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Fate and removal of nutrients in bioretention systems

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ABSTRACT

Phosphorus and nitrogen in different forms are the primary concern in surface water bodies nowadays since it causes eutrophication. A bioretention system, an example of green stormwater infrastructures reduces nutrients through biological processes such as plant uptake and microbial conversion of nitrogen known as bioremediation. In this study, the performance of two types of bioretention system in managing nutrients from urban stormwater runoff was investigated. Total phosphorus (TP) was reduced by 85% up to 86% in both bioretention types while total nitrogen (TN) was reduced by 49 and 55% in type A and type B bioretention, respectively. Among the plants species used in the study, *Rhododendron indicum* Linnaeus was identified as the most appropriate plant that should be used in bioretention systems considering factors such as number of flower per plants, plant decay rate, cost of plant, number of plant per reactor, and TN and TP uptake by plants. Based on the results, 25–32% of TN and 47–59% of the TP load were absorbed by the soil medium. This finding signified that filtration was the main removal mechanism for nutrients in bioretention.

Keywords: Bioretention; Green stormwater infrastructure; Nonpoint source pollution control; Nutrients

1. Introduction

Bioretention was first developed in 1980s and applied to residential and industrial landuses including gardens, parking lots, sidewalks, streets, and highways [1]. Bioretention systems are composed of porous media and vegetation designed to receive stormwater runoff from highly urbanized/impervious areas such as parking lots, roads and roofs, and suburban areas [2–4]. The polluted stormwater runoff was collected into the bioretention and improves its quality through filtration by typically soil media. In addition, bioretention reduces storm water pollutants through biological processes such as uptake by plants also known as phytoremediation and microbial conversion of nitrogen also known as bioremediation [5]. Bioretention systems also demonstrated its feature as an effective low impact development strategy through its high hydraulic capacity thereby managing the stormwater peak flow, runoff volume, and stormwater pollution, and maintaining the groundwater recharge and stream baseflow [6]. Bioretention systems are generally

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small, esthetically pleasing and reported to achieve a number of more sustainable stormwater runoff management objectives. Other beneficial attributes of bioretention related to plants include mitigation of urban heat island effect through direct shading and indirect evaporative cooling, sequestration of carbon dioxide, and promotion of urban biodiversity evident through higher number of species, species richness, diversity, and composition in bioretention system [7,8].

Nutrients such as phosphorus and nitrogen in different forms are the primary concern in surface water bodies since discharging high nutrient loadings can cause eutrophication or algal bloom. The cause of high variability in nutrient removal in bioretention systems is due to the complexities of chemistry of these pollutants making it difficult to attain relatively similar removal efficiencies especially when applied to different site and environmental conditions. For some instances, nutrient removal by bioretention systems may be high but in other, treatment efficiencies may be low or the bioretention system itself might be a source of nutrient due to possible leaching. Phosphorus may be removed through filtration for particle-bound and chemical sorption for dissolved forms. Possible leaching of phosphorus may result from improper media selection especially for soil with high organic content. On the other hand, only complicated biological nitrification–denitrification reaction can primarily remove nitrogen forms. Nitrogen removal may be increased by considering internal water storage layers to force an anoxic zone in the bioretention system.

This study investigated the performance of two types of lab-scale bioretention system in managing nutrients in urban stormwater runoff. Particularly, the factors affecting the removal of nutrients through mass balance were evaluated and several factors to be considered in selecting the most appropriate plant species were also identified.

