THE ROLE OF TROPICAL SHRUB WITH ENHANCED BIORETENTION MEDIA IN NUTRIENT RICH RUNOFF TREATMENT

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ABSTRACT

Bioretention systems with sedges as vegetation for the system are one of the popular Best Management Practices (BMPs) in temperate countries. However, there are lack of studies using shrub in tropical countries, which has been used widely as landscape plants. In recent years, use of additives for nutrient removal from water bodies has been proven to be successful in various applications but the potential of using waste material as additives in bioretention has not been fully discovered. In this study, the effect of tropical shrub with enhanced bioretention media, which contain 4 different types of additives from waste materials (cockle shell, newspaper, coconut husk and printed paper) was examined. Natural runoff with high pollutant concentration was used in this study. Comparison between 20 bioretention mesocosm planted with and without Red Hot Chinese Hibiscus (*Hibiscus rosa-sinensis*) showed that tropical shrub with well-developed root systems played an important role in maintaining hydraulic conductivity within the range stated in various guidelines. Results show that after 16 weeks of runoff test, mean of hydraulic conductivity for mesocosm without shrub was ranging from 79 to 286mm/hour, whereby for mesocosm with shrub, the hydraulic conductivity was maintain within 170 to 190 mm/hour. For total suspended solid (TSS) and total phosphorus (TP) mass removal, mesocosm with shrub containing cockle shell has higher TSS and TP removal (95.7% and 93.3% respectively) compared to standard mesocosm (85.4% and 84.9% respectively). For total nitrogen (TN) mass removal, mesocosm with shrub containing newspaper (80.4%) perform better compared to standard mesocosm (57.4%), which proven that with selected bioretention media, *Hibiscus rosa-sinensis* is recommended to be used for bioretention system in tropical climate to treat nutrient rich runoff.

Keywords: Best Management Practices (BMPs), Bioretention Media, Nutrient Removal, Stormwater Treatment, Tropical Shrub

1. INTRODUCTION

Various municipal land uses and activities in urbanization has resulted in increasing in non-point source pollutant, such as that affected the quality of receiving waters (DID, 2011). The excessive increase of nutrient concentration contributed by municipal grey water, fertilizers from urban agricultures and landscapes has led to eutrophication and degradation of habitat quality due to harmful algal blooms (Davis et al., 2006; Davis and Liu, 2013). Among the various treatment technologies available for stormwater, bioretention has become one of the most popular Best Management Practices (BMPs) due to its ability to provide a variety of benefits especially in targeted pollutant removal (Bratieres et al., 2008; Hatt et al., 2008).

Extensive laboratory studies and site monitoring has demonstrated the effectiveness of bioretention systems in removing nutrients from stormwater, especially TSS and TP, which achieved more than 90% removal for TSS and more than 80% removal for TP (Barrett et al., 2013; Bratieres et al., 2008; Carpenter et al., 2010; Lucas et al., 2011). However, TN removal performance remain variable, ranging from removal of 59% to leaching of 75% (Davis, 2006; Brown and Hunt, 2011) due to its complexity in chemistry associated with the removal mechanisms of nutrients (Davis et al., 2009). Besides the inconsistency in nitrogen removal, Paus et al. (2014) reported that the useful lifespan of BR filter media is limited by three factors: pollutant breakthrough, pollutant accumulation that exceeded the soil reference values and hydraulic failure due to clogging with particles. Therefore, it is important to understand the influence of design configurations of bioretention, especially the type of vegetation and bioretention media used, in order to increase the sustainability by maximizing the pollutant removal efficiency and minimizing the clogging problem (Le Coustumer et al., 2012).

