Experiences on the implementation of a pilot grey water treatment and reuse based system at a household in the slum of Kyebando-Kisalosalo, Kampala

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ABSTRACT

Grey water constitutes the largest fraction of domestic wastewater. It causes environmental sanitation and pollution problems if it is not managed well. If treated, grey water can be a resource for a variety of uses. A pilot system was constructed in February 2013 to treat grey water from a four-member household for sub-surface irrigation of local vegetables. A hydraulic loading rate (HLR) of 60 L m\(^{-2}\) d\(^{-1}\) and an organic loading rate (OLR) of 519–1,580 g BOD\(_5\) m\(^{-2}\) d\(^{-1}\) were implemented on a multi-media filter of gravel, charcoal, geotextile and mulch (charcoal being the predominant layer) operated as a batched type-system, with a 36-hour retention time. The system was operated for 3 months, during which it showed remarkable removal efficiencies of 90.8 ± 5.4 and 96.1 ± 3.0% after 36 hours for chemical oxygen demand (COD) and biochemical oxygen demand (BOD), respectively, and 95 ± 3.1% for faecal coliforms (FC). The removal efficiencies at 36 hours, of total nitrogen (TN), total phosphorus (Tot-P), total suspended solids (TSS) and total dissolved solids (TDS) were 39.0, 30.1, 85.2 and 78.6%, respectively. Plant response to sub-surface irrigation with treated grey water was largely masked by rainy season and the effluent had a limited effect on the soil.

Key words | grey water, household, reuse, sub-surface irrigation, treatment

INTRODUCTION

Grey water refers to wastewater from laundry, bathtubs, showers, kitchen sinks and washing dishes (Eriksson et al. 2002). Grey water comprises 50–80% of the total residential wastewater generated (Al-Jayyousi 2005). Grey water usually receives the least attention compared to other environmental aspects like solid waste and black water, particularly in low- and medium-income counties where it is often discharged untreated into storm water drains and, if they exist, sewers (Morel & Diener 2006). Globally, the use of treated wastewater and grey water is emerging as an integral part of water demand management, promoting preservation of high quality fresh water as well as reducing pollutants in the environment and overall supply costs (Lu & Leung 2003). In the wake of growing pressure on fresh water resources around the world, and increasingly scarce, expensive and/or politically controversial new supply (Allen et al. 2010), efforts are underway to identify new ways of meeting water needs. The use of treated grey water is straightforward for non-potable uses, thereby replacing and thus reducing the demand for potable water. In Jordan, water resources are characterized by scarcity, variability and uncertainty, creating the need to reuse/recycle wastewater (Al-Jayyousi 2002). Grey water use is not limited to countries with a dry climate such as Jordan. In the Mediterranean region and European countries, the use of recycled water has also increased. Use of treated grey water is among the potential alternative sources of water, although previously considered unusable, an attractive addition to water-management options, for example, irrigation (Gross et al. 2008; Allen et al. 2010).
Urbanization in many developing cities, for instance Kampala, is virtually synonymous with the formation of dense human settlements; often inhabited by low-income earners who lack or have inadequate sanitation, lack safe drinking water and live in degraded environments (Kulabako et al. 2009). Kyebando-Kisalosalo Zone is a peri-urban area in Kampala with a population of about 25,000 residents. Grey water in the area is discharged into poorly developed earth drains, undeveloped plots of land or onto open surfaces. In large quantities, the grey water ponds cause odour nuisance, unpleasant aesthetic appearance and potential public health risks.

There is insufficient literature and experience regarding the practical applications of treating and using grey water in developing countries, especially when linked to urban agriculture. Yet, urban agriculture plays an important role in the survival of residents in low-income communities in developing countries. Experiences of the treatment and use of grey water in urban agriculture are needed to support future scaling up of such interventions. The objective of this study, therefore, was to assess existing grey water management practices, determine the quantity and quality of grey water produced in Kyebando-Kisalosalo and design and construct a household grey water management system as well as monitor its performance.

MATERIALS AND METHODS

Household interviews, focus group discussions and key informant interviews

A household survey was conducted to assess the existing grey water management practices in the slum zone of Kyebando-Kisalosalo in Kawempe Division, Kampala City. During the household surveys, questionnaires were administered at the household on a one-to-one basis, by interviewing the respondent and registering their responses on a structured questionnaire. The household questionnaires were designed to collect information on the household structure, socio-economic status, water sources and water use, water consumption, grey water and sanitation practices and current grey water reuse activities, in the cases where they existed.

The sample size for the household interviews was determined using Neyman’s equation:

\[
\text{Sample size, } n = \frac{N}{1 + Ne^2}
\]  

(1)

Based on the local council (LC) data, population (N) was 25,000 people. From Equation (1), \( e \) is the 95% confidence level, equal to 0.0395. The sample size \( n \) was calculated according to Equation (1). An average of four persons per household was adopted, thereby giving the total number of questionnaires to be administered to the study area as 150 questionnaires (one questionnaire per household).

