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Soil column studies on the performance evaluation of engineered soil mixes for bioretention systems

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ABSTRACT

The type of filter media in bioretention systems plays an important role in influencing treated run-off quality. Sand and planting soil that are commercially available in the local market vary considerably in their physicochemical properties, thereby resulting in variable hydraulic conductivity and effluent run-off quality. An engineered soil with consistent properties is therefore advantageous as a filter media as it ensures that pollutant (total suspended solids [TSS], total nitrogen [TN] and total phosphorus [TP]) removal guidelines are met. Small column tests were therefore conducted on various soil mixes as a rapid evaluation tool for the optimum engineered soil mix. Amendments such as compost, coconut fibre, water treatment residues (WTR) and recycled concrete aggregate (RCA) were incorporated at various proportions and homogeneously mixed with sand. Results indicated that column 3 with sand, WTR and compost could satisfy pollutant removal guidelines with TSS, TN and TP removals averaging at 93.4, 59.8 and 92.7%, respectively. Coconut fibre could also potentially be used as an alternative organic source but RCA was not suitable as an amendment for the enhancement of P removal due to its influence on the effluent pH levels which was notably high.

Keywords: Bioretention systems; Engineering soil mix; Nitrogen; Phosphorus; Stormwater run-off; Total suspended solids

1. Introduction

As the proportion of impervious land area increases in Singapore, much of the stormwater run-off conveying pollutants dislodge from these surfaces and is transported into the concretized drains and waterways. With the vast network of waterways and approximately two-thirds of Singapore's land surface constituting as its water catchment, sustainable stormwater management is therefore of paramount importance. Stormwater quality management and reducing potential impacts of stormwater pollution

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are important considerations for water resource management in Singapore [1]. The Active, Beautiful and Clean Waters (ABC Waters) Programme was therefore launched by the Public Utilities Board (PUB), Singapore's national water agency. Under this programme to visualize a community surrounded by pristine waterways and reservoirs, bioretention systems are ABC Waters Design Features which can be implemented to cleanse stormwater run-off at the source. Besides serving as an effective element for the removal of nonpoint source pollutants emerging from the developments and public spaces, these bioretention systems also detain stormwater and help to slow down the run-off into the drains and canals.

In a bid to improve stormwater run-off quality by bioretention systems, the porous filter media constitutes a crucial component to remove pollutants from the stormwater run-off prior to its entry into the waterways. Besides that, it should also balance other competing needs [2]. The filter media to be used for bioretention systems should provide for adequate infiltration capability, but yet at the same time provide for sufficient retention time to support plant growth. It should also supply sufficient nutrients for plants yet at the same time, not leach excessive nutrients into the waterways. Sandy loam media is favoured to facilitate infiltration while high clay contents are detrimental [3]. Conversely, fine fractions in soil are usually the most chemically active to aid pollutant removal. Therefore, there is a need to strike a balance between both the extents of infiltration and pollutant removal efficiencies [2,3].

Through a series of physical–chemical mechanisms such as filtration, sedimentation, sorption and precipitation, different bioretention media are capable of differing extents of pollutant removal efficiencies. To date, studies have documented efficient removal of total suspended solids (TSS) with removal efficiencies of above 80% [3,4]. Nutrient (N and P) removal efficiencies, however, are more highly variable. TP removal appeared to be correlated with filter media depth, with 70–85% removal as the depth increased from 60 to 80 cm [5]. As a rule of thumb, the use of filter media with low phosphorus-index [6] or orthophosphate content [7] could provide for efficient P adsorption and minimized P leaching. Total nitrogen (TN) removal exists as a challenge, due primarily to the mobility of nitrates through the soil column. These, therefore resulted in extremities in the observed TN-removal efficiencies which could range from –164 to 38% for different filter media types [4,8]. With the existence of such variabilities in treated run-off quality, particularly in nutrient (N and P) removal, the requirement of a consistent engineered mix is crucial to ensure the quality of treated run-off satisfying the local guidelines.