The role of plants in bioretention systems has been well established for temperate countries. The choice of plants should not only be based on their treatment performance, but also on their capacity to survive in potentially stressful growth conditions, such as drought periods (Bratieres et al., 2008). Various laboratory studies has shown that the role of plants is important in improving the effluent quality compared to non-vegetated systems (Glaister et al., 2014; Lucas et al., 2008; Read et al., 2008; Zhang et al., 2011). Zhang et al.'s (2011) study reported that different plant species demonstrated different capacity in nutrient uptake and selected vegetation was found to play a critical role in determining nitrogen (N) removal performance (Hatt et al., 2008). In minimizing clogging problem, Brastieres et al. (2008) reported that occupation of filter media by roots is necessary to achieve optimal performance. The appropriate choice of vegetation could limit the decrease of hydraulic conductivity due to clogging (Le Coustumer et al., 2012). *Carex appressa*, an Australian native species has been a popular choice for current bioretention design due to its thick root structure that is able to remove nutrient and minimize clogging and its ability to withstand stressful growth condition, (Bratieres et al., 2008; Glaister et al., 2012; Le Coustumer et al., 2012; Read et al., 2008; Zinger et al., 2012). However, due to different climate and rainfall regime, the performance of native species in tropical climates remains unknown. There is a need to define plant species from tropical climate zones which are suitable for stormwater bioretention system.

In terms of bioretention media, Palmer et al. (2013) reported that unless specific design features are incorporated, N and P removal can be variable or poor. Recent studies showed that amendment on bioretention media formulated for N and P removal have been proven successful. Use of water treatment residuals (WTRs) (Glaister et al., 2014; Palmer et al., 2013) and iron enhanced sand (Erikson et al., 2012) as additives in bioretention media has been proven its ability to enhance TP removal. For TN removal, incorporation of submerged zone with carbon source resulted in higher TN removal, ranging from 59.8% to more than 90% (Guo et al., 2014; Payne et al., 2014). This has shown the importance of "engineering" the bioretention media so as the overall pollutant removal required by design manuals are met. There is a need to evaluate vegetated enhanced bioretention media using tropical shrub to treat nutrient rich runoff under tropical climate. This study investigates the effects of two design configurations on hydraulic conductivity and nutrient removal performance of bioretention systems under nutrient rich runoff: tropical shrub and enhanced bioretention media.

2. METHODOLOGY

2.1 Media Selection and Mesocosm Preparation

In this study, the standard bioretention media containing 60% medium sand, 20% top soil and 20% compost, consistent with design recommendations for bioretention (CFWP & MDE, 2000; DID, 2011) was used as base line study. Four types of enhanced bioretention media, containing shredded printed paper, coconut husk, cockle shell and shredded newspaper respectively were used to compare its effect on plant growth, hydraulic conductivity and nutrient removal with standard bioretention media (STD). For enhanced bioretention media (PP - printed paper, CH - coconut husk, CS - cockle shell, NP – newspaper), 10% additives by volume was used to replace the compost in the standard mixture. Shredded printed paper and newspaper was prepared by cutting into uniform size of 3mm x 15mm using Dino Superstar cross cut paper shredder. Coconut husk with were purchased directly from the supplier and sieved into size 0.15mm – 4 mm. Cockle shells were manually collected from beach, rinsed using tap water, oven dried, crushed and sieved to obtain a mean size ranging from 0.15mm – 2mm. The bioretention media were measured by volume, verified by weight to ensure consistent composition in every mesocosm and was identically mixed in concrete drum mixer before transferring into mesocosm.

Twenty mesocosm was constructed using 300mm diameter polyvinyl chloride (PVC) pipes mounted on 10mm thick PVC base plate with vertical sampling port at the base. The main structure of PVC pipe consists of 600mm depth to hold bioretention media, 150mm free board for extended detention of water and 50mm gravel drainage layer. The interior surface of the pipe was roughened to prevent the preferential flow along the edge. The mesocosm were placed in specially constructed greenhouse with clear roof, located in Universiti Sains Malaysia Engineering Campus, which allows full natural sunlight. Five types of media (STD, PP, CH, CS and NP) were evaluated in this experiment with thouree replicates for vegetated mesocosm and one for non-vegetated mesocosm.