For each of the five cells (A to E) in Kyebando-Kisalosalo Zone, 30 questionnaires were administered. Using village leaders, households with different socio-economic status were selected in order to obtain information representative of the entire slum of Kyebando-Kisalosalo. Village leaders were used to give an estimation of the population in the study area; they also acted as guides while distributing the questionnaire. Housing was used as a proxy for socio-economic status, with people in poor houses considered to be poor, those in medium quality houses considered to be middle income and those in good houses were considered to have a relatively higher income. Houses with temporary walls made of mud and wattle, roof comprising old iron sheet often with rags and stones to support old sheets and rags from being blown off by the wind were considered poor. Houses with semi-permanent walls made of brick and cement, but walls not plastered and iron sheet roof with roofing iron nails intact were considered to be of medium quality. Houses with permanent walls made of bricks and plastered/painted walls, roof of iron sheet or clay tiles in good condition were considered to be good.

One focus group discussion (FGD) was conducted with six women and four men, who were randomly selected with every two women and two men coming from a different cell, and from households with varying socio-economic status. Key informant interviews (KIIs) were also conducted in the study area. These supplemented the quantitative data and yielded qualitative information that was used to understand practices of grey water disposal problems and factors affecting the quantity, quality and willingness to reuse the grey water.
Quantifying grey water generated

The grey water generated in the study area was collected and poured in buckets calibrated with known volumes. A total of three buckets, one for each stream (kitchen, laundry and bathroom) were distributed to each of the three households. The measurement of the grey water was done consecutively for 5 weeks, on weekdays and weekends inclusive, since laundry activities were largely carried out at weekends. Bathroom grey water posed a challenge to collect, given the open and non-plumbed nature of bathrooms. Calibrated buckets were attached to the outlets where the bathroom grey water flowed, but this was possible only for raised bathrooms as well as those which emptied into drainage channels so that there was space to insert a bucket into which the exiting grey water poured. Most bathrooms were shared among a large number of users. Grey water including that from bathrooms was collected from two of the three households studied.

Selection criteria

Selection and design of a grey water treatment and reuse system was done, based on: (1) space requirements; (2) cost of construction; (3) ease of operation and maintenance; and (4) simplicity and compatibility with housing units in slums. The final selection of households in which to implement a pilot grey water treatment unit took into account the following additional criteria: (5) willingness to reuse treated grey water; (6) socio-economic status; and (7) distribution of adults and children in the household.

Design and implementation

Treatment tank

A hydraulic loading rate (HLR) of 68 L m$^{-2}$ d$^{-1}$ and an organic loading rate (OLR) of 46.7 g 5-day biochemical oxygen demand (BOD$_5$) m$^{-2}$ d$^{-1}$ were used to dimension the grey water pilot unit. Drums that could accommodate this hydraulic loading and organic loading were selected. Since availability of the material locally was paramount, drums of diameter 550 and 600 mm were locally available with a height of 850 and 1,100 mm, respectively. The 600 mm diameter drum was used as the treatment tank. To reduce complexity of the system, no pretreatment unit was utilized. The treatment tank consisted of filter media, geotextile and earthworms, whose placement is described below.

Filter media

Filter materials such as charcoal, sawdust and wood shavings, with lower bulk densities than sand, are readily available as residual waste material in the study area. The following charcoal parameters were adopted: effective grain size $D_{10} = 1.4$ mm and $D_{60} = 3.1$ mm; and a uniformity coefficient ($D_{60}/D_{10}$) of 2.2. Finer charcoal particles were eliminated as they can lead to rapid clogging of the system, whereas larger particles would allow fast flow with less treatment. Sieving of the charcoal was done via 5, 2.8, 1.4 and 1 mm sieves, and the charcoal retained on the 1 and 2.8 mm sieves was mixed together; 40% by weight from the 1 mm sieve and 60% by weight from the 2.8 mm sieve, to obtain the desired effective grain size and uniformity coefficient. A geotextile polymer was applied on top of the charcoal and after that, a mulch layer was placed comprising wood shavings of 80 mm thickness and a 70 mm thickness of gravel passing through a 10 mm sieve but retained on a 5 mm sieve. To this layer, 50 adult earthworms of the species *Lubricina* were applied. Table 1 shows the layer thicknesses and properties of the individual layers, while Figure 1 shows the section through the filter.

Garden

For 60 L household$^{-1}$ d$^{-1}$ of grey water, a garden of 3 m by 2 m was considered suitable. Hydraulic loads typically
range from 2 to 15 L m$^{-2}$ d$^{-1}$ depending on the plant water requirement and the evaporation rate. Too little water stresses the plants and makes them sensitive and can also lead to soil salinization (Ridderstolpe 2004). A hydraulic loading of 10 L m$^{-2}$ d$^{-1}$ was adopted based on the grey water generation rate. For irrigation purposes, the quantity of water needed for the plant growth and the soil type has to be determined, otherwise the grey water may accumulate and leach into the groundwater and subsequently lead to contamination (WHO 2006).

**Perforated distribution pipe**

An unplasticized polyvinylchloride (uPVC) perforated pipe was used for sub-surface irrigation of the grey water garden in both the pilot treatment unit and the control. Pipes of 31.75 mm diameter were laid down in the garden with holes of diameter 3 mm at a spacing of 100 mm. The pipes were 100 mm below the surface to ensure that the grey water was applied directly to the root zone of plants (Bergdolt et al. 2011). Clogging was prevented by the head pressure between the tank and the distribution pipe. Using a tee-shaped vent along the length of the distribution pipe, aeration was provided to prevent foul conditions and gravel was lined along the pipe to prevent clogging by the back-filled soil.

A control unit was set up, consisting only of the tank, in which there was no treatment of grey water. Thus, the grey water in the control entered the sub-surface irrigation system from the tank, without treatment.

