Reuse potential of laundry greywater for irrigation based on growth, water and nutrient use of tomato

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SUMMARY

Greywater is considered as a valuable resource with a high reuse potential for irrigation of household lawns and gardens. However, there are possibilities of surfactant and sodium accumulation in soil from reuse of greywater which may affect agricultural productivity and environmental sustainability adversely. We conducted a glasshouse experiment to examine variation in growth, water and nutrient use of tomato (*Lycopersicon esculentum* Mill. cv. Grosse Lisse) using tap water (TW), laundry greywater (GW) and solutions of low and high concentration of a detergent surfactant (LC and HC, respectively) as irrigation treatments. Each treatment was replicated five times using a randomised block design. Measurements throughout the experiment showed greywater to be significantly more alkaline and saline than the other types of irrigation water. Although all plants received sixteen irrigations over a period of nine weeks until flowering, there were little or no significant effects of irrigation treatments on plant growth. Soil water retention following irrigation reduced significantly when plants were irrigated with GW or surfactant solutions on only three of twelve occasions. On one occasion, water use measured as evapotranspiration (ET) with GW irrigation was similar to TW, but it was significantly higher than the plants receiving HC irrigation. At harvest, various components of plant biomass and leaf area for GW irrigated plants were found to be similar or significantly higher than the TW irrigated plants with a common trend of GW ≥ TW > LC ≥ HC. Whole-plant concentration was measured for twelve essential plant nutrients (N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn, Mo and B) and Na (often considered as a beneficial nutrient). Irrigation treatments affected the concentration of four nutrients (P, Fe, Zn and Na) and uptake of seven nutrients (P, K, Ca, Mg, Na, Fe and B) significantly. Uptake of these seven nutrients by tomato was generally in the order GW ≥ TW > HC ≥ LC. GW irrigated plants had the highest concentration of P, Na and Fe which were 39-85% higher than the TW irrigated plants. Compared with tap water irrigated plants, greywater irrigated plants removed only 6% excess B, but substantially greater quantity of Na (83%) and Fe (86%). These results suggest that laundry greywater has a promising potential for reuse as irrigation water to grow tomato.

Keywords: Evapotranspiration; Greywater; Irrigation; Nutrient uptake; Surfactants; Water use

Introduction

Greywater is the non-toilet component of household wastewater that originates predominantly from laundries and bathrooms of residential buildings. Greywater is a potentially reusable water resource for irrigation of household lawns and gardens (Al-Jayyousi, 2003) as diversion of laundry effluent into gardens and lawns is technically possible without treatment (Jeppesen, 1996).

Laundry greywater usually contains varying levels of suspended solids, salts, nutrients, organic matter and pathogens (Christova-Boal et al., 1996; Howard et al., 2005) which arise from washing of clothes using detergents. Although public health risks associated with reuse of greywater are well studied (Ottoson and Stenström, 2003; Gross et al., 2005), information on the interaction of soils and plants with greywater is limited (Eriksson et al., 2003).

Laundry detergents contain a range of chemical substances that include surfactants, builders, bleaching agents and auxiliary agents or additives (Smulders, 2002). A large proportion of the ingredients of laundry detergents are essentially non-volatile compounds dominated by salts. Some of the salts present in greywater can be beneficial to plants, particularly nutrients, although a balanced concentration of nutrients is required to avoid nutrient deficiency or toxicity in plants. Possibilities of accumulation of sodium (Misra and Sivongxay, 2009) and boron (Gross et al., 2005) in soil from greywater irrigation may affect soil properties and plant growth adversely. Although there are no reports currently available to indicate how growth and

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nutrient deficiency or toxicity symptoms may arise in plants irrigated with laundry greywater, it has been suggested that high pH (pH>9) and high concentrations of sodium (with Sodium Adsorption Ratio, SAR > 10), zinc and aluminium in greywater may reduce plant growth with direct and indirect effects on soil properties (Christova-Boal et al., 1996).