2.2 Plant establishment

For this study, Red Hot Chinese Hibiscus (*Hibiscus rosa-sinensis*) was selected as it is a fast-growing and easy-to-propagate native tropical shrub. It is commonly used in landscaping due to its flexibility for any soil type and its ability to tolerate with dry weather and short term inundation. A total of 50 Red Hot Chinese Hibiscus was cultivated individually in 15cm diameter polybags using standard bioretention media. After 3 months of cultivation, 15 plants with a similar height were selected and trimmed into size of 20cm height and 15cm canopy. The selected plants were repotted into mesocosm for establishment. The height of plant, size of canopy and number of flowers were recorded weekly throughout the dosing period for plant growth calculation.

2.3 Runoff Selection

Natural pollutant was used to simulate the actual condition on site for this study. Runoff from surrounding municipal drain located nearby Universiti Sains Malaysia Engineering Campus was identified as target, which received mixture of pollutant source from municipal grey water, urban agriculture and runoff from the street. The concentration for TSS, TN and TP was 754.1 ± 181.3 mg/L, 11.32 ± 1.39 mg/L and 5.70 ± 0.57 mg/L respectively. The runoff was collected weekly from the municipal drain and transferred to a 500L tank located at the greenhouse for the experiment. The 500L tank equipped with auto-mixer to ensure constant mixing of the sediment and pollutant.

2.4 Experimental Procedure and Data Analysis

The mesocosm was established for 3 months (March to May 2014) before the runoff test, which each mesocosm was watered with 10L dechlorinated tap water weekly for plant root development, washing out of labile organic matter and settling of bioretention media. During the runoff test (dosing period), 17.5L of runoff was dosed to each mesocosm weekly for 15 weeks (June to September 2014). Study showed that with the treatment of first flush, approximately 90% of the average runoff will be treated (Froehlich, 2009). Based on the assumption of 30% average annual rainfall in Peninsular Malaysia (2200mm) is first flush, divided into 52 weeks and catchment area of 5%, each mesocosm was dosed with 17.5L (12.5mm x 0.0707m2x 100/5 ≈ 17.5L). To ensure even distribution of influent applied to each mesocosm, the runoff was divided into 5 passes of 3.5L using jugs, passing through a polyvinyl chloride plate with 2mm holes to promote even distribution of flow.

Water quality samples were collected weekly at the site, inflow and outflow during the 15 weeks of dosing period. Volume of the effluent was recorded for water balance calculation. Unfiltered samples were analysed for TSS, TN and TP. TN and TP concentration were determined by using Hach DR3900 Spectrophotometer using Hach Methods 10071 and Hach Methods 8190 respectively, according to Standard Method 4500-N and 4500-P (Eaton et al., 2005). Saturated hydraulic conductivity (k_s) of the mesocosm was measured during the first week, eighth week and end of dosing period, using single ring infiltration test method (Le Coustumer et al., 2008). The pH and temperature was measured using YSI handheld multi-parameter meter. All statistical calculations were computed with the software IBM SPSS version 22 and MS Excel 2010.

Plant height growth rate was calculated by:

$$\Delta H = (\frac{H_f - H_i}{H_i} x100\%) \quad [1]$$

Where:

ΔH = Height growth rate (%)
H_i = Initial height (cm)
H_f = Final height (cm)

Plant height growth ratio was calculated by:

$$R_H = \frac{\Delta H_{media}}{\sum \Delta H_{media}} \quad [2]$$

Where:

R_H = Height growth ratio
ΔH_{media} = Average height growth rate for each media type (%)
$\Sigma\Delta H_{media}$ = Total average height growth rate

Plant canopy growth ratio was calculated by:

$$\Delta Canopy = \frac{Canopy_f - Canopy_i}{Canopy_i} x100\% \quad [3]$$

Where:

$\Delta Canopy$ = Canopy growth rate (%)
$Canopy_i$ = Initial canopy width (cm)
$Canopy_f$ = Final canopy width (cm)

