Effectiveness of Rain Garden Facilities in Nitrogen and Phosphorus Removal through Bioretention Columns

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Abstract - A major concern in water quality problem is eutrophication which is caused by the nutrients, namely nitrogen and phosphorus. Previous studies have reported inconsistent nitrogen and phosphorus removal from stormwater runoff using bioretention. The objective of this study is to examine and evaluate the efficiency of rain garden in nitrogen and phosphorus removal by varying the types of the mulch layers in a bioretention column and further select the best to be used in rain garden design. Three (3) bioretention columns with size of 46mm in diameter and a height of 400mm were is used for this study where the inflow and outflow runoff will be collected and analyzed to measure the nutrient concentration. Filter media at the depth of 200mm consisted of river sand with soil mix of 80% fine sand and 20% coarse sand were used. Three different types of mulch layer wood chip, tea waste and coconut fibers were applied at the top of filter media at a height of 50mm. Phosphorus concentration in the bioretention column was reduced by 73.9% using woodchip, 23.1% using tea leaves and 50% using coconut fibres. Lower removal efficiency was seen for nitrogen where 24.4% using woodchip, 0% for tea leaves and 4.4% using coconut fibre. Woodchip was seen to be favourable compared to the other two mulch layer due to it removal efficiency in removing both phosphorus and nitrogen from the incoming stormwater runoff. The absorption capacity is seen as the main factor that affects the removal rate.

Keywords – rain gardens; bioretention; nutrient concentration; stormwater runoff

I. INTRODUCTION

Urban stormwater runoff that flows through road surfaces, parking areas, vehicle and buildings carries a broad range of pollutants that are transported to rivers and other water bodies which effects the environment and ecology negatively. Effects on receiving waters include oxygen depletion, eutrophication, species stress, and toxicity [1]. Bioretention systems are designed to remove both dissolved pollutants and particulate matter from stormwater runoff [8]. Another advantage of bioretention systems is their ability to significantly reduce stormwater volumes through infiltration and evapotranspiration [9].

Nitrogen and phosphorus, the primary nutrients implicated in eutrophication, enter water bodies via a variety of pathways [2]. Eutrophication causes algae growth on water surfaces which leads to oxygen depletion and high turbidity levels in aquatic ecosystem. The presence of nitrogen in stormwater runoff may come from fertilizers, atmospheric deposition and nutrient cycling while presence of phosphorus may also come from fertilizers, atmospheric deposition and other sources such as soil erosion, animal waste and detergents.

Currently, bioretention systems also known as biofilters or rain gardens are used widely as an effort to mitigate effects that is harming the environment. Bioretention has been demonstrated to be promisingly efficient in the removal of phosphorus and organic nitrogen from infiltrating runoff [2]. Bioretention is a vegetated infiltration practice for managing stormwater runoff from developed areas [6].

Engineering manuals for the design of bioretention gardens commonly originate from United States of America (USA). However, there have been an extensive bioretention documents published in other countries in recent years. In a typical configuration, bioretention includes a layer of approximately 75 to 100 cm of an engineered soil/sand/organic media, supporting a mixed vegetated layer [5]. The soil typically has a high sand content to provide rapid infiltration but with low levels of silt and clay to promote attenuation of pollutants during the infiltration [1]. A 5 to 8 cm shredded hardwood mulch layer is added on the surface to maintain soil moisture and filter incoming sediment [2]. Figure 1 shows a diagram of the common bioretention design layers.

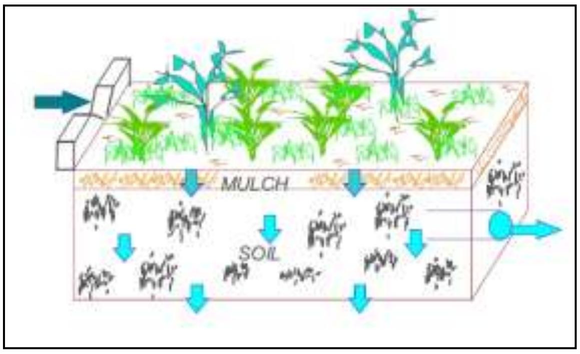

Figure 1 Diagram of bioretention facility [2]

Bioretention gardens have shown impressive pollutant removal through laboratory studies by Davis *et al*. [1] [2] where reduction in concentration of copper, lead, and zinc (>92%) [1], phosphorus (70 to 85%) [2] and ammonium (60 to 80%) [1].

