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Assessment of greywater quality and performance of a pilot-scale decentralised hybrid rainwater-greywater system

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ABSTRACT

Decentralised hybrid rainwater-greywater systems can switch between climate-independent greywater during dry seasons or climate-dependent rainwater during monsoon seasons, resulting in higher water savings than either rainwater harvesting or greywater recycling systems alone. However, hybrid systems are not widely adopted due to a lack of data on untreated rainwater and greywater quality and a paucity of case studies on pilot-scale systems. This study aimed to monitor untreated greywater quality from two full-scale greywater recycling systems and to assess the performance of a decentralised hybrid rainwater-greywater treatment system operating on a pilot-scale under controlled conditions. Both mixed greywaters sourced from washbasins and ablution activities, and from washbasins, showers, baths, and laundry discharges must be treated prior to reuse: untreated greywater was frequently contaminated with faeces (20/32 samples tested positive for *Escherichia coli*), and exceeded the allowable Malaysian limits for both recreational waters with body contact (Class IIB) and irrigation waters (Class IV) for total coliforms (27/32), biochemical oxygen demand (BOD_5) (19/32), chemical oxygen demand (COD) (12/32), colour (8/32), turbidity (24/32), ammonia (NH_3-N) (16/32), phosphates (PO_4-P) (28/32), and manganese (Mn) (4/14). Principal component analysis yielded 4 principal components: organic matter from food and body residues; detergents; faecal contamination; and ammonium salts. The pilot-scale hybrid treatment system featured a multimedia filter (MMF), a granular activated carbon filter (GAC), and ozone disinfection. A hydraulic loading rate of 10 L/min produced the highest overall removal efficiencies as longer retention times allowed more pollutant adsorption. Overall, the pilot-scale system removed 52% COD, 53% BOD_5, 14% NH_3-N, 67% PO_4-P, 81% colour, 81% turbidity, 50% total suspended solids (TSS), 53% of total coliforms, 63% copper (Cu), and 29% zinc (Zn) from greywater sourced from a mixture of showers/baths and laundry. The GAC was the most effective at removing COD, colour, turbidity, and Zn. Finally, a series of dilution experiments of greywater with rainwater and mains water was conducted to emulate real scenarios during the practical implementation of hybrid systems with mains water top-up. Greywater dilution had little impact on removal efficiency of colour, turbidity, TSS, and TDS, and dilution of greywater with either mains water or rainwater is recommended to ensure that pH, BOD_5, COD, NH_3-N, and PO_4-P are within Class IIB limits.

1. Introduction

The onset of water scarcity has driven diversification of available water sources forward, particularly in densely populated urban areas. Both roof-harvested rainwater and recycled greywater are promising substitutes for high quality mains water for non-potable applications such as toilet flushing and irrigation (Ghisi and Ferreira, 2007). Rainwater is rainfall precipitation collected from roofs (Huston et al., 2009), whereas greywater is domestic wastewater collected from washbasins, showers and/or baths, and washing machines (Eriksson et al., 2002).

Rainwater harvesting and greywater recycling systems are

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typically installed separately at the risk of increased capital costs: Ghisi and Ferreira (2007) estimated rainwater harvesting and greywater recycling systems to cost USD 1224 each to form a total of USD 2448 collectively for both systems, while a hybrid rainwater-greywater system only costs USD 1,929, which is a 21% cost reduction. Moreover, installing either rainwater harvesting or greywater recycling system constrains the maximum water savings achievable. For example, in highly urbanised areas with arid climates, both multi-storey commercial buildings and domestic households cannot maximise water savings by recycling rainwater alone as rainwater quantities are limited by inconsistent rainfall precipitation and small roof areas. On the other hand, unlike rainwater harvesting systems, greywater recycling systems are climate-independent, and generate a consistent supply of low quality greywater for non-potable reuse all-year-round. However, the water savings from recycling greywater is limited in buildings that are infrequently occupied: domestic households save more water when recycling rainwater as opposed to greywater (Ghisi and Mengotti de Oliveira, 2007). A hybrid rainwater-greywater system is proposed to reduce the dependence of water savings on building occupancy, roof areas, and climate, and to normalise the inconsistencies in rainwater quantity while simultaneously improving greywater quality. Rainwater or greywater can be used in lieu of high-quality mains water top-up in a hybrid system to ensure that water demand is always met. Hybrid rainwater-greywater systems are climate-independent, and may utilise either rainwater during the monsoon seasons or greywater during the dry seasons (Loux et al., 2012), and subsequently feature higher water savings than rainwater harvesting or greywater recycling alone (Leong et al., 2017b). Additionally, hybrid systems simultaneously manage stormwater at the source by reducing surface runoff and flooding risks through capturing rainwater (Kim and Yoo, 2009) in addition to concentrating pollutants in domestic wastewater sent to centralised wastewater treatment plants (Penn et al., 2013).