Plant canopy growth ratio was calculated by:

$$R_{Canopy} = \frac{\Delta Canopy_{media}}{\sum \Delta Canopy_{media}} \quad [4]$$

Where:

R_{Canopy} = Canopy growth ratio
$\Delta Canopy_{media}$ = Average canopy growth rate for each media type (%)
$\Sigma\Delta Canopy_{media}$ = Total average canopy growth rate

Plant flower ratio was calculated by:

$$R_F = \frac{F_{media}}{\sum F_{media}} \quad [5]$$

Where:

R_F = Flower ratio
F_{media} = Number of flower for each media type
ΣF_{media} = Total flower

Plant maturity was indicated by blooming of flowers. Plant maturity ratio was calculated by:

$$R_M = \frac{M_{media}}{\sum M_{media}} \quad [6]$$

Where:

R_M = Maturity ratio
M_{media} = Number of plant achieved maturity for each media type
ΣM_{media} = Total plant achieved maturity

Volume reduction was calculated by:

$$\Delta Vol = \frac{(Vol_{in}) - (Vol_{out})}{Vol_{in}} x100\% \quad [7]$$

Where:

ΔVol = Volume reduction (%)
Vol_{in} = Influent volume (L)
Vol_{out} = Effluent volume (L)

Mass removal efficiency was calculated by:

$$\Delta M = \frac{(C_{in} x Vol_{in}) - (C_{out} x Vol_{out})}{C_{in} x Vol_{in}} x100\% \quad [8]$$

Where:

ΔM = Mass removal efficiency (%)
C_{in} = Influent concentration (mg/L)
C_{out} = Effluent concentration (mg/L)

3. RESULTS AND DISCUSSION

3.1 Plant growth and water balance

Plant growth performance was used to evaluate the adaptability of Hibiscus rosa-sinensis in enhanced bioretention media as compared with the standard mesocosm (STD). Plant's height ratio, canopy ratio, flower and maturity ratio was calculated using Eq. [1] to [6] (Figure 1). Plants with fast growth rates in nutrient rich environment are deemed suitable for phytoremediation and bioretention system (Zhang et al., 2011) as they are assumed to take up nutrients quickly and efficiently to support their fast growth (Chen et al., 2014). It has been reported that vegetation in bioretention systems take at least 12 months to establish and effective in nutrient removal (Hatt et al., 2008). Therefore, if the type of plant chosen can achieved maturity within short period, the establishment period for the bioretention system can be shortened. The result has shown that Hibiscus rosa-sinensis generally grow well in most of the bioretention media (all media types except for PP) and able to achieve maturity within 6 months period.

Significant higher maturity ratio and highest number of flower produced in CS indicated that with bioretention media enhanced with cockle shell able to accelerate the plant growth. This may be attributed the calcium ion that released from the cockle shell as previous studies have proven that calcium is required for cell elongation in both shoots and roots (Burstrom, 1968) and the application of mixture of gypsum and limestone (containing calcium ion) will have positive effect on the physical and chemical characteristics of the soils (Ahmet, 2011). Slightly poorer plant growth rate in PP and some of the NP indicated that the plant root might be sensitive to the chemicals used for printing, such as bleaching chemical for printing paper, wax and paraffin that used for printing ink to dry faster.

