An Experimental Study of Greywater Irrigated Green Roof Systems in an Arid Climate

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Abstract

Green roofs provide multi-functional benefits to the built environment. They minimize urban heat island effects, enhance biodiversity, reduce carbon footprints, provide hydraulic benefits to urban runoff, and improve overall environmental sustainability. However, their application is limited or rare in arid climates. On the other hand, greywater is becoming a popular alternative water resource in water-scarce regions. A greywater-fed green roof system was developed and studied in the city of Al Ain, United Arab Emirates (UAE). The effluent (treated greywater) from the green roofs can be used to irrigate amenity plantations. Two intensive and two extensive green roof prototypes were constructed, planted with reed canary grass (*Phalaris arundinacea* L.), and irrigated with greywater. The greywater influents and the green roof effluents were monitored for changes in greywater quality. The study showed that the intensive system performed well, which is attributable to the greater depth of soil media. Treated greywater effluent from the green roofs met the local standards for recycled wastewater-based irrigation for a number of parameters (pH, electrical conductivity, salinity, and total dissolved solids), but exceeded the maximum allowable limits for turbidity, COD, and sodium ions (Na^+), which may be because of the short retention time of the experiment. Both the intensive and the extensive systems were inefficient in reducing the total bacterial count of the greywater.

1 Introduction

Climate change and water management are two of the most critical challenges to sustainable urban development. Emissions of greenhouse gases coupled with increases in urban impervious areas has clear environmental consequences such as flooding and urban heat island effects (Carter 2011). These could likely be mitigated through the adaptation of various natural and human systems. However, the built environment has the unique constraint of limited space, which can be effectively countered by the adaptation of green infrastructure within an urban dwelling (Gill et al. 2007). More specifically, sustainable urban drainage systems (SUDS) (Stovin et al. 2013) or water sensitive urban design (WSUD) systems (Beecham and Chowdhury 2012) are becoming more popular throughout the world. The use of SUDS or WSUD is an important component of strategies for creating liveable cities. Such cities require the design of structures that have multiple benefits for urban environments. Green roofs, which can tolerate heat and moisture stress and can perform many heat reducing functions, as well as urban runoff attenuation and quality enhancement, now receive significant attention (Razzaghmanesh, Beecham and Kazemi 2014a).

Green roofs can mitigate stormwater runoff quantity and improve its quality. In addition, they facilitate the provision of a sustainable built urban environment (Palla et al. 2008). The performance of green roofs as a stormwater source control mechanism appears to be excellent, retaining about 85% (measured via runoff volume) and reducing peak outflow to around 95% (Palla et al. 2008). The nutrient contents of green roof effluents originate in the media (soil material) and the fertilizer added to the green roof plants. Therefore fertilizer use in green roofs is an important decision issue in the design process (Berndtsson 2010). In particular, extensive green roofs have been shown to be greatly effective in the removal of pollutants from storm runoff, even though the concentration of pollutants accumulates over time. Apparently, this is because the system gradually settles down and the pollutant leaching occurs within the soil media after a rainfall event or irrigation (Razzaghmanesh, Beecham and Kazemi 2014b).

Green roofs provide both environmental and non-environmental benefits. These include a reduction in cooling costs due to reduced energy consumption (Takebayashi and Moriyama 2007; Alexandri and Jones 2008); a reduction in noise pollution (Dunnett and Kingsbury 2004; van Renterghem and Booteldooren 2009); a reduction in air pollution because of lower temperatures and enhanced the air quality (Currie and Bass 2008; Feng et al. 2010); an increase in amenity and aesthetic value (Fernandez-Cañero et al. 2013); encouragement of biodiversity by becoming wildlife habitats (Dunnett et al. 2008; Gedge and Kadas 2005); a reduction in flood risk and the removal of pollutants from urban runoff (Berndtsson 2010; Razzaghmanesh, Beecham and

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Kazemi 2014a); and an increase in infrastructure value (Nagase and Dunnett 2010).

The cooling mechanism of green roofs can be explained by the latent flux of evapotranspiration. Wet soil reduces the incoming thermal flux into the roof and produces a counter flux, thereby acting as a passive cooler. In winter, the outgoing thermal flux produced in green roofs could be 40% higher than a well-insulated high solar energy absorbing traditional roof system (Lazzarin et al. 2005). Hydrologically, the flow regime through the green roof is governed by three important variables: rainfall intensity and duration; properties of the substrate media such as hydraulic conductivity and the degree of saturation; and a drying process which is governed by evapotranspiration (Palla et al. 2008).

Green roofs are classified as extensive or intensive, and their media depth can be up to 100 mm or over 300 mm respectively (Berndtsson 2010). The selection and optimization of green roof layers are the most important design issues. Intensive green roofs can support larger plants and bushes, but they require regular maintenance, care, and watering. They are suitable for underground garages and heavy buildings and can be planted with bushes, ornamental plants and trees. On the other hand, extensive green roofs use smaller plants. Unlike the intensive systems, extensive green roofs are almost maintenance free. They are suitable for buildings that have light weight and low height and utilize self-regenerative plant species such as *Sedum* spp., and various shrubs and bushes. Both types of green roofs are successfully installed in many European cities and they effectively reduce the pressure on both urban drainage and sewerage systems (VanWoert et al. 2005; Stovin et al. 2012; Razzaghmanesh, Beecham and Kazemi 2014a).

The idea of using greywater in green roofs was investigated in semi-arid regions such as Australia, where supplementary irrigation water may be required, depending on the types of plants and green roof materials (Razzaghmanesh, Beecham and Kazemi 2014b). However, in arid regions, rainfall is very rare and rain-fed irrigation is not a common practice. In this research, we studied the use of greywater for irrigating green roofs. Greywater can be defined as domestic wastewater excluding that which originates from the toilet (Eriksson et al. 2002) and the kitchen (Al-Jayyousi 2003; Li et al. 2008). The generation of greywater depends on gender, age, habits, lifestyle, living standards and the easy availability of water (Chowdhury et al. 2015).