2. Materials and methods

2.1. Lab-scale bioretention system setup

Two reactors were developed for each lab-scale bioretention types shown in Fig. 1. *Chrysanthemum zawadskii var. latilobum* (A-CL) and *Aquilegia flabellata var. pumila* (A-AP), respectively, were planted in each type A bioretention reactors while *Rhododendron indicum* Linnaeus (B-RL) and *Spiraea japonica* (B-SJ) were planted in each type B bioretention reactors, respectively. The main difference between the bioretention types were the infiltration and ponding capacity incorporated in the design of type B bioretention reactors. Both types of lab-scale bioretention were rectangular box-shaped with length, width, and height aspect ratio of 2.1:1.1:1 and 3.75:1:1.5 for type A and B, respectively. Other physical characteristics of bioretention were listed in Table 1. Fifteen percent of the total facility depth was allotted as ponding depth in both bioretention types. The woodchip mulching occupied 5% of the bioretention depth located below the provided ponding depth. Top soil layer (40% of the facility depth), middle sand layer (20% of the facility depth), and bottom gravel layer (20% of the facility depth) were used as the main filter media in the bioretention system developed. The top soil media was held by coconut mat to prevent erosion into the other media layers. On the other hand, the media setup was held by geotextile filter fabric to prevent *in situ* soil contamination after the real scale application of the bioretention lab-scale.

2.2. Operating conditions, data collection, and analyses

One to two kg of sediments collected from a 520 m^2 impervious road were diluted in 2 m^3 of tap water and used as synthetic stormwater runoff for each experimental run. Each experimental run was conducted during 120 min. The four bioretention reactors were tested using five inflow rates of 2, 3, 4, 5, and 6 L/min. The flow rates were selected based on 10 years average occurrence frequency of rainfall depth which was equivalent to 55, 60, 65, 70, and 75% of rainfall depth occurring in Cheonan city, South Korea. Water samples were collected right after the initial application of artificial stormwater runoff and after 30, 60, 90, and 120 min. Water sampling scheme was based on the assumption that the influent concentration was constant since it came from same source tank. Consequently, manual flow checking was conducted every 10 min to ensure that there will be no changes in flow rate. Similarly, samples were also collected and flow rates were also checked from the discharge of infiltration for type B and outflow ports for both types. Analytical analyses for typical water constituents were performed in accordance with the standard methods for the examination of water and wastewater [9].

The EMC represents a flow-weighted average concentration, computed by dividing the total pollutant mass by the total runoff volume for event duration. In addition, the summations of the runoff and discharge volume were calculated for each storm event to determine the volume reduction capacity of the system. The pollutant mass reduction of the system was calculated by dividing the difference of the summation of influent and summation of effluent loading with the summation of influent loading, also known as summation of loads

