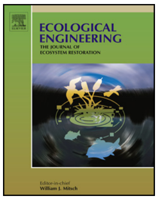
Ecological Engineering 102 (2017) 320–330

Contents lists available at ScienceDirect

Ecological Engineering

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



Effects of submerged zone, media aging, and antecedent dry period on the performance of biochar-amended biofilters in removing fecal indicators and nutrients from natural stormwater

A.R.M. Nabiul Afrooz[a,b,*], Alexandria B. Boehm[a,b]

[a] Department of Civil and Environmental Engineering, 473 Via Ortega, Stanford University, Stanford, CA 94305, USA
[b] Engineering Research Center (ERC) for Re-inventing the Nation's Urban Water Infrastructure (ReNUWIt), USA

ARTICLE INFO

Article history:
Received 22 September 2016
Received in revised form 17 February 2017
Accepted 19 February 2017
Available online 27 February 2017

Keywords:
Low impact development
Biofilters
Bioretention media
Saturated zone
Biofilm
Stormwater

ABSTRACT

Biochar has demonstrated promising performance as an amendment to biofilter soil media in removing fecal indicator bacteria (FIB) from simulated stormwater. However, there is no study that investigates its efficacy in treating natural stormwater runoff. Additional information, including the effects of antecedent dry period, microbial biofilm, and presence of a saturation zone on the performance of biochar-augmented biofilters are needed to inform their field implementation. This study uses laboratory column experiments to monitor FIB (enterococci and *Escherichia coli*) and nutrient removal capacity of biochar-amended biofilters for 140 days using natural stormwater. Our study also investigates the effects of antecedent dry days (ADD) and the presence of a saturation zone (SZ) on the performance of lab-scale biochar-amended biofilters. The results suggest insignificant influence of the ADD and SZ on FIB removal performance, however biofilters with a SZ perform significantly better in removing nitrate-nitrogen compared to those without a SZ. In addition, it appears that the presence of biofilm augments nutrient removal capacity but reduces FIB removal capacity. Our observations indicate that biochar-amended biofilters are able to treat (to comply with recreational water quality standard for FIB) urban stormwater runoff for the duration of the experiment. Nitrate- and ammonium-nitrogen removal in the biologically aged biofilters is found to be 50–60% while the total dissolved phosphorus and the organic nitrogen removal is 20–30%. Our results inform full-scale design of biochar-amended biofilters in order to meet the total maximum daily load (TMDL) and municipal separate storm sewer system (MS4) permitting requirement for FIB and nutrients.

1. Introduction

Biofilters are common green stormwater infrastructure that can be used to reduce, capture, and treat urban stormwater runoff. Currently, a majority of these infiltration systems uses a conventional soil mix as the biofilter soil media (BSM), consisting of either loamy sand, sand/compost or sand/native soil (Sage et al., 2015; Hsieh and Davis, 2005a). Yet, the performance of conventional BSM is inconsistent and inadequate for removing contaminants from urban stormwater runoff that pass through the biofilters. For example, in multiple studies, conventional stormwater biofilters have been reported to leach both microbial and chemical contaminants into the stormwater as it exits the biofilters (García-Albacete et al., 2014; Hathaway et al., 2009; Chandrasena et al., 2012; Zhang et al., 2012). Such findings motivate ongoing work (Bratieres et al., 2008; Li et al., 2012; Hsieh and Davis, 2005b; Li et al., 2014; Mohanty et al., 2013; Mohanty and Boehm 2014; Mohanty et al., 2014; Li et al., 2016; Poresky et al., 2016) to identify effective BSM for removing stormwater contaminants, including pathogens, pathogen indicator bacteria, and nutrients.