There are few or no scientific activities concerning green roofs in arid regions of the Gulf Cooperation Council (GCC) countries. Green roof studies in the arid climate zones of Australia and the United States have been published (Santamouris 2014; Monterusso et al. 2005; Razzaghmanesh, Beecham and Kazemi 2014a; 2014b; Razzaghmanesh, Beecham and Brien 2014). Most of the studies in Australia were undertaken on extensive green roofs. These studies showed that extensive green roofs provide difficult growing conditions for plants, particularly in semi-arid regions (Durhman et al. 2004). This is because the plants selected for green roof systems must be able to tolerate increased wind velocities, greater sun exposure, more extreme heat, drought conditions, and shallow root depths. Williams, Hughes et al. (2010), Williams, Rayner et al. (2010) and Farrell et al. (2012) investigated the impacts of climate on green roof systems in the eastern and southeastern Australian regions. Razzaghmanesh, Beecham and Brien (2014) showed that in a dry climate, plants perform better in intensive green roofs with a mild (1°) slope.

Our hypothesis is that green roofs improve the quality of greywater such that it can subsequently be reused for irrigation of ornamental plants or can be drained to existing sewer lines. We investigated the efficiency in removing pollutants from greywater of two (in duplicate) prototype-scale green roof systems of extensive and intensive design in the city of Al Ain, UAE.

2 Materials and Methods

The study area was located in the city of Al Ain, UAE at 24.2075° N and 55.7447° E. The average annual temperature in the area is between 13 °C and 44 °C, occasionally rising above 46 °C or falling below 10 °C. The warmest season is experienced between May and September with minimum temperatures as high as 31 °C and an average temperature >40 °C. The sunshine hours vary in the range 10.65 h/d to 13.65 h/d, and there is rarely cloud cover except in the month of February. The probability of rainfall is also very low and scattered over the year. Periodically, thunderstorms occur in August, light rain in March and moderate rain around February. The average annual rainfall is 96 mm to 120mm. The relative humidity typically ranges from 13% (very dry) to 88% (very humid) over the course of a year. Over the course of the year, typical wind speeds vary from 1 m/s (light air) to 8 m/s (fresh breeze), rarely exceeding 11 m/s (Weather Spark 2012).

The experiment was conducted using four green roof prototypes made of steel, two intensive (INT 1 and INT 2) and two extensive (EXT 1 and EXT 2), as shown in Figure 1. The same sizes and designs were used in all cases, except for the depth of soil. Each green roof prototype has an area of 0.66 m^2 (110 cm long and 60 cm wide). The surface of the prototype was coated with a layer of tar and the irrigation water was allowed to drain freely through a sand filter to the tap. The first (lowest) layer is a double layer of 2 mm polyethylene filter (geotextile), which was covered by a 20 mm deep layer of gravel (2 mm to 5 mm size). The gravel layer formed the drainage section of the roof. Another polyethylene filter (geotextile) layer overlaid the gravel layer and was covered by an upper layer of sand (30 cm and 60 cm deep for the extensive and intensive prototypes, respectively). Locally available reed canary grass (*Phalaris arundinacea* L.) was planted in equal quantities in all four prototypes. The plant is a strong, deep-rooted perennial grass, having linear leaves 3 cm to 25 cm long and 4 mm to 10 mm wide. The plant has a high biomass and deep roots, and it is drought tolerant. It is relatively palatable and resistive to overgrazing, which makes it a very useful pasture species (Robertson 2008). Figure 1 shows the schematic and photos of the green roof prototypes constructed for the study. The prototypes were kept in ambient conditions.