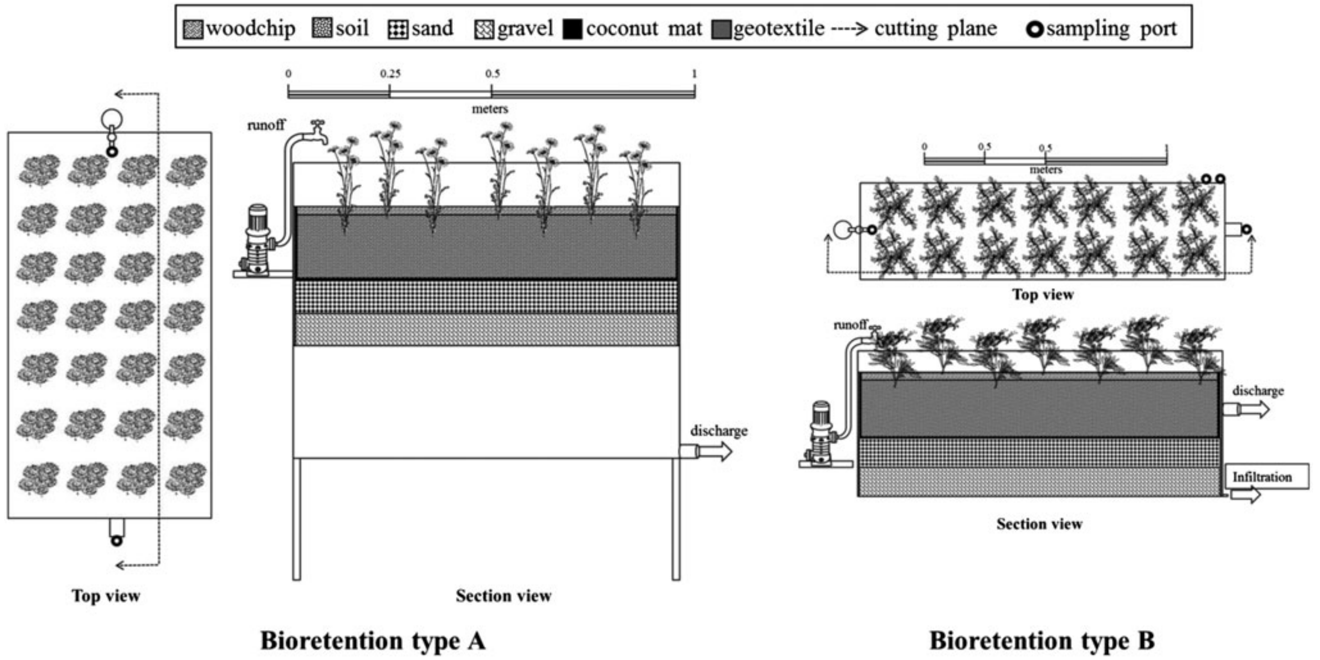

Fig. 1. Schematic diagram of each type of lab-scale bioretention system developed.

Table 1
Physical characteristics of lab scale bioretention systems

Bioretention type	Surface area m^2	Storage volume m^3	Total volume m^3
A	0.475	0.094	0.19
B	0.6	0.178	0.36

method. Lastly, the factors considered in mass balance were the retained in the soil, retained in the system other than soil, discharged, and infiltrated loads. Results were statistically analyzed using SYSTAT 12 and Origin Pro 8 package software including normality test and analysis of variance. Pearson correlation coefficient (*r*) was used to determine the dependence between each water quality parameter. Shapiro–wilk normality test was used to determine the distribution of data, and one-way ANOVA was used to analyze the difference between the variance of the each water quality parameters. Significant differences between parameters were accepted at 95% confidence level, signifying that probability (*p*) value was less than 0.05.

3. Results and discussion

3.1. Hydraulic condition and characterization of pollutants in each bioretention system

Five test flow rates were used in each bioretention developed. A total of 12, 12, 13, and 14 experimental runs were conducted in A-CL, A-AP, B-RL, and B-SJ bioretention systems, respectively. The average (mean ± standard deviation) inflow volumes were 0.46 ± 0.21, 0.47 ± 0.21, 0.49 ± 0.2, and 0.47 ± 0.19 for A-CL, A-AP, B-RL, and B-SJ, respectively. There was no significant difference between the inflow volume in all the bioretention systems signifying that these bioretention were all subjected to almost same condition and can therefore be compared ($p > 0.05$). Meanwhile the mean ± standard deviation antecedent dry days (ADD) were 3.11 ± 1.66, 3.1 ± 1.51, 3.41 ± 5.23, and 3.31 ± 5.04 for A-CL, A-AP, B-RL, and B-SJ, respectively. Fig. 2 shows the average water balance in each bioretention system developed. No significant differences were identified between the volumes reduced by type A bioretention, A-CL and A-AP and between type B bioretention, B-RL, and B-SJ (A-CL and A-AP: $p > 0.05$; B-RL and B-SJ: $p > 0.05$).However, the volume reduced by B-RL and B-SJ were 16–19% significantly greater than A-CL and 14–17% greater than A-AP (A-CL and B-RL; $p < 0.001$; A-CL and B-SJ; $p < 0.001$; A-AP and B-RL;

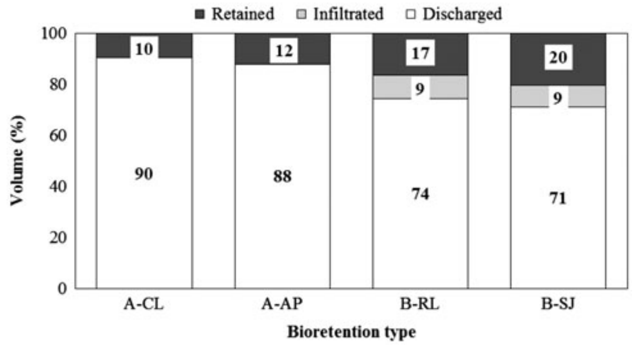

Fig. 2. Average water balances of all types of bioretention systems.

