Nitrogen Removal in Bioretention System

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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.

stormwater quality bioretention nitrogen saturated zone additives

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 [1][2].

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 [2][3]. The main reason for inadequate N removal in the traditional bioretention system is the lack of a denitrification process and anaerobic condition [4][5]. 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 [2]. Several published studies describe the link between the removal of N and SZ via the provision of an anoxic zone to improve microbial activity [6][7][8][9]. The denitrification process is unstable; in some cases, it has been found that there was no significant effect of SZ on TN removal [10][11]. 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) [12][13]. The presence of carbon sources has the main role in SZ enhancement [14][15][16]. To improve the denitrification process, different forms of carbon sources have been used, including woodchips, newspapers, sawdust, and sulfur [16][17][18]. Adding a carbon source within SZ enhanced TN [14][15]. 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) [19]. 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 [15]. Up to 95.42% of NH_4 is retained in the soil media [20]. Different saturated zone depths have been suggested, ranging from 150 to 600 mm [21][22][18][23]. In terms of cost, Xu and Zhang [23] recommended that the best SZ depth for TN removal was 450 mm, and including SZ would mean more excavation work and higher costs. Table 1 shows a list of studies with different SZ depths and removal efficiency.

Table 1. 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 (*Phragmites australis*)	200–600	sandy loam:sand:peat moss (50:40:10)	Newspaper 5%	Column	35–73	−23–62	80	China	[18]
No	150	Silt + clay (70:30)	No	Field	68	-	-	USA	[24]
Carex appressa	300	loamy sand or Skye sand filter media	No	Column	77–96.5	-	95–99.7	Australia	[25]
Hymenocallis speciosa	200–300	Sandy loam:sand (50:50)	Wood chips 5%	mesocosms	19–74	-	54–91	China	[15]
Radermachera hainanensis Merr, *Ophiopogon japonica*	400–600	10 local red soil and 80 fine sand	No	Column	68.36–83%	43.03–79.5	95.42–97.69	China	[20]
Dianella revoluta (*Blueberry lily*), Microlaena stipoides (*Weeping Grass*), Carex appressa (*Tall sedge*)	450	Sandy loam	No	Mesocosms	−150–65	-	-	Australia	[26]
Buffalograss (*Buchloe dactyloides*), Big Muhly (*Muhlenbergia lindheimeri*).	150	Sand:Silt:Clay (88:10:2) (73:18:9) (94:2:4)	Shredded hardwood bark	Column	59–79	-	-	Australia	[27]
Baumea juncea, *Melaleuca*	300	Sandy loam	Jarrah woodchips	Column	93	67 as NO_X	95	Australia	[28]

Plant	Depth SZ (mm)	Soil Type (%)	Carbon Source (%)	Type of Study	Removal Efficiency (%)			Site Location	Ref.
					TN	NO_3	NH_4		
lateritia, *Baumea rubiginosa* and *Juncus subsecundus*									
No	100	Sand:Biochar (7:3)	No	Column	20–30	50–60	50–60	Stanford	[9]
No	559	Sand:Topsoil:Compost (6:2:2)	No	Column	-	42–63	-	USA	[29]

wn to be because are used hredded 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 [30][10][31][32][33][34][35]. 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 [31][11]. 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 [11].

Furthermore, the available carbon source in this layer promotes the denitrification process [36][31][37]. The denitrification process could be provided by the inclusion of a low-porosity layer at the bottom of the soil media [31]. Providing denitrification conditions in soil media is encouraged, especially in wet climates [38]. The inclusion of a saturated zone (SZ) in the bioretention system is not necessary for tropical countries with rainfall depth of over 2000 mm [38][8][3]. Overall, amendment materials improve nitrogen removal and offer a promising approach for bioretention enhancement [12]. The common additives that have been used as absorptive, nitrifier, and denitrifier materials are shown in Table 2. However, most studies on this topic do not study the removal of nitrate and nitrite and focus only on the reduction of TN.