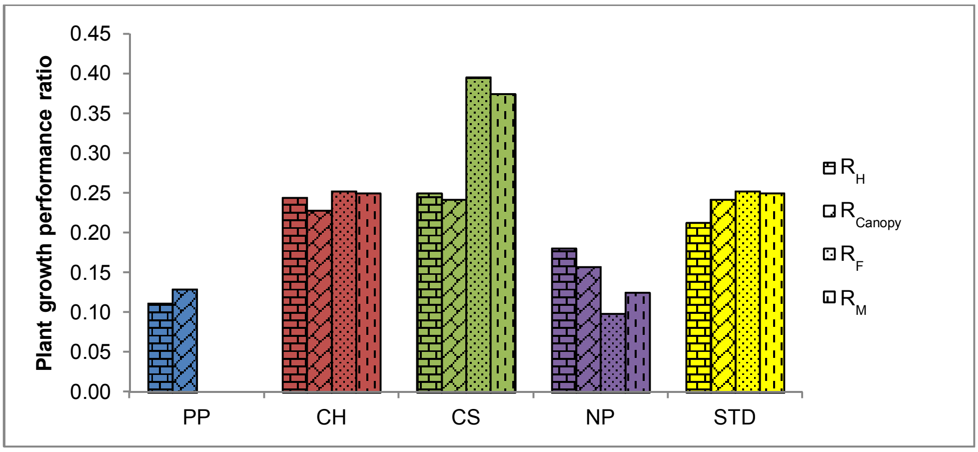

Figure 1. Plant growth performance ratio comparison (R_H: Height ratio, R_{Canopy}: Canopy ratio, R_F: Flower ratio and R_M: Maturity ratio) for 5 types of bioretention media. (PP: Printed Paper; CH: Coconut Husk; CS: Cockle Shell; NP: Newspaper; STD: Standard)

Result from water balance calculation (Figure 2) showed that runoff retention ability in all vegetated mesocosm is higher compared to non-vegetated mesocosm. In terms of comparison between vegetated mesocosm, the average volume reduction were highly correlated with average plant growth ratio (r=0.9). Mesocosm that has higher plant growth rate demonstrated higher inflow volume reduction, which again proven that the plant growth rate is one of the important factors to not only attenuate runoff flow, but also increase the water uptake. This has shown the potential of *Hibiscus rosa-sinensis* as tropical shrub that can be used for bioretention as it has dense foliage that resulted in high evapotranspiration rate and thick root system that able to retain moisture in bioretention media.

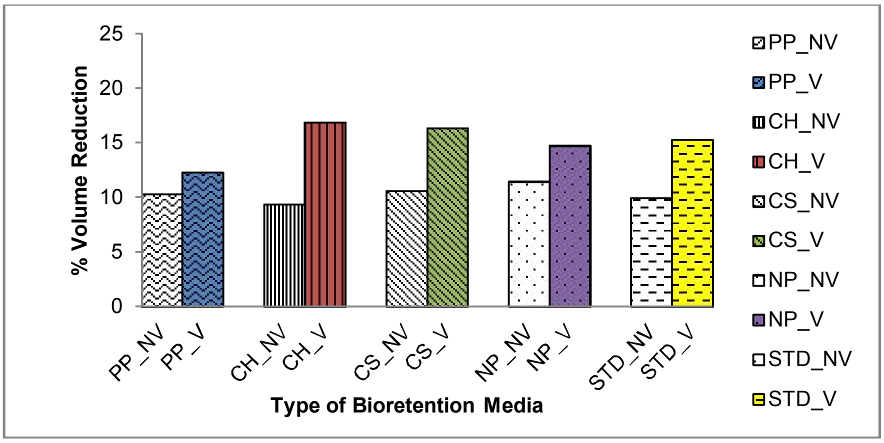

Figure 2. Comparison of water balance for vegetated and non-vegetated mesocosm using 5 types of bioretention media. (NV: non-vegetated; V: vegetated) (PP: Printed Paper; CH: Coconut Husk; CS: Cockle Shell; NP: Newspaper; STD: Standard)

3.2 Hydraulic Conductivity

As runoff storage and holdup ability is a key performance metric in bioretention system (Davis, 2008), hydraulic conductivity (k_s) has become one of the key parameter to determine the success of the system. Lower k_s provides longer hydraulic retention time, improves nutrient removal but it reduces runoff capture and increases bypass flow due to reduced infiltration rate (Liu et al., 2014). Higher k_s increases runoff capture but resulted in lower nutrient removal as there might be insufficient hydraulic retention time for microbial activities and adsorption mechanism to take place, and lower ability to retain moisture for plant growth. In this study, k_s within 100-200 mm/hour was selected as recommended range, based on the comparison of hydraulic conductivity requirements in selected BMP manuals from various countries under different climates (DID, 2011; PUB, 2011; Water by Design, 2012; NJDEP 2009; DEP, 2006).

