Journal of Water Resources Management, Vol. 1 No. 2 (2023) p. 1-5

JOWRM

Journal of Water Resources Management

Journal homepage: https://journal.water.gov.my

e-ISSN: 2811-3578

Column Study on Potential Enhancement in Bioretention Media to Treat Mix Development Area Runoff

Hui Weng Goh[1], Nor Azazi Zakaria[1,a], Tze Liang Lau[1,b], Keng Yuen Foo[1,c], Chun Kiat Chang[1,d*]

[1]River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia,
Engineering Campus, Seri Ampangan, 14300, Nibong Tebal, Penang, Malaysia

Email: [a]redac_gohhuiweng@usm.my , [b]redac01@usm.my , [c]celau@usm.my , [d]k.y.foo@usm.my , [e]redac10@usm.my

Received 10 September 2023;
Accepted 20 November 2023;
Available online 25 December 2023.

Abstract: Bioretention system was widely used as one of the Best Management Practices (BMPs) in Malaysia. In recent years, enhancement of filter media by using additives has been proven to be successful in various applications for nutrient removal from water bodies. This has shown that there is potential of using enhanced bioretention media in treating urban runoff, especially for mix development areas. A preliminary study has been conducted using various recyclable materials such as crushed cockle shells (CH), shredded newspaper (NP), shredded printed paper (PP) and coconut husk (CH) to enhance bioretention media in nutrient removal. Result shows that PP has the best performance to be used as additives in filter media of bioretention for total suspended solids (TSS, 97.4% compared to 84.5% for standard composition), total phosphorus (TP, 88.77% compared to 84.7% for standard composition) and total nitrogen (TN, 61.6% compared to 37.2% for standard composition) removal. CH was showing similar result with standard column (SC) due to the similar infiltration rate. Further trials will be required to test in larger column with vegetation to examine the overall performance of the whole bioretention system.

Keywords Additives; Best Management Practices (BMPs); bioretention media; nitrogen (N) and phosphorus (P);

1. Introduction

Here In recent decades, the rapid development in urban area has led to significant changes in both volume and quality of stormwater runoff, particularly the increase of nutrient inflow to the water body. Urban runoff, especially from mix development areas in developing countries, is accelerated with more nutrients, such as phosphorus and nitrogen. These extra nutrients are supplied by municipal and commercial grey water, fertilizers from landscapes and urban agricultures. As results, excessive growth of algae due to eutrophication has changed the natural food web in lakes and rivers, reduced the amount of dissolved oxygen in the water and cause aquatic animal and plant death rates to increase. In Malaysia, for a river to be classified as ‘clean’, which is at least class IIb and above, Department of Environment, Malaysia has set the following criterion for TSS, N and P: TSS not exceeding 50mg/L, nitrite-nitrogen not exceeding 0.4mg/L, nitrate-nitrogen not exceeding 7mg/L, ammoniacal nitrogen not exceeding 0.3mg/L and total P not exceeding 0.2mg/L (DOE, 2012; Goh et al., 2014).

In response to this, bioretention is one of most widely used Best Management Practises (BMPs), due to its flexibility in terms of size, location, configuration and appearance (Bratieres et al., 2008a)

Bioretention systems are storm-water management systems typically consisting of anexcavated basin filled with engineered filter media and planted with vegetation. The recommended composition of engineered filter media in bioretention systems consists of 50 — 60 % of medium sand, 20 — 25 % loamy sand or sandy loam top soil and 12 — 20 % of leave compost (DID, 2011). Initial studies of bioretention systems documented that they offer considerable potential to retain total suspended solids (TSS) and metals, while providing encouraging results for nutrient retention (Davis et al, 2001). However, there is still a considerable amount of uncertainty about long-term nutrient retention, particularly in relation to phosphorus (P) and nitrogen (N). Various studies have shown that TN mass removal were ranging from 33 to 79% (Barrett et al., 2013; Chen et al., 2013; Davis et al., 2006; Dietz, 2007) and TP mass removal were ranging from 70 to 85% (Roy-Poirier et al., 2010). TP leaching often observed in field evaluation (Dietz and Clausen, 2006; Hunt et al., 2006), which appears that the phosphorus content of the soil used in original bioretention media is critical to phosphorus performance removal (Davis, 2007).