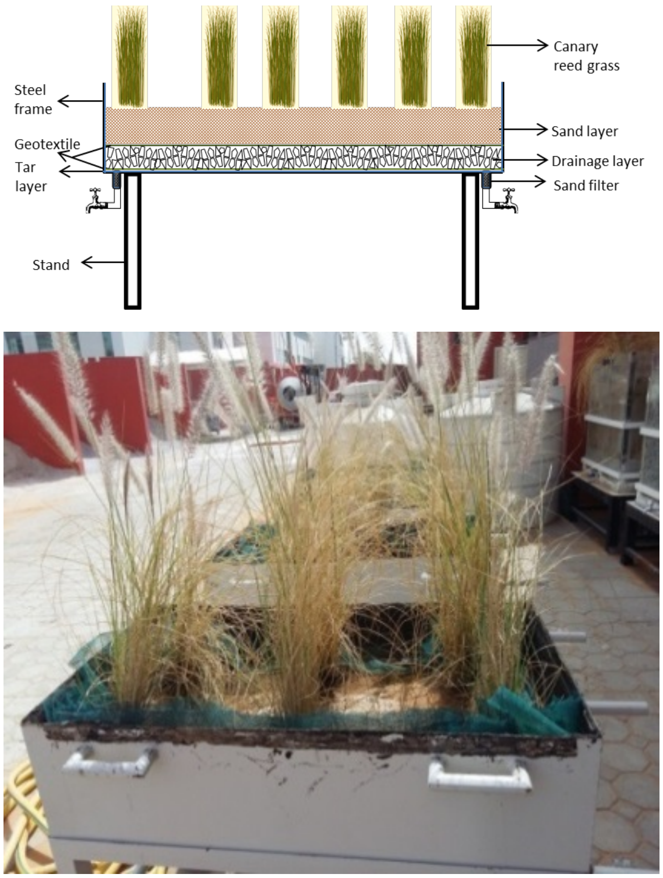

Figure 1 **Schematic (top) and picture (bottom) of the green roof prototypes.**

Two replicates of each of the extensive and intensive prototype models were made in order to have some degree of certainty for the results. The greywater used for irrigation in the prototypes was obtained from a laundry machine and the quality was tested each time a new sample was received. The green roof prototypes were irrigated daily (at 10:00 h) with the same amount of raw greywater (6 L to 7 L) while the exit tap (drain) was kept open and the samples were collected immediately from the exit tap. The experiment was conducted for 11 consecutive days (2015-02-02–12), and repeated for another 11 consecutive days (2015-02-18–28). After the first 11 day period, the prototypes were backwashed and the plants were irrigated using municipal water (desalinated water). The parameters monitored were pH, electrical conductivity (EC), turbidity, total dissolved solids (TDS), oxidation reduction potential (ORP), salinity, calcium ions (Ca^{++}), sodium ions (Na^+), potassium ions (K^+), nitrate as NO_3^-, nitrate as nitrogen (NO_3–N), chemical oxygen demand (COD), and total coliform bacteria. A Horiba U-52 multi-parameter water quality meter was used to measure pH, EC, turbidity, TDS, ORP and salinity. Portable Horiba LAQUAtwin compact water quality meters were used to measure Ca^{++}, Na^+, NO_3^- and K^+. A HACH DR/4000U spectrophotometer was used to measure NO_3–N and COD. The numbers of total coliform bacteria (TCB) were counted using a HACH paddle tester (Cat No. 26109-10). The results obtained were compared to the local standards for wastewater reuse for irrigation purposes (ADRSB 2010; DM 2011).

2 Results and Discussion

A summary of the data (descriptive statistics) obtained in the experiment is shown in Table 1.

Table 1 **Summary of the result (descriptive statistics) of the experiment.**

Parameters	Extensive green roofs			Intensive green roofs			Local discharge limit for recycled wastewater*
	Mean	Median	Std Dev	Mean	Median	Std Dev	
pH	8.82	8.35	1.40	8.49	8.19	0.96	6–8
ORP, mV	100.5	113.7	43.51	119.1	125.0	31.98	
EC, mS/cm	2.52	2.73	0.96	1.99	2.05	0.58	
Turbidity, NTU	97.49	71.93	73.20	64.97	16.30	101.7	5.0
Salinity, ppt	1.39	1.50	0.43	0.96	1.01	0.38	
TDS g/L	1.67	1.77	0.60	1.06	1.27	0.60	2.0
Ca^{++}, mg/L	679.6	575	463.4	978.6	1050	504.2	
Na^+, mg/L	6396	6500	1441	4400	4850	1335	200
K^+, mg/L	984.6	885	308.2	900.9	830	333.1	
NO_3^-, mg/L	653.6	555	256.2	345.5	340	64.15	50
NO_3–N, mg/L	5.67	4.30	4.19	2.32	2.15	1.26	5
COD, mg/L	229.7	207	103.4	101.6	71	73.68	150
TCB, count/100 mL	6.7E+7	1.0E+8	4.5E+7	4.9E+7	1.0E+7	4.6E+7	1.0E+3

*The maximum permissible concentration for unrestricted irrigation in the Emirates of Abu Dhabi and Dubai, UAE (DM 2011; ADRSB 2010).

2.1 pH

The observed pH level in the outflows of both sets of units was consistently within the range 7.24–8.95 (Figure 2a), except in a few cases where the values were >10. This finding agrees with the results of Berndtsson et al. (2009) and Razzaghmanesh, Beecham and Kazemi (2014a). The mean values were 8.82 and 8.49 and the standard deviations were 1.40 and 0.96 for the extensive and intensive prototypes respectively. Significant differences in effluent pH values were not observed between the two systems. Overall, the results fall within the pH range of 6 to 8, as stipulated in the local guidelines for unrestricted irrigation using recycled water (ADRSB 2010; DM 2011). In the earlier stage of the experiment, the pH value of the systems increased from day 1 to day 6 (Figure 2b), making the pH of the effluent higher than that of the influent raw greywater (a negative sign in Figure 2b). The trend then took the opposite direction with a positive difference after day 6. This is most likely due to the reduction in the pH level after the systems were affected by a rainfall–sandstorm event and had to be backwashed with tap water to unclog the drains. After day 6, the positive difference in the pH values between the raw and the effluent decreases until it becomes negative, showing that the accumulation continued in the prototype systems and that green roofs are very much influenced by changes in meteorological conditions, as stated by Palla et al. (2008) and Razzaghmanesh, Beecham and Kazemi (2014b). Similar patterns occur in most of the parameters analyzed in this study.

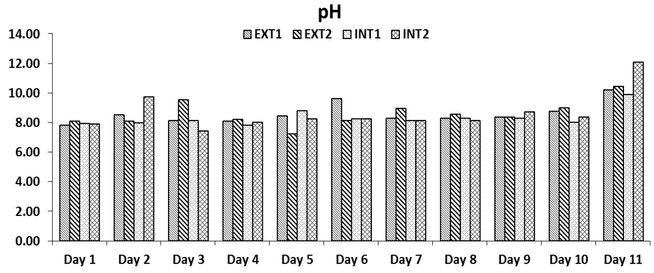

Figure 2a Average pH of green roof effluents (EXT and INT indicate extensive and intensive systems respectively).