In accordance to the ABC Waters Design Guidelines [9], stormwater treatment objectives were specified for TSS, TN and TP removal. However, due to the varying physicochemical properties of the commercially available sand and planting soil in the local market, influence on the treated run-off quality can be adverse, should they be used as a bioretention filter media. In a bid to ensure the compliance of these guidelines, this paper provides a preliminary phase of evaluation of various engineered soil mixes to be potentially developed for bioretention systems in Singapore. In the choice of materials used for the engineered soil mixes, considerations include its ability to support healthy plant/tree growth, cost-effectiveness, availability in local market, hydraulic conductivity in the range of 50–200 mm/h [1] and its ease of preparation by local landscape contractors.

2. Materials and methods

2.1. Experimental setup

Seven bioretention soil columns were set up for the evaluation of various engineered soil mixes. The clear acrylic columns were 300 mm in height and had an internal diameter of 34 mm. All columns were filled with a 2 cm height supporting gravel layer (particle size range of 3.0–6.0 mm) at the base, followed by 2 cm height coarse sand (particle size range of 0.5–1.3 mm) and 200 mm of filter media to mimic the configuration of a typical bioretention system. An additional gravel layer was included in the topmost layer to aid in the distribution of run-off across the entire cross-section of each soil column.

Various materials were mixed homogeneously in varying proportions to make up the engineered soil mixes (Table 1), each column filled with engineered soil mix occupying a bed volume (BV) of 182 ml. Components included recycled materials such as water treatment residuals (WTR) and recycled concrete aggregates (RCA), and organic materials such as plant-based compost and coconut fibre. WTR1 was obtained from a local drinking water treatment plant in Singapore whereby, alum was added for the coagulation process whereas WTR2 was obtained from a water treatment plant in Sri Lanka. Each engineered soil mix was loosely packed into the acrylic column and watered down using deionized water. Watering was done as a form of hydraulic compaction prior to operation of bioretention soil columns. The overall organic content of the soil were measured using the loss of ignition method. Clean crucibles were filled

Table 1
Engineered soil mixes

Bioretention soil columns	Component (% by dry weight)	Organic content (% by weight)
Column 1	Sand (100)	0.4
Column 2	Sand (85), WTR1 (10), compost (5)	7.0
Column 3	Sand (80), WTR1 (10), compost (5), silt (5)	7.4
Column 4	Sand (88), WTR1 (10), coconut fibre (2)	6.3
Column 5	Sand (98), coconut fibre (2)	1.9
Column 6	Sand (90), RCA (10)	0.4
Column 7	Sand (90), WTR2 (10)	2.4

with approximately 3 g of soil and subjected to ignition at 550˚C until no further weight loss was observed.

2.2. Stormwater quality

Baseline stormwater flow collected from a local canal was used as the influent into the bioretention soil columns. As the initial concentrations of phosphate and TSS from the canal were relatively low, phosphates and TSS were subsequently added to mimic the concentrations present in urban stormwater run-off. From rainfall event 31 onwards, dipotassium phosphate was spiked at 1.8 mg/L (PO_4^{3-}). From rainfall event 32 onwards, soil was spiked in to achieve the targeted pollutant concentration of 100 mg/L (TSS) to represent the typical stormwater quality in Singapore [10,11].

2.3. Operation of bioretention soil columns

All columns were flushed daily with 20 BVs of deionized water to stabilize the soil columns prior to the application of the influent stormwater. Each rainfall event of 15 mm (volume of run-off per storm event was 420 ml) was conveyed through the top of each soil column via a multichannel peristaltic pump (Cole-Parmer, USA, IL) and the treated run-off was collected at the bottom using PE bottles. A total of 60 storm events (i.e. 136 BV) were simulated for the bioretention column study.

2.4. Water quality analyses

All influent stormwater and treated run-off water quality analyses were conducted in accordance to the Standard Methods for Water and Wastewater Analysis [12]. TSS was measured by the gravimetric method and filtered using glass fibre filter papers (Whatman, GF/F, UK). TP was analysed using PhosVer 3 with Acid Persulfate Digestion Method (Hach method 8190) [13]. TOC and TN were measured using the TOC analyser (Shimadzu, TOC-L, USA) and ion chromatography using the Dionex ion chromatography system (Dionex LC20, USA). Prior to the measurement of ions concentration using ion chromatography system, the samples were filtered using a 0.45 μm pore size filter paper (Pall Corporation, GN-6, USA).

