Journal of Environmental Management 147 (2015) 24–33

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Comparison of filter media materials for heavy metal removal from urban stormwater runoff using biofiltration systems

H.S. Lim [a, *], W. Lim [b], J.Y. Hu [b, c], A. Ziegler [a], S.L. Ong [b, c]

[a] Department of Geography, National University of Singapore, 117570 Singapore, Singapore
[b] Department of Civil & Environmental Engineering, National University of Singapore, 117576 Singapore, Singapore
[c] NUS Environmental Research Institute, National University of Singapore, 117411 Singapore, Singapore

ARTICLE INFO

Article history:
Received 28 December 2013
Received in revised form
16 April 2014
Accepted 22 April 2014
Available online 27 September 2014

Keywords:
Heavy metals
Biofiltration
Urban runoff quality

ABSTRACT

The filter media in biofiltration systems play an important role in removing potentially harmful pollutants from urban stormwater runoff. This study compares the heavy metal removal potential (Cu, Zn, Cd, Pb) of five materials (potting soil, compost, coconut coir, sludge and a commercial mix) using laboratory columns. Total/dissolved organic carbon (TOC/DOC) was also analysed because some of the test materials had high carbon content which affects heavy metal uptake/release. Potting soil and the commercial mix offered the best metal uptake when dosed with low (Cu: 44.78 μg/L, Zn: 436.4 μg/L, Cd, 1.82 μg/L, Pb: 51.32 μg/L) and high concentrations of heavy metals (Cu: 241 μg/L, Zn: 1127 μg/L, Cd: 4.57 μg/L, Pb: 90.25 μg/L). Compost and sludge also had high removal efficiencies (>90%). Heavy metal leaching from these materials was negligible. A one-month dry period between dosing experiments did not affect metal removal efficiencies. TOC concentrations from all materials increased after the dry period. Heavy metal removal was not affected by filter media depth (600 mm vs. 300 mm). Heavy metals tended to accumulate at the upper 5 cm of the filter media although potting soil showed bottom-enriched concentrations. We recommend using potting soil as the principal media mixed with compost or sludge since these materials perform well and are readily available. The use of renewable materials commonly found in Singapore supports a sustainable approach to urban water management.

1. Introduction

Urban stormwater runoff consists of a broad range of pollutants that have a significant negative impact on receiving waters (Laurenson et al., 2013). Increasingly stringent regulations on stormwater discharge led to the growth of stormwater best management practices (BMPs) in many developed countries. BMPs are also known as Low Impact Development (LID), Water Sensitive Urban Design (WSUD), Sustainable Urban Drainage Systems (SUDS), Innovative Stormwater Management and ABC Waters design in different parts of the world. These systems are built to 1) reduce hydrologic and water quality disturbance to urban and downstream waterways; 2) make use of stormwater as an alternate water resource (Roy-Poirier et al., 2010; Barbosa et al., 2012).

Biofiltration systems are increasingly popular. They adopt natural processes such as filtration, adsorption, vegetation uptake and biotransformation to slow down stormwater runoff rates, reduce the runoff volumes and retain pollutants before their discharge into receiving waters. The general design includes a topsoil filter layer that supports vegetation and promotes mechanical and chemical processes of pollutant removal. Hence, its composition plays an important role in pollutant removal. A gravel layer at the bottom improves drainage (Davis et al., 2001). A transition layer with intermediate grain sizes is sometimes placed in-between to limit the migration of filter layer materials to the gravel layer.

The filter media typically includes a soil-based material (sandy loam being the usual guideline material), organic matter, or other materials (e.g. vermiculite, perlite) that are added in various proportions to provide sufficient hydraulic conductivity for water drainage, pollutant removal and support for vegetation growth (Davis et al., 2009). A mulch layer is usually added on top to retain moisture and heavy metals (Davis et al., 2001, 2003; Muthanna et al., 2007; Hatt et al., 2008).

Biological waste material (e.g. coconut, water treatment sludge, tea leaves, rice husk etc) can also be used in biofiltration systems as they have the potential to remove heavy metals via ion exchange,

* Corresponding author. Tel.: +65 65163851.
E-mail addresses: hanshe_lim@hotmail.com, hanshelim@gmail.com (H.S. Lim).

http://dx.doi.org/10.1016/j.jenvman.2014.04.042
0301-4797/

surface adsorption and complexation (Sud et al., 2008; Gadd, 2009). Using them as filter media material supports a waste minimisation strategy that reflects sustainable urban stormwater management (Barbosa et al., 2012). Published work found that coconut coir, compost and sludge are able to achieve high metal removal rates (Seelsaen et al., 2007; Gadd, 2009; Bhatnager et al., 2010; Chiang et al., 2012). Coconut coir and compost contain humic substances, cellulose, lignin and carboxyl groups that have a high tendency to bind metals especially between pH range 6–8 via surface complexation and ion exchange processes (Quek et al., 1998; Pinõ et al., 2006; Hasany and Ahmad, 2006). The drinking water treatment process produces sludge that is disposed at landfills. This material has a high heavy metal removal potential due to its large surface area to volume ratio, highly reactive surface and potential reuse via regeneration (Ippolito et al., 2011; Chiang et al., 2012).

Singapore is a highly urbanized island with limited land and water resources. Recent interest in BMPs arose from the need to reduce water quality impacts of stormwater runoff for environmental protection and also for water harvesting. Urban runoff is now being treated and re-used as drinking water. Heavy metals are important pollutants in Singapore's environment because they are toxic at low concentrations and accumulate in living organisms. They originate mainly from vehicles, roads and industrial activities dispersed across the island nation (Joshi and Balasubramanian, 2010; Yuen et al., 2012). Biofiltration systems are suitable because they have the potential to improve urban water quality, can be designed as small systems, provide an aesthetics effect and increase biodiversity in a highly urbanized setting (Kazemi et al., 2011). However, the limited availability of sand in the country means that other types of materials must be considered as alternatives for the filter media.