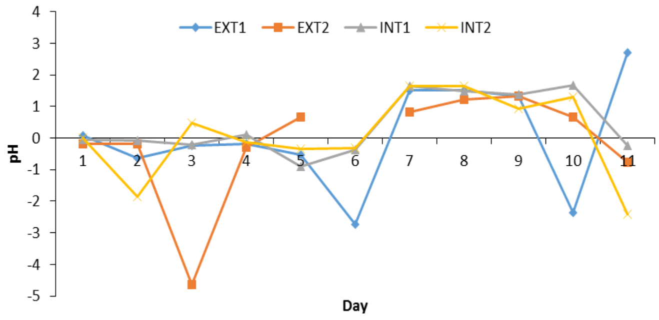

Figure 2b Changes of pH in the green roof effluents (pH of raw greywater – pH of effluent).

2.2 Oxidation Reduction Potential

On average, the observed values of ORP in the intensive systems were higher (~8%) than those of the extensive systems (Figure 3a). Although both designs improved ORP (Figure 3b), it is noteworthy that the backwash (day 6) improved ORP in all the systems. A higher ORP value in the intensive system indicates the system's effectiveness in improving the oxygen content of the greywater. The mean and standard deviation of ORP were ~100.53 mV and 19.12 mV, and ~43.51 mV and 31.98mV, for the extensive and intensive systems respectively.

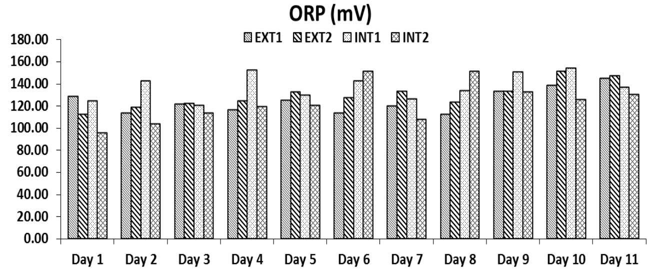

Figure 3a Average ORP of green roof effluents (EXT and INT indicate extensive and intensive systems respectively).

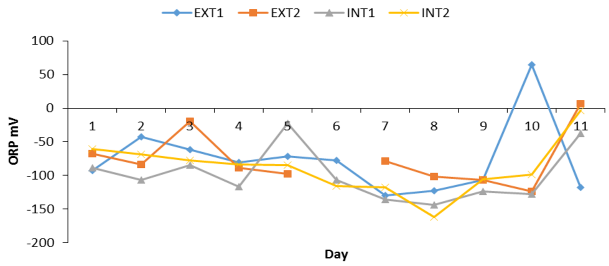

Figure 3b Changes of ORP in the green roof effluents (ORP of raw greywater – ORP of effluent).

2.3 Electrical Conductivity

The mean values of EC were ~1.99 mS/cm and 2.52 mS/cm for the intensive and extensive systems respectively. The EC values in the extensive system were ~20% higher than those of the intensive system. In almost every experiment (Figure 4a), conductivity in the extensive system exhibited a higher value, which indicates that the intensive system performed better than the extensive system. The removal efficiency of the intensive system at the beginning of the experiment was ~70%. After the backwash in day 6, the efficiency dropped to zero (Figure 4b) in all systems before it makes a U-turn back to the positive axis. There are no discharge limits for EC for the recycled wastewater (ADRSB 2010; DM 2011); however, the EC levels for both systems were far below the maximum permissible range (for wholesome water) of 160 mS/cm to 1600 mS/cm (RSB 2010).

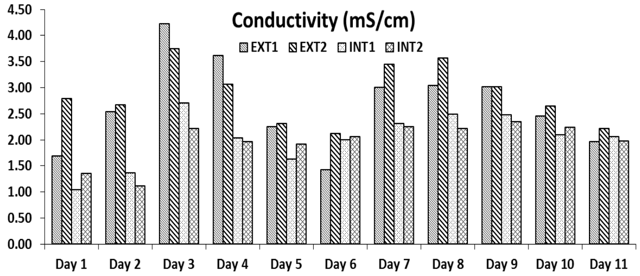

Figure 4a Average electrical conductivity of green roof effluents (EXT and INT indicate extensive and intensive systems respectively).

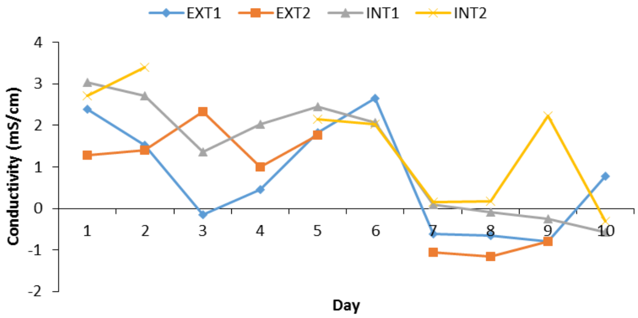

Figure 4b Changes of electrical conductivity in the green roof effluents (conductivity of raw greywater – conductivity of effluent).

2.4 Turbidity

The turbidity levels from the two systems were in the range 11.64 NTU to 194 NTU (Figure 5a), with a mean value of 17 NTU and 60 NTU for the intensive and extensive systems respectively. The percentage removal was as high as 75% in the intensive and ~57% in the extensive system. Similar to the pattern reported by Razzaghmanesh, Beecham and Kazemi (2014a), Figure 5b shows that the removal rate gradually increases from day 1 to day 11 in all systems. Even in the period day 1 through day 6, the pattern remains relatively stable, which suggests that the system could go a long way to effectively reducing the turbidity to a reasonable level. The turbidity levels in the effluents exceeded the recommended level of 5 NTU (ADRSB 2010).

