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Effects of changing hydraulic and organic loading rates on pollutant reduction in bark, charcoal and sand filters treating greywater

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Greywater flows and concentrations vary greatly, thus evaluation and prediction of the response of on-site treatment filters to variable loading regimes is challenging. The performance of 0.6 m × 0.2 m (height × diameter) filters of bark, activated charcoal and sand in reduction of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (Tot-N) and total phosphorus (Tot-P) under variable loading regimes was investigated and modelled. During seven runs, the filters were fed with synthetic greywater at hydraulic loading rates (HLR) of 32–128 L m^{-2} day^{-1} and organic loading rates (OLR) of 13–76 g BOD_5 m^{-2} day^{-1}. Based on the changes in HLR and OLR, the reduction in pollutants was modelled using multiple linear regression. The models showed that increasing the HLR from 32 to 128 L m^{-2} day^{-1} decreased COD reduction in the bark filters from 74 to 40%, but increased COD reduction in the charcoal and sand filters from 76 to 90% and 65 to 83%, respectively. Moreover, the models showed that increasing the OLR from 13 to 76 g BOD_5 m^{-2} day^{-1} enhanced the pollutant reduction in all filters except for Tot-P in the bark filters, which decreased slightly from 81 to 73%. Decreasing the HLR from 128 to 32 L m^{-2} day^{-1} enhanced the pollutant reduction in all filters, but decreasing the OLR from 76 to 14 g BOD_5 m^{-2} day^{-1} detached biofilm and decreased the Tot-N and Tot-P reduction in the bark and sand filters. Overall, the bark filters had the capacity to treat high OLR, while the charcoal filters had the capacity to treat high HLR and high OLR. Both bark and charcoal filters had higher capacity than sand filters in dealing with high and variable loads. Bark seems to be an attractive substitute for sand filters in settings short in water and its effluent would be valuable for irrigation, while charcoal filters should be an attractive alternative for settings both rich and short in water supply and when environmental eutrophication has to be considered.

1. Introduction

Greywater, i.e. wastewater from household washing activities such as dishwashing, laundry and showering (Jefferson et al., 2000), is often treated on-site in small units connected to detached households. The need for simple solutions with easy operation and maintenance means that influent greywater is treated more or less directly upon entering the unit and, consequently, the system has limited capacity to level out peak loads. The treatment units are challenged by large diurnal variations in flows and concentrations of pollutants, but also variations in weekly and seasonal loading patterns. In a Danish study, the daily greywater flow and concentrations of COD during the working week varied considerably, from 30 to 71 L p^{-1} d^{-1} and 25 to 650 mg COD L^{-1}, respectively (Eriksson et al., 2009). Local conditions strongly influence greywater flows and composition. Halalsheh et al. (2008) reported averages of 30 L p^{-1} d^{-1} and 2570 mg COD L^{-1} for water-restricted rural communities in Jordan, while Morel and Diener (2006) reported averages of 225 L p^{-1} d^{-1} and 212 mg COD L^{-1} for an ecological sanitation garden in Malaysia.

Abbreviations: BOD_5, Biochemical Oxygen Demand; C_{in}, Influent Concentration; C_{out}, Effluent Concentration; COD, Chemical Oxygen Demand; DO, Dissolved Oxygen; E, Efficiency; EC, Electrical Conductivity; HLR, Hydraulic Loading Rate; OLR, Organic Loading Rate; *p*, Probability Value; R^2, Coefficient of Determination; SS, Suspended Solids; SU, Standard Unit; AMRT, Apparent minimal residence time; Tot-N, Total Nitrogen; Tot-P, Total Phosphorus; ΔHLR, Change in Hydraulic Loading Rate; ΔOLR, Change in Organic Loading Rate.

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Filter systems are a commonly used option for on-site wastewater treatment. Conditions with fluctuating hydraulic and organic loads under peak conditions can lead to a temporary break-down of the filter system, so-called episodic failure (Beal et al., 2008). High hydraulic loads increase the infiltration rate and thereby reduce the exchanges between mobile water in macropores and water retained in micropores (Boller et al., 1993). Low hydraulic loads, on the other hand, result in greater relative exchange between the mobile and retained water (Stevik et al., 1999) and thus prolong the residence time (Rodgers et al., 2005). Increased contact time of the water with the active biofilm allows for more efficient reduction of pollutants. When the flux of organic matter to the biofilm increases, the biological activity of the microorganisms is stimulated (Wilson et al., 2011) and thereby also the mineralisation rate of organic matter (Wijeyekoon et al., 2004). However, under high organic loads, a dense biofilm can develop and restrict the flux of substrate into the interior of the biofilm (Wijeyekoon et al., 2004). This results in microbial starvation and lost areas of microbial activity, leading to partial biofilm detachment and, consequently, emission of pollutants (Li et al., 2011).

The capacity of filters to remove pollutants differs between materials due to different characteristics such as porosity, specific surface area and reactivity, adsorption capacity and ability to promote biofilm development (Rolland et al., 2009). To avoid clogging or breakthrough conditions, it is necessary to balance the hydraulic and organic loading against the material properties (Torrens et al., 2009). This requires knowledge about the capacity of the particular filter material to buffer high variations in water flow and organic loading.