One of the major stormwater biofilter design goals is to maximize the removal efficiency of microbial contaminants and nutrients, primarily due to the associated public and ecological health implications, respectively. Runoff-associated fecal indicator bacteria (FIB) contamination is one of the major sources of surface water impairment in the U.S (Cahoon et al., 2016). On the other hand, capturing nitrogen and phosphorus from stormwater is crucial for preventing algal blooms in receiving waters, as well for boosting soil fertility to support the vegetation in stormwater best management practices (BMPs) (Mallin et al., 2009). Additionally, engineered stormwater biofilters with enhanced FIB and

---

* Corresponding author at: Department of Civil and Environmental Engineering, 473 Via Ortega, Stanford University, Stanford, CA, 94305, USA.
E-mail addresses: rnabiul@stanford.edu, rnabiul@gmail.com (A.R.M. Nabiul Afrooz).

http://dx.doi.org/10.1016/j.ecoleng.2017.02.053
0925-8574/

nutrient removal-capacity may help cities in the US comply with total maximum daily load (TMDL) and municipal separate storm sewer system (MS4) regulatory requirements. Stormwater biofilters remove contaminants primarily via BSM where the targeted contaminants undergo a combined process of physical, chemical, and biological removal (Subramaniam et al., 2015).

In addition to effectively removing contaminants, an ideal BSM needs to be cost-effective, easily sourced, and sustainable. Using a bulk aggregate (i.e., sand), modified with either organic or mineral additives, can be effective for removing contaminants, maintaining hydraulic characteristic, and relatively inexpensive (Subramaniam et al., 2015). Sourcing the organic and mineral additives from recycled materials could lead to a sustainable stormwater management system (Hengen et al., 2016). Other efforts have been made to source BSM from recycled rubber (e.g., tire crumb), scrap iron (e.g., zero-valent iron, iron-oxides), scrap wood (e.g., wood chips), industrial by-products (e.g., coconut coir, high-carbon wood ash, biochar) and waste biomass (e.g., biochar) (Mohanty et al., 2013; Seelsaen et al., 2006; Joyner and Waldrop 2008; Lim et al., 2015; Chang et al., 2012). Note that pyrogenic carbonaceous materials, such as biochar, are good candidates for BSM not only because of their low material cost but also due to their porous structures, high specific surface areas, functional groups, and hydrophobicity (Inyang and Dickenson, 2015).

Biochar—a pyrolyzed biomass produced from waste biomass—shows particular promise as a low-cost, sustainable BSM. The production of biochar from the anoxic pyrolysis of discarded biomass makes it a carbon negative material due to low greenhouse gas (GHG) emissions and potential for long-term carbon sequestration (Lehmann and Joseph, 2015). Biochar can also be produced as a by-product of biodiesel, and used for amending agricultural soil to enhance crop yields (Inyang and Dickenson, 2015; Chan et al., 2008). The addition of biochar to sand for use as BSM in biofilters has reportedly improved both FIB and nutrient removal capacity of the BSM. FIB removal has been reported to increase by more than 3-log depending on the particle size, feed stock, and pyrolysis temperature of the biochar as well as type of the FIB (Mohanty and Boehm, 2014). While complete mechanistic understanding of enhanced microbial removal in biochar-amended media is yet to be achieved, increased removal has been attributed to higher surface area, lower surface charge, and stronger hydrophobicity of biochar compared to sand (Mohanty et al., 2014; Abit et al., 2012). Additionally, research has also been conducted on biochar derived from various feedstock and pyrolyzed at different temperature to evaluate its nutrient recovery capacity from aqueous solution (Mohan et al., 2014). Biochar addition also has demonstrated potential to increase nutrient removal from stormwater in at least two studies. One study—performed using gasified biochar derived from wood waste pallet—reports up to 47 and 85% of phosphorus and nitrogen from stormwater, respectively (Reddy et al., 2014). Another study used two types of biochar (i.e., derived from wood and poultry litter) to investigate ammonium-nitrogen (NH_4^+-N) absorption in biochar particles: 74 and 37% NH_4^+-N removal was observed by wood and poultry litter biochar, respectively (Tian et al., 2014). These results underscore the potential of biochar as a promising amendment for BSM in removing FIB and nutrients from stormwater.