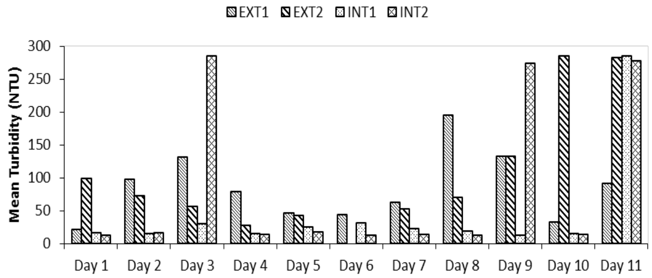

Figure 5a Mean turbidity of green roof effluents.

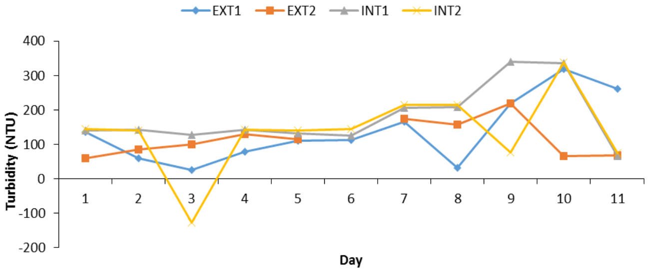

Figure 5b Changes of turbidity in the green roof effluents (turbidity of raw greywater – turbidity of effluent).

2.5 Salinity

The salinity concentration in the effluent of the extensive systems was ~33% higher than that of the intensive systems. The salinity levels were in the range 0.3 ppt to 1.9 ppt (parts per trillion) with mean values of 1.39 ppt and 0.96 ppt and standard deviations of 0.43 ppt and 0.38 ppt for the extensive and intensive systems respectively. The average percentage removal for the extensive system was ~14%, whereas for the intensive system it was ~45%. Both systems exhibited an accumulation of salts (Figures 6a and 6b) as the removal percentage of the intensive system was reduced from ~77% to 40% by the end of the experiment. The extensive system gained salinity rather than removing it. The salinity accumulated in the effluents may be sourced from the soil and sand media used in the systems. The maximum allowable limit for salinity in the recycled wastewater is not available in the local regulations (ADRSB 2010; DM 2011), but the salinity levels were far below the recommended guideline value of 1000 mg/L (equivalent to 10^9 ppt) for the protection of aquatic ecosystems (South Australian EPA 1999).

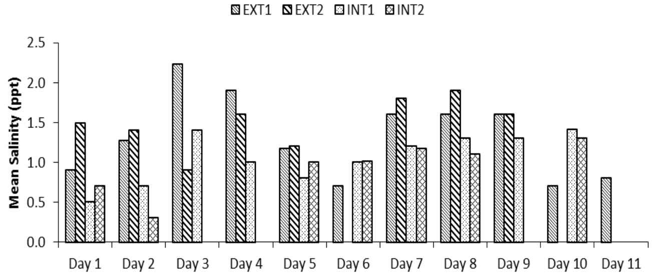

Figure 6a Mean salinity of green roof effluents.

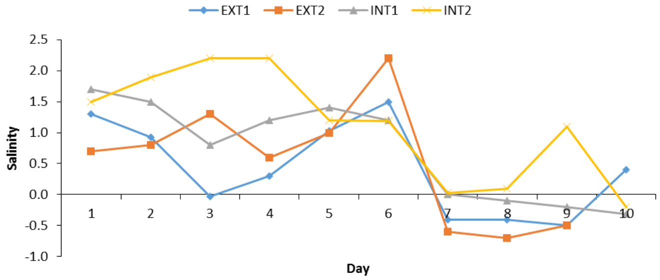

Figure 6b Changes of salinity in the green roof effluents (salinity of raw greywater – salinity of effluent).

2.6 Total Dissolved Solids

The mean TDS values of effluents from the extensive and intensive systems were ~1.7 g/L and ~1.3 g/L, respectively. The TDS removal capacity of the intensive system was higher than that of the extensive system (Figure 7a). This is because of the greater depth of the soil–sand medium in the intensive system. Figure 7b shows the difference in TDS between the raw greywater and the treated effluent. It shows that the systems performed well until the backwash on day 6; thereafter the efficiency dropped significantly. In some cases, effluent TDS concentration was higher than raw greywater TDS concentration. The reason is that the retained solids in the soil–sand media were loosened during the backwash and then released with the effluent. In most cases, the TDS concentration was well below the maximum guideline level of 1.5 g/L to 2.0 g/L (ADRSB 2010; DM 2011).

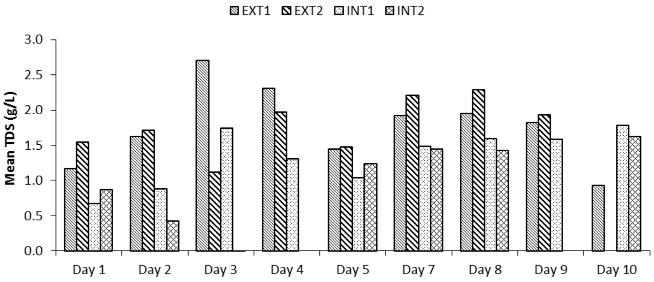

Figure 7a Mean TDS of green roof effluents.

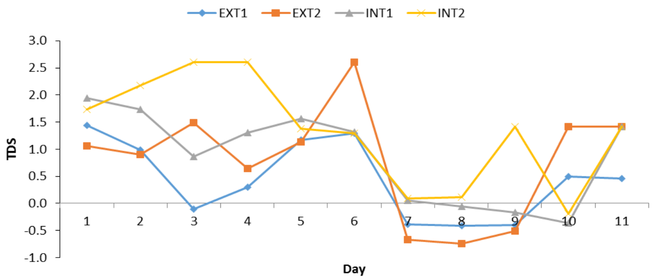

Figure 7b Changes of TDS in the green roof effluents (TDS of raw greywater – TDS of effluent).