Soil and sand are perhaps the most commonly used filter materials for greywater treatment. Bark and charcoal are receiving increasing attention as filter media because of their light weight, large specific and active surface, high porosity and high carbon content (Dalahmeh et al., 2012). The possibility of recycling spent bark and charcoal as a soil conditioner or disposing of these materials by incineration adds value to their use as filter media. In previous studies we showed that the organic nature and active surface of bark and the large specific surface of charcoal provide high capacity for the removal of organic matter by adsorption (Dalahmeh et al., 2012) and by biofilm (Dalahmeh et al., submitted for publication). Moreover, bark filters can achieve 2–3 log reductions in enterohaemorrhagic *Escherichia coli* and bacteriophage PhiX (Lalander et al., 2013), making pine bark a good medium for hygenisation of greywater. Studies on the performance of sand and soil filters are extensive and describe not only steady state conditions but also changing conditions, as well as overloading events (Coetzee et al., 2011; Hatt et al., 2007; Healy et al., 2007; Suschka, 1987). In contrast, only limited knowledge is available on the performance of bark and charcoal filters in greywater treatment in response to changing hydraulic and organic loading regimes.

The overall aim of the present study was to describe and evaluate the performance of bark, activated charcoal and sand filters subjected to a series of variable loading regimes with synthetic greywater. The capacity of the filter materials in terms of dynamics of organic matter and phosphate reduction and nitrogen transformation in synthetic greywater was investigated under three different hydraulic loadings with constant organic loading rate and three different organic loadings with constant hydraulic rate. Based on the results from a previous study on the performance of bark and charcoal in greywater treatment at constant hydraulic and organic loading rates, our starting hypotheses were that: charcoal and bark filters can cope with high and fluctuating organic loads due to their high porosity and specific surface; bark performs less efficiently with high hydraulic loading due to the degradability of the bark material; and sand filters are less efficient due to their low porosity and specific surface.

2. Materials and methods

2.1. Filter materials

The three filter materials pine bark (bark), activated charcoal (charcoal) and sand were each manually packed to a depth of 60 cm in two replicate acrylic columns with diameter 20 cm. The columns were then covered with black plastic to prevent penetration of sunlight. The filter materials were sieved to give different size fractions and then mixed to give an effective size of 1.4 mm and a uniformity coefficient of 2.2. The particle size distribution was analysed according to ASTM (1998). Specific filter surface area was determined according to Brunauer et al., (1938) and was 0.73 $m^2 g^{-1}$ for bark, >1000 $m^2 g^{-1}$ for charcoal and 0.14 $m^2 g^{-1}$ for sand. Constant head hydraulic conductivity was determined according to Jacob and Clarke Topp (2002) and was 330, 500 and 360 cm h^{-1} for bark, charcoal and sand filters, respectively. The initial porosity of the filters was 73, 85 and 34%, respectively, according to data taken from Dalahmeh et al. (2012). Apparent minimal residence time (AMRT), measured as the time lapse between the greywater dosage and the first outflow from the filters, was determined repeatedly throughout the experiment.

2.2. Feed characteristics and loading regimes

The bark, charcoal and sand filters were fed with synthetic greywater prepared by dissolving: 125 g standard nutrient broth (Oxiod, Sollentuna, Sweden); 16 g YES washing-up gel (Procter and Gamble, Stockholm, Sweden); 16 g washing powder (Ariel, Procter and Gamble, Geneva, Switzerland); 16 g hair shampoo (VO5, Upplands Väsby, Sweden); 10 g maize oil (El Nada, Al-Asher for products, 10th Ramadan City, Egypt) and 4% (v/v) wastewater from primary sedimentation effluent at the Kungsängen municipal sewage treatment plant (Uppsala, Sweden) in 25, 50, 100, 200, and 400 L of tap water. This yielded greywater BOD_5 values ranging from 2400 to 125 mg L^{-1}. The synthetic greywater was prepared once a week and stored refrigerated at 2–4 °C. The composition of the synthetic greywater covered a wide range of organic matter, nitrogen, phosphorus and microbial contamination found in natural greywater in different scenarios, e.g. low (Bongumusa et al., 2007; Halalsheh et al., 2008) medium (Morel and Diener, 2006) and high water consumption settings (Vinnerås et al., 2006). The levels of phosphorus in the synthetic greywater are similar to those found in greywater produced in countries where most detergents contain phosphorus (Halalsheh et al., 2008). The HLR was set to 32–128 L m^{-2} day^{-1} based on US EPA guidelines for sand filters (US EPA, 2002).

Greywater was pumped intermittently into the filters three times a day, at 9.00, 16.00 and 20.00 h, in amounts representing 70, 10 and 20% of the total daily load, respectively, based on a hydrograph for greywater generation in a typical household in a rural community in Jordan (Ghunmi et al., 2008). The synthetic greywater was sprayed as close to the top surface of the filters as possible to minimise potential wall flow. The top surface was covered by a 3-cm layer of gravel to evenly distribute the water. The temperature of the greywater used was approximately 25 °C and the ambient air temperature surrounding the filters was 27 ± 4 °C.

During the 150-day experiment, the hydraulic loading rate (HLR) and the organic loading rate (OLR) were varied periodically every 3 weeks (Table 1 and Fig. 1) except in the first run, which lasted for 24 days. In a previous experiment using the same filters, it was found that they reached steady state operation in terms of BOD_5 reduction after 3 weeks at 25 ± 4 °C ambient temperature.

The experiment was divided into two trials; the first with successively increasing HLR (Trial 1) and the second with successively