In recent years, use of additives for nutrient removal from water bodies has been proven to be successful in various applications, such as use of oyster shell for phosphorus removal in constructed wetland (Wang et al, 2013), use of

**Corresponding author: redac_gohhuiweng@usm.my*

coconut shell for nitrate removal from groundwater (Bhatnagar and Sillanpaa, 2011). This has proven that the potential of using additives in filter media of bioretention has not been fully discovered. Kim (2003) has conducted a study to identify potential additives to be used as electron donor and carbon source for nitrate removal in bioretention. Among the 6 types of organic additives (alfalfa, newspaper, leaf mulch compost, sawdust, wood chips, and wheat straw) and 2 types of inorganic additives (sulphur particles with and without

limestone) tested, newspaper, wood chips, and small sulphur particles with limestone were found to have better nitrate removal rate (Kim et al., 2003).

In this study, 4 types of potential additives (coconut husk, newspaper, printed paper and cockle shell) were chosen as potential additives, based on the selection criteria and past related research. The main objective of the study was to preliminarily evaluate the modified bioretention filter media for its capacity to remove N and P from urban runoff, to serve as a baseline for comparison with the performance of full scale lab study.

1.1 METHODS

Selection of Runoff

Natural runoff was used in all the experiment to simulate the actual condition on site. Runoff from a major drain in Parit Buntar area was identified as target location for runoff treatment. Weekly monitoring was conducted for 3 months period on TN and TP concentration and the range of TN and TP concentration for the drain was 6.9 - 11.2 mg/L. and 1.88 - 3.88 mg/L respectively, which is much higher than typical range in urban runoff (2.1mg/L. for TN concentration and 0.2mg/L for TP concentration) to facilitate rapid saturation for experimental purposes. The runoff was collected in bulk on Feb 2014 and kept in the fridge for the experiment (Gohetal., 2014).

Selection and Preparation of additives

In this study, shredded newspaper (NP), printed paper (PP), coconut husk (CH) and cockle shell (CS) were chosen as potential additives. Shredded newspaper and printed paper was prepared by cutting into uniform size of 3mm x 15mm using Dino Superstar cross cut paper shredder. Coconut husk with size 0.15mm — 4 mm were purchased directly from the supplier. Cockleshells were collected from Pantai Bersih, Butterworth, Malaysia. The cockle shells were manually chosen, rinsed daily using tap water for 30 days, oven dried, crushed and sieved to obtain a mean size ranging from 0.15mm — 2mm.

Media Composition and Experiment Setup

The objectives of the experiment were to investigate the maximum adsorption ability of the selected additives mixed in bioretention filter media and to determine the trend of nitrogen and phosphorus removal over time. MSMA recommended filter media composition (20% leave compost, 20% top soil and 60% medium sand) was selected as basic composition for evaluation (DID, 2011). Top soil and medium sand were dried in oven (105°C) for 16 hours and passed through 2mm sieve. Leave compost were air dried and passed through 4mm sieve. Density test was conducted to convert the volume of the selected additives and filter media component (including medium sand, top soil and leave compost) to weight.

5 columns were constructed using 50mm diameter PVC pipes with 750mm length (Goh et al, 2014). The outlet and filter media was separated with geotextile fabric. 4 columns was filled with filter media composition suggested in MSMA added with 10% of different additives (by volume) and the columns were filled up until 500mm height. An additional column with MSMA recommended filter media composition (standard column) without additives was used as baseline study. All columns were subjected to regular inundation by water for 3 days immediately after soil mixing to achieve hydraulic compaction of the media.

During the experiment, each column was dosed with 200ml of natural runoff simultaneously in every 3 hours, 5 times a day. The dosing was done daily until nutrient leaching or clogging in column observed. Influent samples are taken daily and effluent samples are taken after every 6 hours from each column. The collected samples were analysed for total suspended solids (TSS), total nitrogen (TN), ammoniacal nitrogen (AN), nitrite (NO,-N), nitrate (NO;-N) and total phosphorus (TP) concentration. Total nitrogen, nitrite, nitrate and total phosphorus concentration were determined by using Hach DR3900 Spectrophotometer (Hach, 2013). Total nitrogen was tested using Hach Methods 10071, nitrate using Hach Methods 8039, nitrite using Hach Methods 8507 and total phosphorus using Hach Methods 8190. Ammoniacal nitrogen was tested using Nessler method with digesting vials and was measured using Hach Methods 8038.