2.7 Calcium Ions

It is evident from Figures 8a and 8b that the Ca^{++} content in the effluent changes over two periods, before and after the backwash on day 6. On average, the first period (before backwash) has an average Ca^{++} concentration of 966 mg/L and 1383 mg/L for the extensive and intensive systems respectively. In the second period (after the backwash on day 6), the respective values have dropped to 336 mg/L and 493 mg/L. The variability was also reduced after the backwash. Generally, the accumulation of calcium in the intensive system was ~19% higher than in the extensive system, suggesting that the calcium content is likely sourced from the gravel (drainage layer) and sand–soil layer of the systems.

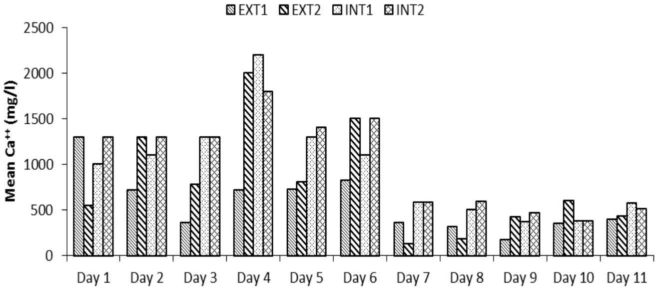

Figure 8a Mean calcium ion (Ca^{++}) concentration of green roof effluents.

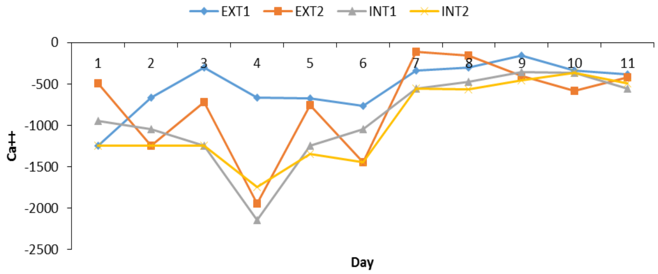

Figure 8b Changes of calcium ions (Ca^{++}) in the green roof effluents
(Ca^{++} of raw greywater – Ca^{++} of effluent).

2.8 Sodium Ions

The sodium ion (Na$^+$) is often combined with chloride (Cl$^-$) or sulfate (SO$_4^{2-}$) to form a salt. Figure 9a shows that the concentration of Na$^+$ steadily increased in both systems, regardless of their design, although it is ~20% higher in the extensive system. The mean value of Na$^+$ of the extensive and intensive systems were ~6395 mg/L and ~4400 mg/L respectively. From Figures 9a and 9b, it is evident that at the beginning of the experiment, the extensive and intensive systems remove Na$^+$ from the greywater by amounts of 34% and 75% respectively. However, as time continues, the removal ability of the systems reaches zero, and later the sodium content of the effluent started to increase, making its concentration in the effluent higher than that in the raw influent greywater. The initial reduction of Na$^+$ was probably because of adsorption to the media particles and the accumulation in the later stage was probably sourced from the retained Na$^+$ in the media. The Na$^+$ in the effluents exceeded the guideline value of 200 mg/L (DM 2011).

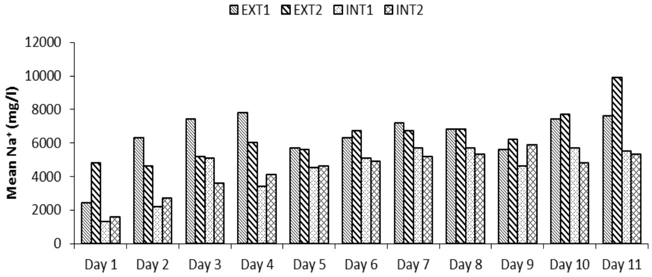

Figure 9a Mean sodium ions (Na$^+$) of green roof effluents.

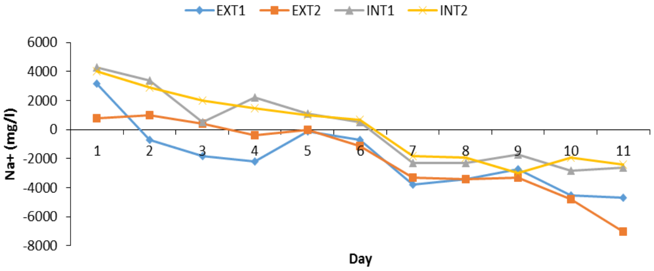

Figure 9b Changes of sodium ion (Na$^+$) in the green roof effluents
(Na$^+$ of raw greywater – Na$^+$ of effluent).

2.9 Potassium Ions

Similar to Ca$^+$, the K$^+$ content in the raw greywater was less than that in the effluent from the green roof systems. The values remain almost constant over the period of the experiment (Figure 10a), although those from the extensive system were a bit higher (~5%) than those from the intensive system. The means and standard deviations of K$^+$ were ~985 mg/L and 901 mg/L, and ~308 mg/L and 333 mg/L, for the extensive and intensive systems respectively. The rate at which K$^+$ accumulated in the system and the average percentage of accumulation was small in comparison to the Ca$^+$ ion accumulation. The maximum allowable limit for K$^+$ was not found in the local regulations for recycled wastewater, but the concentrations exceeded the guideline value of 12 mg/L for wholesome water (RSB 2010).

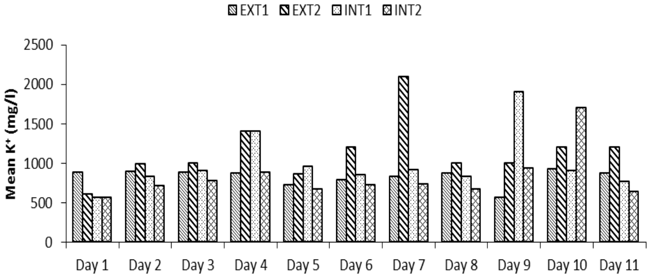

Figure 10a Mean potassium ions (K^+) of green roof effluents.