3. Results and discussion

All bioretention soil columns were evaluated on their pollutant removal performances with respect to local guidelines on stormwater treatment objectives for TSS, TN and TP removal (Table 2). The baseline stormwater quality that was initially applied to the columns had average TSS, TN and TP concentrations at 7.8, 1.6 and 0.22 mg/L, respectively. To further investigate the removal performances of the engineered soil, TP and TSS were spiked in starting, from rainfall events 31 and 32 onwards, which corresponded to BV 70 and 72, respectively.

Due to the use of unwashed sand for this preliminary study on the investigation of various engineered soil, the pollutant removal performances of all seven bioretention columns stabilized at a later phase, despite initial flushing of 20 BV with deionized water.

3.1. TSS removal efficiencies

The initial influent TSS concentrations which fluctuated from 2.1 to 43.2 mg/L, resulted in the concurrent fluctuation of TSS-removal efficiencies during the initial 31 rainfall events. This was also a phenomenon observed by [14] prior to the stabilization of the filter media. In the subsequent phases, TSS was spiked into the influent to more accurately represent the concentrations in typical stormwater run-off in Singapore [10,11]. With the average TSS concentration in the influent measured to be 77.9 mg/L, average TSS removals for all soil columns were higher than 89.7% (Fig. 1). Averaged TSS-removal efficiencies presented

Table 2
Stormwater quality objectives for Singapore [9]

	Stormwater treatment objectives
Total suspended solids	80% removal or less than 10 mg/L (90% of all storm events)
Total nitrogen	45% removal or less than 1.2 mg/L (90% of all storm events)
Total phosphorus	45% removal or less than 0.08 mg/L (90% of all storm events)

in Fig. 1 were obtained after the stabilization phase for each column. Effluent concentrations, which averaged from 5.3 to 7.6 mg/L, fell within the range of the stormwater treatment guidelines. Although column 3 contained silt, this did not interfere with the removal efficiency of TSS following stabilization of all the soil columns.

3.2. TN removal efficiencies

Unlike TSS-removal efficiencies which was characterized by gradual increase and stabilization over multiple BV of simulated storm events, TN-removal efficiencies were comparably less predictable. TN-removal efficiencies stabilized from 42nd BV onwards for columns 1 and 2, and for columns 3 and 5, stabilization occurred from the onset of 20th and 25th BV, respectively. The remaining columns, however, approached stabilization at a much later stage. Average TN removals after the stabilization of soil columns are represented in Fig. 2. Although column 3 experienced the most extreme levels of TN-removal efficiencies at the initial phases (0–20 BV), its TN-removal performance gradually improved over time and approached an average of 59.8% upon stabilization. TN-removal efficiencies for columns 2, 4 and 5 were observed to be lower at 39.7, 31.6 and 38.7%, respectively.

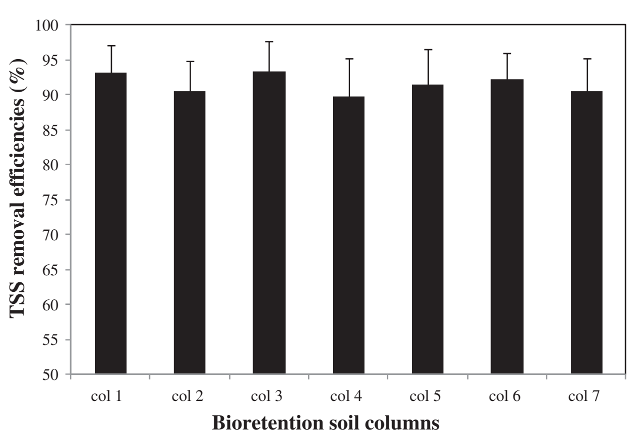

Fig. 1. Average TSS removal efficiencies by engineered soil columns.