**Implementation**

The various steps in the implementation of the grey water treatment unit are presented pictorially in Figure 2.

A tank with a diameter of 600 mm and height of 1,100 mm was used as the treatment tank for the system, and was calibrated at 100 mm intervals. For plumbing works, a pipe was connected as shown in Figures 1 and 2. To prevent possible vandalism, the tank was encased in masonry; however, this would not be necessary in secured areas. In addition to implementation of the grey water treatment system, a control unit was set up. The control unit did not have any filter media. The grey water to be applied to the treatment unit was divided into two parts with one part being applied to the treatment unit and the other part to the control unit. Both systems were connected to, and discharged into, a sub-surface irrigation system in which local vegetables were grown.

**Operation and maintenance**

Grey water generated during a given day was collected into a bucket and fed into the system using a small bucket to ensure uniform distribution of the grey water over the filter media. Grey water was fed into the multi-layer filter system, and percolated through the filter...
material in an unsaturated flow. The pilot and control systems were run as batch systems; freshly collected grey water was poured into the pilot and control once and left in these systems for 36 hours before opening the outlet pipe to the garden. From the literature, retention time for physical systems averaged 16 hours (Li et al. 2013) but those systems were not set up in Africa and their influent grey water was of a slightly better quality than that utilized in this study. In the studies conducted by Li et al. (2009), the concentration of BOD and chemical oxygen demand (COD) were much less as compared to concentrations obtained in this study. Therefore, a higher retention time of 36 hours was chosen in our study. The pilot system was fed with an average of 60 L of grey water per day, an approximate amount that was generated daily at the household considered. Since the control system had a smaller cross-sectional area, the control system received 25–30 L of grey water per day.

Monitoring

Field observations, water sampling and analysis

Field observations on colour and solid particles in the grey water, and plant response were carried out twice every week. Soil sampling and analysis was taken after every 2 weeks. Possible operation challenges such as clogging and odours were also noted. Furthermore, any concerns by the users of the system and recommendations were recorded. Influent and effluent samples were taken from the pilot system over a period of 5 weeks. Influent samples were collected when the system was fed with grey water and effluent samples were
collected after 12, 24 and 36 hours. This means that the grey water was ponding in the system in the first 12 hours, before the effluent water was let out of the system. Parameters analysed were: COD, BOD, pH, total dissolved solids (TDS), total suspended solids (TSS), faecal coliforms (FC), electrical conductivity (EC), total nitrogen (TN), total phosphorus (Tot-P), ortho-phosphorus, ammonium nitrogen (NH4-N) and methyl blue active substances (MBAS). The standard methods of examination were used (APHA/AWWA/WEF 1998).

Soil sampling and analysis

Using an auger, undisturbed soil samples were recovered at a depth of 150 and 300 mm from three locations in the gardens connected to the pilot treatment system and one location in the control. Samples were collected in polythene bags and transported to the soil science laboratory at the College of Agriculture and Environmental Sciences (CAES), Makerere University for analysis within 3 days from collection. The samples were air dried at room temperature rather than sun drying or oven drying in order to prevent evaporation of nutrients especially nitrogen. Samples were collected before and after 4 weeks of feeding grey water into the garden.

The parameters tested were organic carbon (OC), nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), pH and proportion of sand silt and clay in the soil.

To determine the effect of grey water on plant performance, which is defined as plant response to irrigation with grey water, the plants were collected from the pilot and control systems and analysed for moisture content at the laboratory in the College of Agricultural and Environmental Sciences (CAES). The dry weight was determined by drying in an oven at 105 °C overnight.

RESULTS AND DISCUSSION

Interviews regarding sources and quantities of grey water

Three different sources of water were used in the area: 97.3% of the respondents used tap; 2.0% used spring water whereas <1.0% used rainwater. Forty-eight per cent (48.0%) of the respondents reported using four to six jerry cans (each jerry can has a volume of 20 L) of water per day; 35.3% used one to three jerry cans; 8.7% used seven to nine jerry cans and about 8.0% used more than ten jerry cans of water per day. The range of quantities of grey water generated depended on the family size and whether or not laundry was done on that day, just as indicated by Morel & Diener (2006).

Grey water in Kyebando-Kisalosalo Zone was mainly disposed onto the open surface (61.3%) and unlined earth storm water drains (9.3%). Some respondents reported disposing grey water into septic tanks (8.7%) and soak pits (4.7%). Prior information was given, by the interview team, to the respondents on what constitutes a septic tank and a soak pit, and thus, the respondents answered with knowledge. A combination of methods, for example, the soak pits for bathroom wastewater and open surface disposal were also used in the area; these contributed to 16.0% of the disposal methods. Most respondents avoided unsightly conditions caused by disposal of grey water near their dwellings by disposal of the grey water into storm drains.

Respondents reported that their methods of grey water disposal resulted in problems such as odour, vectors and filthy appearance, with 54.7% of the respondents reporting a combination of these problems. Separately, filthy appearance, odours and vectors were reported by 7.3, 3.3 and 0.7% of the 150 respondents, respectively. Quite a high percentage (34%) were comfortable with their disposal methods, reportedly because the disposal methods did not directly affect them.

The percentage of respondents who were willing to use treated grey water was 65.3%, while 20.7% were not willing and 14% could not state whether they were willing to use grey water. From the focus group discussions (FGDs), the people who agreed to use grey water had made their choice hinged on the quality of the water after treatment; the water quality had to be good for them to accept reuse. The focus group was mainly concerned with the color of the grey water after treatment.