Daily data was combined to obtain mean influent concentration, mean effluent concentrations and concentration reductions for the filter media treatment. The mean influent concentrations (Cin) were calculated by:

$$\overline{C_{inf}} = \frac{C_{inf_1}+C_{inf_2}+\cdots+C_{inf_n}}{n} \quad (1)$$

where C_{inf} is the influent concentration taken from each sample daily (mg/L) and n is the total number of samples taken daily. The mean effluent concentrations ($\overline{C_{eff}}$) were calculated by:

$$\overline{C_{eff}} = \frac{C_{eff_1}+C_{eff_2}+\cdots+C_{eff_n}}{n} \quad (2)$$

where C_{eff} is the effluent concentration taken from each sample daily (mg/L) and n is the total number of samples taken daily. The % concentration reductions (C_R) were calculated using:

$$C_R = \frac{\overline{C_{inf}}-\overline{C_{eff}}}{\overline{C_{inf}}} \times 100\% \quad (3)$$

Infiltrated volumes (V) were also measured for use in pollutant mass balance calculation. The accumulated nitrogen and phosphorus mass removed by the entire soil layer, including ammonium, nitrite and nitrate, was calculated by difference between input and output mass. Cumulative mass removal (M_{total}) for each parameter was calculated using:

$$M_{total\,(t)} = \sum_{i=1}^{t} V_{inf_i}\overline{C_{inf_i}} - V_{eff_i}\overline{C_{eff_i}} \quad (4)$$

RESULTS AND DISCUSSION

Fig. 1. shows the cumulative mass of TSS, TP, TN, AN, NOx removed from each columns over 7 days of dosing. Fig. 2 compares the influent and effluent concentrations for columns containing different types of bioretention media. It was found that clogging occurred in columns NP and CS after day 4 of the experiment. Hence, only results for columns PP and CH will be shown in Fig. 1. and Fig. 2 for comparison with standard column (SC).

Possible reason for clogging happened in NP column was due to the texture of additives was too thin and when mix with clay content in top soil, it blocked the voids in the soil and the soil infiltration rate drop drastically. Clogging in column with CS probably due to the size of crushed cockle shell used was too small (lesser than 400um) and caused the blocking in geo-textile. Overall, infiltration systems for all columns were shown to reduce over time due to combination of hydraulic and sediment loading. Vegetation and the sizing of bioretention have an important influence on hydraulic conductivity (Le Coustumer et al, 2012). Therefore, the actual performance of each proposed additives could not be concluded by using the mini column tests as it was not full scale designed system with plants.

All columns showed constant TP removal with average between 84.7% (standard) to 88.77% (PP). These results generally agreed with values from various researchers (Davis et al., 2006; Barrett et al., 2013) and performed better than some of the previous studies (Bratieres et al., 2008b; Dietz and Clausen, 2005). Average effluent concentration from the 3 columns (SC, CH and PP) remained below the average TP concentration of normal runoff, which is 0.31mg/L (Duncan, 2006). For phosphorus removal in bioretention system, there are two main mechanisms

1.2 File Naming and Delivery

Please title your files in this order 'journal acronym_submission year_authorslastname'. Submit both the source file and the PDF to the Guest Editor.

Artwork filenames should comply with the syntax "aabbbbbb.ccc", where:

- a = artwork component type
- b = manuscript reference code
- c = standard file extension

Component types:

- gr = figure
- pl = plate
- sc = scheme
- fx = fixed graphic.

1.3 Footnotes

Footnotes should be avoided if possible. Necessary

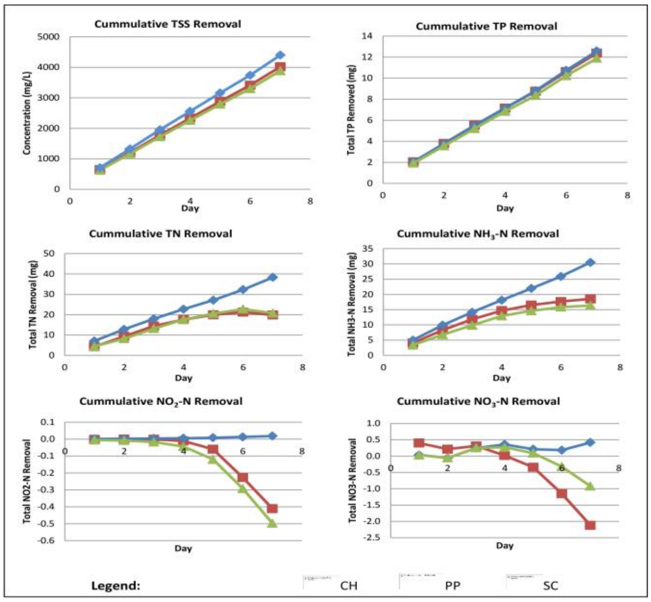

Fig. 1. shows the cumulative mass of TSS, TP, TN, AN, NOx removed from each columns over 7 days of dosing.

Fig. 1. Accumulated mass removed from bioretention media with different additives (CH-coconut husk, PP — printed paper and SC — standard column) over time for: total suspendedsolids (TSS), total phosphorus (TP), total nitrogen (TN), ammoniacal nitrogen (NH3-N), nitrite (NO:-N) and nitrate (NO3-N).