Based on the studies by Debusk and Wynn[3] and Hsieh and Davis [4], it shows that the selection of filter media plays an important role in removing pollutants especially nitrogen and phosphorus. From a study conducted by Hsieh et al. [4] on phosphorus removal, the column media with high hydraulic conductivity overlying one with low hydraulic conductivity was more efficient in total phosphorus removal that ranged from 67% to >98% compared to the column media with low hydraulic conductivity overlying high hydraulic conductivity as less permeable soil layer at the bottom of the column increases the retention time between dissolved phosphorus and media.

Hsieh *et al.* [6] also conducted a study on nitrogen removal whereby two different columns with different filtration media configuration gave different removal rate where the first column was designed for high-rate infiltration and second column was designed for runoff retention. The second column proved greater net mineral nitrogen removal efficiency compared to the first column as water was held longer in the filtration media to allow nitrification and denitrification to occur.

Table 1 display the removal efficiency for pollutant of a 6 hours bioretention column test conducted by Hsieh and Davis [4].

Table 1 Characteristic and Results of 6h Bioretention Column Test (Hsieh and Davis) [4]

Experiment number	Mass ratio (%)			Experimental set	Infiltration rate (cm/min)	Removal efficiency (%)					
	Mulch	Soil	Sand			TSS	O/G	Lead	TP	Nitrate	Ammonium
1[a]	0	0	100(I)	A,B	0.84±0.01	>96	>96	>98	85±1.5	11±16.7	8±3.4
2[a]	0	0	100(II)	A	8.15±0.18	>96	>96	96±0.7	10±3.1	1±0.7	15±0.8
3[a]	2	93(I)	5(I)	A,B	0.28±0.04	29±2.9	>96	>98	47±3.4	1±0.6	6±2.2
4[a]	2	93(II)	5(I)	A	0.95±0.01	88±0.9	>96	>98	41±4.5	14±2.2	24±0.8
5[a]	2	93(III)	5(II)	A	0.40±0.02	91±0.3	>96	>98	48±4.0	8±0.7	16±1.1
6[a]	91	0	9(I)	A	0.28±0.01	86±1.0	>96	75±2.0	4±4.5	43±3.2	16±1.9
7[a]	0	0	100(I)	—	0.81±0.02	—[e]	>96	66±7.0	84±1.3	13±6.4	5±1.7
8	3	0	97(I)	B	0.77±0.01	>96	>96	>98	61±4.5	9±0.4	9±2.0
9[b]	2	21(I)	77(I)	C-1	0.32±0.02	66±2.5	>96	>98	47±4.6	3±0.8	2±1.1
10[b]	8	26(I)	66(I)	C-1	0.31±0.01	94±0.6	>96	>98	50±3.8	4±0.7	7±1.0
11[b]	6	32(I)	62(I)	C-1	0.30±0.01	93±0.9	>96	>98	39±4.0	4±0.5	7±0.8
12[b]	0	24(I)	76(I)	C-1	0.30±0.01	93±0.5	>96	>98	39±3.5	2±0.5	5±2.2
13[c]	3	43(I)	54(I)	B,C-2	0.48±0.02	>96	>96	>98	83±1.4	13±59	26±2.6
14[c]	3	24(I)	73(I)	B,C-2	0.66±0.01	>96	>96	>98	57±2.7	24±2.9	17±2.1
15[c]	11	19(I)	70(I)	B,C-2	0.71±0.02	>96	>96	>98	54±2.7	27±1.1	20±1.2
16[d]	2	17(II)	81(II)	D	5.40±0.15	>96	>96	97±0.2	24±3.8	6±1.5	11±0.6
17[d]	2	72(III)	26(II)	D	1.15±0.02	92±0.3	>96	>98	72±0.8	9±0.9	19±0.6
18[d]	2	49(III)	49(II)	D	1.93±0.01	93±0.3	>96	>98	74±0.9	8±0.5	20±0.5

[a]Native media.
[b]Column with upper Soil I layer.
[c]Column with synthetic media I (mixture of Soil I/mulch/sand I).
[d]Column with upper Soil II or Soil III layer.
[e]Influent without suspended solids; (I),(II),(III): Different types of sands and soils—see Table 2.

