Ecological Engineering 102 (2017) 625–635

Contents lists available at ScienceDirect

Ecological Engineering

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

Green walls for greywater reuse: Understanding the role of media on pollutant removal

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ARTICLE INFO

Article history:
Received 16 November 2016
Received in revised form 15 February 2017
Accepted 18 February 2017
Available online 10 March 2017

Keywords:
Green infrastructure
Green walls
Greywater
Reuse
Filter media
Removal processes

ABSTRACT

Green walls offer multiple benefits to urban environments, but they are major water consumers and not optimal for use in dry climates. If green walls were engineered to treat greywater, they could become cost-effective and more widespread. However, it is not clear what impact watering green walls with greywater has on the life cycle of plants and media types, so each element needs to be assessed and optimised. This work presents the first step, by testing a range of potentially suitable media: (1) hydraulically slow coir, rockwool and fyto-foam, and (2) hydraulically fast perlite, vermiculite, growstone, expended clay and river sand. An unvegetated column experiment was conducted over two months with accelerated greywater dosing to assess the hydraulic and pollutant removal performance. The two best performing media were then further tested to identify the underlying pollutant removal processes. *Slow* media showed higher and more consistent pollutant removal performance than *Fast* media, averaging around 90%, 50%, 30%, 70% and 80% removal of total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD) and *Escherichia coli* (*E. coli*) respectively . However, *Slow* media were prone to clogging and therefore unsuitable as the sole media in greywater green walls. *Fast* media exhibited on average around 80%, 30%, 15%, 30% and 20% of TSS, TN, TP, COD and *E. coli* removal respectively, with no measurable clogging issues. Perlite was found to have the best hydraulic and treatment performance among the *Fast* media while coco coir was the best *Slow* media. Biological processes were found to be the dominant mechanism for nitrogen and COD removal in coir, which provided sufficient retention time for denitrification processes. For perlite, with lower retention times, physico-chemical processes dominated removal, showing the importance of media properties. Biological processes significantly contributed to TP removal in all tested media types. This study shows a significant difference in the processes that govern the pollutant removal performance of coir and perlite media and suggests that a combination of both might prove to be the best option for their optimal application in green walls for greywater reuse systems.

1. Introduction

Greywater recycling and reuse is becoming an increasingly popular practice in developed countries with rising concerns over fresh water availability, both now and into the future (Nolde, 2000; Pinto and Maheshwari, 2010; Gross et al., 2015). Although different greywater treatment systems are in use (Li et al., 2009), green, vegetated treatment infrastructure is still considered to be one of the most environmentally friendly and inexpensive solutions for treatment of greywater and wastewater (Boyjoo et al., 2013; Vymazal, 2005). To date, research on vegetated greywater treatment systems has focused on constructed wetlands (e.g. Gross et al., 2007a; Paulo et al., 2013) and it has generally been reported that, if well maintained, consistent and high removal rates of a range of pollutants can be expected thus opening possibilities for low cost greywater reuse, with minimal investment in small scale disinfection unit (Gross et al., 2007b). The major limitation of current green treatment technologies is that these systems require significant horizontal space (such is the case with constructed wetlands; e.g. Akratos and Tsihrintzis, 2007; Melbourne Water, 2013), which is rarely available in dense urban environments. Another limita-

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http://dx.doi.org/10.1016/j.ecoleng.2017.02.045
0925-8574/

tion is that the choice of appropriate vegetation for these systems is limited and may not complement surrounding aesthetics.

Green walls, or vegetated walls, represent one of the green technologies that do not require much (or any) space, and are currently used mainly for increasing amenity of urban spaces and temperature control of residential and office buildings (Perini et al., 2011). Green walls are a solution made out of plants grown in media filled planter boxes, suspended on a side of buildings. In addition to providing effective thermal insulation and energy savings for the buildings (Pérez et al., 2014; Jim and He, 2011), green walls offer other benefits such as increased liveability and noise mitigation (Perini and Rosasco, 2013; Azkorra et al., 2015). However, all these benefits are outweighed by their high construction and maintenance costs (Perini and Rosasco, 2013). Green walls also have high water demand, consuming 0.5–20 L/m^2 of potable water per day (DEPI, 2014). This is a major concern given that these systems are most effective in arid climates where these water demands are less likely to be met.