Published work based on laboratory and field studies show that the filter media materials may contribute heavy metals to the environment through leaching (Dietz and Clausen, 2006; Hatt et al., 2008). Ideally, the materials should contain negligible amounts of heavy metals. The depth of the filter media may also affect its performance. Higher metal uptake may occur in longer columns because there is more material for adsorption/ion-exchange and a longer contact time for these processes to take place (Sousa et al., 2010; Acheampong et al., 2012). However, longer columns may experience higher leaching rates from the mobilization of heavy metals within the media (Davis et al., 2003; Feng et al., 2012).

The objective of this study is to examine the heavy metal removal potential of five materials commonly found in Singapore to test their suitability as filter media material for biofiltration systems. The study uses laboratory columns and soil as a control for comparison with other materials. While published column studies on BMPs usually use soil as the main component with varying proportions of compost or other materials, we filled the columns with 100% treatments of each material to test their heavy metal removal potential. The study examined the leaching potential of the materials, investigated the effect of metal concentration/depth of filter media on metal removal, and quantified the metal accumulation in these materials. The heavy metals studied were Copper (Cu), Zinc (Zn), Cadmium (Cd) and Lead (Pb), because these are the predominant metals found in Singapore urban runoff (Joshi and Balasubramanian, 2010). Total/dissolved organic carbon (TOC/DOC) is included in sample analysis because some of these materials have high carbon content which provides an energy source for microbial processes that remove nutrient or heavy metals as well as plant growth. However, DOC leaching out of the media may also increase the mobility of heavy metals out of the columns (e.g. McLaughlan and Al-Mashaqbeh, 2009; Blecket et al., 2011).

2. Methods and materials

2.1. Materials tested

The filter media materials we tested were chosen using the criteria that they were commonly used and easily available to landscaping contractors in Singapore: potting soil (control), coconut coir, compost, sludge and a commercial mix. The potting soil is classified as loamy sand and has low organic matter content compared with compost and coconut coir (Table 1). The coconut coir fibre consists of coconut husk and hairy fibre chopped into different sizes, producing a highly porous and heterogeneous mix. The compost is horticultural waste made up of leaves and bark material found within Singapore. The sludge is a grey-coloured cake obtained from a local drinking water treatment plant which uses aluminium sulphate for the coagulation process. The sludge had already been de-watered in a filter press at the treatment plant. It was further dried in our laboratory and hammered into relatively uniform sand-sized particles to obtain a texture similar to potting soil. The commercial mix was added as a comparison with the other materials. The commercial material is a patented mix that consists of light granular particles (EnviroMix®). It is often used as a media for green roofs in Singapore. The estimated cost and lifetime of each media is given in Table 1.

Table 1
Properties of the materials tested.

	Potting soil	Coconut coir[a]	Compost	Commercial	Sludge[b]
pH	6.44	4.76	6.79	7.17	6.46
LOI (%)	6.6	96.2	75.7	2.6	38.0
Sand (%)	75.3	–	29.3	15.1	90.5
Silt (%)	18.3	–	57.7	5.9	9.2
Clay (%)	2.9	–	0.36	0.12	0.3
Cu (mg/kg)[c]	5.6	115.0	24.7	137.9	19.1
Zn (mg/kg)[c]	35.2	10.9	89.7	153.7	71.5
Cd (mg/kg)[c]	0.13	0.013	0.38	0.70	0.086
Pb (mg/kg)[c]	9.0	0.21	17.8	46.3	9.8
Expected lifespan (year)[d]	>1	0.5–1	0.5–1	Often longer than vegetation lifespan	Unknown
Estimated cost (USD/kg)[e]	0.12	0.4–0.79	0.16	0.79	–

[a] It was not possible to use the hydrometer method to determine particle size for Coconut coir as it floats on the surface and does not sink at all within 24 h.

[b] Sludge contains iron, aluminium hydroxides, sediment and humic substances removed from raw water as well as coagulating agents added to water, such as activated carbon and polymers (Makris and O'Connor, 2007). The pH of our Sludge is slightly acidic in comparison to other sludge studied, which is slightly alkaline (pH = 8.1, Chiang et al., 2012). The Sludge from the drinking water treatment plants in Singapore is aluminium-based (alumuinium sulphate being the coagulant used). The pH falls within the expected range of 6.5 ± 0.3 for this type of sludge according to ASCE characterization (Ippolito et al., 2011). Aluminium toxicity should not be an issue at this pH value.

[c] Metal extraction was conducted based on the USEPA 3051A method. Note that this is just an extraction method which does not involve complete digestion of the materials tested but provides a comparison for metals retained in the media at two different depths of each media.

[d] Approximate estimate based on information from landscape contractors. Lifespan is expected to vary depending on plant grown, whether the material is used indoors or outdoors. Generally, coconut coir will disintegrate relatively quickly in a tropical environment. Compost is quickly taken up by plants in the tropical environment. There is no information about the lifespan of Sludge as this is a relatively new material used as filter media.

[e] Estimated cost is based on information from various suppliers of the materials in Singapore. Currently, the higher price of coconut coir may be because this material is imported into Singapore whereas the other materials (e.g. potting soil, compost) are locally available. There is no price information for Sludge because we obtained it free from the water treatment plant. Conversion rate from Singapore dollar (SGD) to US Dollar is approximately 1SGD = 0.79 USD.