A review on nitrogen removal for urban stormwater runoff in bioretention system

Manal Osman 1,*, Khamaruzaman Wan Yusof 1, Husna Takaijudin 1, Goh Hui Weng 2, Marlinda Abdul Malek 3, Nor Ariza Azizan 2, and Aminuddin Ab. Ghani 2

1 Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
2 River Engineering and Urban Drainage Research Centre (REDAC), Engineering Campus, Universiti Sains Malaysia, Seri Ampangan, 14300 Nibong Tebal, Penang, Malaysia
3 Institute of sustainable Energy (ISE), Universiti Tenaga National, 43000, Selangor, Malaysia
* Correspondence: manal_17005662@utp.edu.my

Abstract: A bioretention is one of stormwater best management practices (BMPs) for runoff quantity and quality control. The removal efficiency of different pollutants under this system is generally satisfactory, except nitrogen which is deficient in some of the present bioretention system. This is due to, nitrogen has a complex biogeochemical cycle and is more difficult to remove because it is highly soluble. Thus, the removal processes of nitrogen are typically slower processes than other pollutants. This study summarized the recent studies focusing on nitrogen removal for urban stormwater runoff in bioretention system and discussed the recent advances in bioretention system. The performances, influencing factors, and design enhancements in bioretention system are comprehensively reviewed in this paper. The review of current literature reveals that, bioretention shows a greater promise in their ability to remove nitrogen from stormwater runoff. Combining nitrification and denitrification zones with adding carbon source and selecting different plant species in a bioretention system showed the beneficial influence in promoting nitrogen removal in bioretention system. More work on the nitrogen transformations through bioretention system and the relationships between various factors and their combined effects on nitrogen removal need to be explored.

Keywords: Stormwater runoff; Bioretention; Nitrogen removal; Leaching

1. Introduction

Urban areas are constantly expanding in terms of space and density. The urban population is expected to increase to 66% by 2050. As a result of growing population and urbanization, water pollution was increased [1], [2], [3]. Stormwater runoff has considerable impact on water pollution. It has long been recognized as a source of nonpoint source pollutants [4], [5]. Worldwide, excessive nitrogen pollution has been identified in the large portion of water bodies. Furthermore, future land use activities are expected to intensify increase nitrogen loading [6]. Therefore, nitrogen became a primary concern in saltwater management [7]. There are several alternatives for stormwater runoff control, which include filter strips, infiltration trenches, vegetated roofs, permeable pavement, rain gardens, bioretention and swales [8]. Bioretention is widely used around the world and considered to be a good alternative for treating stormwater runoff. The removal efficiency of stormwater runoff pollutants such as total suspended solid (TSS), chemical oxygen demand (COD), biological oxygen demand (BOD), and total phosphorus (TP) in bioretention studies are generally satisfactory; however, nitrogen removal is deficient in some of present operating bioretention system [10], [11], [12], [13], [5], [14].
This paper therefore summarized the recent studies focusing on nitrogen removal for urban stormwater runoff in bioretention system. It discussed the recent advances in bioretention and factors affecting to enhance nitrogen removal.

