 50 to 100 mm [20,73]. Many researchers

have eliminated the mulch layer and substituted it by mixing compost or additives within soil media [63,74]. Applying a mulch layer to the top portion of a bioretention system can enhance nitrogen removal [65,75].

Goh et al. [28] mentioned that the mulch layer can be excluded when applying bioretention systems in tropical countries because the high rainfall and a short dry period mean the soil is wet most of the time and provides water for plant survival. Moreover, sandy soil is used largely in tropical regions and has a high porosity and experiences less clogging compared with the clay soil that has been used in temperate countries. The mulch layer maintains moisture conditions for plants during dry periods. The use of mulch in the top layer of the system is recommended in temperate regions such as the USA and Australia, which have a longer dry period than tropical regions [76,77].

2.5. Influence of Vegetation

Vegetation is essential to bioretention systems. It slows down runoff flow, provides comfortable atmospheric conditions, and creates an aesthetic view, among other benefits. Plants also absorb pollutants, minimizing pollution levels and enhancing microbial activity [78–80]. They also help to manage stormwater quality [46,51,81] in bioretention systems by reducing total nitrogen (TN) (by 59–79%) [6] and NO_x (NO_3 , NO_2) levels [82]. Although plants enhance nitrogen (N) removal through assimilation [26], they also contribute to the uptake of 57% (from 95.4%) of all dissolved N removal [51]. Plant-containing bioretention systems achieve an NO_x removal rate of 54% (compared to 15% for systems with no plants) [26].

The nutrient uptake of plants is directly influenced by several factors, including root structure, density, plant size [79], biomass, growth rate, and soil media nutrients [83]. Long roots are perforated in dry climates [84]. As a plant's roots extend deeper into the soil, the assimilation process is enhanced, thus increasing nitrogen retention [6,85]. Also, the physical and chemical properties of soil can change significantly based on vegetation type [86]. Interestingly, the high density and long roots of the plant lead to high nitrification and the denitrification of bacteria, which increases nutrient removal [77,87]. Furthermore, high biomass and high growth rate promote nutrient removal [88]. Plant selection depends on plants' resistance to environmental conditions, such as dry periods, and their ability to treat pollutants under such conditions [79]. Without vegetation, biofiltration systems experience collaging problems and a loss of porosity in filter media over time [89,90]. Meanwhile, plant roots increase filter media porosity and can prevent collage nutrients [91]. Plants can also affect hydrologic factors, such as infiltration and hydraulic conductivity, in biofiltration systems [82,92–94]. Studies indicate that vegetated systems have a higher infiltration rate than unvegetated systems [37,95]. Moreover, planted systems are more permeable than unplanted ones [87]. The hydraulic conductivity of a bioretention system can be affected by the type and morphology of plant roots [95]. For example, silky roots (which overlap) decrease hydraulic conductivity, whereas thick roots (which do not overlap) result in better performance [82,95]. Furthermore, plants differ significantly in terms of removal efficiency, and this factor is critical to plant selection [96]. It is ideal to select an appropriate native plant because such plants have already adapted to the local environmental conditions [97]. Another important factor is plant diversity, as diversity improves the performance of bioretention systems, especially concerning N removal [87,90,98,99]. Thus, multispecies planting can help bioretention systems resist variable environment conditions [100]. Wu et al. [63] found that a bioretention system containing two plant species removed more NO_3 and NH_4 than a system with only one species. Specifically, mixing deep-rooted species with shallow-rooted species ensures the removal of pollutants from multiple filter media layers [61,101].

3. Common Approaches to Nitrogen Removal in Bioretention

This section discusses the popular approaches for enhancing bioretention systems and simultaneously describes the benefits and disadvantages of each approach.

3.1. Saturated Zone

The gravel layer is a lower part of the conventional system of bioretention that contains fine, medium, or coarse-grade gravel. This layer is the more porous layer of the bioretention system. The primary function of the gravel layer is to collect and transport the treated water to the outlet pipe or surrounding soil, as well as to prevent the washout of engineered soil [20,102].