Surfactants are a class of synthetic compounds commonly found in greywater as residues of laundry detergents (Smulders, 2002) and other household cleaning and personal care products (Eriksson et al., 2003). Surfactants have been also detected in various wastewater (e.g. municipal wastewater, Brunner et al., 1988) and in groundwater in areas after long-term land application of wastewater effluent (Field et al., 1992). Surfactants are not only used in the detergent industry, but also in agriculture and horticulture as soil conditioners to improve soil structure, infiltration and to control erosion (Abu-Zreig et al., 2003). Surfactants in irrigation water (including greywater) are known to modify the hydraulic conductivity of soils significantly (Abu-Zreig et al., 2003; Shafran et al., 2005) and it has been suggested that significant accumulation of surfactants in soils may ultimately lead to water repellent soils with adverse impacts on agricultural productivity and environmental sustainability (Shafran et al., 2005; Wiel-Shafran et al., 2006). The extent to which surfactants can modify the soil-water balance (Kuhnt, 1993) and influence water use and plant growth is not well known.

Although surfactants have been used in agriculture for decades to improve application of herbicides and other chemical products to plants (Parr and Norman, 1965), some plants grown in hydroponic systems with added surfactants have exhibited phytotoxic symptoms (Bubenheim et al., 1997; Garland et al., 2000; Garland et al., 2004). When untreated greywater is used to irrigate plants growing in soil, the fate of surfactants in greywater irrigated soil-plant systems is not well known.

The aim of this study is to evaluate the reuse potential of laundry greywater by examining growth, water and nutrient use of tomato (*Lycopersicon esculentum* Mill. cv. Grosse Lisse) which is a common plant in many household gardens in Australia. In this study, tomato plants were irrigated with laundry greywater and surfactant solutions to separate the effects of detergent surfactants alone on soil-plant system from surfactants combined with other pollutants (as in greywater).

Materials and methods

We conducted an experiment in a glasshouse using soil from the Agricultural Field Station complex (27°36′36″S, 151°55′48″E, 693 m elevation) of the University of Southern Queensland, Toowoomba, Australia. The soil at the experimental site is a moderately deep, well structured Red Ferrosol (Isbell, 1996) that is a fertile soil distributed throughout Australia and developed from olivine basalt of lower Miocene age containing kaolinite and hematite with small amounts of montmorillonite clays (Beckmann et al., 1974).

Sufficient soil (approx. 60 kg) was collected from the top 10 cm depth in the field and was brought to the laboratory for drying and sieving to reduce aggregate size to <4.75 mm. Subsamples of this soil (<2 mm fraction) was analysed for a range of soil properties. The soil contained 38.5% sand, 20.7% silt and 40.8% clay, and organic carbon of 35 g kg^{-1}. Volumetric soil water content at water potentials (ψ) of -10 and at -1500 kPa were 36.5 and 27.0%, respectively. The pH and EC (Electrical Conductivity) of the soil at a soil-water ratio of 1:5 were 6.35 and 30.7 $\mu S\ cm^{-1}$, respectively; and CEC (Cation Exchange Capacity) was 16.3 $cmol_c\ kg^{-1}$.

Preparation of pots

Air-dry soil was first mixed with sufficient tap water to increase its water content to 32% by weight (approx. 1.2 times the plastic limit of soil) and kept covered under a plastic sheet for over-night equilibration. After equilibration, soil was mixed for uniform distribution of moisture and was packed in PVC pots (190 and 160 mm, top and bottom diameter respectively, and 190 mm height). Soil was compacted to a final depth of 150 mm in each pot to achieve a bulk density of 1.05 Mg m^{-3}. This bulk density was chosen to simulate soil conditions in a recently prepared garden bed for this soil (Misra and Sivongxay, 2009). For uniform compaction, soil in each pot was compacted in three layers of 50 mm thickness and the surface of the each compacted layer was slightly disturbed with a spatula before packing the next layer to reduce soil layering. Average soil volume in each pot with a soil depth of 150 mm was found to be 3.66 L. The volume of soil, its initial gravimetric water content and the bulk density were used to estimate various components of water balance (including water use or evapotranspiration, ET) for each pot. As water balance components are commonly expressed in depth of water (in mm or cm), average soil surface area measured for the pots was used to estimate water use and related parameters in mm.

Irrigation treatments

Twenty pots were placed on the glasshouse bench using a randomised block design to allocate four irrigation treatments randomly in each of five blocks (replicates). Irrigation treatments used for the experiment included:
Tap water (TW) – sampled from a designated tap in an adjacent laboratory;
Greywater (GW) – laundry greywater as detailed below;
Low concentration of surfactant (LC) – to represent average detergent surfactant concentration of 15 mg L^{-1} that may be found in greywater (see below);
High concentration of surfactant (HC) – to cover a wide range of surfactant concentrations that may be present in laundry greywater (150 mg L^{-1}).

