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Monitoring Drainage Water Quality during Green Roof Irrigation Trials Using Synthetic Greywater

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Authors' contributions

This work was carried out in collaboration between both authors. Author MS managed the literature searches and the analyses of the study, performed the statistical analysis and wrote the first draft of the manuscript. Authors MS and KH together designed the protocol. Authors MS and KH both read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate the potential for substituting green roof mains water irrigation by irrigation using lightly loaded synthetic greywater.
Study Design: The planted green roof system was designed to be operated and tested within a glasshouse.
Place and Duration of Study: Schools of Engineering, and Plant Sciences, The University of Reading, for 28 days commencing 28th of May 2012.
Methodology: A trial was conducted for comparing two planting schemes using *Sedum* and *Stachys Byzantina* and a third unplanted control. The three sets of growing boxes were subdivided between substrate depths of 10 cm and 20 cm. By further subdivision, half of each set were watered using mains water, and half using a synthetic greywater. The soil composition and water quality of the drainage (filtrate) water were monitored. Statistical analysis of the results was conducted.
Results: Consistency was observed in influent pH and EC, in both mains and greywater samples. Influent Na concentrations were higher in the greywater samples due to detergent content. The Na mass balance calculations for all boxes showed that some Na mass was unaccounted for when comparing aggregated concentrations in influent, plant tissue and soil with the aggregated Na mass in filtrate, plant tissue and soil water. It was concluded that this was likely to be due to retained/ponded irrigation water in the boxes, difficulties in attaining homogenous box flushing and the underestimation of soil Na. The variation in substrate depth affected all results. The plants themselves seemed to have little significant influence on the measured parameters, with the exception of the accumulation of Na mass in plants irrigated with greywater.

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Conclusion: No improvement was observed in the quality of the greywater following filtration through the soil matrix. For longer term watering using greywater, a choice of Na resistant species should be considered, although the *Sedum* species used in this trial showed no recorded adverse growth effects due to Na accumulation.

Keywords: Rainwater harvesting (RWH); Sedum and Stachys green roofs; irrigation of green roofs with greywater; sodium accumulation in green roof species; BSI-standard greywater.

1. INTRODUCTION

Climate change and greater urban populations are contributing to the increasing frequencies of water scarcity events. The United Nations [1] estimates that the percentage of global populations living in urban areas will increase from the current 51% to 67% by 2050. This increase in urban populations exacerbates existing urban environmental problems, including air and water pollution, the urban heat island effect, the availability of and accessibility to clean water resources. The World Water Organisation predicts that by 2025, two thirds of the global population will face water shortages [2]. Furthermore, the application of rainwater and mains water for uses including green roof irrigation becomes constrained during drought conditions.

Green roof technology can assist in mitigating climate change effects in urban areas. A study by the USEPA [3] suggested that within US urban areas, roof cover occupies around 20% to 25% of the total land area. To optimise the benefits from green roofs, vegetation must be kept healthy and sufficiently irrigated.

In order to decrease the potential demand for irrigating green roofs using potable water, it has been suggested that greywater may provide a significant alternative water resource for this application [4]. The average person in the United Kingdom uses around 150 litres of water per day [5], and a significant percentage of this water may potentially be suitable for reuse.

In the UK, greywater is defined as water originating from sources including baths, showers, washbasins and laundry waters [6]. Noticeable differences in greywater quality are suggested by Hyde and Maradza [4] due to its organic and physical pollutants arising from various prior uses. Other factors affecting the chemical composition of greywater include; the variety of cleaning and personal care products available and the chemical composition of mains water [7]. Christova-Boal et al. [8] tested the chemical composition of kitchen and bathroom greywaters indicating that kitchen greywater contains a wider variety and greater concentrations of pollutants. This suggests that even in a single household, the greywater is likely to be of variable quality. Consequently, irrigation using greywater from any specific source could potentially produce variable effects on plants and substrates [9], suggesting that greywater requires analysis prior to evaluation of suitability for particular uses.

The objectives of the research included: 1) an assessment of the quality of greywater following application and filtration through substrate; 2) assessment of the effects that greywater irrigation produces on plants and soils within the green roof system; 3) evaluation of whether or not the application of greywater is a viable alternative to the use of mains water for irrigation of green roofs; both in terms of filtrate water quality and also in the potential effects on plants from sodium (Na).