From this study conducted by Hsieh and Davis [4] shown in Table 1, it was found that the bioretention columns and on-site facilities were excellent in removing Oil and Grease (O/G) and lead (Pb). For Total Suspended Solid (TSS), it shows good removal in the column studies compared to field studies. However, removal of nitrate and ammonium was found to be ineffective during the column studies.

Mulch layer is one of the main filtration media in the bioretention as it has its own advantages which lead to it being evaluated in this project. According to Debusk and Wynn [3], the mulch layer acts as a media to promote plant growth, maintain the infiltration rate into the soil layer and reduce pollutant concentration. Davis *et al.* [1] mentioned that a thin layer of wood mulch in the bioretention can help to avert erosion from occurring, avoid the soil layer from extreme drying and contribute to the stormwater treatment process.

Other than that, Hsieh and Davis [3] found that the mulch layer acts as filter for the incoming TSS, prevents underlying media from clogging, maintains the soil during dry weather and provides nutrients for future vegetation.

Pine bark, tree fern, rice husk and wood fibres are a number of natural materials mentioned by Ray *et al*. [7] that is used to remove dissolved pollutants from aqueous media as they are inexpensive compared to activated carbon and synthetic resin. From the research conducted by Ray *et al.* [7], the common garden store variety hardwood mulch can be used to remove water soluble pollutants such as heavy metals and toxic organic compounds that are normally found in stormwater runoff.

II. METHODOLOGY

A. Bioretention Column Setup

Three bioretention columns with a diameter of 46mm and a depth of 400mm hold 280mm of the filtration media were setup. Each column was filled with 30mm gravel, 200mm sand mixture (80% fine sand and 20% coarse sand) and topped with 50mm layer of mulch. The columns were setup to match bioretention design specification in a laboratory setting whereby information regarding the pollutant removal (nitrogen and phosphorus) will be collected and analyzed. Figure 1 shows the sketch of filter media depth in the bioretention column.

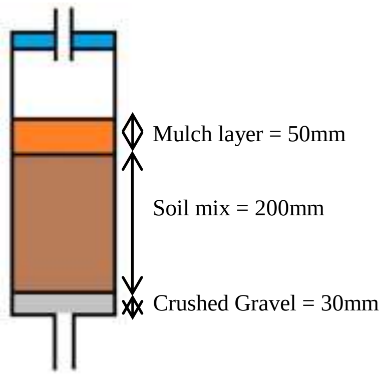

Figure 2 Filter Media Depth

B. Mulch Layer

As the main focus will be on the efficiency of the mulch layer in removing the concentration of nitrogen and phosphorus, there will be three different types of mulch that will be used which area:

i. Tea waste
ii. Wood chip/saw dust
iii. Coconut fibre

These materials are commonly used as organic mulch in landscaping, inexpensive and easily available. Organic mulch is preferred over inorganic mulch as it adds nutrients to the soil as it decomposes. Before putting the mulch layer in the bioretention column, all of the materials were soaked in distilled water and air dried in an oven for 12 hours to remove any contaminants that may have been present. After drying and placed inside the bioretention column, it is once again flushed with 1 litre of distilled water to cleanse and ensure that water is able to transmit through the mulch layer and down into the underlying soil layer. The bioretention column is left for 24 hours before the laboratory experiment begins to allow water dry out from the filter media.

C. Experimental Work Analysis

An analog pump with a maximum capacity of 100rpm was used to supply the stormwater runoff into the bioretention columns. An early run was conducted to test the maximum flow rate of the pump which was 42mL/min at 100rpm. The experiment was run in a 6 hour period where a volume of 9 litres stormwater runoff was pumped through the bioretention column. Therefore, a constant flow rate of 25mL/min was kept throughout the whole experiment.