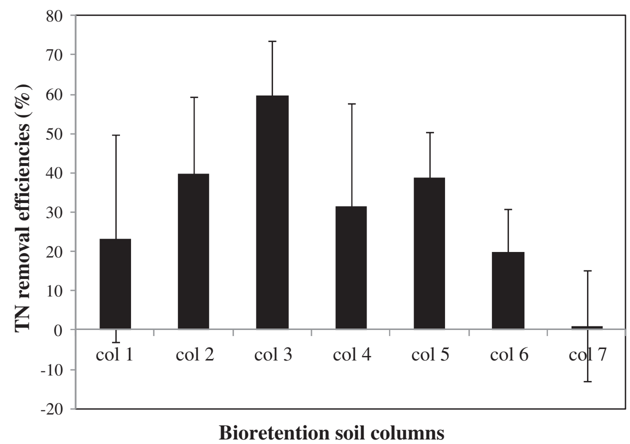

Fig. 2. Average TN removal efficiencies by engineered soil columns.

A comparison between columns 4 and 5 indicated that the lower TN-removal efficiency by column 4 could be a result of N leaching from WTR1. Average TN concentrations in effluents from columns 4 and 5 were 1.4 and 1.2 mg/L, respectively. With the organic fraction of WTR1 measured to be at 20% (by weight) and the overall organic content of the engineered mix at 6.3%, leaching of organic N could have resulted in the poorer TN removal. This was confirmed from the organic N from column 4, which averaged at 0.97 mg/L as compared to 0.5 mg/L for column 5.

Column 2 with compost and column 4 with coconut fibre had an overall organic carbon content of 7.0 and 6.3%, respectively. Correspondingly, their effluent TN concentrations averaged at 1.3 and 1.4 mg/L, respectively. These values were noted after both the columns had attained stability in TN removal. Nitrates and organic-N concentrations in effluent from column 2 was measured to be 2.3 and 0.8 mg/L, respectively, while that for column 4, at 2.1 and 0.9 mg/L. The use of compost, albeit at a higher overall organic content for column 2, resulted in better TN removal as compared to coconut fibre in column 4. Although such small amounts of organic matter could be beneficial for plant growth, high amounts could be detrimental on the treated run-off quality. The addition of organic matter, especially compost, into filter media has been noted to result in negative nitrate removal [15] due to its leaching phenomenon, hence resulting in higher effluent concentrations then the influent [2].

When silt was incorporated into column 3, a slight variant of column 2, the removal of TN was notably higher at 59.8%. This corresponded to the lower TN concentrations in the effluent, which averaged at 0.7 mg/L. The average was slightly skewed by a sudden one-time occurrence of high TN concentration of 14.6 mg/L in the influent (at storm event 27 i.e. 61 BV). Despite the sudden influx of TN, the effluent TN was observed to be 2.6 mg/L in contrast to the effluents from other columns where TN levels were in the range of 7.1–12.3 mg/L. Despite the presence of compost and WTR1, which can potentially leach N (both organic and nitrates), the inclusion of a small percentage of silt could have resulted in the formation of micro-pockets [6] of anoxic zones within the soil column. This, together with the presence of organic carbon, could be the driving factor for denitrification and hence the lower nitrates and TN concentrations in the effluent.

Besides evaluating the averaged N removal performance, the overall TN-removal efficiencies over time is also an important consideration (Fig. 3). The control (column 1) with sand only had comparatively lower TN removal efficiencies with more intense fluctuations as compared to columns 2 and 3. Although columns 2 and 3 experienced extreme TN leaching in contrast to column 1 during the initial period prior to stabilization, these two engineered mixes fared better at coping with fluctuating TN-removal performances upon stabilization, although no distinct plateau were observed unlike that for TSS and TP.