2.1 Stormwater runoff characteristic

Water pollution is a major challenge in urban areas, it causes chemical, physical, and biological damage to the environment [4], [15]. It further contributes to ecological degradations and health risks [4], [15], [16]. There are two sources, namely, point source and non-point source pollution. Point source control has been significantly attributed to the implementation of standards, systematic laws, and high quality engineering measures [4], [17]. Meanwhile, non-point source pollution has become a leading source of water pollution [18]. It mainly caused by agricultural runoff, atmospheric deposition, and urban stormwater [19]. Stormwater can accurately define as the runoff from pervious and impervious surfaces in the urban areas [20]. It can include some of sewer discharges, flow from impervious surfaces such roads and parking lots, and flow from open spaces and construction. Groundwater flooding also may act as a contributory source, especially during heavy storm events [21]. As a runoff accelerated from these lands, it carries more pollutants to water bodies and increases loading of toxic contaminants. Excess pollutants impact water quality when water and soil containing pollutants wash into nearby waters or leach into ground waters [22], [23]. Stormwater pollutants can be classified as gross and dissolved pollutants. Gross pollutants include sediments of different sizes such as vegetation, plant debris, paper, plastic and others. Dissolved pollutants include nutrients, heavy metals, and hydrocarbons. The dissolved pollutants mainly result from emissions, fluid leaks from vehicles, and agricultural operations [24]. Pollutants leaching from these lands to surface water may occur as direct runoff, or by infiltration through the root zone and discharge to surface water [25]. There are typical pollutants characterizing stormwater runoff, Total suspended solids (TSS), nitrogen (N), phosphorus (P), Biochemical oxygen demand (BOD), and Chemical oxygen demand (COD) are the most common pollutants [26]. The classification of pollutant load according to Water Quality Standards [27] is shown in Table 1.

### Table 1. Water Quality Standards [27].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Classes *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Ammonia</td>
<td>mg/L</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>mg/L</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>TP</td>
<td>mg/L</td>
<td>&lt;1</td>
</tr>
<tr>
<td>BOD</td>
<td>mg/L</td>
<td>&lt;10</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>&lt;25</td>
</tr>
<tr>
<td>TSS</td>
<td>mg/L</td>
<td>&lt;25</td>
</tr>
</tbody>
</table>

* Class I = excellent, class II = good, conventional treatment is required, class III = extensive treatment is required, class IV = for major agricultural activities which may not cover minor application to sensitive crops, class V = Bad which don’t meet any of the above mentioned classes.

Nitrogen represents a highest rated nutrient in stormwater runoff [7]. Nitrogen concentrations in stormwater may differ according to land use activity [6] as shown in Figure 1.
2.2. Best management practices (BMPs) and Low impact development (LID)

In order to minimize the environmental impact of water pollution, it was necessary to establish water quality monitoring and intelligent watershed management [35], [36]. Best management practices (BMPs) and Low impact development (LID) are a water management approaches that manage runoff as close as possible to its source. Such practices include, filter strips, infiltration trenches, vegetated roofs, permeable pavement, rain gardens, bioretention and swales [8]. They are commonly used for water quantity and quality control. Water quantity control is measured to curb post construction flash flood problems while erosion and sediment control is measured to minimize erosion and sedimentation problems during construction. Water quality control, intended to reduce post construction non-point source pollution problems, the primary objective of stormwater quality control is to achieve good water quality standards [37]. The use of these practices for water quality control considered to be a cost-effective [38], [39], [40]. They take advantage of natural processes such as infiltration to reduce the volume and rate of runoff at the same time improve water quality [41], [42]. The advantages of the infiltration process include groundwater recharge, runoff volume reduction, low stream flow augmentation, and water quality enhancement [43]. They also enhance pollutant mitigation by promoting water infiltration and evapotranspiration to improve water quality [44]. The target for a minimum reduction in annual pollutant loads for the common pollutants, according in BMPs and LID alternatives shall be in accordance with Table 2 [26].

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Reduction Targets (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>80</td>
</tr>
<tr>
<td>TN</td>
<td>50</td>
</tr>
<tr>
<td>TP</td>
<td>50</td>
</tr>
</tbody>
</table>