To determine the nutrient content from stormwater**,** stormwater influent and effluent was collected for each bioretention column (i.e. two samples obtained from each bioretention column). Each sample was tested and analyzed for nitrogen and phosphorus concentration. Three runs were conducted for each bioretention column. The stormwater sample collected was from a drain outlet between a parking lot and an open field. The nitrogen concentration was tested using the Nessler Method where the unit is in mg/L NH_3-N. Phosphorus concentration was tested using the Acid Persulfate Digestion Method where the unit is in mg/L PO_4^{3-}.

III. RESULT AND DISCUSSIONS

A. Particle Size Distribution

Although particle size distribution of the sand is not the main focus of the project, however, it is important in terms of the hydraulic performance of the bioretention column. Therefore, sieve analysis was conducted to determine the particle size distribution of the selected coarse and fine sand. The ratio of the soil mix was 80% fine sand and 20% coarse sand. Below shows the sieve analysis result of the soil mix:

Table 2 Soil Mix Sieve Analysis Result

Size (mm)	Weight Retained (g)	% Retained	Total passing (%)
3.350	0	0.00	100.00
2.000	1.5	0.15	99.85
1.180	668.3	66.85	33.00
0.600	323.2	32.33	0.67
0.425	5.9	0.59	0.08
0.300	0.6	0.06	0.02
0.212	0.2	0.02	0.00
0.150	0	0.00	0.00
0.063	0	0.00	0.00
Pan	0	0.00	0.00
Total	1000	100	

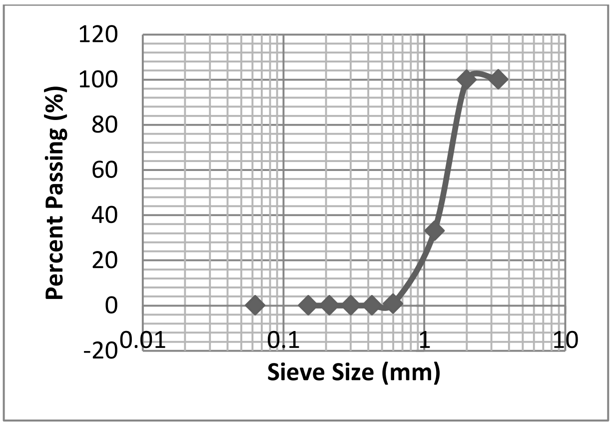

Figure 3 Soil Mix Particle Size Distribution

According to Biofiltration Filter Media Guidelines by the Facility of Advancing Water Biofiltration (2009), the particle size distribution of the soil mixture should range between 0.075mm to 4.75mm sieve for it to be a well-graded filter media. From Table 2 and Figure 3, the particle distribution for the soil mix was within the range thus, acceptable to be used in the bioretention column.

B. Nitrogen and Phosphorus Removal

Table 3, 4 and 5 summarizes the results obtained pertaining to the nitrogen and phosphorus removal concentration from the bioretention columns for all the runs conducted based on Nessler Method for nitrogen concentration and Acid Persulfate Digestion Method for phosphorus concentration. For each different mulch layer, the experiment was run for 3 times in all bioretention columns to obtain an average removal rate. After setting up the bioretention columns, it was all flushed with distilled water and left for 24 hours before starting the experiment. Any pollutant that were present in the filter media has been assumed to be washed out.

Table 3 Nitrogen and Phosphorus Concentration using Woodchip

	Influent	Effluent		
Run 1	**Stormwater Runoff**	**Column 1**	**Column 2**	**Column 3**
Nitrogen (mg/L)	0.55	0.46	0.44	0.47
Phosphorus (mg/L)	1.37	0.39	0.46	0.32
Run 2				
Nitrogen (mg/L)	0.75	0.62	0.57	0.56
Phosphorus (mg/L)	1.33	0.38	0.26	0.34
Run 3				
Nitrogen (mg/L)	0.44	0.32	0.26	0.29
Phosphorus (mg/L)	1.32	0.29	0.35	0.37