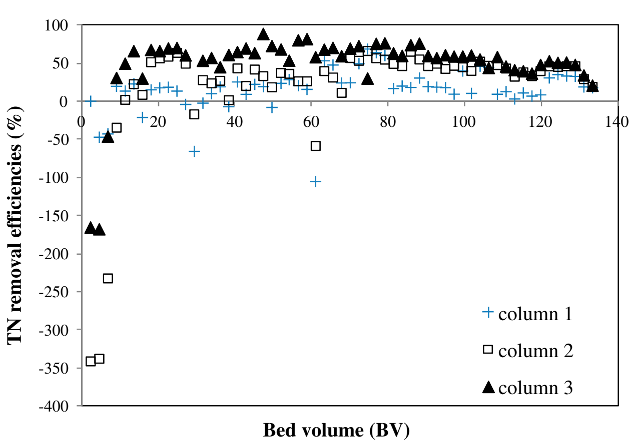

Fig. 3. Overall TN removal efficiencies for columns 1–3.

Based on the total input from the 60 simulated rainfall events, the total load of TN and nitrate-N introduced into each soil column was 43.2 and 18.4 mg, respectively. Ammonia-N originating from the run-off was low at 0.2 mg, whereby no ammonia-N were detected in the influent on most occasions. The input pollutant mass was also compared to the overall mass leaching the soil columns in the treated effluent. Column 1, with only sand as the media, removed on 17% of the TN load while an overall leaching of nitrate-N (−10% nitrate-N removal) was observed. Other columns experienced overall leaching of TN load except for columns 3, 5 and 6 with load removals of 46, 31 and 15%. Nevertheless the nitrate-N load removal was only present in columns 2–5 where removals ranged from 33 to 70%, whereby the highest nitrate-load removal of 70% was observed for column 3. In addition, the silt present in column 3 could have provided for micro-pockets of anoxic regions within the soil column, thereby effectively providing the environment for denitrification in the presence of organic carbon. The soil columns with high nitrate-N mass removal corresponded to the highest organic content in columns 2–4 which could be explanatory to the denitrification process occurring within the soil columns. Although column 7 also contains moderate amounts of organic content (% by weight), the overall negative nitrate-N removal could be due to the leaching of N arising from the ammonification and nitrification processes, resulting in a larger outflow of nitrate-N as compared to what was input through the influent. The organic-N load observed in the effluent from column 7 was 44% more than the input load in the influent. A separate test on WTRs 1 and 2 revealed that the per cent organic content for both were 20 and 24%, respectively, by weight. The higher organic content from WTR2 could also have resulted in the leaching of the organic-N from column 7. This hence resulted in overall leaching of TN from column 7.

3.3. Total phosphorus removal efficiencies

Total phosphorus (TP) removal was observed to be higher than 80.5% after stabilization phase except for columns 1 and 5 where moderate TP removal was observed (Fig. 4). The high TP removals were attributed to the presence of WTR1, WTR2 and RCA. WTR, comprising of clay, organic matter and metal coagulant (dominated by aluminium hydroxide) has been shown to be capable of highly dissolved phosphate

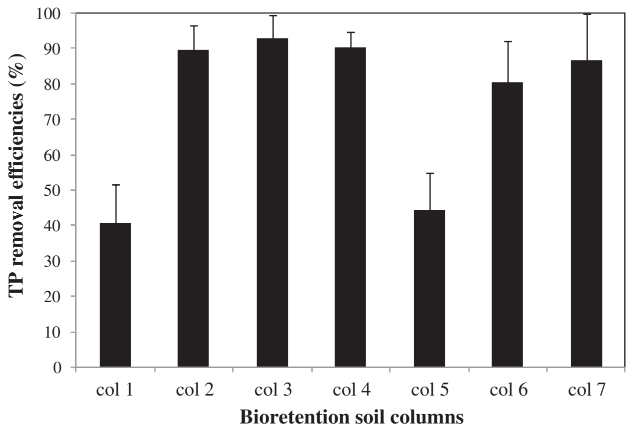

Fig. 4. Average TP removal efficiencies by engineered soil columns.