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Substrates, plants and treatments

An experimental period of 28 days commenced on 28th May 2012. Thirty-two 0.4 m by 0.6 m planting boxes were each drilled with eight holes, for water drainage and filtrate sample collection. The substrate used was John Innis (JI) Compost No. 2, and no additional fertiliser or nutrient was added. In many practical applications, a growing medium for green roofs would usually be mixed with a second growing medium or soil conditioner. However in this study, a single JI substrate was used for testing how well a green roof could be sustained by drawing upon the higher nutrient content associated with an un-mixed compost.

Sixteen boxes were filled with 10 cm of substrate, and the other sixteen with 20 cm of substrate in order to test the influence of depth and volume upon the chemical/inorganic holding capacity of the substrate. Two species of plant were tested: *Stachys byzantina* and *Sedum*.

Twelve boxes were planted with *Stachys byzantina* another twelve with *Sedum*, with the remaining eight containing bare soil as a baseline parameter. The *Sedum* mat was cut to completely fill, and to give sufficient plant density in the *Sedum* boxes. In each *Stachys* box, six plants were used to give a high coverage of leaf material. The mature plants specimens were bedded one week before the experiment began to allow for some establishment.

The boxes were then further divided into sub-groups irrigated with either synthetic greywater or with mains water. Boxes were placed in greenhouses in order to control the irrigation volumes.

2.1.2 Sodium accumulation and toxicity to plants

Sodium can be toxic to plants, hindering growth and development [10]. The conservative nature of Na leads to accumulation, tending to cause plant health effects and, in some cases, plant death.

2.1.3 Synthetic greywater recipe and production

The British Standard BS8525 synthetic greywater recipe [6] was selected for irrigation of the planted boxes, although it was modified to exclude tertiary effluent. This was primarily intended to reduce the variability of constituents that could arise from the tertiary effluent. The adapted recipe can be seen in Table 1.

Table 1. Adapted British Standards (8525) basic bathroom synthetic greywater recipe

Components	Amounts
Mains water	9913 ml
Shower gel (Johnson's baby soft wash)	8.6 ml
Oil (sunflower)	0.1 ml

The tertiary effluent was replaced by an equivalent volume of mains water as shown in Table 1. Synthetic greywater was produced in 10 litre batches to ensure consistency and, when necessary, was stored at 4℃ for up to 24 hours [11].

2.2 Sampling

2.2.1 Moisture content and plant irrigation

A soil moisture probe was used to estimate the moisture concentration in each box, which was used to determine the subsequent irrigation regime. Soil moisture was measured daily between 12.00 and 13.00 hrs. The volume of water delivered was just sufficient to meet the plants' varying moisture requirements. Whilst the bare soil and *Stachys* boxes were irrigated when the moisture content fell below 0.25 m^3/m^3 due to higher moisture requirements, *Sedum* was irrigated when moisture fell below 0.20 m^3/m^3 as it has a high drought tolerance [12].

2.2.2 Plant and soil sampling

Samples were taken on the start date and on the 28^{th} day of the study. A small diameter soil corer was used to take five samples from each box through the entire depth of the substrate in both the 10 cm and 20 cm boxes'. The five samples were combined to form one representative sample of each box. These combined samples were oven dried at 40℃. At the same time, plant tissue sampling was undertaken by removing 5 leaves from each plant near the top of the stem. These leaves were added to an aggregated sample, dried and crushed to form a representative sample from each box.

2.2.3 Influent and filtrate sampling

Influent and filtrate, mains and greywater samples were collected on days 1 and 29. Influent mains water samples were collected from the greenhouse water mains. The BSI [11] suggests that synthetic greywater samples are taken one hour after its production for analysis purposes. Filtrate samples were collected by irrigating boxes manually, at a slow pace, with 500 ml every 5 minutes until dripping occurred. The water retention times of the boxes and the water holding capacity varied in relationship to the soil depths and plant types.

2.3 Measurements and Methods

2.3.1 Water quality measurements and visual assessment of plants

Influent and filtrate water quality were tested for pH, Total Dissolved Solids and Electrical Conductivity (EC) on days 1 and 29 of the experimental period, using ion selective electrodes. The growing boxes were photographed every seven days for the purpose of visual assessment of plant colour and growth.