Table 2. 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]	*Buxus sinica* and *Lolium perenne* L.	Soil:Sand:Woodchips (65:30:5)	No	Column	>63.4	-	-	China	[39]
Organic matter	*Phragmites australis* (Common Reed); Typ—*Typha latifolia* (Broadleaf Cattail); *Scv*—	Sand:Silt:Clay (91.7 ± 0.3) (2.3 ± 0.3) (6.0 ± 0.0)	No	Plastic containers	48–52	-	-	China	[40]

Additives in Filter Media	Plant	Soil Description (%)	SZ	Type of Study	Removal Efficiency (%)			Site Location	Ref.
					TN	NO_3	NH_4		
	Scirpus validus (Soft-stem Bulrush); *Sca*—*Scirpus acutus* (Hard-stem Bulrush); *Cap*—*Carex praegracilis* (Common field sedge); *Cam*—*Carex microptera* (Smallwing Sedge)								
Sorbtive media	Daylilies ‘Stella d’Oro’ (*Hemerocallis spp.*) and Switchgrass ‘Shenandoah’ (*Panicum virgatum*); Butterfly Milkweed ‘Tuberosa’ (*Asclepias tuberosa*), Windflower (*Anemone canadensis*), Columbine (*Aquilegia canadensis*), New England Aster ‘Purple Dome’ (*Symphyotrichum novae-angliae*), Blue False Indigo ‘Capsian’ and ‘Midnight Prairiebliss’ (*Baptisia australis*), Sneezeweed ‘Red+Gold’ (*Helenium autumnale*), and Cardinal Flower	Sand:Compost (60:40)	No	Field	67	-	-	USA	[8]

Additives in Filter Media	Plant	Soil Description (%)	SZ	Type of Study	Removal Efficiency (%)			Site Location	Ref.
					TN	NO_3	NH_4		
	(*Lobelia cardinalis*)								
peat soil, coconut chaff, vermiculite, medical stone, Fly ash, green zeolite,	Buxus microphylla, Ophiopogon japonicus	Soil:Sand:Wood chips (30:65:5)	No	Column	-	-	-	China	[41]
hardwood mulch	prairie cord grass (*Spartina pectinata*), sumpweed (*Iva annua*).	Sand:shredded hardwood:sandy loam (50:20:70)	No	Field	56	33	-	USA	[42]
N\A	Ti plant (*Cordyline fruticosa*), Rosea variegata (*Graptophyllum pictum*), Bamboo grass (*Bambusoideae*), Umbrella plant (*Cyperus alternifolius*)	Sand	No	Column	40.3–45.5	-	-	Malaysia	[43]
cockleshell, newspaper, coconut husk and printed paper	Red Hot Chinese Hibiscus (*Hibiscus rosa-sinensis*)	Sand:Silt:Clay (60:20:20)	No	Mesocosm	80.4	-	-	Malaysia	[3]
WTR	N\A	Loamy sand	No	Field	41	−45	-	USA	[36]
Wood chips, Bottom ash	No	Sand	No	Lab-scale-container	40–55	-	-	Korea	[44]
Aquatic plant detritus, Terrestrial	No	Sandy loam	No	Column	60–63	-	95–97	China	[45]

3. Combination of Modified Media and Saturated Zone

Additives in Filter Media	Plant	Soil Description (%)	SZ [21]	Type of Study	Removal Efficiency (%)			Site Location	Ref.
					TN	NO_3	NH_4		
plant detuitus.						[47]			
WTR, coconut fiber, RCA 8	No	Sandy 4	No	Column	59.8 3 [48]	4 -	-	Singapore	[46]
Proprietary blend of coconut fibres, water treatment residue (WTR), soil, and sand X 2	Talipariti tilaceum [14] 3	3 3 Sandy	No	Field	46	[49] -	[21][36][37] - [50]	Singapore	[12] [35] [12]
Fly ash, crushed straw	Fescue (*Festuca ovina* L.)	Sand:fly ash:crushed straw (90:5:5)	No	Column	76.8–95.3	87.5–97.4	85.1–98.3	China	[31]

he latest nce the through ocess of r part of ntaining y of soil Microbial aturated Lopez- with SZ) NH_4 and 74% and ompared and rice nd RHB give a better performance than the traditional system. The efficiency of the amendment material depends on the CEC and surface area [12]. 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% [21]. At present, limited research has been conducted to examine the feasibility of this strategy.

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