2.3. Bioretention as a promising BMPs and LID
Bioretention was being employed as a stormwater best management practice (BMP) for stormwater quantity and quality control. In recent years, there has been an increasing interest in bioretention for stormwater quality treatment. It is typically used to treat stormwater that has run over pervious and impervious surfaces in urban areas [45]. Bioretention can be easily defined as the process in which biological processes and rapid infiltration occur along with the storage of water to reduce pollutants [46]. It can be a good process to treat runoff because it maximizes water storage, so water can be infiltrated easily [47], [48]. It also reduces runoff volume, which leads to pollutant reduction [49], [50]. The facility size of bioretention is often designed for treating the first flush of stormwater [48]. Water quality enhancements can be obtained through infiltration and sedimentation. Filtration through vegetation is the primary mechanism for pollutant removal. Then settling of particles, and infiltration into the subsurface zone. As runoff travels through the system, the vegetation reduces peak velocity while infiltration reduces flow volume, which promotes pollutant removal [51]. In addition to direct plant nutrient uptake, the vegetation increases microbial activity through nitrifying and denitrifying process which lead to increase nutrients removal [52]. Bioretention consists of basins or trenches that are filled with porous media and planted with vegetation for treating stormwater runoff as shown in Figure 2. Bioretention media are generally composed of sand mixed with small amounts of silt, clay and organic matter (Mulch) [34]. The organic matter has several functions. It retains moisture in the plant root zone, provides a medium for biological growth and decomposition of organic matter, and provides some filtration of pollutants as well as protecting the soil bed from erosion [53].

2. Nitrogen removal processes

Nitrogen compounds include an organic and inorganic forms that are very essential for biological life. The most important inorganic forms of nitrogen are, ammonium (NH₄⁺), nitrate (NO₃⁻) and nitrite (NO₂⁻). Gaseous nitrogen may exist as dinitrogen (N₂), nitrous oxide (N₂O), nitric oxide (NO₂ and N₂O₃) and ammonia (NH₃). The organic forms are dissolved organic N, and particulate organic N [54], [55], [56]. Nitrogen is primarily present as organic and dissolved form [57]. Nitrogen has a complex biogeochemical cycle and is more difficult to remove because it is highly soluble [58], [59]. Thus, the removal processes of nitrogen are typically slower processes than other pollutant removal [59]. The efficient removal of nitrogen is significantly dependent on physical processes, biological processes, and chemical reactions [60]. The main processes include assimilation (as N uptake), adsorption, ammonification, nitrification and denitrification [61], [62]. Nitrogen removal process such as assimilation, nitrification, and denitrification always occur at varying rates [63], [64]. Assimilation is the process in which inorganic nitrogen forms (NH₄⁺, NO₂⁻, NO₃⁻) are transformed into plant biomass by microorganisms and stored as organic Nitrogen [6]. This organic nitrogen is temporary stored in plant tissues and may release back to the effluent [62] due to low denitrification [65]. The release of N occurs when assimilation exceeds denitrification process [66].
the conversion of organic nitrogen to ammonium (NH₄⁺) [5]. Nitrification is usually defined as the biological oxidation of ammonium to nitrate with nitrite [67].

\[
2\text{NH}_4^+ + 3\text{O}_2 \rightarrow 2\text{NO}_2^- + 2\text{H}_2\text{O} + 4\text{H}^+ \tag{1}
\]

\[
2\text{NO}_2^- + \text{O}_2 \rightarrow 2\text{NO}_3^- \tag{2}
\]

Denitrification is the process in which nitrate is converted into dinitrogen gas (N₂) then can be removed to atmosphere or fixed by the plant root [65], [68], [69], [70], [71], [72]. The simplified nitrogen cycle is shown in Figure 3.

\[
\text{NO}_3^- \Rightarrow \text{NO}_2^- \Rightarrow \text{NO} \Rightarrow \text{N}_2\text{O} \Rightarrow \text{N}_2 \tag{3}
\]

\[
6\text{CH}_2\text{O} + 4\text{NO}_3^- \rightarrow 6\text{CO}_2 + 2\text{N}_2 + 6\text{H}_2\text{O} \tag{4}
\]

**Figure 3.** Simplified nitrogen cycle [60].

Nitrogen removal is a major area of interest within the field of stormwater quality control. The previous works intensively focused on nitrogen removal in bioretention system [9], [67], [73], [74], [75], [76]. The nitrogen removal in bioretention has been always highly variable and dependent on some factors such as vegetation, soil filter media, influent concentrations, and hydraulics factors [10], [61], [68], [77], [78], [79], [80], [81], [82], [83].