Quantity of grey water

Results from quantifying grey water from Kyebando-Kisalosalo revealed that about 42% of the grey water came from laundry, 22% from bathing, 14% from kitchen activities
and the rest from other activities such as cleaning the house floor and windows. On average, the quantity of grey water generated was 65 L per household per day. The quantity of grey water generated varied from the three households, probably due to the different household dynamics and socio-economic status (Lu & Leung 2003; Morel & Diener 2006; Kulabako et al. 2009). Most of the households use four to six jerry cans of 20 L capacity of water per day, which agrees with Kulabako et al. (2010) who estimated that on average a household used four jerry cans (80 L) with a daily per capita use of 16 L.

**Quality of grey water**

The characteristics of grey water for samples taken every week for 5 weeks are shown in Table 2. Grey water is differentiated from black water by the relationship between organic material and nutrients present. Black water has BOD:N:P of 100:20:1 while the ratio obtained for the grey water was 100:1.50:0.52 which did not differ very much from the values of Muellegger et al. (2003) of 100:4:1, meaning the system was operated with grey water with characteristics similar to those found in the literature.

From the start of operation of the grey water treatment system, anaerobic conditions were experienced by production of foul odours before opening the effluent to start flowing out at 12 hours. However upon opening the valve for the effluent to start flowing out into the garden, and with continued operation, the foul odours disappeared.

**Physico-chemical characteristics of the influent**

EC values ranged between 687 and 2,230 μS cm⁻¹ and the pH ranged between 5.43 and 6.65. For irrigation, EC should not exceed 3,000 μS cm⁻¹ (Morel & Diener 2006) and therefore on average the grey water met this requirement very well, even without treatment. The values of EC obtained in this study were within the range of values obtained in a study conducted in Homa Bay where the values varied between 60 and 4,470 μS cm⁻¹ (Kotut et al. 2011). The high values of EC can be attributed to laundry grey water (Kulabako et al. 2009). The mean pH was within the national standards of 6.0–8.0 for disposal of wastewater (NEMA 1999). The low levels of pH, down to 5.43, could be dependent on the source of water and possibly result from dirty dishes being kept overnight and washed in the morning (Kulabako et al. 2010; Kotut et al. 2011).

Varying concentrations of TDS, TSS and TS were obtained in the influent grey water. The mean value of TDS was 768 mg L⁻¹, which was below the discharge standard (1,200 mg L⁻¹) according to NEMA (1999). The mean value of TSS was 5,176 mg L⁻¹, much higher than the required discharge standard of TSS equal to 100 mg L⁻¹ according to NEMA (1999). Therefore, the grey water required treatment before disposal.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean (n = 5)</th>
<th>Std. error (n = 5)</th>
<th>Std. deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD (mg L⁻¹)</td>
<td>5,992</td>
<td>8,658</td>
<td>7,307</td>
<td>493</td>
<td>1,102</td>
</tr>
<tr>
<td>BOD₃ (mg L⁻¹)</td>
<td>2,445</td>
<td>7,442</td>
<td>4,667</td>
<td>983</td>
<td>2,198</td>
</tr>
<tr>
<td>Faecal coliforms (cfu 100 mL⁻¹)</td>
<td>0.0024 × 10⁷</td>
<td>7.56 × 10⁷</td>
<td>4.2 × 10⁷</td>
<td>1.7 × 10⁷</td>
<td>3.79 × 10⁷</td>
</tr>
<tr>
<td>EC (μS cm⁻¹)</td>
<td>687</td>
<td>2,230</td>
<td>1,540</td>
<td>292</td>
<td>652</td>
</tr>
<tr>
<td>pH</td>
<td>5.43</td>
<td>6.65</td>
<td>6.23</td>
<td>0.23</td>
<td>0.51</td>
</tr>
<tr>
<td>Tot-P (mg L⁻¹)</td>
<td>4.3</td>
<td>34.2</td>
<td>24.1</td>
<td>3.5</td>
<td>7.9</td>
</tr>
<tr>
<td>NH₄-N (mg L⁻¹)</td>
<td>4.3</td>
<td>74.7</td>
<td>28.7</td>
<td>12.6</td>
<td>28.1</td>
</tr>
<tr>
<td>TN (mg L⁻¹)</td>
<td>22.0</td>
<td>153.1</td>
<td>69.9</td>
<td>28.7</td>
<td>64.2</td>
</tr>
<tr>
<td>TDS (mg L⁻¹)</td>
<td>342</td>
<td>11,100</td>
<td>769</td>
<td>146</td>
<td>326</td>
</tr>
<tr>
<td>TSS (mg L⁻¹)</td>
<td>1,772</td>
<td>11,100</td>
<td>5,176</td>
<td>1,573</td>
<td>3,518</td>
</tr>
<tr>
<td>TS (mg L⁻¹)</td>
<td>2,872</td>
<td>12,800</td>
<td>6,071</td>
<td>1,746</td>
<td>3,904</td>
</tr>
<tr>
<td>MBAS (mg L⁻¹)</td>
<td>0.52</td>
<td>0.96</td>
<td>0.74</td>
<td>0.22</td>
<td>0.32</td>
</tr>
</tbody>
</table>
The high value of TSS could be due to the presence of food particles in the kitchen grey water and the multiple use of grey water before discharge, for different uses, e.g., laundry and house cleaning could have increased its TSS concentration. Another possible explanation could be from laundry activities which contributed more water than the kitchen water, which has also been reported in the literature (Halalsheh et al. 2008; Gross et al. 2008; Ghuinmi et al. 2011).