Although green walls are becoming increasingly popular, since they provide multiple benefits, they are still to be fully developed as effective wastewater treatment systems. Kew et al. (2009) trialled the use of stormwater as an alternative source of water to irrigate green walls, but the irregularity of its generation and subsequent need for storage were found to be significant operational challenges. Greywater is a more promising candidate given its consistent production and high levels of nutrients to support healthy plant growth. Greywater production in excess of the green wall's irrigation demands could also be treated by these systems, providing an alternative water source for toilet flushing and irrigation of surrounding landscapes. This approach would transform green walls from water consumers to water producers, offering another benefit to outweigh their costs. Although this concept has been put forward by a few product developers (e.g. Gunther, 2013), there is a limited number of published studies on design, operations and governing processes in such systems. Masi et al. (2016) is a rare study that examined performance of green wall for greywater recycling and reuse. Green wall systems used in this study consisted of pots filled with a mix of light expanded clay aggregates (LECA) with coco coir and LECA with sand which were planted with five different plant species, and irrigated by office building greywater. Although this study found the effluent from the system complied with standards for land irrigation and toilet flushing (with UV disinfection) in India, it is not clear whether greywater treatment was primarily attributed to plants or the media in the system. It is also unclear how these media mixes would perform under varying greywater loading and drying conditions, and what underlying processes were driving pollutant removal throughout experimental phase.

A review of the grey literature revealed a few attempts to develop green walls for greywater treatment (Bussy, 2009). However, these studies have relied on black-box experiments, not examining processes within the systems, or how to enhance them. It is therefore necessary to understand the role of each green wall element in greywater treatment and pollutant capture, including media, plants and structural design, so that optimal treatment systems can be produced.

Studies of other vegetated filtration systems such as biofilters have demonstrated that media plays a critical role as it provides the physical support for plants and facilitates the primary removal processes for pollutants such as sediment, phosphorus and heavy metals (see, for example, Bratieres et al., 2008). Although biofilters have previously been designed to treat greywater (Fowdar et al., 2017), media used in these systems, such as sand and gravel, is different from media found in green walls. Due to their vertical position on the wall, in order to reduce the load on their supporting structures, green walls require lightweight media. Additionally, biofilters are usually constructed with a saturated zone at the bottom of the filter increasing water retention time, allowing plants more contact time with water and creating a pollutant buffer (Fowdar et al., 2017). This design feature is hard to implement on vertical structures such as green walls, due to weight increase caused by stored water in the saturated zone. This change causes different pollutant removal mechanisms to be dominant in greywater biofilters and green walls.

Similarly to green walls, vegetated green roof systems are usually constructed using lightweight media due to their limitation in weight (Oberndorfer et al., 2007). However, greywater treatment has never been trialled on lightweight green roofs, and it is not clear how pollutants from greywater would affect their media. Additionally, fertilisers are commonly used on green roof systems causing pollutants to leach, making them ineffective water treatment systems (Oberndorfer et al., 2007; Gregoire and Clausen, 2011).

Lightweight materials such as perlite, vermiculite, coir, rockwool, foam, and potting soil are commercially used for green wall construction. Water and air retention capacities and most physical properties of these media types are well understood (Papadopoulos et al., 2008; Londra, 2010). However, commercial green wall systems are not used for greywater treatment and the effect of greywater on these materials and their pollutant removal performance is not clear. Perlite and coir have been successfully trialled for removal of metals (Shukla et al., 2009), dyes (Vijayakumar et al., 2012), suspended solids (Todt et al., 2014), but no research has given in-depth analysis of their ability to remove nutrients from domestic greywater. Masi et al. (2016) examined the effects of coir mixed with expanded clay, demonstrating that coir had significant impact on pollutant removal from greywater, but it was not shown how coir would perform as a sole media in green wall. Nilsson et al. (2013) showed the potential of two engineered mineral-based materials that are very similar to perlite in removing nitrogen, phosphorus and bacteria from blackwater, but because of the engineered nature of materials, they are expensive and not commonly available. Pumice stone and kanuma soil could be potential candidates for green wall media because of their good performance in phosphorus (Karimaian et al., 2013) and metal removal (Bhakta and Munekage, 2012), as well as overall removal of pollutants from domestic wastewater sources (Itayama et al., 2006). In summary, for all of these commonly used lightweight materials, there is a paucity of knowledge regarding their capacity for nutrient, chemical oxygen demand (COD) and microorganism uptake, the processes governing the removal of a wider range of pollutants, or their ability to cope with the flow dynamics of greywater.

The overall aim of this research is to develop green walls for greywater treatment based on the principles of other vegetated treatment technologies that will be both cost effective and able to provide multiple other benefits. This paper reports on the first stage of the research which aimed to (1) identify suitable media that can provide the physical support for plants and contributes significantly to pollutant removal, and (2) understand the processes governing pollutant removal of these media. Recommendations are then made for optimal media use in greywater green walls.

2. Materials and methods

Two separate laboratory-scale experiments were conducted to (1) identify the optimal media for use in greywater recycling green walls and (2) understand their driving pollutant removal mechanisms. The first experiment compared the pollutant removal and infiltration capacities of eight different potential green wall media using a one-dimensional column study. The second column study was designed to identify the underlying processes governing pollutant removal by the two most promising media identified in the first experiment. Results from both experiments were combined