Table 4 Nitrogen and Phosphorus Concentration using Tea Leaves

	Influent	Effluent		
Run 1	Stormwater Runoff	Column 1	Column 2	Column 3
Nitrogen (mg/L)	0.55	0.76	0.77	0.69
Phosphorus (mg/L)	1.37	0.99	0.98	1.05
Run 2				
Nitrogen (mg/L)	0.75	1.04	1.07	0.87
Phosphorus (mg/L)	1.33	1.03	0.99	0.97
Run 3				
Nitrogen (mg/L)	0.44	0.63	0.87	0.86
Phosphorus (mg/L)	1.32	0.94	1.28	1.08

Table 5 Nitrogen and Phosphorus Concentration using Coconut Fibre

	Influent	Effluent		
Run 1	Stormwater Runoff	Column 1	Column 2	Column 3
Nitrogen (mg/L)	0.55	0.53	0.54	0.53
Phosphorus (mg/L)	1.37	0.68	0.66	0.71
Run 2				
Nitrogen (mg/L)	0.75	0.74	0.72	0.72
Phosphorus (mg/L)	1.33	0.61	0.59	0.61
Run 3				
Nitrogen (mg/L)	0.44	0.39	0.42	0.41
Phosphorus (mg/L)	1.32	0.72	0.74	0.71

All of the mulch layers were able to reduce the phosphorus concentration from the stormwater runoff as seen in Table 5, Table 6 and Table 7. The bioretention column with woodchip as the mulch layer reduce an average of 1.34mg/L P PO_4^{3-} of effluent to 0.35mg/L PO_4^{3-} of influent, a reduction of 73.9% of phosphorus concentration. From table 6, mulch layer that uses tea leaves reduces the phosphorus concentration an average from 3% to 29%. For the bioretention that uses the coconut fibre based on the results in Table 7, the phosphorus was reduced at an average of 44.8% to 54.5%.

In Table 6, for nitrogen removal, the tea leaves were unable to show any capability in reducing the nitrogen concentration from the stormwater runoff. Instead, the effluent increased from an average of 0.58mg/L NH_3-N from influent to 0.84mg/L NH_3-N, a 44.8% increment of nitrogen concentration in the bioretention column. In a book written by Deborah L. Martin and Grace Gershuny, they mentioned that tea leaves is a good compost material as it is high in nitrogen content which acts as a natural fertilizer to the plant. The microorganism in the tea leaves absorbs the nitrogen and uses it to break down the organic matters and later release it back into the soil.
Thus, the efficiency for tea leaves in removing nitrogen is 0% for all the 3 runs conducted as seen in Table 6.

Table 6 Removal Efficiency

	Woodchip			Tea leaves			Coconut Fibre		
	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Nitrogen (%)	16.4	22.7	34.1	0	0	0	3.6	2.7	6.8
Phosphorus (%)	70.1	75.2	74.2	26.3	24.8	16.7	50.4	54.9	45.5