The raw (influent) COD and BOD$_5$ values ranged between 5,992 and 8,658 mg L$^{-1}$, and between 2,445 and 7,442 mg L$^{-1}$, respectively, and were well above the discharge standards of 100 and 30 mg L$^{-1}$, respectively (NEMA 1999). This gave the actual organic loading of 519–1,580 g BOD$_5$ m$^{-2}$ d$^{-1}$, compared to the design organic loading of 46.7 g BOD$_5$ m$^{-2}$ d$^{-1}$. The large difference between the actual and the design loading could be attributed to the low per capita consumption, which rendered it necessary for the residents to use the grey water for multiple purposes before disposing of it. The values of COD obtained in this study are comparable to those obtained by Katukiza et al. (2014b), who obtained 9,225 ± 1,200, 71,250 ± 1,011 and 4,675 ± 750 mg L$^{-1}$ of COD in the grey water generated by laundry, in the kitchen and in the bathroom, respectively. The COD/BOD$_5$ ratio was 1.56, which suggested that the grey water might not be easily biodegradable, as wastewater with a COD/BOD$_5$ ratio below 2–2.5 is considered less easily degraded (Morel & Diener 2006). The per capita consumption of water in the area was small (16 L person$^{-1}$ d$^{-1}$), and this gave rise to multiple uses of grey water before discharge. Consequently, the levels of COD and BOD$_5$ increased. Other sources of organic compounds were fats, oils and other substances used for cooking, and residues from soap and detergents (Ridderstolpe 2004). Ghuinmi et al. (2011) in a related study conducted in Jordan attributed the high levels of COD to laundry water, a likely explanation since this fraction was the largest.

The Ortho-P, Tot-P and TN and NH$_4$-N of raw grey water ranged between 3.7 and 19.9 mg L$^{-1}$, 16.4 and 34.2 mg L$^{-1}$, 22.0 and 155.1 mg L$^{-1}$, and 4.3 and 74.7 mg L$^{-1}$, respectively. The values were above the discharge standards for disposal of wastewater. The maximum values for disposal are 10 mg L$^{-1}$ for both Tot-P and TN for disposal according to Uganda Standards (NEMA 1999).

The high values of Ortho-P, Tot-P and TN could well be attributed to the soaps and detergents that are used for softening the water (Ridderstolpe 2004). High levels of TN could also be from kitchen grey water due to the proteins present as suspended material (Del Porto & Steinfield 2000). TN values (22.0–153.1 mg L$^{-1}$) were within the range of 0.6–488 mg L$^{-1}$ reported by Carden et al. (2007), while the values reported by Al-Hamaiedeh & Bino (2010), 38–61 mg L$^{-1}$, overlapped the lower values in this study, but were slightly lower, perhaps due to differences in the source of grey water investigated.

**Surfactants**

The influent concentration of MBAS was 0.74 ± 0.22 mg L$^{-1}$. Surfactants are a major cause of hydrophobicity in the soil (Travis et al. 2010). Since the treated grey water was to be used for irrigation, the concentration of surfactants in the influent had to be determined. The influent concentration of MBAS was less than 10 mg L$^{-1}$, the national discharge standard (NEMA 1999).

The presence of MBAS was mainly attributed to laundry and kitchen activities (Gross et al. 2008; Dalahmeh et al. 2011) since soaps and detergents were used during washing of clothes and dishes. The values obtained were far less than the range of 17–40 mg L$^{-1}$, reported by Morel & Diener (2006). The variation could be due to the socioeconomic status and types of detergents used since the average values reported were for Jordan.

**Microbial characteristics in the influent**

The freshly produced grey water exhibited a range of 0.0024 × 10$^7$ to 7.56 × 10$^7$ cfu (100 mL)$^{-1}$ faecal coliforms with a mean of 4.2 × 10$^7$ cfu (100 mL)$^{-1}$. Katu Katukiza et al. (2014b) measured the highest concentrations of E. coli of 2.05 × 10$^7$ cfu (100 mL)$^{-1}$ and total coliforms of 1.75 × 10$^8$ cfu (100 mL)$^{-1}$ in grey water from the bathroom. These values are compared to those obtained in our study, considering that total coliforms are normally higher in concentration that faecal coliforms. Faecal coliforms were studied as they are an indicator of faecal pollution. Faecal pollution or the presence of faeces, measured by the concentration of faecal coliforms, is the primary source of...
pathogens in grey water (Ridderstolpe 2004). The high variability of faecal coliform counts was due to the different uses of water in the study area. One explanation for the presence of faecal coliforms could be due to the fact that grey water favours their growth (Ottosson & Stenström 2003). Another explanation could be hygiene conditions, variation in water economy, soiled infant clothes, variation in the period in which items being cleaned had been left soaking in the cleaning water and washing of faecally contaminated laundry (Ottosson & Stenström 2003; Ridderstolpe 2004; Kulabako et al. 2009; Kotut et al. 2011).