2.3.2 Sodium extraction preparation (Soil)

Ammonium nitrate was used to extract Na from the dried soils. Ten grams of dried soil was sieved through 2 mm gauze, and placed in a centrifuge tube with 25 ml of 1 mol/litre ammonium nitrate. Samples were shaken for two hours then centrifuged at 3600 rpm for 10 minutes. The solution was filtered through No. 540, Whatman filter paper; with the first 5ml of filtered solution being discarded before analysis. Na concentration were analysed using a Corning 410 flame photometer.

2.3.3 Sodium extraction preparation (influent and filtrate water)

Water samples were filtered through Whatman no. 540 paper filters before being analysed using a Corning 410 flame photometer.

2.3.4 Sodium extraction preparation (leaf tissue)

Sodium was extracted from plant material by nitric acid digestion; 0.25 g of dried and ground plant material was placed in Kjeldahl tubes. 5 ml of concentrated AnalaR nitric acid was added to all tubes and capped with glass bubbles for vapour control. The tubes were left to stand for 24 h. Tubes were placed in a digestion block and heated at 60℃ for 3 hours, after which the temperature was gradually increased to 110℃ for a further 6 hours of digestion. The glass bubbles were washed in to the digestion tubes using double deionised water to collect residue built up during the digest. This process dilutes the nitric acid before the digest liquid is filtered using Whatman 540 filter paper. Digest liquid was placed in 100 ml volumetric flasks which were made up to 100 ml with double deionised water. The Na concentrations were measured using flame photometry.

2.3.5 Soil moisture content of the samples analysed for Na concentrations

The amount of water associated with a given volume or mass of soil (soil moisture or water content) is highly variable and can change significantly within different time scales. Soil properties are more stable whilst dry and therefore should be referred to as being of a given dry soil weight. To obtain an accurate Na concentration per gram of dried soil 10 g of soil was placed in a foil boat of known weight; and dried at 105℃ over a 24 hour period. The samples were then reweighed with the difference between the sample weight before and after drying equalling the soil moisture content.

3. RESULTS AND DISCUSSION

3.1 Influent Composition

The conductivity and pH measurements of the mains water and greywater taken over the 28 days showed little change. The pH of the greywater was not dissimilar to that measured in other studies, having a range between pH 6-9 [13,14]. The pH measurements also fell within the recommended ranges set by the British Standards [11] of between pH 7-8. The electrical conductivity (EC) of the greywater was low in comparison to some other studies [15] that suggest EC results of 1000 $\mu S.cm^{-1}$ and above. Furthermore, some literary sources tend to show a greater variability in their conductivity results than in this study. The composition of the synthetic greywater, being made to a largely standard recipe of contaminants, meant that only small variations of EC between mains water and synthetic greywater samples were expected.

A higher Na concentration in greywater was expected in comparison to mains water, since the Johnsons "Soft wash" soap contains Sodium Chloride. It also contains other chemical constituents: Sodium Laureth Sulfate, Sodium Lauroamphoacetate, Sodium Hydroxide and Sodium Benzoate. The increase in Na over time (Table 2) in both mains and greywater was principally attributed to the fluctuating concentrations of Na in mains water.

3.2 Total Dissolved Solids (TDS)

When comparing filtrate samples of mains and greywater irrigated boxes, the TDS results presented few differences. The soil-water interactions seem to have led to a fairly consistent TDS content of filtrate waters. The observation made was that, in this set of tests, the substrate had a greater influence on TDS concentration in filtrate water, than initial differences between main and greywater composition.

The boxes containing plants showed a greater decrease in filtrate TDS over the soil control. TDS in the filtrate from boxes with 20 cm of substrate was less than that from boxes with 10 cm substrate (Tables 3 and 4). The filtrate water TDS from bare soil boxes was stable in comparison. The results conflict with Hardin et al. [16] who found that filtrate TDS from vegetated roofs increased over time. Their experiment however, was conducted over a 5 month period and was based on irrigation using mains water. Coleman et al. [17] found that the TDS of filtrate increased over time, although this was unexpected. Their results suggested that increases in TDS were likely to be due to the release of exudates from plant roots and/or microbial release of ions upon decomposition of dead plant roots. [17] concluded that plants directly or indirectly influenced filtrate TDS concentrations.