2.1. The effect of vegetation

Vegetation is an essential component of bioretention. It plays a critical role in the performance of nitrogen removal [78], [61]. The previous studies showed that the vegetated bioretention removed a greater amount of nitrogen than non-vegetated. As runoff travels through the system, the vegetation reduces peak velocity while infiltration reduces flow volume, which promotes pollutant removal [51]. Barrett et al. [10] compared the pollutant removal efficiency of bioretention systems for different media and plant species. The results showed a significant improvement in nutrient removal of the filter with the presence of plants. The presence of vegetation enhanced nitrogen removal, it had a significant effect on TN and NO₃⁻ removal [78], [10], [84]. A current study about nitrogen removal from stormwater runoff in mountainous cities was conducted by Wang et al. [68] using different stepped bioretention systems with different plant species. The results have shown a higher nitrogen removal rate. It was confirmed that the plant species play an important role for nitrogen removal.

Native species are more effective than exotic ones [61]. There are wide variations in nitrogen removal by different plant species in bioretention studies as shown in Table A1, appendix A. The variation
among plant species in nitrogen removal is due to differences among species in plant size and plant uptake [65], [85]. Plant uptake rate usually depends on the plant growth rate and plant type [80], [81]. Each plant species in different growth stages has a different uptake rate [81], [86].

The higher biomass and better plant growth; the higher plant uptake and better nitrogen removal [87]. Plant uptake contributed towards \( \text{NH}_4^+ \) and \( \text{NO}_3^- \) removal [80]. \( \text{NO}_3^- \) retention occurs by the two mechanisms; plant uptake and denitrification [88]. The rapid growth rate of the plant contributes to TN removal [89]. A study by Milandri et al. (2012) [90] found that rapid growth rate of turf-grasses Pennisetum and Stenotaphrum was effective in \( \text{NH}_3 \) (97%) and \( \text{NO}_3^- \) removal (>80%). A study by Chen et al. (2014) [91] showed that TKN concentration was significantly higher in the leaves and roots compared to the stems of the E. tapos plants. Plant root also affects nitrogen removal, the thick root the higher nitrogen removal [89]. In addition to direct plant nutrient uptake, the vegetation increases microbial activity through nitrifying and denitrifying process which lead to increase nitrogen removal [52].

### 2.2 The effect of soil filter media properties

Soil filter media plays an important role in the pollutants removal from stormwater [79]. Soil filter media supplies plants by suitable medium for growth and provides a well-drained soil [117]. Several studies have focused on nitrogen removal using different bioretention media. Lintern et al. [77] emphasized that TN removal efficiency was more affected by filter media depth for shallow rooted plants systems. A two studies were conducted by Davis et al. [11], [12] on the removal efficiency of nutrients from a synthetic stormwater runoff using shallow bioretention depths. Results indicated good removal efficiency of total Kjeldahl nitrogen while nitrate reduction was poor. Soil filter media depth plays important rule in N removal. A deeper media layer with a lower infiltration rate is needed to provide more detention time under anoxic condition for the denitrification process [118]. Filter media can reduce the peak flow successfully by storing water within the filter media layers and increasing retention time. Increasing filter media depth offers better removal efficiency of nitrogen [120]. The deeper filter media has more effect on nitrogen and ammonia removal due to reduction in runoff volume [121], [97]. However, it did not show any effect on enhancing nitrate removal [84]. Higher nitrate removal rates were observed with the soil media contained higher organic matter [122]. Ideal bioretention contains 50%–60% sand and 40%–50% mixture of loam or sandy loam or loamy sand. Clay content should be 5%–8%. Too much clay may reduce infiltration into the media [81].

### 2.3 The effect of nitrogen concentration

The nitrogen uptake rate is more influencing by inflow concentration [80] [81]. Low concentration of TN and \( \text{NO}_3^- \) can be effectively removed through denitrification process [68]. \( \text{NH}_4^+ \) in the effluent was lower than those in the influent of bioretention for different concentrations which may attributed to removal by the adsorption process in the bioretention media [67], [74]. Investigations by Bucˇiene´ and Gaigalis. [123] revealed that nitrogen in effluent might positively correlate with its concentration in the runoff. \( \text{NO}_3^- \) concentration in the effluent was linearly increased with increasing TN concentration in the effluent [70]. A comprehensive load reduction always better under lower concentration than high concentration [121]. Increasing influence nitrogen concentration led to the lower nitrogen removal [124].