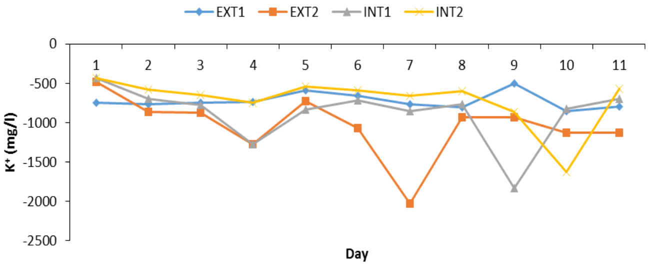

Figure 10b Changes of potassium ions (K^+) in the green roof effluents
(K^+ of raw greywater – K^+ of effluent).

2.10 Nitrate Ions

The nitrogen (as nitrate, NO_3^-) concentrations in the effluents exhibited two distinct behaviours, one before and one after the backwash on day 6 (Figure 11b). The NO_3^- concentration was high after the backwash. The amount of NO_3^- removed in the effluents did not vary significantly, but differed significantly before and after the backwash (Figure 11b). The amount of NO_3^- from the extensive system was ~30% higher than that of the intensive system (Figure 11a), and the intensive systems showed much more consistency in their output than the extensive systems. The mean values of NO_3^- were ~650 mg/L and 345 mg/L for the extensive and intensive systems respectively, both of which exceeded the maximum allowable limit of 50 mg/L (DM 2011).

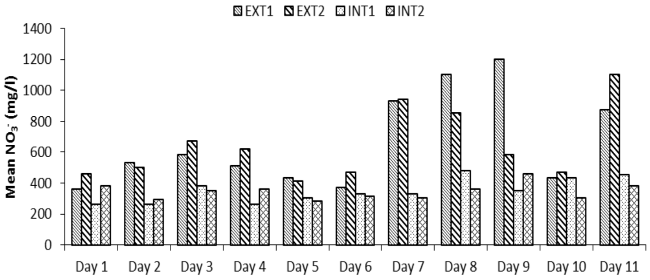

Figure 11a Mean nitrate (as $NO3^-$) of green roof effluents.

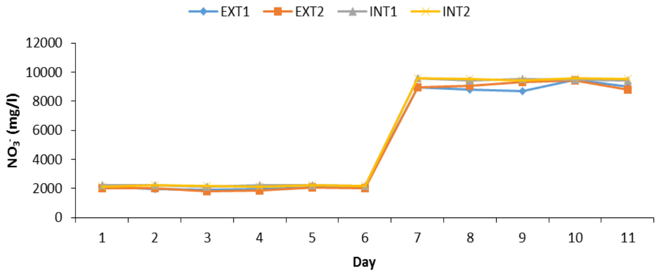

Figure 11b Changes of nitrate (as NO_3^-) in the green roof effluents
(NO_3^- of raw greywater – NO_3^- of effluent).

2.11 Nitrate Nitrogen

The NO_3–N concentrations showed inconsistent results in the extensive system (Figure 12a), but showed a definite pattern (Figure 12b) before and after the backwash of the systems on day 6. The mean values of NO_3–N were ~5.67 mg/L and 2.32 mg/L for the extensive and intensive systems respectively. The removal of NO_3–N can be explained by the denitrification of nitrate to nitrogen by heterotrophic bacteria. The percentage removals of NO_3–N were very high at the beginning of the experiment period (~79% and 93% for the extensive and intensive systems respectively). Similar results were found by Razzaghmanesh, Beecham and Kazemi (2014a) and Berndtsson et al. (2009). However, after the backwash (day 6), the concentration of NO_3–N increased significantly in the effluents, becoming higher than that of the raw greywater. Similar incidences of nitrogen leaching were reported by Moran et al. (2005) and Monterusso et al. (2005), and the leaching was attributed to the plant types, their establishment on the roof, and the type of the soil media (Hathaway et al. 2008).

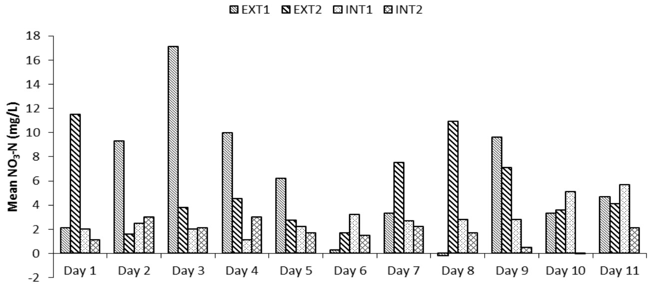

Figure 12a Mean nitrate (NO3–N) of green roof effluents.

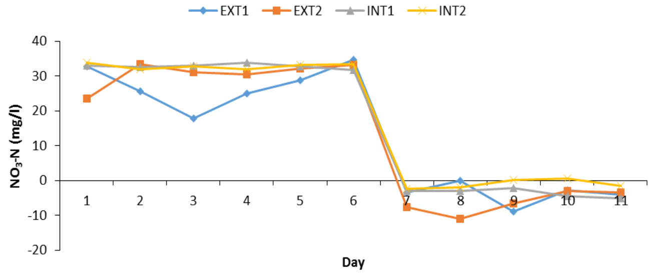

Figure 12b Changes of nitrate (NO3–N) in the green roof effluents
(NO3–N of raw greywater – NO3–N of effluent).