High transpiration rates and water uptake by plants is a likely factor in the decrease of filtrate TDS in this study. Boxes containing *Stachys* showed a decrease in the filtrate TDS over the duration of the experiment, with *Stachys* planted in the 20 cm of substrate showing the largest differences (Table 4) when compared to *Sedum*. TDS concentrations in filtrate from bare soil boxes seemed relatively stable in comparison. The results indicated that TDS constituents (organic and inorganic) were being absorbed by the plants, causing a decrease in TDS constituents in the drainage water.

3.3 pH

The influent and filtrate water results suggest that once the water had interacted with the soil matrix the pH decreases (Tables 2, 3 and 4). This is further confirmed by decreased pH in both mains and greywater filtrate samples and is suggested

Table 2. Influent composition of mains water and greywater, using averages of three box tests run in parallel, with n=3

Day	pH		Conductivity (µS cm^{-1})		Sodium (mg/l)	
	Mains water	Greywater	Mains water	Greywater	Mains water	Greywater
0	8	7.6	560	610	13.6	22.7
28	7.7	7.3	580	600	18	29.2

Table 3. Composition of filtrate water collected from boxes containing 10 cm substrate (Averaged analytical results from three boxes run in parallel, n=3; and n=2 for soil only boxes)

Parameters	Substrate depth	10 cm			
	Irrigation type	Mains water		Greywater	
	Box type	Day 1	Day 29	Day 1	Day 29
TDS (mg/l)	Soil	4500	4200	5100	3000
	Sedum	6530	2200	2730	1200
	Stachys byzantina	3330	4200	4870	3500
pH	Soil	6.2	6.5	6.6	6.8
	Sedum	6.3	6.8	6.5	6.8
	Stachys byzantina	6.9	6.85	6.6	6.9
Conductivity (µS cm^{-1})	Soil	3420	4510	4950	4840
	Sedum	3540	2280	2080	1580
	Stachys byzantina	3360	2350	4720	3720

Table 4. Composition of filtrate water collected from boxes containing 20 cm of substrate (Averaged analytical result between three box tests run in parallel, n=3; n=2 for soil only boxes)

Parameters	Substrate depth	20 cm			
	Irrigation type	Mains water		Greywater	
	Box type	Day 1	Day 29	Day 1	Day 29
TDS (mg/l)	Soil	3300	5600	5000	5300
	Sedum	6300	5070	9730	5670
	Stachys byzantina	7800	4270	10730	5200
pH	Soil	6.7	6.1	6.4	6.6
	Sedum	6.6	6.2	5.6	6.2
	Stachys byzantina	6.2	6.6	6.7	6.7
Conductivity (µS cm^{-1})	Soil	3310	5780	4740	5110
	Sedum	5770	4900	8190	5270
	Stachys byzantina	6950	4200	9780	4950

by [18] to be due to the soil-water interaction. The soil showed little or no changes in pH. If the experimental period was extended a difference in pH may have been observed between the greywater and mains water irrigated boxes, attributed to a variance of the chemical composition of the two waters.

However, comparable work by [8] demonstrated that with more highly polluted greywater (laundry water) being used for irrigation, and an extended experimental period, soils are more severely affected. The experiments led to observations of higher soil pH, soil micro-nutrient deficiencies, sodium and zinc accumulation and plant health deterioration. Anwar [18] explains that if soil pH were to exceed pH 9, dissolution of organic material and dispersion of soil particles can occur. Dissolved organic matter is likely to leach out of the soil, leading to degradation over time, affecting plant health and survival. Anwar [18] suggest greywater affects the soils once used for irrigation. Product variability, activity in which greywater is generated and the quality of water supply will all contribute to the composition of the greywater, therefore affecting its pH [19]. Substrate depths seem to have little effect on pH of soil and filtrate water. The results have shown that a deep substrate leads to higher variability of pH values when compared to the shallower substrate boxes. This is likely due to the higher irrigation volumes applied to 20 cm substrate boxes. Results indicate that in the short term, soil and filtrate pH values were not adversely affected by irrigation with synthetic greywater. The presence of plants seems to have little impact on soil and filtrate pH, however; this may be due to the short experimental period.