Effluent quality

Treatment effects on physico-chemical characteristics

The pH in the effluent increased to a range of 5.43–7.34 with a mean of 6.54, 6.99 and 6.96 at 12, 24 and 36 hours, respectively. EC values in the influent (687–2,230 μS cm⁻¹) were lower than the effluent concentrations, with mean values of 2,261.4, 2,376.4 and 2,434.0 μS cm⁻¹ at 12, 24 and 36 hours, respectively. The values obtained for pH and EC of the effluent at the different hours are within the range required by FAO guidelines for slight to moderate restricted irrigation (pH, 6.4–8.4; EC, 700–3,000 μS cm⁻¹) for reuse of grey water for irrigation (Dalahmeh et al. 2014). The increase in EC after the grey water treatment system could be due to conversion of organic nitrogen to mineral nitrogen and organic phosphorus to ortho-phosphorus which is responsible for the conductivity as well as loss of water from the system through evapotranspiration, resulting in an increase in the TDS and dissolved mineral content of the treated grey water (Travis et al. 2010).

Suspended solids

The mean values of TDS obtained were 1,122, 1,181 and 1,218 mg L⁻¹ at 12, 24 and 36 hours, respectively. The average values of TDS in the effluent were below the value quoted in the recommended standards for irrigation (<1,200 mg L⁻¹) according to the Ugandan NEMA (1999). The average TDS concentration in the effluent was higher than that in the influent with increases of 68.5, 78.6 and 85.7% at 12, 24 and 36 hours, respectively. The removal efficiency of TDS reduced with time (Table 3). The large variability in TDS between the time intervals in Table 3 could be because grey water contains a great deal of detergents which have salts and bulking agents. When the grey water degrades, the salts disintegrate and are released leading to higher concentrations than inflow.

The mean values of TSS in the effluent obtained were 1,596, 1,150 and 1,127 mg L⁻¹ at 12, 24 and 36 hours, respectively. The average values for TSS were thus far above 100 mg L⁻¹, the discharge standards for wastewater in Uganda (NEMA 1999). The average removal efficiency for TSS was 76.1, 85.2 and 86.7% at 12, 24 and 36 hours, respectively (Table 3). It can be noted that the efficiency to remove suspended solids increased with the maturity of the system. The efficiency of removal of suspended solids was initially low, since pores had not been filled, and thus

<table>
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<th>12 Hours</th>
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<th>36 Hours</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>–68.5</td>
<td>91.0</td>
<td>–78.6</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>76.1</td>
<td>16.0</td>
<td>85.2</td>
</tr>
<tr>
<td>TS (mg/L)</td>
<td>56.6</td>
<td>14.2</td>
<td>62.7</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>73.0</td>
<td>25.4</td>
<td>89.6</td>
</tr>
<tr>
<td>BOD₅ (mg/L)</td>
<td>65.6</td>
<td>25.1</td>
<td>92.3</td>
</tr>
<tr>
<td>FC (cfu 100 mL)</td>
<td>43.3</td>
<td>42.0</td>
<td>92.5</td>
</tr>
</tbody>
</table>
once the pores were filled, removal efficiency increased. The geotextile had mulch above it, therefore it was not possible to observe build-up of solids on the geotextile.

The suspended matter was removed by the mulch, geotextile membrane and filter material though straining and adsorption of the solid particles (Ridderstolpe 2007). The removal efficiencies with respect to suspended matter in grey water treatment units can be 62% for mulch, 56% for small scale grey water treatment techniques and 65–85% for vertical flow filters, respectively (Morel & Diener 2006; Pidou et al. 2007; Dalahmeh et al. 2011). Therefore, the removal efficiency of suspended matter was according to the available literature, even though it was below 99% for stratified sand filters (Healy et al. 2007).

**Removal of organic matter**

The high level of BOD$_5$ (519–1,580 m$^{-2}$d$^{-1}$) when discharged in water can cause the dissolved oxygen content to reduce which may have devastating effects on the aquatic ecology and quality of underlying grey water.

COD and BOD$_5$ in the effluent were compared with those of the influent to determine the efficiency of the system in removing organic matter. The removal efficiencies were high (Table 3) for COD and BOD$_5$ at 12, 24 and 36 hours, respectively. The removal efficiencies were as high as reported in the literature. In studies treating grey water with crushed lava rock as the filter medium, Katukiza et al. (2014a) achieved 85.9% removal efficiencies of COD when operating under a varying HLR and 90.5% when operating at a constant HLR regime. Table 3 shows a large variability of percentage removal of COD and BOD$_5$, especially after 12 hours. The first week and third week showed the largest variability in treatment removal efficiency and this happened when organic matter had begun to decompose. However, the 600 mm biochar layer beneath the mulch has the ability to buffer the variability due to organic matter release from the mulch. The removal of COD and BOD was lowest at 12 hours (Table 3), probably because when the grey water is poured all at once over the surface of the filter, there is a risk that some biofilm will slough and some solids will be re-suspended, needing time to stabilize. The BOD$_5$ and COD concentrations’ decrease correlated with the decrease in suspended solids thus implying that significant high values of COD and BOD were mainly from the suspended matter.