$p < 0.001$; A-AP and B-SJ; $p < 0.001$). These results emphasized the importance of infiltration mechanism incorporated in flow attenuation capabilities of bioretention systems. The larger in storage volume of B-RL and B-SJ compared to A-CL and A-AP was also considered as an affecting factor. As shown in Fig. 3(a), the volume ratio (outflow volume/inflow volume) was dependent on the inflow rate. As the inflow rate in the bioretention, the volume ratio also increased implying that greater inflow rate resulted to less reduced volume in all the bioretention systems developed. On the other hand, longer HRT in the systems developed yielded to less volume ratio (Fig. 3(b)). A-CL and A-AP resulted to almost similar trend. Similarly the trend observed in B-RL and B-SJ volume ratio with respect to volume reduction was almost same. Apparently, greater volume ratio may be observed from B-RL and B-SJ compared to A-CL and A-AP due to the infiltration mechanism that supports in volume reduction of type B bioretention systems.

One of the critical and commonly used factors in estimating the pollutant removal efficiency of a treatment system is by determination of EMC [10]. A-CL, A-AP, B-RL, and B-SJ significantly reduced the inflow EMC (EMC_{in})of nutrients including TN, TP, NO_3-N, and NH_4-N by 0.81 ± 0.7–0.99 ± 0.64, 0.43 ± 0.23–0.47 ± 0.19, 0.5 ± 0.65–0.69 ± 0.59, and 0.11 ± 0.6–0.19 ± 0.39 mg/L, respectively, in the outflow EMC (EMC_{out}) with p less than 0.05. Among the bioretention systems developed, only B-SJ significantly reduced the PO_4–P EMC_{in} from 0.02 ± 0.01 mg/L to EMC_{out} amounting to 0.01 ± 0.01 (B-SJ: $p = 0.03$; other bioretention except B-SJ: $p > 0.05$).

3.2. Fractional distribution of nutrients

Nitrogen and phosphorus compounds have relatively distinct and complicated removal mechanism compared to particulates and heavy metals. Runoff infiltration time and ADD were identified to have significant effect in the complicated nitrogen compound transformation in bioretention [11]. Based on Fig. 4(a), the N-forms reduction was almost in the same ranges. Greater mean NH_4-N reduction ranging from 40 to 54% was exhibited by A-CL, A-AP, B-RL, and B-SJ compared to NO_3-N which was only about 35–41% signifying that there was a possibility that nitrification process occurred in the bioretention system developed. Nitrification process usually occurs with the help of nitrifying bacteria such as *nitrosomonas* which converts NH_4^+ to NO_2^-. Other causes of NH_4-N removal were associated with sorption and ion exchange processes in bioretention soil [12,13]. It was observed that both nitrification and photosynthesis contributed to the nutrient removal in each bioretention systems through the mean difference in outflow and inflow dissolved oxygen which was 0.13, 0.11, 0.37, and 0.39 for A-CL, A-AP, B-RL, and B-SJ, respectively. Compared to the study of Hsieh and Davis, 2005, the systems developed reduced greater NO_3-N loading [14]. The use of woodchip mulching and