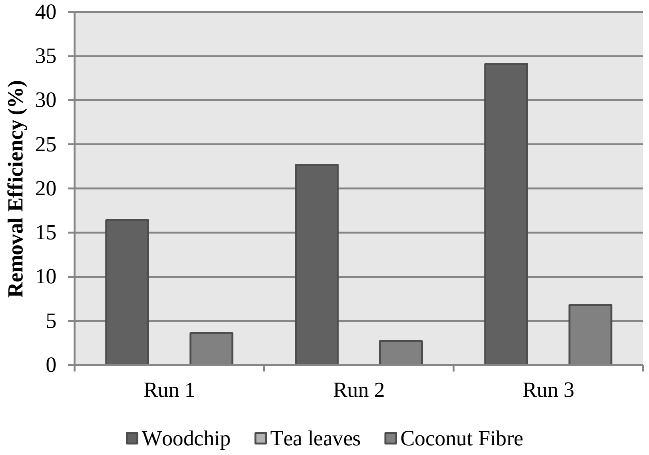

Figure 4 Removal Efficiency for Nitrogen from Bioretention Column

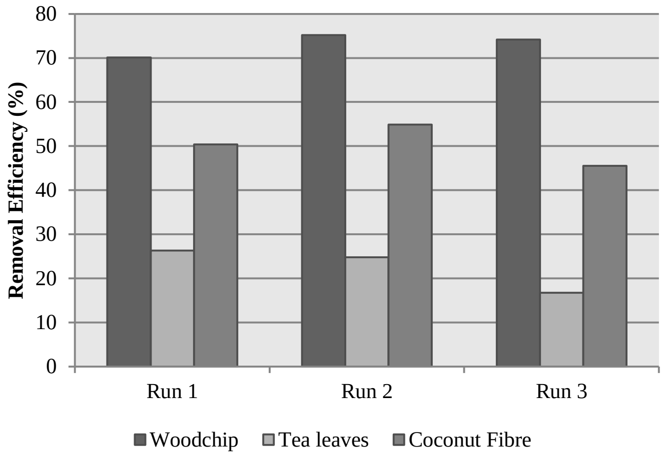

Figure 5 Removal Efficiency of Phosphorus in Bioretention Column

Comparing the three different mulch layers for nitrogen and phosphorus removal from Figure 4 and Figure 5, the woodchip has the best capability with an average efficiency of 24.4% for nitrogen and 73.2% for phosphorus. One main factor is the surface area of the woodchip is larger compared to tea leaves and coconut fibre which enables it to absorb better from the stormwater runoff. Larger surface area allows higher absorption from the stormwater runoff and water retention. As the surface area get smaller, in this case tea leaves and coconut fibre, the capability to absorb water decreases which causes the pollutant from incoming stormwater runoff to immediately infiltrate the underlying soil. Although coconut fibres has an irregular pore matrix due to the uneven particle size where it is more porous and less permeable compared to the tea leaves, it performed better in removing nitrogen and phosphorus than the tea leaves with an average removal efficiency of 4.4% for nitrogen and 50.3% for phosphorus. As mentioned earlier, tea leaves has been mentioned to be a good compost in most landscaping articles which made it not efficient in removing the nutrient concentration especially nitrogen.
The time taken for water to pond in the bioretention column with woodchip as the mulch layer is 8 minutes and 25 seconds, longer compare to the tea leaves, 5 minutes 33 seconds and coconut fibre, 5 minutes and 25 seconds. This shows that the large surface area of the woodchip particles absorbs the water from incoming runoff and when all the pores are filled, the water flows to the underlying soil layer which takes time for the bioretention column to be filled with water and the ponding to reach a depth of 50mm. This contributes to longer contact time between the pollutant and filtration media as the pollutant is absorb by the organic matter in the mulch and soil mix layer. Therefore, the absorption and retention capacity does affect the pollutant removal efficiency in the bioretention column which supports the justification.

IV. CONCLUSION AND RECOMMENDATION

Bioretention is seen as an attractive stormwater management practice that can be implemented in Malaysia as it shows the ability of removing pollutant from the stormwater runoff. Out of the three organic mulch layer, woodchip has the highest nitrogen and phosphorus removal efficiency with an average removal efficiency of 24.4% for nitrogen removal and 73.2% for phosphorus removal.

From an economical point of view, although the woodchip shows favourable results, the coconut fibre would be the best option implemented for rain gardens in Malaysia. For a large scale bioretention system, a large woodchip volume would be needed. Woodchip is an expensive landscaping material in Malaysia as it has other uses in the manufacturing industry. Coconut fibre is a more feasible option to be implemented in a large scale field as it can be obtain easily as coconut husk is thrown out and the hard shell which contain the water and flesh is kept to be sold commercially.

This experiment can be improved by using a bigger size bioretention column as previous study conducted have mostly used bigger diameter bioretention column. Besides that, the type of soil used in the mix should be varied not only between coarse and fine sand but also loam, silt and clay according to the composition that has been set in Guidelines for Soil Filter Media Bioretention Systems by Facility of Advancing Water Biofiltration (2008), to improve the permeability of the bioretention column. By having different composition in the filtration media, the absorption rate and water retention capacity would be greater which can promote a higher removal rate. The higher the absorption rate, the higher possibility for the pollutant removal is decreased in the bioretention system. Thus, a future study on correlation between the permeability coefficient and pollutant removal can be conducted to further investigate the efficiency of bioretention in removing pollutant.

As the nitrogen removal rate was very low, further research work can be continued by applying a vegetation layer in the bioretention column. The vegetation layer can further enhance the absorption, especially of nitrogen from the stormwater runoff as it is used for plant growth.

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