Despite these advantages, the widespread adoption of hybrid systems is hampered by poor public perception of greywater quality and a lack of existing pilot-scale systems to provide confidence on recycled water quality (Domènech and Saurí, 2010). Data on the physicochemical and microbiological characteristics of untreated and treated greywater is necessary to facilitate health risk assessments and widespread adoption of decentralised greywater recycling systems. Past studies on the physico-chemical (Friedler, 2004) and microbiological (Birks and Hills, 2007) characteristics of greywater have been limited to Europe, presenting a knowledge gap as few studies have been conducted in Asia although greywater varies with inhabitant lifestyles cultures and greywater sources (Friedler, 2004). Similarly, there is limited literature on pilot-scale systems which recycle and reuse rainwater and greywater at the pilot-scale. Lin et al. (2005) utilised a pilot-scale electrocoagulation and flotation treatment train to reclaim 28 m^3/day of greywater. Friedler et al. (2006) compared the performance of three parallel treatment systems in a pilot-scale system treating light greywater from showers and baths, and found that both RBCs and MBRs are viable options for on-site greywater treatment. Mendez et al. (2011) compared roof runoff quality from pilot-scale and full-scale roofs, and concluded that harvested rainwater required first-flush diversion, filtration, and disinfection. Santos et al. (2012) utilised a coarse filter and UV disinfection to treat light greywater from washbasins and showers, and recommended addition of coagulants to remove dissolved and colloidal BOD. Similarly, Oh et al. (2015) utilised a sand filter-activated carbon-ozonation pilot-scale system to treat light greywater. However, no study has examined the effect of combining rainwater with greywater in a storage tank prior to treatment, and their effects on the removal efficiency of the hybrid treatment system and subsequent effluent quality. This presents a knowledge gap as a full-scale hybrid rainwater-greywater treatment system may dilute treated greywater with rainwater instead of high quality mains top-up water to maximise mains water savings, help the final effluent meet urban reuse water quality standards, and ensure that end-use appliances connected to the effluent storage tank supplies enough water to fulfil building water demand.

This study is an extension of a previous longitudinal rainwater quality monitoring survey on six full-scale rainwater harvesting systems in Malaysia (Leong et al., 2017a). The objectives of this study were to: (i) monitor the physico-chemical and microbiological quality of real untreated greywater from two full-scale greywater recycling systems in Malaysia; (ii) evaluate and optimise the performance of a decentralised hybrid pilot-scale rainwater-greywater treatment system; and (iii) compare effluent quality to existing Malaysian water quality standards for recreational waters with body contact (Class IIB) and irrigation waters (Class IV).

2. Materials and methods

2.1. Greywater sampling

Only 2 full-scale greywater recycling systems were selected for monitoring in the state of Selangor, Malaysia to provide data for untreated real greywater as greywater recycling systems are scarce in Malaysia. Fig. 1 illustrates the geographical location of both sites, and Table 1 summarises the site characteristics. Site 1 is a commercial site that generates mixed greywater from washbasins in bathrooms and ablution activities, whereas Site 2 is a domestic site that generates mixed greywater from washbasins in bathrooms, showers and/or baths, and laundry discharges.

Prior to sample collection, all glass bottles were washed and autoclaved at 120 °C for 15 min. Grab samples of untreated greywater were collected with 500 mL Duran glass bottles from on-site greywater storage tanks at both Sites 1 and 2. The 500 mL glass bottles were submerged into the centre of the greywater storage tanks to obtain a sample of the greywater concentration at both the top and bottom of the storage tanks. Samples were collected at a bimonthly interval from November 2014–June 2015 (8 months), although heavy metals were only tested on the April–June 2015 samples due to funding limitations. Samples were transported to the laboratory within 6 h, and stored at 4 °C until analysis. Microbiological analysis was conducted within 24 h, and the other parameters within 48 h. 16 samples were collected and analysed from each site, forming a total of 32 samples.

2.2. Hybrid pilot-scale treatment system

The hybrid pilot-scale treatment system consists of an influent polyvinyl chloride (PVC) storage tank, a multi-media filter (MMF) or sand filter, a granular activated carbon (GAC) filter, an in-line ozone injection system, two centrifugal pumps, and an effluent PVC storage tank. Fig. 2 illustrates the two main modes of operation investigated in the hybrid rainwater-greywater pilot-scale treatment system: single-pass and recirculation. Table 2 summarises equipment characteristics.

Untreated greywater was sourced from a mixture of showers, baths, and laundry discharges from a third site: an industrial office building located at coordinates 3.0692105, 101.5965965. Greywater was transported by lorry and pumped into the 1.3 m^3 polyvinyl chloride (PVC) influent storage tank situated in Monash University Malaysia, similar to the procedures described by Oh et al. (2015), and volumetric ratios were adjusted by draining the tank as necessary. On the other hand, a rainwater tank was installed onsite