The inclusion of a saturated zone (SZ) in the bioretention system has a positive effect on the reduction of nitrogen (N), especially nitrate (NO_3) and nitrite (NO_2). Among the research community, this is a well-known principle. The SZ is used mainly to provide anaerobic conditions as well as plant survival between events in the dry season [102,103]. The main reason for inadequate N removal in the traditional bioretention system is the lack of a denitrification process and anaerobic condition [45,67]. An anaerobic condition is essential for NO_3 removal to complete the deoxidation or denitrification process. The denitrification process is the process of releasing gaseous nitrogen in the forms of N_2O , NO , and N_2 [102]. Several published studies describe the link between the removal of N and SZ via the provision of an anoxic zone to improve microbial activity [21,63,76,104]. The denitrification process is unstable; in some cases, it has been found that there was no significant effect of SZ on TN removal [12,105]. This may be due to the presence of a carbon source in the soil media that has been converted into NH_4 . Furthermore, some studies have found that SZ does not affect NO_x removal (amendment media and SZ) [106,107]. The presence of carbon sources has the main role in SZ enhancement [26,108,109]. To improve the denitrification process, different forms of carbon sources have been used, including woodchips, newspapers, sawdust, and sulfur [109–111]. Adding a carbon source within SZ enhanced TN [26,108]. The presence of SZ can also enhance TN and NO_3 removal, whereas NH_4 reduction is not dependent on the presence of a saturated zone (SZ) [51]. On the other hand, NH_4 removal in a bioretention system without a saturated zone is more efficient. Increasing the depth of the saturated zone has a negative effect on NH_4 removal [108]. Up to 95.42% of NH_4 is retained in the soil media [112]. Different saturated zone depths have been suggested, ranging from 150 to 600 mm [11,23,111,113]. In terms of cost, Xu and Zhang [113] recommended that the best SZ depth for TN removal was 450 mm, and including SZ would mean more excavation work and higher costs. Table 3 shows a list of studies with different SZ depths and removal efficiency.

Table 3. Pollutant removal efficiency in the bioretention system enhanced with the SZ under different sites.

Plant	Depth SZ (mm)	Soil Type (%)	Carbon Source (%)	Type of Study	Removal Efficiency (%)			Site Location	Ref.
					TN	NO ₃	NH ₄		
Bulrushes (<i>Phragmites australis</i>)	200–600	sandy loam:sand:peat moss (50:40:10)	Newspaper 5%	Column	35–73	–23–62	80	China	[111]
No	150	Silt + clay (70:30)	No	Field	68	-	-	USA	[114]
<i>Carex appressa</i>	300	loamy sand or Skye sand filter media	No	Column	77–96.5	-	95–99.7	Australia	[115]
<i>Hymenocallis speciosa</i>	200–300	Sandy loam:sand (50:50)	Wood chips 5%	mesocosms	19–74	-	54–91	China	[108]
<i>Radermachera hainanensis</i> <i>Merr</i> , <i>Ophiopogon japonica</i>	400–600	10 local red soil and 80 fine sand	No	Column	68.36–83%	43.03–79.5	95.42–97.69	China	[112]
<i>Dianella revoluta</i> (Blueberry lily), <i>Microlaena stipoides</i> (Weeping Grass), <i>Carex appressa</i> (Tall sedge)	450	Sandy loam	No	Mesocosms	–150–65	-	-	Australia	[116]
Buffalograss (<i>Buchloe dactyloides</i>), Big Muhly (<i>Muhlenbergia lindheimeri</i>).	150	Sand:Silt:Clay (88:10:2) (73:18:9) (94:2:4)	Shredded hardwood bark	Column	59–79	-	-	Australia	[6]
<i>Baumea juncea</i> , <i>Melaleuca lateritia</i> , <i>Baumea rubiginosa</i> and <i>Juncus subsecundus</i>	300	Sandy loam	Jarrah woodchips	Column	93	67 as NO _x	95	Australia	[81]
No	100	Sand:Biochar (7:3)	No	Column	20–30	50–60	50–60	Stanford	[104]
No	559	Sand:Topsoil:Compost (6:2:2)	No	Column	-	42–63	-	USA	[117]

3.2. Filter Media Additives

Recently, it has been suggested that additives can be used to enhance filter media because they are known to be effective in eliminating nitrogen (N). Waste products are mainly used to improve bioretention efficiency because they are cost-effective, require less effort, and can solve environmental issues. Several types of additives are used as a layer or mixed with soil media, including newspapers, woodchips, sawdust, wheat straw, Skye sand, shredded hardwood bark mulch, and water treatment residuals (WTR). In addition, the bilayer media concept is also used to enhance the bioretention system; it involves different layers of modifier media with various mechanical and chemical properties. The wide range of layer properties including porosity, permeability, particle size, water holding capacity, moisture content, bulk density, CEC, and pH would provide adsorption, nitrification, and denitrification conditions [7,12,39,75,118,119]. The bilayer of bioretention forms an anaerobic condition and increases nitrogen removal by applying a low-porosity layer in the lower portion of the media, which results in best nitrogen removal [39,105]. The less-permeable layer in the bottom of the bioretention media decreases water flow, thereby impeding the diffusion of oxygen and forming an anoxic zone [105].