3.4 Electrical Conductivity

The Electrical conductivity of the filtrate water increased as it passed through the soil matrix (Tables 3 and 4) which was also seen in results presented by [20]. The boxes containing 20 cm of substrate produced higher conductivity value filtrate water, likely due to the larger soil volume and higher water retention time. The results suggested that the soil influenced the filtrate conductivity to a higher degree than the constituents in the synthetic greywater. However, these results may vary, dependent on the type of greywater used for irrigation and substrate composition.

The soil (Tables 5 and 6) and filtrate samples collected from planted boxes (both 10 cm and 20 cm) suggested a decrease in conductivity over

Table 5. Results of soils analysis from boxes containing 10 cm of substrate (Averaged analytical result between three box tests run in parallel, n=3; n=2 for soil only boxes)

Parameters	Substrate depth	10 cm			
	Irrigation type	Mains water		Greywater	
	Box type	Day 1	Day 29	Day 1	Day29
pH	Soil	5.6	5.7	5.8	6.1
	Sedum	6.1	6.2	6	5.9
	Stachys byzantina	6	5.9	5.8	5.7
Conductivity (µS cm^{-1})	Soil	420	420	510	450
	Sedum	430	240	220	260
	Stachys byzantina	470	450	380	320

Table 6. Results of soil analysis of boxes containing 20 cm of substrate (Averaged analytical result between three box tests run in parallel, n=3; n=2 for soil only boxes)

Parameters	Substrate depth	20 cm			
	Irrigation type	Mains water		Greywater	
	Box type	Day 1	Day 29	Day 1	Day 29
pH	Soil	5.5	6.1	5.7	6.6
	Sedum	5.6	6.1	5.5	6.2
	Stachys byzantina	6	6.6	5.8	6.7
Conductivity (µS cm^{-1})	Soil	440	360	510	350
	Sedum	490	340	390	330
	Stachys byzantina	470	330	540	440

the experiment period. This was expected as it was assumed that plants would absorb some charged ions. Due to increased Na concentrations in plant tissue, it was assumed that other unmeasured, charged ions were also absorbed by the plants, contributing to an overall decrease in filtrate water conductivity.

Stevens et al. [21] produced tables of conductivity values associated with risk to plant health. When comparing EC results of this study to that of the results presented by [21] it suggests that irrigation with synthetic greywater poses insignificant impact on 95% of the garden plants. [21] highlights that garden plants as part of their study are those plants that are not grown within a household or are classified as a crop plant. This result is likely to be due to similarities in the conductivity of both the influent mains and greywater samples. Plant health was affected by the type of irrigation received. Visual inspection revealed that *Stachys* irrigated with greywater seemed to deteriorate over the course of the experiment. This could be linked to greywater irrigation, but other factors including over watering and green house temperatures could cause poor health. *Sedum* showed no signs of being adversely affected by the greywater irrigation; furthermore, the possibility had to be considered that plant growth could even have been enhanced.

3.5 Sodium Analysis: Sodium Concentration of Water Samples and Soils

Na concentrations in the filtrate (Table 7) of all boxes increased as it passed through the soil matrix due to ionic exchange between the soil and the influent water. It may therefore be suggested that a longer retention time of influent water equated to a larger quantity of Na becoming entrained. The results seem to support this suggestion, since the 20 cm substrate boxes, due to their larger drainage area, had higher Na concentration in the filtrate samples compared to the 10 cm substrate boxes.

When irrigating, all boxes displayed signs of water ponding in the lower parts of the substrate. A higher presence of water or moisture lower in the substrate may have led to increased Na concentration due to its highly soluble nature and leaching potential. The presence of moisture weakens the bond between Na and the soil allowing it to be transported in the box. An experiment was conducted on a 20 cm bare soil box, to establish the moisture differences between the top and bottom layers of substrate. This confirmed that after irrigation, more moisture is present in lower layers compared with the top. A soil moisture probe was used to test the top 5cm and the bottom 5cm of the substrate and compared how the moisture varied after 1, 3 and 7 days. The results showed that the moisture content in the bottom 5 cm of the soil was consistently higher with 44%, 27% and 34% more moisture present after 1 day, 3 days and 7 days respectively. Due to a constant presence of moisture in lower parts of the substrates, it is likely that Na, due its high solubility, was kept in an aqueous state during the experiment, once extracted from the soil. Using the standard soil moisture method to determine when boxes should be irrigated, may have led to inconsistent degrees of soil moisture saturation. The moisture content was measured in the top 5 cm of soil. It is now known that the moisture concentrations of the lower parts of the boxes were significantly higher than those of the top. This meant that the moisture content, obtained from the top part of the soil profile did not represent the total moisture concentration in each box. This problem would have caused higher than necessary irrigation rates, meaning that moisture was likely present at the bottom of the boxes in relatively high quantities, for the entire experiment. The presences of moisture at the bottom of the boxes and the higher than necessary irrigation rate could enable large quantities of Na to leach from upper to lower parts of the soil profile. The soil Na, in most boxes increased over the experiment period, which is likely caused by the method of irrigation, whereby the boxes were not irrigated to saturation.