Table 1 Saturated hydraulic conductivity (k_s) requirements in selected BMP manuals from various countries under different climates (DID, 2011; PUB, 2011; Water by Design, 2012; NJDEP 2009; DEP, 2006)

BMP Manual	Urban Stormwater Management (MSMA)	Engineering Procedures for ABC Waters Design Features	Water Sensitive Urban Design (WSUD)	New Jersey Stormwater Best Management Practices Manual	Pennsylvania Stormwater BMP Manual
Country Climate	Malaysia Tropic	Singapore Tropic	Australia Temperate	United States Temperate	United States Temperate
Min. k_s (mm/hour)	13	50	**100***	N/A	75 (3 inches/hour)
Max. k_s (mm/hour)	**200***	**200***	300	250 (10 inches/hour)	450 (18 inches/hour)

*Recommended range based on comparison of guidelines between various BMP manuals

Due to the compressive nature of bioretention media, k_s is expected to change over the service lifetime of a bioretention system (Thompson et al., 2008). Therefore, besides the inflow characteristics, it is important to study the two main design parameters that affect the k_s, which are type of vegetation and bioretention media. Le Coustumer et al. (2007) stated that a small variation in soil characteristic can result a large difference in k_s. This has been demonstrated in comparison between different bioretention media in non-vegetated mesocosm. Although the difference of composition between bioretention media is only 10%, the k_s ranged from 82 mm/hour (STD) to 217 mm/hour (PP) at the beginning of the study and the range getting wider at the end of the study (79 mm/hour for STD to 286 mm/hour for PP). The reduced k_s over time in CS, CH and STD may be due to two reasons: hydraulic compaction of media and fine particles produced from degradation of organic matters that clog the media over the time. The high k_s for both PP and NP may be attributed to cellulose fiber and lignin content in the paper that expands after water adsorption and preferential flow created in the media allow infiltrating water flow through the system (Kim et al., 2003; Stander et al., 2010).

Comparison between vegetated and non-vegetated mesocosm showed that vegetation played an important role in maintaining the k_s in bioretention system (Figure 3). The appropriate choice of vegetation can limit clogging and indirectly increase pollutant removal by limiting the volume of water bypassing the system through overflow (Le Coustumer et al., 2012). Towards the end of dosing period (week 16), all the vegetated mesocosm achieved the recommended k_s range, which is within 100-200 mm/hour. The dense root system of *Hibiscus rosa-sinensis* has demonstrated its ability to hold the soil and reduce the expansion of the media for PP and NP that has higher k_s and for CH, CS and STD, the thick root able to penetrate through and prevent compaction of media. It can be seen that the hydraulic conductivity will tend towards a common value, ranging between 170-190 mm/hour when the plant achieved maturity, attributed to the well-developed root system of tropical shrub, regardless type of bioretention media.