2.12 Chemical Oxygen Demand

COD in the effluents was in the range 41 mg/L to 405 mg/L. The mean values for COD were 230 mg/L and 102 mg/L and the standard deviations were 103 mg/L and 74 mg/L for the extensive and intensive systems respectively. COD in the extensive systems exceeded the recommended levels (DM 2011) of 150 mg/L (unrestricted irrigation) and 200 mg/L (restricted irrigation). The average removal capacity of the intensive system was ~40% higher than that of the extensive system (Figures 13a and 13b). The intensive systems had a removal efficiency of ~90%, whereas for the extensive systems it was ~79%. The green roof systems performed well in reducing COD in the greywater. The COD removal mechanism can be best explained by the mechanical filtration of greywater through the porous media, the biodegradation of organic matters, and the adsorption of organics on soil and sand surfaces.

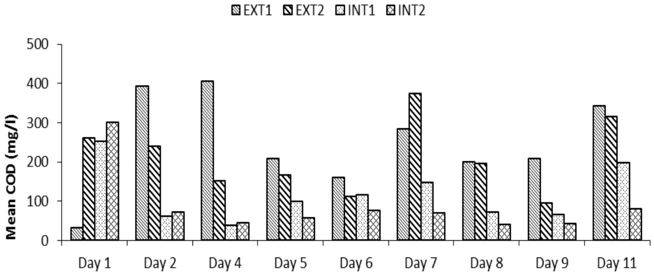

Figure 13a Mean COD of green roof effluents.

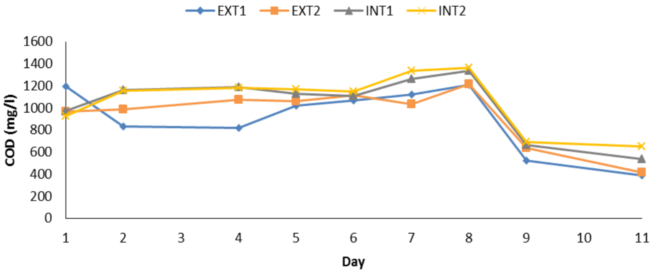

Figure 13b Changes in COD in the green roof effluents (COD of raw greywater – COD of effluent).

2.13 Total Coliform Bacteria

Neither the intensive nor the extensive systems performed well in reducing total coliform bacteria from the greywater. The systemsbehaved almost identically in this regard with TCB counts greater than the recommended maximum level of 10^3/100 mL (DM 2011; ADRSB 2010). The total coliform count of raw greywater was 10^7/100 mL, and the effluents from the extensive green roof systems both had TCB counts of 10^7/100 mL. In the intensive systems, the bacterial counts were reduced to 10^6/100 mL and 10^4/100 mL on day 7 and day 9 respectively. The ineffectiveness of green roof systems in reducing bacterial counts is because grey-water is retained in the systems, and the systems have shallow depths of media (soil and sand). Less depth indicates less particle surface area available for the adsorption of negatively charged bacteria.

Green roof systems are composed of porous media and vegetation. The quality of the greywater is improved through the filtration process, the adsorption of pollutants in soil media, biological processes such as uptake by plants (phytoremediation), and through microbial conversion (bioremediation). Because of the low retention time in this study, some of the quality parameters in the effluents did not meet the local standards for irrigation using recycled wastewater (ADRSB 2010; DM 2011). It is expected that better effluent quality can be achieved with an increased retention time. The effluent quality can also be improved by adopting a permeable pavement with an underlying reservoir to store the effluent from the green roof. A recent study showed that greywater improves its quality significantly after 24 h retention in the permeable pavement reservoir (Chowdhury et al. 2015). However, both the green roof and permeable pavement were ineffective in reducing bacterial counts. Therefore, a disinfection process is necessary.

3 Conclusion

Greywater-fed green roof systems in arid regions can improve overall environmental sustainability. First, they can serve as onsite treatment systems for greywater and the effluents can either be reused for irrigation to amenity plantations or can be discharged into an existing sewer inlet. This will help to promote a decentralized management of urban wastewater in the region. Second, they can reduce potable water consumption by recycling and reuse of greywater for gardening purposes. In some arid regions, particularly in the UAE, the domestic water consumption rate is extremely high. In a recent study conducted by Chowdhury and Rajput (2015), the water consumption rate in the city of Al Ain, UAE was more than 2500 L/capita/day in villa-type accommodations; interestingly, it was identified that more than 80% of this water is used for outdoor activities (gardening, car washing, and suchlike). Therefore, reuse of greywater for non-potable outdoor activities (e.g. watering of amenity plantations) can effectively reduce water consumption without affecting the local lifestyles. Third, adoption of green roofs can minimize the urban heat island effects in the city. Fourth, green roofs can enhance biodiversity by creating habitats for wildlife.

As the world's attention is moving towards sustainable development, measures such as WSUD/SUDS are becoming more popular in communities that hope to create more livable cities in the future. The green roof is one of the features shown to have a positive effect towards the attainment of this common goal. An intensive green roof system performs better, but the adoption of an intensive system is costly. In addition, a greywater fed green roof system requires greywater to be pumped to the roof, which will increase the cost and add greenhouse gas emissions.

A field test with a continuous feed of greywater is essential to enable us to reach a firm conclusion on the effectiveness of the concept. There were some limitations in this study, such as the experiment being restricted by having a short retention period and small sample sizes. Several repetitions of the tests (in different seasons) are recommended to prove the consistency of results. Several other factors that affect the performance of green roofs were not considered in this study, such as different kinds of substrate media, the species of plants chosen and their density, rainfall intensity, concentrations of greywater, and roof inclination. The hydraulic performance of green roofs is an important and well researched area (particularly for stormwater), but it needs to be considered for greywater fed systems as well.

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