Analysis of plant tissues indicated Na accumulation of between 0.55 and 0.72 ($mg^{-1}g^{-1}l^{-1}$) (Table 8). The evidence indicated that irrigation with greywater tends to lead to higher Na absorption in leaf tissue than when compared to those irrigated using mains water, due to the higher concentrations of Na in greywater. The tissue of plants in the 20 cm substrate boxes demonstrated a greater increase in Na concentrations than plants grown in 10 cm substrate. Both a greater volume of soil and a greater volume of water were available to the plants in the 20 cm substrate boxes, thereby meaning that a greater mass of Na was available in those boxes. It is likely that the volume of water applied to the 20 cm box was the greater influence of the increase sodium in these boxes. Due to the duration of the experiment being short, some parts of the soil profile in the 20 cm boxes would not have been penetrated by the root system. However, both the *Sedum* and *Stachys* showed root growth penetrating the soil profile. *Stachys* showed some evidence of penetrating to lower depths of the soil profile, but results due to the experimental timing was inconclusive. It could be suggested that both the *Sedum* and *Stachys* root balls would, in time grow to use the volume substrate available to them.

The most significant result found when undertaking statistical analysis, using an unbalanced ANOVA showed that *Stachys* has the highest percentage increase of Na in the leaf tissue over the experimental period when irrigated with greywater rather than mains water (*p=0.076).* This links well with the visual inspection which showed that greywater irrigation affected *Stachys* more adversely than *Sedum,* since death on the edges of the leaves had occurred, which is indicative of high Na accumulation. It could therefore be suggested that prolonged greywater irrigation to *Stachys* could cause further plant health deterioration.

A mass balance approach was used to establish where Na from the influent water would be stored and lost. Different boxes were irrigated with different volumes of water, dependent on the soil moisture explained above. For each individual box, the total amount of Na applied, through irrigation, was calculated by multiplying the total volume of water irrigated by the average Na concentrations seen in either the mains or greywater samples. In all cases the mass balance equation showed an excess of Na that was not accounted for, either by storage in the plants or soils, or losses through filtrate water.

Table 7. Na results from soil and filtrate analysis of boxes containing 10 cm and 20 cm of substrate (Averaged analytical result between three box tests run in parallel, n=3; n=2 for soil only boxes)

	Substrate depth	Box type	Irrigation type			
			Mains water		Greywater	
			Day 1	Day 29	Day 1	Day 29
Na concentrations from filtrate samples (mg/l)	10 cm	Soil	75.7	125.7	100	114
		Sedum	91.6	95.56	68.8	87.7
		Stachys byzantina	116.2	125	150.3	160.3
	20 cm	Soil	70.4	134.5	105.1	129.1
		Sedum	115.9	136.1	187.3	197.3
		Stachys byzantina	173.8	177.6	242.8	221.9
Na concentrations from substrate samples (mg/l)	10 cm	Soil	45.3	39.8	35.4	44.4
		Sedum	29.2	34.1	25.2	28.8
		Stachys byzantina	31.9	56.9	31.1	48.4
	20 cm	Soil	36	40.1	39.4	38.7
		Sedum	31.1	43.1	33.3	42.6
		Stachys byzantina	32.1	39	34.8	37.8

Table 8. Sodium concentrations of leaf tissue for both 10 cm and 20 cm substrates (Averaged analytical result between three box tests run in parallel, n=3)