Large reductions of COD and BOD$_5$ could be due to adsorption of organic matter on the filter media and biological degradation of proteins, fats and carbohydrates and conversion to humic material (Ridderstolpe 2007; Berger 2012). In addition, organic matter reduction could be as a result of the earthworms that were in the system. COD removal efficiency of 92.3 ± 2.1% was less than 99% for biochar and sand filters according to Berger (2002) and Healy et al. (2007). The inability of the system to achieve high efficiencies could be because of the high concentration of COD that was fed into the system, 7,307 mg L$^{-1}$ on average, while Berger (2002) fed a COD range of 100–500 mg L$^{-1}$ and Healy et al. (2007) fed 3,261–7,322 mg L$^{-1}$. The removal is however close to the 94% removal measured by Dalahmeh et al. (2012). The average efficiency in BOD$_5$ removal was below the range of 97–99% reported by Lalander et al. (2015) for charcoal and sand filters, probably due to higher loading. The inability of the system to remove COD and BOD$_5$ to meet discharge requirement is typical of physical systems (Li et al. 2009).

**Nutrient removal**

TN, Tot-P and NH$_4$N were analysed to determine the removal efficiency of nutrients in the system. The mean values obtained for TN were 47.9, 36.4, 28.8 mg L$^{-1}$ for 12, 24 and 36 hours, respectively. The values obtained were above 10 mg L$^{-1}$, the required discharge values of wastewater discharge in Uganda (NEMA 1999). The reduction in TN from 70 mg L$^{-1}$ could be due to adsorption by the main filter material (charcoal). The reduction of nitrogen could be attributed to organic nitrogen degradation, nitrification and denitrification processes (Healy et al. 2007; Li et al. 2009).

The system had average removal efficiencies of 32, 39 and 43% for TN at 12, 24 and 36 hours, respectively. TN removal efficiency increased with time. However, efficiency became constant as the system matured. TN removal efficiency was far lower using charcoal as the main filter medium compared to 96.6 and 90.94% for biochar and activated charcoal and 86% for a stratified sand filter (Healy et al. 2007; Berger 2012).
The mean effluent concentrations obtained for Tot-P were 18, 17 and 16 mg L\(^{-1}\) at 12, 24 and 36 hours, respectively. The values obtained were above 10 mg L\(^{-1}\), the required discharge values of wastewater discharge in Uganda (NEMA 1999). The reduction in Tot-P and TN could be due to adsorption by the main filter material (charcoal).

The system had average removal efficiencies of 25, 30 and 29% Tot-P at 12, 24 and 36 hours, respectively. Tot-P removal efficiency initially increased with time, but became constant as the system matured. Katukiza et al. (2014a, b) treated grey water using crushed lava rock as the filter medium and achieved Tot-P removal efficiency of 58% when operating under varying hydraulic loading rate (HLR) and 59.5% when operating at constant HLR. The amount of Tot-P removed in this study is much higher than in Dalahmeh et al. (2012) and Berger (2012), probably because their influent grey water had very low Tot-P concentration. Second, the grey water inflow and outflow has low pH in this study; the water was standing during the 36 hours which might lead to anaerobic conditions and the grey water itself contains high tot-P. Further, the small size of the filter and presence of oils from kitchen grey water could have affected the removal rate of Tot-P (Travis et al. 2010). However, in cases where the treated grey water is used for irrigation, TN and Tot-P should not be removed but be monitored (Ghunmi et al. 2011).

**Effect on surfactants**

The mean removal efficiency of MBAS was 45 and 99% at 12 and 24 hours, respectively. The reduction in the concentration of detergents could be due to adsorption on the filter media and biological degradation that took place in the system. The increase in MBAS removal with increasing retention time could be because a biofilm was created in the system that enabled reduction of MBAS (Dalalmeh et al. 2012).

**Effect on microbiological organisms**

The removal of faecal coliforms increased with maturity of the system, whereby, the monitoring was done over a period of 2 months. The mean efficiencies of faecal coliform removal were 43.3, 92.5 and 95.6% at 12, 24 and 36 hours, respectively. Table 3 shows the variations in the efficiency of removal of faecal coliforms at 12-hour intervals over the 5 weeks of monitoring the system. The high variation experienced for efficiency after 12 hours (Table 3) could be due to the immaturity of the system with less biological activity; and during the fourth week of operation, when the mulch had degraded, it could not contribute to further decrease in faecal coliforms and hence the faecal coliforms in the effluent increased. It can be noted from Table 3, that the decrease of faecal coliforms followed the same path as suspended solids thus implying that faecal coliforms could have been attached to suspended matter.

The reduction of the faecal coliforms in the effluent could have been due to adsorption on the filter media (Lalander et al. 2013). The mean removal efficiency for faecal coliforms was 95% at 36 hours for the average inflow concentration of 4.2 \(\times 10^7\) cfu 100 mL\(^{-1}\). The highest reduction of faecal coliforms was below 99.9% for vertical flow constructed wetlands (Gross et al. 2008).

**Effects on soils**

The effluent quality of grey water used did not meet the reuse/discharge standards required for irrigation (FAO Guidelines; NEMA 1999). Table 4 shows the soil chemistry and composition before and 1 month after irrigation with treated grey water. The soil pH of the pilot system, as well

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before irrigation</th>
<th>After irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.19</td>
<td>8.68</td>
</tr>
<tr>
<td>TC, mg L(^{-1})</td>
<td>1.63</td>
<td>1.96</td>
</tr>
<tr>
<td>TN%</td>
<td>0.21</td>
<td>0.19</td>
</tr>
<tr>
<td>Tot-P (ppm)</td>
<td>88.3</td>
<td>71.65</td>
</tr>
<tr>
<td>Na (Cmol/kg)</td>
<td>0.25</td>
<td>0.28</td>
</tr>
<tr>
<td>Ca (Cmol/kg)</td>
<td>30.4</td>
<td>36.40</td>
</tr>
<tr>
<td>K (Cmol/kg)</td>
<td>2.00</td>
<td>3.65</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>21.36</td>
<td>16.67</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>33.64</td>
<td>40.67</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>45.00</td>
<td>42.67</td>
</tr>
</tbody>
</table>
as the control, dropped by about 0.4 and 0.3 pH units, respectively. Both systems experienced an increase in organic carbon, nitrogen and sodium; however, the control had a higher increase in all the aforementioned parameters. The concentration of phosphorus increased in the pilot system but dropped in the control system (Table 4).