However, utilizing biochar in a field-scale biofilter first requires more field representative performance evaluations to gauge its efficacy under complex environmental conditions. There are no published studies that investigate the performance of the biochar-augmented BSM in removing contaminants from natural stormwater for an extended period of time. The durations used in the previous studies range from 3 to 70 h (Abit et al., 2012; Reddy et al., 2014; Mohanty and Boehm, 2015). However, stormwater biofilters in the field will be exposed to natural stormwater for extended periods of time: reported operational life of decades and beyond (Flynn and Traver, 2013; Payne et al., 2014a). The physical, chemical, and biological properties of a BSM are, thereby, likely to change over time, which, in turn, could potentially influence capture and removal of FIB and nutrient in biochar-modified BSMs (Hunt et al., 2008; Zhang et al., 2011; Chandrasena et al., 2016; Passeport et al., 2009). Therefore, it is necessary to evaluate the effects of field conditions (e.g., biological aging and antecedent dry days) on biochar-modified sand biofilter performance. Moreover, the literature has yet to discuss the effects of biofilter design parameters—for example, a saturation zone or vegetated cover—on the performance of biochar-augmented stormwater biofilters. While providing a saturation zone has been reported to increase FIB and nutrient removal efficiency of sand/compost biofilters (Li et al., 2012; Barrett et al., 2012), it remains unknown if the presence of a saturation zone would have a similar effect on the performance of biochar-modified sand filters.

In this study, we evaluated the long-term (i.e., simulated one water-year of hydraulic loading considering average annual rainfall in San Francisco, USA) performance of biochar-augmented stormwater biofilters in removing FIB and nutrients from natural stormwater runoff. While field-scale experiments where test-biofilters are installed in situ would be useful, there are legal barriers to doing so due to the potential for negative impacts of experimental designs on flooding and effluent water quality that precluded us from carrying out such studies. We used laboratory scale biofilters that were exposed to natural stormwater flushes–once – or twice-weekly – to investigate the effects of antecedent dry days (ADD) on performance. In addition, the performance of biofilters with a saturation zone (SZ) was compared with biofilters with no SZ. Moreover, we quantified the amount of active biomass formed on the BSM, caused by natural stormwater exposure, and its effects on the biofilter FIB and nutrient removal performance. Our results address the gap in the data concerning the performance of biochar-augmented biofilters under representative field conditions. This research informs the design of full-scale bioinfiltration systems with biochar-augmented sand used as the BSM.

2. Materials and methods

2.1. Porous media

Ottawa sand (0.6–0.8 mm Fisher Scientific, IL, USA) was mixed with biochar (Swallow Valley Farm, Valley Ford, CA) at a 7:3 proportion (by volume) to prepare the BSM for the laboratory scale biofilters. This volumetric ratio was selected based on the current recommended proportion (20–40%) for organic matter in biofilter soil media (California State Waterboard, 2011). The sand was washed, dried, autoclaved (121 °C, 100 KPa, 15 min), and stored in a sterile container. The details of the preparation procedure are presented in the supplementary material (SM) section: M1.

The biochar particles were crushed, sieved (to obtain sizes smaller than the 0.6 mm), and autoclaved (121 °C, 100 KPa, 15 min) for sterilization. The biochar feedstock consisted of a mix of 60% Monterey Pine, 20% Eucalyptus, 10% Bay Laurel, 10% mixed hardwood and softwood. The pyrolysis was performed over a 6 h period at temperatures ranging from 180 to 395 °C. Based on the feedstock and the pyrolysis temperature, this biochar represents a wood-derived low-temperature biochar.

2.2. Model biofilters

Polyvinyl chloride (PVC) pipes with a 2.5 cm internal diameter and a 15 cm length were glued to end fittings to build model biofil-