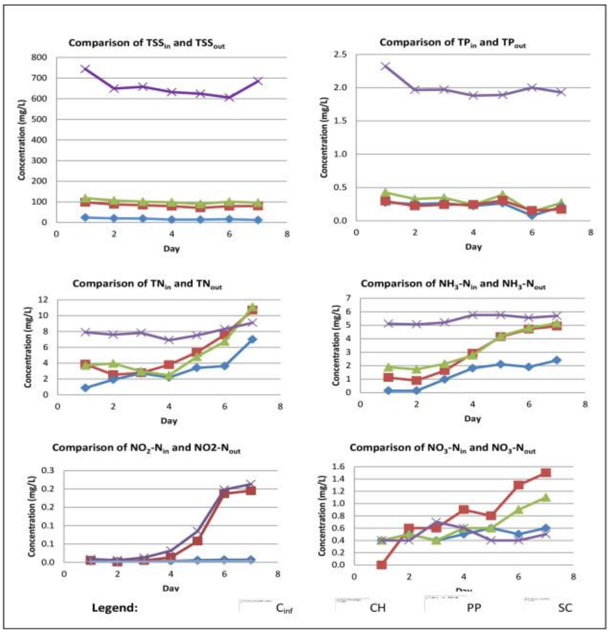

Fig. 2 compares the influent and effluent concentrations for columns containing different types of bioretention media.

Fig. 2. Comparison of influent versus effluent concentration for bioretention media with different additives (CH- coconut husk, PP — printed paper and SC — standard column) over time for: total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), ammoniacal nitrogen (NHs-N), nitrite (NO»-N) and nitrate (NO3-N).

Involved: adsorption and plant uptake. Therefore, in this preliminary study, material adsorption is the main mechanism involved and the columns with additives were found to perform slightly better than the standard column. However, as the optimum ratio of additives and filter media has not been fully established, the overall phosphorus removal performance of the columns is estimated to be higher in full scale lab test with the plants.

The performance of TN removal for all columns reduced gradually over time, especially in SC and CH, which nitrogen leaching started to occur after day 6. Leaching of nitrogen may be attributable to the excessive amount of nitrate and nitrite (NOy) generated in the column. NOy is highly soluble and does not sorb well, therefore removal is reliant on either plant uptake or removal via nitrification (Hatt et al., 2009). As the plant was not included in the system for this study, the generation of NOy in SC and CH seemed to be reasonable.

For ammoniacal nitrogen, all six columns produced similar low removal, as was found in column and site monitoring (Hsieh and Davis, 2005). Labile organic N is mineralized into ammoniacal nitrogen and subsequently nitrified into NOx, between storm events. Some of the resulting NOx will be taken up by plants, while the remainder will be leached from the profile, or removed by denitrification (Lucas and Greenway, 2008). The results has shown that mineralization of organic N is faster in SC and CH, due to higher organic content in the composition. This has explained the reason of NO leaching in both columns while PP column was having higher TN retention rate.

These finding indicates that the coconut husk was having similar properties with leave compost in the standard composition for nutrient retention. This may due to the infiltration rates of the columns as CH and SC were having similar infiltration rate while PP's infiltration rate was lower (average of 200mm/hr in day 1 and 50mm/hr in day 7 for SC and CH, average of 133mm/hr in day 1 and 33mm/hr in day 7 for PP). Hatt (2009) mentioned in the previous study that higher infiltration rates may lead to higher effluent concentration of particulates and this again explained the reason of nitrogen leaching starting from day 5 for CH and SC.

CONCLUSIONS

TP removal was consistent all columns throughout the experiment (84.7%-88.7%). TN removal reduced over time and leaching of nitrogen was observed in SC and CH. Overall, PP has the better performance in terms of both nitrogen and phosphorus removal. On the other hand, CH was showing similar result with standard column (SC) due to the similar infiltration rate. Overall, infiltration rate for all columns were reduced over time due to combination of hydraulic and sediment loading. Therefore, full scale lab study and on site monitoring are recommended to confirm the effectiveness of additives in filter media of bioretention and to enhance the nutrient removal of bioretention system.

Acknowledgement

This work was supported by the Ministry of Higher Education Malaysia under the grant title of "Urban Water Cycle Processes, Management and Societal Interactions: Crossing from Crisis to Sustainability" with grant number as: 203/PKT/6720004. The author would like to acknowledge the technical staff from River Engineering and Urban Drainage Research Centre (REDAC) for their effort and collaboration throughout the study's duration.