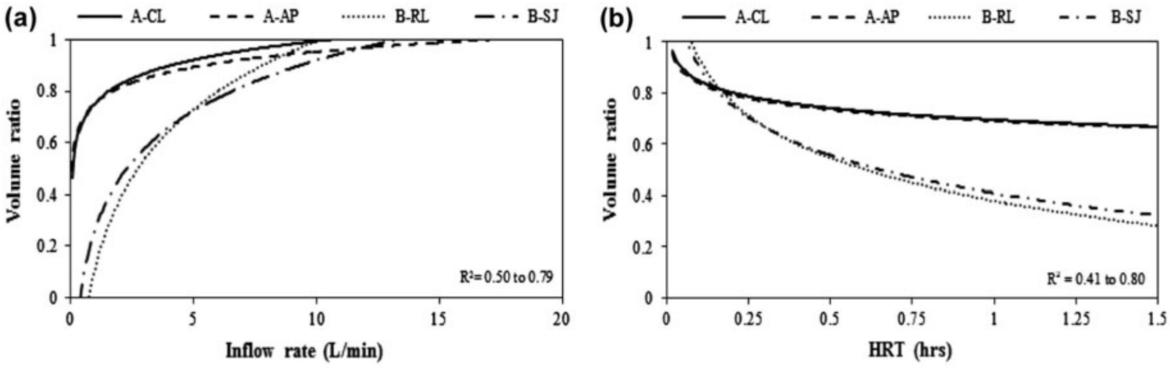

Fig. 3. Logarithmic regression plots of changes in volume ratio with inflow rate (a) and HRT (b).

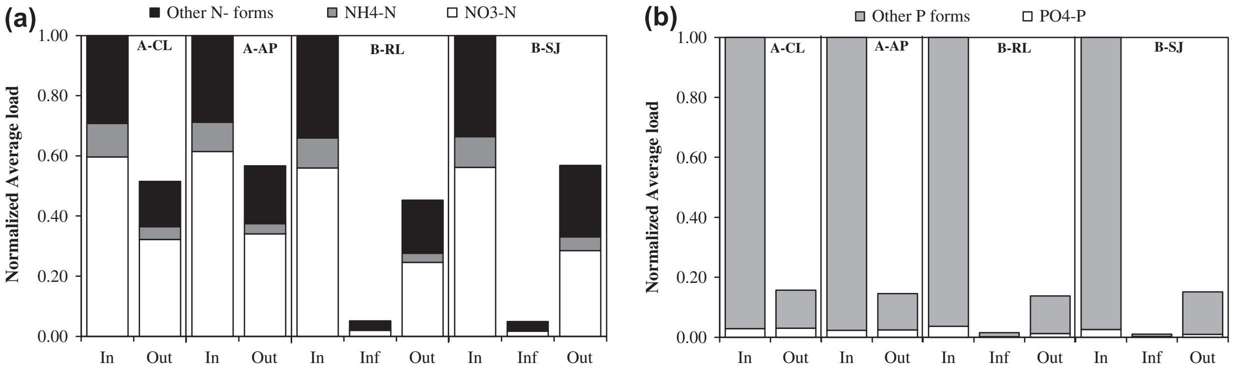

Fig. 4. Normalized average inflow, infiltration, and outflow load fraction of nitrogen (a) and phosphorus (b) forms in each bioretention system.

coconut mat may have contributed to the increased NO_3-N reduction in the bioretention systems developed.

Similarly, the average removal efficiency of TP was almost in same range of 77–81% for A-CL, A-AP, B-RL, and B-SJ (Fig. 4(b)). However, there was an increase in PO_4-P load observed in A-CL and A-AP. The average increase in PO_4-P load was 0.48 and 0.40 mg in A-CL and A-AP, respectively. Meanwhile, B-RL and B-SJ reduced the inflow PO_4-P by 42 and 46%, respectively. The reduced TP load may be available for future use by the vegetation through nutrient cycling and significant phosphorus loadings may be removed through vegetation [5].

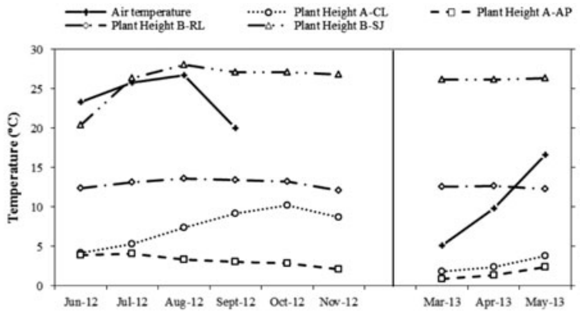

Fig. 5. Plots of monthly changes in air temperature and plant height in all bioretention types.