The drop in soil pH in the pilot system and also in the control could be due to enhanced microbial respirations which produce carbon dioxide (Gross et al. 2008) or as a result of plant growth and occurrence of anaerobic conditions due to concentrated grey water into the soil. The increase in the organic carbon in both control and pilot garden soil happened because the grey water irrigation system contributed to an increase in its concentration (Travis et al. 2010). The soil samples were collected at a depth of 150 and 300 mm using an auger. The plants that were grown were shallow-rooted plants whose roots could grow to that depth. Therefore, the fine roots of the plants did not enter the samples. The higher increase in sodium and nitrogen in the control garden compared to the pilot system is probably due to the high concentrations of sodium and nitrogen in the control system compared to the pilot system where the nutrients have been partly removed. Potassium decreased, probably because it was used by the crops grown.

Plant response

The treated grey water was used for irrigation of plants and the plant response monitored. The dry weight, fresh weight and moisture content of the plants were investigated in the pilot and control systems. Plants that were irrigated using treated grey water (pilot system) had a relatively lower total weight and grew fewer leaves compared to those where untreated grey water (control system) was directly applied (Table 5). Both the control and the pilot systems received grey water at the same frequency but not the same amount since the cross-sectional area of the control garden was smaller than that of the pilot system garden. The Tot-P increased in both soils of pilot garden and those irrigated with raw grey water. This might be linked to intrinsic and available nutrient content of the soil. The mineral part of P may have been adsorbed on the charcoal leaving less in the effluent into the soil. Therefore, the remaining N and P may not be significantly available for plant growth in the pilot garden, but accumulate in the soil. Further, the pilot garden contained more clay and higher pH than the control garden.

During operation of the system over a period of 2 months, no clogging was reported. Nevertheless measures of removing the filter material, washing it and putting it back in the system, or completely replacing it, should be in place once clogging occurs. In addition, more observations were made, for example, initially mild odours were produced, which decreased with maturation of the system. After 3 weeks, the wood shavings decayed and mulch was routinely changed. Sawdust was applied to replace the wood shavings since it was more durable. Second, the grey water was not uniformly distributed by the pipes and thus, the use of ‘controlled clogging’ and mulch beds may be adopted to facilitate better distribution of the grey water. Controlled clogging is a method where a narrow trench is dug and the bottom allowed to clog with a biofilm. Under this condition, when the bottom clogs, water will impound and spread horizontally and infiltration will take place along the trench sides within the garden (Ridderstolpe 2004). Third, the plants in the control experiment performed better than the pilot experiment, and this could be attributed to adsorption of the available nutrient in the treatment system, thus leaving the part that is not available to the crop in the effluent. The plant response due to irrigation was largely masked by the rain season.

CONCLUSIONS

In the study area of Kyebando-Kisalosalo, grey water is mainly disposed onto the surface and earth-lined storm water drains, which, as a result of large loads of grey water, pond on the surface, thereby causing bad odours, filthy appearance and offering potential breeding grounds for disease agents/vectors. The community in Kyebando-Kisalosalo was willing to reuse grey water once it was...
clean enough in appearance (i.e., without obvious colour) and provided they had the assurance that it was safe to use it. About 68 L household$^{-1}$d$^{-1}$ of grey water was generated, which is typical for slum dwellings of low-income countries. The grey water had high and varied organic and microbial pollutants that necessitate treatment before reuse.

The grey water treatment system consisted of multi-media (10 mm layer of gravel, 600 mm layer of charcoal, a geotextile of 2 mm thickness, 70 mm thickness of mulch and wood shavings and earthworms) treated water with high removal efficiencies, especially with respect to COD, BOD and faecal coliforms. The removal efficiencies were 90.8 ± 5.4% and 96.1 ± 3.0% at 36 hours for COD and BOD, respectively, and 95 ± 5.1% for faecal coliforms. The removal efficiencies of total nitrogen, total phosphorus, total suspended solids and total dissolved solids were 39.0, 30.1, 85.2 and 78.6%, respectively.

The treatment system did not meet reuse criteria due to the high concentration of pollutants. However, the high removal rates of COD, BOD and faecal coliforms achieved by the household grey water treatment system can go a long way in improving the environment and public health of the area; and when incorporating local reuse with the production of vegetables, can contribute to improving livelihoods. The vegetables were irrigated through the sub-surface, thus reducing the risk of infecting people who consume them. Also, the vegetables that were irrigated are cooked before consumption, which adds further protection to consumers. Concerning the solids, the system needs further improvement to enhance their removal, and the low levels of N and total-P removal is beneficial when the treated grey water is to be used for sub-surface irrigation as was the case in our study. Further studies should be carried out to determine whether the remaining N and tot-P, which is not taken up by the plants during growth may accumulate and cause negative environmental consequences.

ACKNOWLEDGEMENTS

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