### 2.4 The effect of hydraulic factors

The most important hydraulics factors affecting nitrogen removal efficiency for stormwater are, flow rate, runoff volume and retention time [82], [83]. However, a study as early as 1978 for characterization of urban runoff by Whipple et al. [125] revealed that nutrients loadings in the effluent are directly proportionate to flow rate of the runoff. The ability of bioretention for treating high stormwater runoff volume is relatively low [126]. Therefore, nitrogen removal efficiency can be enhanced with lower runoff volumes [78]. Low stormwater runoff volume can be effectively captured
by bioretention. However, relatively higher stormwater runoff volume may by-pass the system without achieving the desired treatment of pollutants [126]. Retention times in the bioretention need to be adjusted accordingly to prevent nitrate leaching to the effluent [127]. Bioretention with low infiltration rates can effectively remove NH$_4^+$ due to sufficient retention time [128]. Increasing retention time significantly improved nitrate removal and generally enhanced nutrient removal efficiency [129], [82], [130]. Denitrification process needs longer retention time to allow greater nitrate removal [118], [131].

3. Nitrogen leaching

Nitrogen leaching is primarily in dissolved forms [57]. Many studies have indicated that bioretention tend to be an effective stormwater treatment [10], [11], [12], [132]. However, some studies reported nutrient leaching in the effluent of the systems as shown in Table 3. Poor nitrogen removal efficiency and increasing the amount of nitrogen in form of NO$_3^-$ in the effluent has been observed by many researchers [14], [77], [107], [76], [110], [133]. The higher the nitrogen load of stormwater discharged from the bioretention was because of nitrite and nitrate [133]. The large negative efficiency was for nitrate and nitrite [13]. Nitrogen leaching can be attributed to that, soluble forms of some nutrients such as nitrate (NO$_3^-$N) and nitrite (NO$_2^-$N), are difficult to separate from water by filtration process. These nutrients can be leached from the system. Suggesting that the change in chemical species from one to another simply occurs during infiltration [47], [134]. Nitrogen leaching from bioretention is mainly lost as NH$_4^+$ and NO$_3^-$ [135]. The concentration of NO$_3^-$ in the bioretention effluent has always higher than NH$_4^+$. Bioretention exports NO$_3^-$ from the system because of the large nitrate content in the compost. The nitrate leaching is increasing over time [136], [33]. The accumulation of organic matter in bioretention system may contribute to leaching in Organic N and NO$_3^-$ as well as NH$_4^+$ [96], [137], [136]. Ammonia is continuously released due to the mineralization of organic nitrogen to ammonia [5], [138], [139], [140]. However, nitrate leaching always higher than ammonia due to the negative charge of the nitrate ion, therefore, is easier to leach. While ammonia has a positive charge which interacts easily with the media [140]. Some of nitrate leaching assigned to the accumulation of nitrate resulted from the nitrification process [126], [74].

<table>
<thead>
<tr>
<th>System description</th>
<th>NH$_4^+$ (%)</th>
<th>NO$_3^-$ (%)</th>
<th>TN(%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention planted with different types of water tolerant plants</td>
<td>~39</td>
<td>~384 to ~57</td>
<td>~48</td>
<td>[13]</td>
</tr>
<tr>
<td>Bioretention filled with sandy loam soil and shredded wood and planted with different plant species</td>
<td>–</td>
<td>(−205) ± 181</td>
<td>–</td>
<td>[17]</td>
</tr>
<tr>
<td>Bioretention filled with high diversity and low-diversity plant- mix of iron and aluminum oxide</td>
<td>–</td>
<td>−46</td>
<td>−14</td>
<td>[141]</td>
</tr>
<tr>
<td>Bioretention amended by compost</td>
<td>–</td>
<td>−37 to −216000</td>
<td>–</td>
<td>[33]</td>
</tr>
<tr>
<td>Bioretention with no saturation zone planted with Microlaena stipoides and Dianella revoluta</td>
<td>–</td>
<td>−300 to −400</td>
<td>–</td>
<td>[110]</td>
</tr>
<tr>
<td>bioretention box filled with a sandy loam soil and topped with a thin layer of mulch with different plant species</td>
<td>–</td>
<td>(−73) ± 18</td>
<td>–</td>
<td>[11]</td>
</tr>
</tbody>
</table>