3.3. Plant analysis

Fig. 5 shows the relationship between plant height and air temperature. Excluding the months of decay of plants between October and November, the plant height of CL, AP, and RL were highly correlated with air temperature (A-CL: $r = 0.71$; A-AP: $r = 0.97$; B-RL: $r = 0.52$). This result signified that the plant growth rate in bioretention system was dependent on the air temperature and season of Korea. Highest plant height of each system was observed during from June to August whereas the lowest was observed during the months of October to March. Among the plants, A-CL was the only plant that was observed to continuously grow until October. Since B-RL and B-SJ were perennials, stable plant height was evident from September to May 2013 implying that no growth was observed in the plants vertically however, the plants were growing laterally since April 2013. Perennials were usually growing laterally making the plant wide instead of growing vertically. Other factors such as photosynthesis affect the nutrient activity in plants [15]. Photosynthesis is the single basic process by which plants reduces carbon dioxide to increase the biomass of plants. Solar radiation and air temperature were correlated making the photosynthesis more active during summer season and less active during winter season [16]. Shrubs such as A-CL and A-AP bloomed from September to October and May, respectively. On the other hand, the perennials, B-RL and B-SJ, bloomed from April to May and from July to August, respectively. A-AP produced the least number of flower compared to other plant species. Meanwhile, B-RL produced the highest number of flower of 27 per plant followed by B-SJ and A-CL producing nine flowers per plant. Fig. 6 presents the monthly plant and decay rates in each bioretention system. Among the plant species analyzed, SJ attained the maximum value of plant growth rate of 7.4 mm/d in July. On the other hand, the maximum plant growth rate attained by A-CL and A-AP were during the month of March. For A-AP, B-RL, and B-SJ, the plant decay started at September while A-CL started to decay at November. The plant dormancy for A-CL and A-AP were observed from November to February while the B-RL and B-SJ were dormant from November to March. The

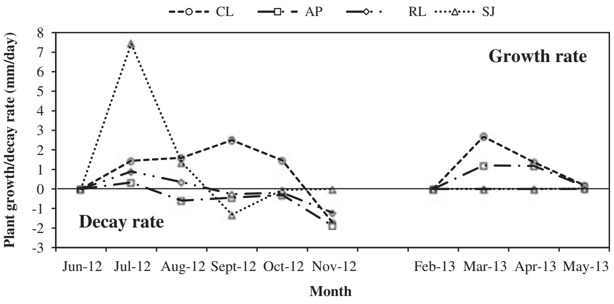

Fig. 6. Average monthly growth and decay rates of plants in each bioretention system.

summary of plant selection criteria is exhibited in Table 2. Based on the different selection criteria, *R. indicum* Linnaeus (B-RL) planted in bioretention type B was the most appropriate plant in bioretention considering the plants used in the study.

3.4. Nutrient mass balance

The complexity of nutrient cycles made it difficult especially for nitrogen cycle to be managed. However, nitrogen cycle was probably the most important nutrient cycle that needed to be studied. Nitrogen was usually the growth limiting plant nutrient in land and nitrate forms of N were very soluble and one of the most common mobile plant nutrients in soil. On the other hand, phosphorus availability is one of factors to determine the risk of phosphorus transport from agricultural land to surface water bodies [5]. The plots of TN and TP fractional distribution in each bioretention system is presented in Fig. 7. The mass balance was calculated by summation of the experimental run inflow nutrient load from 26 February to 11 April 2013 since the new plant life cycle starts every spring season in Korea. Among the plants analyzed in the system, B-RL uptake the greatest TN content amounting to 4% of inflow TN load. On the other hand, A-CL, A-AP, and B-SJ uptake only less than 1% of the inflow TN load. In A-CL, B-RL, and B-SJ, the retained TN load in soil was 14, 18, and 9% greater than the retained TN load in the bioretention system. Only 3% of the TN inflow load was reduced by the infiltration mechanism employed in the design of B-RL and B-SJ, respectively. These findings were associated with the possible occurrence of nitrification and biological uptake. Similarly, the greatest TP uptake by plants amounting to 21% was observed in B-RL. Meanwhile, A-CL, A-AP, and B-SJ uptake was only 11, 2, and 10%, respectively. Difference of 19, 31, 17, and 43% was observed between the TP load retained in the soil and retained in the bioretention system. Good reduction of TP by the bioretention systems developed was associated with retention in soil. Lastly, only 1% of the TP load was associated with the infiltration mechanism. These finding implied that the infiltration mechanism have less contribution to nutrient removal compared to other removal mechanism employed in each bioretention system. However, having less contribution to nutrient removal also implied that the infiltrated volume have better water quality for groundwater recharge. Compared to the studies conducted by reference [17] and reference [18], the plant uptake of N were relatively smaller where in the mean N resorption were 50% for perennials and 57% for the shrubs. On the otherhand, the P resorption for perennials and shrubs based on other studies were not significantly different of greater than 50% [17,18]. The findings of other studies explained the varying value for nutrient uptake by plants in the bioretention systems developed.