Parameters	Substrate depth	10 cm			
	Irrigation type	Mains water		Greywater	
	Box type	Day 1	Day 29	Day 1	Day 29
Sodium per g. leaf tissue (mg/g)	*Sedum*	7.5	8.3	7.5	8.1
	Stachys byzantina	11.4	12.3	11.4	16.3
Sodium per gram of leaf tissue per litre of irrigated water ($mg^{-1}g^{-1}l^{-1}$)	*Sedum*	-	0.67	-	0.72
	Stachys byzantina	-	0.55	-	0.77
	Substrate depth	**20 cm**			
Sodium per g. leaf tissue (mg/g)	*Sedum*	7.5	11.4	7.5	9.3
	Stachys byzantina	11.4	13.6	11.4	17.9
Sodium per gram of leaf tissue per litre of irrigated water ($mg^{-1}g^{-1}l^{-1}$)	*Sedum*	-	0.57	-	0.58
	Stachys byzantina	-	0.52	-	0.67

There are a number of reasons why the Na concentrations may not balance in the mass equation. Firstly it is suspected that there may have been unequal water distribution when the boxes were flushed. It is plausible to assume that water collected during the flushing event was not representative of the entire box. Due to the box design water would have ponded in some areas of the box unable to leave via the drainage holes drilled in the underneath of the box. These ponded areas may have caused Na to accumulate rather than leave the system, possibly leading to a slight under representation of Na concentrations in the filtrate.

The soil sampling method may have led to an under-representation of Na concentrations. If leaching in the soil profile occurred, concentrations of Na would be greater in deeper parts of the substrate. The sampling method took five soil samples for the entire depth of the substrate in each box. The samples were combined and subsampled for further analysis. Higher concentrations of Na would therefore be under represented in the combined sample, since the averaged result would give a lower Na concentration, compared to that in the deeper parts of the substrate. Further analysis is needed at 1 to 2 cm intervals in the soil substrate, to calculate Na concentrations throughout the soil profile.

The mass balance approach was also affected by leakage from the boxes following irrigation. While the watering method was conducted with attention to detail to prevent leakages, it is impossible to achieve 100% certainty, and thus, Na mass would be lost through undetected leakage. As plant roots were not analysed it is possible that some Na, unaccounted for in the mass balance equation is likely to have been absorbed and stored in the root system.

4. CONCLUSION

Green roofs can be an important element of infrastructure in urban areas but management plans are required if their full potential is to be achieved and maintained. If green roofs are to be widely implemented in urban areas, their irrigation requires careful consideration. An increasing scarcity of drinking water resources could lead to green roof irrigation becoming a lower priority requirement. The outcomes of this research established how different plants, substrate depths and types of water can affect filtrate quality, and also how the substrates and plants react to synthetic greywater irrigation. Green roof management plans must be designed to take into account decisions about plant types, substrate types and depths, greywater type and purity, and the long term effects of all of these factors. This study has demonstrated that greywater, if applied appropriately, can be used for green roof irrigation. It is recommended that a periodic self-assessed monitoring programme of filtrate greywater quality is undertaken to check its suitability for application to green roofs and plant health. Assessments of long term use of greywater for irrigation on green roofs are required to assess whether green roofs are capable of receiving sustained greywater irrigation.

This research indicated that after irrigation water had percolated through the John Innes substrate, the water quality decreased. By utilising a 'simple' synthetic greywater composition, variances arising from experimental, operational and system variables were better controlled and less subject to random variations. A substrate should therefore be assessed for its ion-holding and exchange capacity. Further research is required to understand how substrates can be designed and implemented in a green roof context, to improve water quality, for collection and reuse in further applications, for example for toilet flushing.

With respect to greywater types, an increased understanding of the chemical composition of greywater and how the dynamics of green roof systems may benefit from greywater irrigation as well as increase knowledge of planning and implementation of green roofs are required. Further knowledge is required, to gain an improved understanding of the long term effects of greywater or synthetic greywater irrigation of green roof systems, since currently this is limited. Over a longer time period chemicals and dissolved solids are likely to accumulate in the soils and plants [22]. Green roof designs should include hardy plants with a high Na tolerance if irrigated with greywater. The evidence suggests greywater composition will affect the amount of Na accumulation in soils and plant tissues.

Greywater is a precious resource which can be utilised to benefit climate change adaptation and mitigation measures, including green roofs. Greywater has been demonstrated as a viable alternative to potable water, for the application to green roofs provided a strict monitoring process and management regime is in place. The success of such as approach to irrigate green roofs with greywater is also significantly based on green roof design with respect to the choice of plants, the depth and type of substrate and the irrigation levels.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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