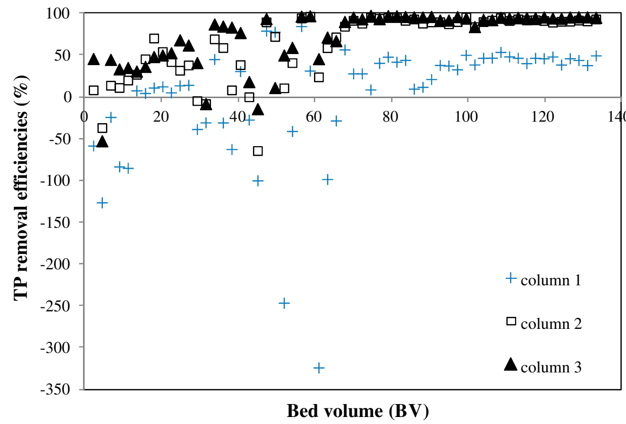

Fig. 5. Overall TP removal efficiencies for columns 1–3.

adsorption [16,17]. RCA, a recycled by-product from the construction industry, was also evaluated as a possible amendment to enhance pollutant removal. Although RCA demonstrated potential as an amendment to enhance TP removal, the pH value of the effluent emerging from column 6 was a concern due to its high value of above 8 and subsequently approaching pH 7–8 only after approximately >90 BV. This hence potentially limits its implementation in bioretention systems as the high pH can be catastrophic to plant growth.

Although the addition of organic matter (compost or coconut fibre in this study) was observed to result in a significant decrease in TP removal (even export), when the phosphorus contained in the organic matter broke down and phosphate ions discharged in the effluent [2,4], such a phenomenon was not a distinctive trait in this column study. Effluent TP concentrations from columns 2, 3 and 4 were observed to be at 0.06, 0.04 and 0.07 mg/L, respectively, after stabilization. Column 3 had the best TP removal, probably also attributable to the presence of silt which can adsorb phosphates [5]. Despite the low TP concentrations experienced in the effluents, initial fluctuations were noted (Fig. 5), with column 1 used as the control for comparison. This was, however, not in agreement with the fact that WTR aids in the adsorption of dissolved P and will hence result in overall enhanced TP removal. An analysis of the breakdown of TP in the effluents revealed that the P in the effluents during the initial phase existed in the particulate form rather than dissolved forms. This also coincided with the TSS removal where an increase was observed after the 66th BV.

Besides the concentration of the TP, particulate P and dissolved P, the overall pollutant P loading into the columns was also evaluated. Throughout the 60 rainfall events, the overall TP, dissolved P and particulate P loads into each column were 11, 5.9 and 5.1 mg, respectively. The higher dissolved P load into the columns was due to the spiking of dipotassium phosphate. All columns except for columns 1, 5 and 6 had TP load removals of at least 85%. This was attributed to the adsorption by WTR, which enabled the high dissolved P load removals. The mass of dissolved P emerging from the effluents of columns 2, 3, 4 and 7 were in the range of 0.5–0.7 mg, with the corresponding mass input of 5.9 mg into each column. Column 6, with RCA, also had moderate TP mass removal of 69% and dissolved P mass removal of 88%. However, the use of RCA is not favourable due to the high pH arising from the concrete aggregates. This may subsequently hinder plant growth within a bioretention system.

4. Conclusion

Engineered soil mix to be potentially used for bioretention systems in Singapore were evaluated using small bioretention soil columns. Through the evaluation of various soil amendments such as compost and coconut fibre for organic source, and WTR and RCA for enhancing P removal, a potential engineered soil mix was developed. Column 3 was found to fulfil specified guidelines for TSS, TN and TP removal in this short-term column studies. With the specified engineered soil, TSS, TN and TP removal averaged at 93.4, 59.8 and 92.7%, respectively. Although compost has previously been noted to leach out N and P, the amount present in this current mix, coupled with WTR, did not influence the effluent run-off quality. Although coconut fibre could serve as an alternative source of organic matter to aid plant growth, it (column 4) resulted in poorer TN removals as compared to column 2 with the incorporation of compost. Likewise, although RCA could potential enhance TP removal, its influence on effluent pH limits its application in bioretention systems.

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