Table 2
Summary of plant selection criteria

Parameter	Unit	Bioretention reactor and plant species			
		A-CL	A-AP	B-RL	B-SJ
No. of flower per plant		8	1	27	9
Growth rate	mm/d	1.6	0.57	0.63	2.94
Decay rate	mm/d	1.72	0.81	0.56	0.68
Cost	$/plant	1	1	1.5	2
No. of plants per reactor		28	28	8	8
TN uptake with respect to inflow load	%	0.3	0.1	4	0.4
TP uptake with respect to inflow load	%	11.3	2.1	20.6	9.6
Flower blooming month/s		September–October	May–June	April–May	July–August

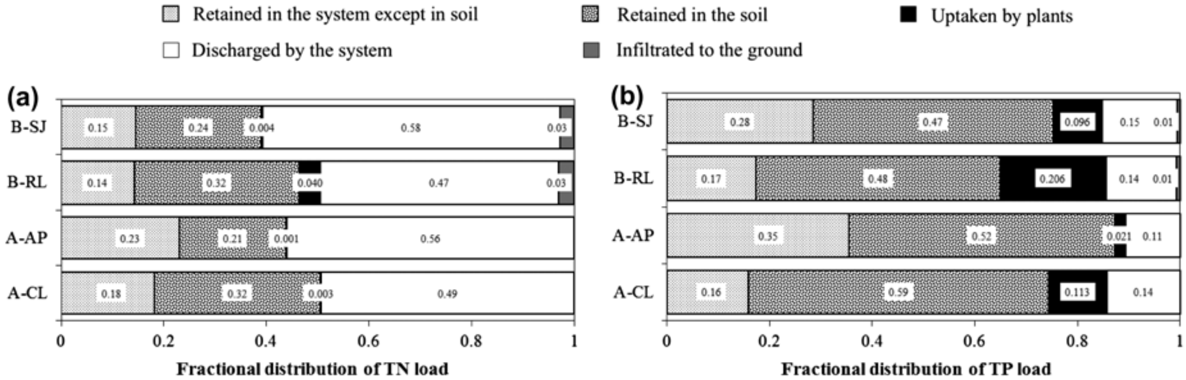

Fig. 7. Plots of TN (a) and TP (b) fractional distribution in each bioretention system.

4. Conclusions

Bioretention systems are commonly employed to highly urbanized land uses due to its good efficiency in reducing the nutrients in urban stormwater runoff. Several treatment mechanisms including sedimentation, filtration, infiltration sorption, biological uptake, evapotranspiration, bioremediation, and phytoremediation were incorporated in the system which made it an advance stormwater management technology compared to other systems. This study investigated, compared and assessed the performance of four bioretention reactors namely A-CL, A-AP, B-RL, and B-SJ. Based on the results, the following conclusions were drawn:

(1) Increasing HRT in the system corresponded to decreasing volume ratio whereas the increasing inflow rate corresponded to increasing volume ratio.
(2) Significant difference was observed between TN, TP, NO_3-N, NH_4-N EMC_{in}, and EMC_{out} signifying that these pollutants were significantly reduced in all the bioretention systems developed ($p < 0.05$).
(3) Based on the plant selection criteria, *Rhondedron indicum* (L.) sweet was considered the best plant that should be applied to bioretention system among the plants used in the study.
(4) Filtration through soil media and retention in the bioretention system were the main nutrient removal mechanisms in the bioretention systems.

Acknowledgments

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