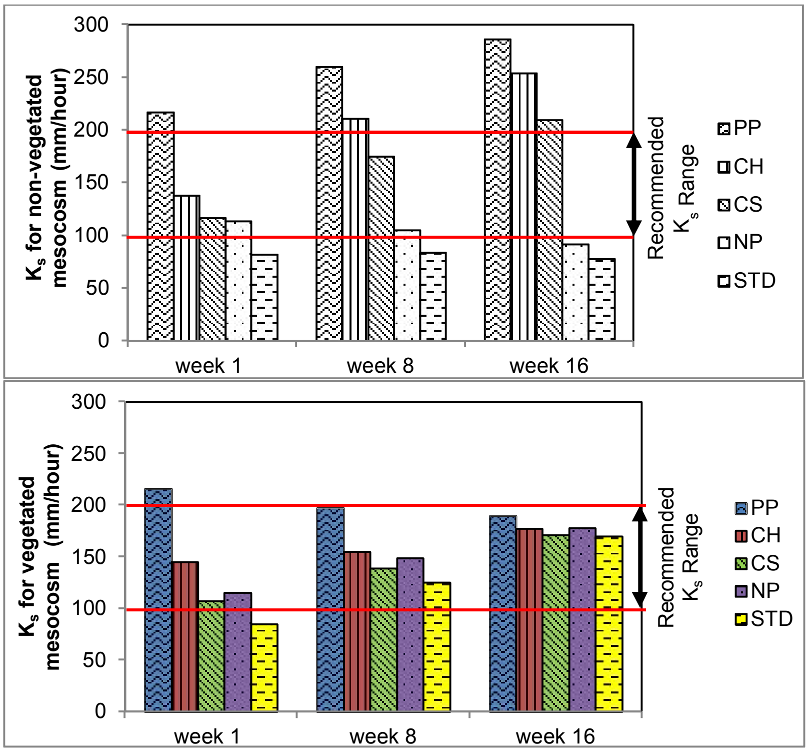

Figure 3. Comparison of saturated hydraulic conductivity (K_s) for non-vegetated and vegetated mesocosm using 5 types of bioretention media. (PP: Printed Paper; CH: Coconut Husk; CS: Cockle Shell; NP: Newspaper; STD: Standard)

3.3 Pollutant Removal

Pollutant load reduction for stormwater runoff in bioretention systems includes reduction of both in volume and pollutant concentration. Therefore, pollutant mass removals were higher than the concentrations removals due to the attenuation of volume by the bioretention media (Liu and Davis, 2013). Different media properties such as porosity, organic content, particle size distribution (PSD) and existing nutrient content may affect the water quality of effluent (Carpenter and Hallam, 2010; Liu et al., 2014). Figure 4 shows the comparison of nutrient removal (TSS, TN and TP) performance of vegetated and non-vegetated mesocosm under different types of bioretention media. In terms of vegetated mesocosm comparison, CS showed highest removal rate in TSS and TP removal (95.7% and 93.3% respectively) compared to STD (85.4% and 84.9% respectively). For TN removal in vegetated mesocosm, NP demonstrated significant improvement (80.4%) compared to STD (57.4%). This has proven that depending on runoff characteristics, different types of bioretention media can be used to remove the targeted pollutant.

TSS and TP removal rate in non-vegetated mesocosm was slightly higher compared to vegetated mesocosm due to the physical removal mechanism. As removal of TSS in bioretention system results from a combination of sedimentation and filtration processes (Davis, 2007) and 85% of the TP in the influent from runoff was particle bound (Blecken et al., 2007), the thick root system of plant affected the sedimentation process. The macropores created by rhizome form preferential flow paths (Arora et al., 2011), which enable infiltrating water to bypass biogeochemically active areas (O'Reilly et al., 2012). However, the difference was not large enough to claim that *Hibiscus rosa-sinensis* imposed a negative effect on nutrient removal performance as all mesocosm performed well in TSS (>85%) and TP (>90%) removal.

For TN removal, reverse condition was observed, where higher removal rate was shown in vegetated mesocosm compared to non-vegetated mesocosm. Previous studies shown that some of the native plants selected for bioretention in temperate countries adapted to low nutrient condition, which the plant might not able to use nutrient efficiently and high nutrient level of runoff could even have negative impact on plant growth (Barrett et al., 2013; Read et al., 2008). Unlike the previous results, *Hibiscus rosa-sinensis* adapted well to the nutrient rich condition and displayed the ability to uptake TN. This has shown the high potential of tropical shrub in phytoremediation and it opens up the possibility for other tropical plants to be considered for bioretention system in tropical climate as native plant species for temperate countries might not be able to adapt to frequent rainfall regime and nutrient rich runoff. Combine with appropriate enhanced bioretention media, *Hibiscus rosa-sinensis* even achieve better nutrient removal performance compared to the standard mixture recommended by BMP manual.