4. Design features that enhanced nitrogen removal

Poor nitrogen removal of bioretention systems has been reported in many studies. Nitrogen removal could be enhanced by reducing the nutrient content of compost or by using little to no compost in the soil media. It’s also recommended for an engineering design within the soil layers to promote N transformations via denitrification [17]. Nitrogen removal mainly depended on nitrification and denitrification, which is significantly affected by DO [141]. Nitrogen removal by denitrification accounted for 79.5% of total nitrogen removed [142]. 80-95% removal efficiency of nitrate was achieved by sorption process for stormwater using different mixed soil media contain carbon content in bioretention system [143]. In the conventional bioretention cell, the media layers
are almost aerobic due to the high content of sand in the media [144]. Efficient NH₄⁺ removal obtains through adsorption by soil media layers. Nitrification occurs in the upper layer of bioretention media [76]. The nitrification process is very important to enhance TN and NH₄⁺ removal which could occur with aerobic condition. The removal of N is often insufficient due to a lack of denitrification [110]. The system without saturation zone is likely to increase nitrification while limiting the denitrification condition [145]. Some additives such as newspaper supported biological denitrification that resulted 80% of nitrate and nitrite mass removals [107]. Wood chips create anaerobic zones in the media for more denitrification process enhancement [146]. Different techniques were used to improve nitrification and denitrification processes in a bioretention system as shown in Table 4.

### Table 4. Percentage of N removal by nitrification and denitrification processes.

<table>
<thead>
<tr>
<th>A technique used</th>
<th>The percentage of nitrogen removed by nitrification</th>
<th>The percentage of nitrogen removed by denitrification</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A large scale column study with different plant species, filter media and depth, pollutant concentration</td>
<td>93</td>
<td>–</td>
<td>[78]</td>
</tr>
<tr>
<td>box prototype bioretention system filled with sandy loam soil and mulch</td>
<td>60 – 80</td>
<td>–</td>
<td>[111]</td>
</tr>
<tr>
<td>Bioretention contains carbon source and anoxic zone</td>
<td>71.1</td>
<td>–</td>
<td>[62]</td>
</tr>
<tr>
<td>saturated zone containing shredded newspaper</td>
<td>–</td>
<td>99</td>
<td>[147]</td>
</tr>
<tr>
<td>two-layered bioretention system amended with wood chips</td>
<td>–</td>
<td>80</td>
<td>[146]</td>
</tr>
<tr>
<td>bioretention amended with biochar and zero-valent iron (ZVI)</td>
<td>–</td>
<td>30.6 – 95.7</td>
<td>[100]</td>
</tr>
<tr>
<td>Bioretention columns with filter media contains 8% organic material</td>
<td>–</td>
<td>60 – 90</td>
<td>[148]</td>
</tr>
</tbody>
</table>