Furthermore, the available carbon source in this layer promotes the denitrification process [27,39,120]. The denitrification process could be provided by the inclusion of a low-porosity layer at the bottom of the soil media [39]. Providing denitrification conditions in soil media is encouraged, especially in wet climates [28]. The inclusion of a saturated zone (SZ) in the bioretention system is not necessary for tropical countries with rainfall depth of over 2000 mm [28,76,103]. Overall, amendment materials improve nitrogen removal and offer a promising approach for bioretention enhancement [106]. The common additives that have been used as absorptive, nitrifier, and denitrifier materials are shown in Table 4. However, most studies on this topic do not study the removal of nitrate and nitrite and focus only on the reduction of TN.

Table 4. The characteristics and removal efficiency investigated in amended bioretention systems at different sites.

Additives in Filter Media	Plant	Soil Description (%)	SZ	Type of Study	Removal Efficiency (%)			Site Location	Ref.
					TN	NO ₃	NH ₄		
WTR ¹ , GZ ² , M ³ , F ⁴ , V ⁵ , T ⁶ , C ⁷	<i>Buxus sinica</i> and <i>Lolium perenne</i> L.	Soil:Sand:Woodchips (65:30:5)	No	Column	>63.4	-	-	China	[48]
Organic matter	<i>Phragmites australis</i> (Common Reed); Typ— <i>Typha latifolia</i> (Broadleaf Cattail); Scv— <i>Scirpus validus</i> (Soft-stem Bulrush); Sca— <i>Scirpus acutus</i> (Hard-stem Bulrush); Cap— <i>Carex praegracilis</i> (Common field sedge); Cam— <i>Carex microptera</i> (Smallwing Sedge)	Sand:Silt:Clay (91.7 ± 0.3) (2.3 ± 0.3) (6.0 ± 0.0)	No	Plastic containers	48–52	-	-	China	[121]
Sorbitive media	Daylilies ‘Stella d’Oro’ (<i>Heemerocallis</i> spp.) and Switchgrass ‘Shenandoah’ (<i>Panicum virgatum</i>); Butterfly Milkweed ‘Tuberosa’ (<i>Asclepias tuberosa</i>), Windflower (<i>Anemone canadensis</i>), Columbine (<i>Aquilegia canadensis</i>), New England Aster ‘Purple Dome’ (<i>Symphyotrichum novae-angliae</i>), Blue False Indigo ‘Capsian’ and ‘Midnight Prairiebliss’ (<i>Baptisia australis</i>), Sneezeweed ‘Red+Gold’ (<i>Helenium autumnale</i>), and Cardinal Flower (<i>Lobelia cardinalis</i>)	Sand:Compost (60:40)	No	Field	67	-	-	USA	[76]
peat soil, coconut chaff, vermiculite, medical stone, Fly ash, green zeolite,	<i>Buxus microphylla</i> , <i>Ophiopogon japonicus</i>	Soil:Sand:Wood chips (30:65:5)	No	Column	-	-	-	China	[122]
hardwood mulch	prairie cord grass (<i>Spartina pectinata</i>), sumpweed (<i>Iva annua</i>).	Sand:shredded hardwood:sandy loam (50:20:70)	No	Field	56	33	-	USA	[123]
N\A	Ti plant (<i>Cordyline fruticosa</i>), Rosea variegata (<i>Graptophyllum pictum</i>), Bamboo grass (<i>Bambusoideae</i>), Umbrella plant (<i>Cyperus alternifolius</i>)	Sand	No	Column	40.3–45.5	-	-	Malaysia	[22]
cockleshell, newspaper, coconut husk and printed paper	Red Hot Chinese Hibiscus (<i>Hibiscus rosa-sinensis</i>)	Sand:Silt:Clay (60:20:20)	No	Mesocosm	80.4	-	-	Malaysia	[103]
WTR	N\A	Loamy sand	No	Field	41	–45	-	USA	[27]
Wood chips, Bottom ash	No	Sand	No	Lab-scale- container	40–55	-	-	Korea	[124]
Aquatic plant detritus, Terrestrial plant detritus.	No	Sandy loam	No	Column	60–63	-	95–97	China	[125]
WTR, coconut fiber, RCA ⁸	No	Sandy	No	Column	59.8	-	-	Singapore	[126]
Fly ash, crushed straw	Fescue (<i>Festuca ovina</i> L.)	Sand:fly ash:crushed straw (90:5:5)	No	Column	76.8–95.3	87.5–97.4	85.1–98.3	China	[39]

¹ water treatment residuals; ² Green zeolite; ³ medical stone; ⁴ fly ash; ⁵ vermiculite; ⁶ turf; ⁷ coconut husk; ⁸ recycled concrete aggregate.