References

[1] Barrett, M. E., Limouzin, M. & Lawler, D. F. 2013. Effects of media and plant selection on biofiltration performance. Journal of Environmental Engineering (United States), 139(4), 462-470.

[2] Bhatnagar, A. & Sillanpai, M. 2011. A review of emerging adsorbents for nitrate removal from water. Chemical Engineering Journal, 168(2), 493-504.

[3] Strunk, W., Jr., & White, E. B. (1979). The elements of style (3rd ed.). New York: MacMillan. Bratieres, K., Fletcher, T., Deletic, A., Alcazar, L., Le Coustumer, S. & McCarthy, D. Removal of nutrients, heavy metals and pathogens by stormwater biofilters. 11th International Conference on Urban Drainage, 2008a.

[4] Bratieres, K., Fletcher, T., Deletic, A. & Zinger, Y. 2008b. Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. Water Research, 42(14), 3930-3940.

[5] Chen, X_, Peltier, E., Sturm, B. S. & Young, C. B. 2013. Nitrogen removal and nitrifying and denitrifying bacteria quantification in a stormwater bioretention system. Water Research, 47(4), 1691-1700.

[6] Davis, A. P. 2007. Field performance of bioretention: Water quality. Environmental EngineeringScience, 24(8), 1048-1064.

[7] Davis, A. P., Shokouhian, M., Sharma, H. & Minami, C. 2001. Laboratory study of biological retention for urban stormwater management. Water Environment Research, 73(1), 5-14.

[8] Davis, A. P., Shokouhian, M., Sharma, H. & Minami, C. 2006. Water quality improvement through bioretention media: Nitrogen and phosphorus removal. Water Environment Research, 78(3), 284-293.

[9] DID. 2011. Urban Stormwater Management Manual for Malaysia (2nd Edition). Department of Irrigation and Drainage Malaysia (DID), Kuala Lumpur, Malaysia.

[10] Dietz, M. E. 2007. Low impact development practices: A review of current research and recommendations for future directions. Water, Air, and Soil Pollution, 186(1-4), 351-363.

[11] Dietz, M. E. & Clausen, J. C. 2005. A field evaluation of rain garden flow and pollutant treatment. Water, Air, and Soil Pollution, 167(1-4), 123-138.

[12] Dietz, M. E. & Clausen, J. C. 2006. Saturation to improve pollutant retention in a rain garden. Environmental science & technology, 40(4), 1335-1340.

[13] DOE. 2012. Malaysia Environmental Quality Report. Strategic Communication Division, Department of Environment Malaysia (DOE), Putrajaya, Malaysia.

[14] Duncan, H. 2006. Urban stormwater pollutant characteristics. Australian runoff quality: A guide to water sensitive urban design, Ed. Wong, THF, Engineers Australia.

[15] Goh, H. W., Zakaria, N. A, Lau, T. L. & Foo, K. Y. Preliminary Study on Potential Additives in Filter Media of Bioretention for Nutrient Removal. 13th International Conference on Urban Drainage (ICUD 2014), 2014 Kuching, Sarawak.

[16] Hach, C. 2013. DR 3900 USER MANUAL 04/2013, EDITION 05. Germany.

[17] Hatt, B. E., Fletcher, T. D. & Deletic, A. 2009. Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. Journal of Hydrology, 365(3), 310-321.

[18] Hsieh, C. & Davis, A. 2005. Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff. Journal of Environmental Engineering, 131(11), 1521-1531.

[19] Hunt, W., Jarrett, A., Smith, J. & Sharkey, L. 2006. Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. Journal of Irrigation and Drainage Engineering, 132(6), 600-608.

[20] Kim, H., Seagren, E. A. & Davis, A. P. 2003. Engineered bioretention for removal of nitrate from stormwater runoff. Water Environment Research, 75(4), 355-367.

[21] Le Coustumer, S., Fletcher, T. D., Deletic, A., Barraud, S. & Poelsma, P. 2012. The influence of design parameters on clogging of stormwater biofilters: A large-scale column study. Water Research, 46(20), 6743-6752.

[22] Lucas, W. C. & Greenway, M. 2008. Nutrient retention in vegetated and nonvegetated bioretention mesocosms. Journal of Irrigation and Drainage Engineering, 134(5), 613-623.

[23] Roy-Poirier, A., Champagne, P. & Filion, Y. 2010. Review of bioretention system research and design: past, present, and future. Journal of Environmental Engineering, 136(9), 878-889.

[24] Wang, Z., Dong, J., Liu, L., Zhu, G. & Liu, C. 2013. Study of oyster shell as a potential substrate for constructed wetlands. Water Science & Technology, 67(10), 2265-2272.