A Bioretention system with poor N removal can be enhanced by retrofitting of the saturated zone to create anaerobic conditions for the effective denitrification process. It is well known that, high removal efficiency of nitrogen requires the ability of the system to provide aerobic and anaerobic conditions to ensure good removal and avoid leaching of nitrogen in all forms [54]. Aerobic conditioning can be achieved through soil filtration media layer while anaerobic condition requires saturated zone to increase the bacterial activity in the denitrification process. The saturated zone facilitates nitrate removal, the system with saturation zone can efficiently remove nitrate more than without saturation zone due to denitrification process [149], [150]. The system without saturation zone is capable to remove ammonium and incapable to remove nitrate. Increasing the saturation zone depth was not affected a NH₄⁺ removal. Whereas ON and NO₃⁻ removal significantly enhanced by increasing the saturation zone depth due to increased denitrification and mineralization processes [151], [152]. NO₃⁻ was significantly correlated with the saturated zone depth [68]. Saturated zone at a soil depth (at least 0.75 m) can provide a greater nitrogen removal [114]. Anaerobic zone would have a remarkable effect on denitrification and a very little opportunity in the nitrification process. However, magnification also can take place in anaerobic zone [144]. The system with saturation zone combined with adding carbon source performed better in nitrogen removal. Adding carbon sources to a saturation zone was very effective in increasing the denitrification process and improving plant growth [87]. Denitrification process is generally limited by contact time under anoxic conditions. As
such, a deeper media layer and lower infiltration rate are needed for more denitrification process [118]. The denitrification rate will be increased with the supply of soil, water content as it determines the oxygen transfer rate from the atmosphere to the sites where biological degradation takes place [153], [154]. As suggested by Klein and Logtestijn (1994) [153], the minimum volumetric water content for denitrification in loam soil should be 40%. NO$_3^-$ was significantly correlated with the saturated zone depth [68]. Table 5 shows some of different design features to improve nitrogen removal in bioretention systems.

### Table 5: Design features to improve nitrogen removal.

<table>
<thead>
<tr>
<th>Design features to improve nitrogen removal</th>
<th>TN (%)</th>
<th>NH$_4^+$ (%)</th>
<th>NO$_3^-$ (%)</th>
<th>Ranking</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioretention column with less permeable soil layer</td>
<td>82</td>
<td>83</td>
<td>84</td>
<td>High</td>
<td>[128]</td>
</tr>
<tr>
<td>Wood chips</td>
<td>88</td>
<td>-</td>
<td>-</td>
<td>High</td>
<td>[130]</td>
</tr>
<tr>
<td>Saturation zone</td>
<td>49.8</td>
<td>-</td>
<td>-</td>
<td>Medium</td>
<td>[114]</td>
</tr>
<tr>
<td>Combination of saturated to unsaturated sequence</td>
<td>-</td>
<td>-</td>
<td>91</td>
<td>High</td>
<td>[130]</td>
</tr>
<tr>
<td>Newspapers</td>
<td>80.4</td>
<td>-</td>
<td>-</td>
<td>High</td>
<td>[155]</td>
</tr>
<tr>
<td>Planted treatments with saturation zone</td>
<td>93</td>
<td>95</td>
<td>67</td>
<td>High</td>
<td>[87]</td>
</tr>
<tr>
<td>Bioretention with biochar and poultry litter</td>
<td>-</td>
<td>90</td>
<td>-</td>
<td>High</td>
<td>[156]</td>
</tr>
<tr>
<td>Bioretention planted with vegetables</td>
<td>47</td>
<td>-</td>
<td>-</td>
<td>Medium</td>
<td>[157]</td>
</tr>
<tr>
<td>Saturated zone containing shredded newspaper</td>
<td>-</td>
<td>-</td>
<td>99</td>
<td>High</td>
<td>[147]</td>
</tr>
<tr>
<td>Bioretention amended with biochar</td>
<td>-</td>
<td>-</td>
<td>30.6 – 95.7</td>
<td>Medium-high</td>
<td>[100]</td>
</tr>
<tr>
<td>columns study for anoxic sand packed amended with wheat straw, wood chips, and sawdust</td>
<td>-</td>
<td>-</td>
<td>95</td>
<td>High</td>
<td>[158]</td>
</tr>
<tr>
<td>Bioretention amended with biochar coupled with saturated zone</td>
<td>20 – 30</td>
<td>50 – 60</td>
<td>50 – 60</td>
<td>Low-medium</td>
<td>[152]</td>
</tr>
<tr>
<td>Bioretention combined with saturated and unsaturated conditions</td>
<td>-</td>
<td>-</td>
<td>42 – 63</td>
<td>Medium-high</td>
<td>[129]</td>
</tr>
</tbody>
</table>

Combining nitrification and denitrification zones in bioretention system with adding carbon source showed beneficial influence in promoting nitrogen removal from stormwater runoff [159].