3.3. Combination of Modified Media and Saturated Zone

The combination of modified filter media (as a mixture or as a layer) and the saturated zone (SZ) is the latest development in nitrogen removal enhancement [11]. This configuration is considered the best since the development has improved the conditions of nitrification and denitrification [127]. Nitrification occurs through enhanced soil media, especially in the dry season, and denitrification via SZ. In this approach, the process of nitrogen removal occurred in steps through soil media, where ammonium (NH_4) was adsorbed in the upper part of the filter media and transferred by the nitrification process to nitrate (NO_3) [128]. The addition of additives containing a carbon source increases NH_4 adsorption. Furthermore, these additives improve the microbial activity of soil media, thereby enhancing the removal of NO_3 by microorganism assimilation and dissimilation [106]. Microbial activity plays a critical role in minimizing NO_3 compared with soil adsorption [129]. The combination of the saturated zone and modified media in the bioretention system promotes the nitrogen cycle [11,27,120]. Emma V. Lopez-Ponnada et al. [26] conducted a field study and compared the modified system (combined woodchips layer with SZ) and the traditional bioretention system without any modification. The findings have shown that removals of NH_4 and NO_x (NO_2 , NO_3) in the modified system were 83% and 81%, respectively, and for the traditional system 74% and 29%, respectively. Some of the studies applied modifiers as a mixture with the media [130]. Xiong et al. [106] compared the performance of the traditional system and retrofitted media with biochar or iron-coated biochar (ICB) and rice husk (RHB). The results have shown that with the inclusion of the SZ, the enhancement media with ICB and RHB give a better performance than the traditional system. The efficiency of the amendment material depends on the CEC and surface area [106]. Another study was undertaken using various materials for waste modification, including flyash, shells, ceramsite, pyrite, quartz, grinding slag, bottom ash, electric arc furnace slag (EAFS), and basic oxygen furnace slag. The results showed that the retrofitted media with bottom ash yielded the best performance with TN removal, indicating an improvement from 58% to 70% [11]. At present, limited research has been conducted to examine the feasibility of this strategy. Table 5 summarizes recent studies that have used this method. Almost all these studies achieved significant removal of N forms.

Table 5. Recent studies on the combination method.

Soil Depth (mm)	Soil Description (Layered in mm, Mixture in %)	Type of Media	SZ Depth (mm)	Plant	Removal Efficiency (%)			Ref.
					TN	NH_4	NO_3	
500	Sandy loam:Peat moss: CaCO_3 (95:5)	Mixture	300	<i>Phragmites australise</i>	-	13–92	–24–53	[131]
457	Sand:Biochar (65:35)	Mixture	305	<i>Muhlenbergia</i> (Muhly grass)	95	-	-	[132]
800	Sandy loam:WTR (85:15)	Mixture	400–800	<i>Iris lactea var chinensis</i>	75	>90	85	[21]
950	Topsoil:Silica Sand:Zeolite:Ceramist (200:250:250:250)	Layered	850	<i>Zoysia matrella</i> (ZM), <i>Iris pseudacorus</i> .	49.8 ± 22	-	-	[63]
605	Sand:River rock:Woodchips: (300:300:50)	Layered	605	dwarf pentas (<i>Pentas lanceolata</i>), blue daze (<i>Evolvulus glomeratus</i>)	90	83	81 as NO_x	[26]
550	Soil:(peat soil, perlite, vermiculite, cocoanut fiber and carbonized rice husk) (90:10)	Mixture	150	<i>Codiaeum variegatum</i>	58–70	-	-	[11]
1050	Soil:sand:ceramsite:quartz sand:gravel:pyrite:pebble (400:150:100:100:300)	Layered	350	No	89	87	-	[133]
400	Mixed sand and surfactant modified activated carbon	Layered	450	No	-	-	94	[134]

4. Conclusions

A bioretention system is a green infrastructure system widely introduced in Australia, the U.S., China, and Singapore. The literature has discussed the adequacy of the bioretention system in terms of nitrogen reduction. To achieve good performance, many factors should be considered when designing a bioretention system, such as nitrogen concentration, climate, hydrological factors, land use, and surrounding buildings. Furthermore, soil and plant selection should be appropriate for environmental conditions. Three approaches have been introduced for nitrogen-removal enhancement in a bioretention system. The first is the saturated zone (SZ), which is the most common method and is used worldwide. The use of modifier materials in soil media is the second and less common option. This principle is intended to be implemented in tropical regions with wet soil media and short dry periods. The third strategy is to integrate two previous methods into the same system. This technique has been upgraded recently, including via retrofitting soil media and SZ, which is more effective than previous approaches and less widespread. Further research is needed to study the effectiveness of modification materials and their ability to provide nitrification and denitrification conditions through soil media. Moreover, the merging of retrofitted media and SZ is a recent and revolutionary technique that deserves further research. Overall, previous studies have shown that the bioretention system is a promising tool to improve the quality of stormwater.

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