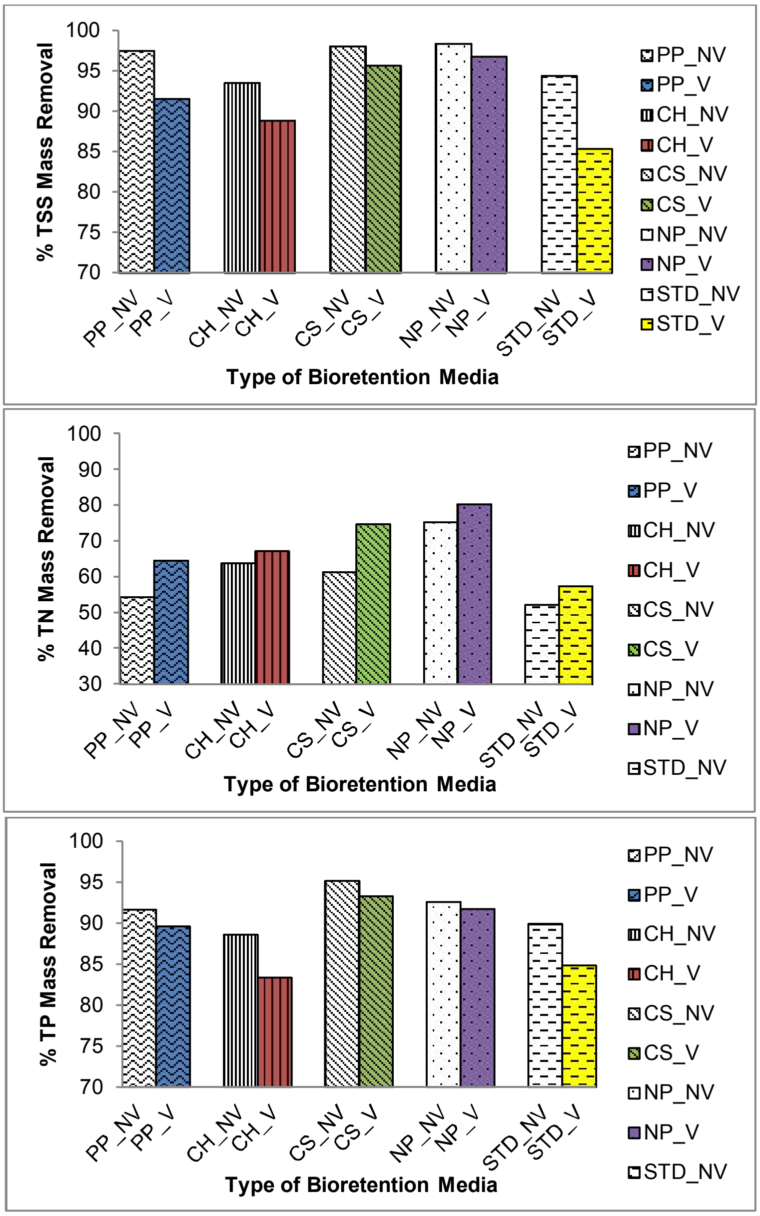

Figure 4. Comparison of TSS, TN and TP mass removal efficiency for vegetated and non-vegetated mesocosm using 5 types of bioretention media. (NV: non-vegetated; V: vegetated) (PP: Printed Paper; CH: Coconut Husk; CS: Cockle Shell; NP: Newspaper; STD: Standard)

4. CONCLUSIONS

This study investigated the influence of tropical shrub and enhanced bioretention media on hydraulic conductivity and nutrient removal performance of bioretention systems under nutrient rich runoff. The results showed that *Hibiscus rosa-sinensis* is able adapt to nutrient rich runoff and grow well under various enhanced bioretention media, especially CS. Its ability to maintain the hydraulic conductivity within the recommended range, reduce inflow volume and remove TN significantly through evapotranspiration and plant uptake indicated that with appropriate bioretention media, *Hibiscus rosa-sinensis* has the potential to be used for phytoremediation and will be suitable for bioretention system in tropical climates.

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