### 5. Conclusions

This study reviewed the existing recent advances in nitrogen removal for stormwater runoff in bioretention system. Many studies have indicated that bioretention tend to be effective for nitrogen removal. However, some studies reported nitrogen leaching. Hence, nitrogen has a complex biogeochemical cycle and is more difficult to remove because it is highly soluble. Thus, the removal processes of nitrogen are typically slower processes. It is mainly depended on physical, biological processes and chemical reactions. The main processes include assimilation, adsorption, ammonification, nitrification and denitrification. In conclusion, advanced nitrogen removal can be achieved by selecting appropriate processes. Combining nitrification and denitrification zones with adding carbon source in a bioretention system showed the beneficial influence in promoting nitrogen removal from stormwater runoff. It is a promising way for stormwater runoff treatment as it effectively enhances nitrogen removal. Additionally, the proper selection of plant species can facilitate nitrogen removal, particularly where nitrogen concentrations are of critical concern. Nonetheless, more work on nitrogen transformations through bioretention system and factors
affecting them needs to be explored. The relationships between various factors and their combined effects on nitrogen removal in bioretention is required corresponding with mathematical models for better design optimisation. In addition, greater focus is required in the development of bioretention design criteria which can promise for more nitrogen removal enhancement.

Author Contributions: M. O investigation, writing and original draft preparation, K. Y and H. T review and supervision, H. W supervision, review and editing, N. A review, editing and formal analysis, M.A funding and resources, A. G project administration.

Funding: This research was funded by Universiti Tenaga National, Malaysia, iRMC Bold 2025, grant code (RJO10436494).

Acknowledgments: The authors would like to acknowledge the support given by Universiti Teknologi PETRONAS, and River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia.

Conflicts of Interest: The authors declare no conflict of interest.
## Appendix A

### Table A1: Summary of Nitrogen removal by different plant species in bioretention studies.

<table>
<thead>
<tr>
<th>Site Name</th>
<th>NH₃</th>
<th>NO₃</th>
<th>NO₂</th>
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<th>TN</th>
<th>TDN</th>
<th>ON</th>
<th>DON</th>
<th>PON</th>
<th>Use of C source</th>
<th>Use of plant</th>
<th>Type of plants used</th>
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<td>chokeberry (Aronia prunifolia), winterberry (Ilex verticillata), and compact inkberry (Ilex glabra compacta)</td>
<td>Dietz and Clausen (2006) [92]</td>
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<td>yes</td>
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<td></td>
<td>no</td>
<td>yes</td>
<td>Southern wax myrtle (Myrica cerifera), Virginia sweetspire (Itea virginica), winterberry (Ilex verticillata), inkberry (Ilex glabra)</td>
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<td>Charlotte, N.C., US</td>
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<td>Blueflag iris (Iris virginica), cardinal flower (Lobelia cardinalis), common rush (Juncus effusus), hibiscus (Hibiscus spp.), red maple (Acer rubrum), sweet pepperbush (Clethra alnifolia), Virginia sweetspire (Itea virginica), wild oat grass (Chananthium latifolium)</td>
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<td>red maple (Acer rubrum), sweet bay (Magnolia virginica), Virginia sweetspire (Itea virginica), liriope (Liriope sp.), verbena (Verbea sp.), and</td>
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<td>Use of plant</td>
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2. Laboratory study

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<td>Swamp Foxtail Grass (Pennisetum alopecuroides) Flax Lily (Dianella brevipedunculata), two woody shrubs, Banksia (Banksia integefolia), Bottlebrush (Callistemon pachyphyllus)</td>
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