In these experiments, we collected laundry greywater using the Dynamo liquid detergent (Colgate-Palmolive Pty Ltd, Sydney) throughout the experiment without any fabric softener. A T-shaped flow splitter was connected to the washing machine that allowed greywater sample of at least 15 L. Each sample of greywater was approx. 6.7% of the total greywater generated from the wash and rinse cycles together (Howard et al., 2005). As storage of untreated greywater is not a recommended practice for health reasons (Jeppesen, 1996) and most constituents of greywater are potentially degradable, all untreated laundry greywater was used as soon as possible (within 4 h of collection) to irrigate GW designated pots.

Prior to the irrigation experiment, laundry greywater was initially sampled from two washes separately for rinse and wash cycles to determine the surfactant concentration of LC and HC irrigation water. The greywater samples were analysed with the MBAS (Methylene Blue Active Substance) method to determine anionic surfactant concentration (Method 5540C, APHA, 2005). The surfactant concentration in laundry greywater was 15.5 mg L^{-1} (SE = 4.2, n = 4). An industrial grade detergent surfactant Gardilene® HS80AU (Albright&Wilson (Australia) Ltd, Sydney) was used to prepare LC and HC irrigation water by dissolving 15 and 150 mg of the surfactant, respectively in 1 L of distilled water. Gardilene® HS80AU is an off white powder, 80% of which includes the anionic surfactant sodium alkylbenzene sulfonate (also known as sodium dodecylbenzene sulfonate or sodium $C_{10\text{-}16}$ alkylbenzene sulfonate).

Experimental procedure

A portable weather station was mounted at approx. 1 m height above the glasshouse bench adjacent to the pot experiment to record air temperature and relative humidity at hourly intervals throughout the experiment. Daily maximum and minimum air temperature during the experimental period was in the range of 10.8-28.9 °C and relative humidity 31-72%. Daily estimates of reference crop evapotranspiration (ET_0) with the FAO 56 method (Allen et al., 1998) was also collected for the experimental site (Jeffrey et al., 2001; QDNRM, 2008).

Before planting, a spoon of Osmocote® fertilizer (7.97 ± 0.33 g) was mixed uniformly with the top 5 cm of soil. The fertilizer contained all essential macro- and micro- nutrients required for plant growth. Five seeds of tomato (*Lycopersicon esculentum* Mill. cv. Grosse Lisse) were planted in each pot on 21 August 2006 and were thinned to a single seedling per pot 19 days after planting. Each pot was placed over a PVC dish, slightly elevated with wooden disc inserts, to collect drainage.

Irrigation treatments (TW, GW, LC and HC) were given to all pots 4 days before planting and subsequently at a frequency of 1-2 irrigations per week for a period of 9 weeks. Full irrigation was given to each pot until drainage. During irrigation, irrigation water was added slowly at the centre of the pot to ensure that it was distributed throughout the pot and to avoid water flow along the soil-pot interface. Frequency of irrigation varied over time to avoid significant water deficit to plants. Within the first four weeks of planting, irrigation was given every 5th day. Afterwards, it was applied every 3rd or 4th day until flowering. Plants were harvested soon after flowering on 24 October 2006 for final measurements.

Measurements

The volume of irrigation water and drainage for each pot was measured throughout the experiment. Net amount of irrigation water retained in soil during an irrigation event was measured by weighing each pot before irrigation and 2-4 h after irrigation (when drainage ceased) with an electronic platform balance of 32 kg capacity (±0.01 g). Soil water content was additionally measured in eight pots (2 replicates of 4 treatments) using TDR (time domain reflectometry) sensors (each consisting of three, 10 cm long, parallel waveguides) inserted into the soil in each pot from the top. The weight of each pot (with or without a TDR sensor) was used to estimate net amount of irrigation water retained at each irrigation and loss of water from pots via evapotranspiration (ET) from previous irrigation.

A Trase system (Model 6050X1, Soil Moisture Equipment Corporation, USA) was used to obtain TDR readings (apparent permittivity, k_a). TDR sensors were calibrated separately by packing the experimental soil in four pots at the same bulk density and initial soil moisture content as the soil used for the irrigation experiment. After installation of TDR sensors, all pots were irrigated to saturation with tap water and allowed to dry in a laboratory bench for over a fortnight. Temporal variation in TDR readings and the weight of the pots were used from saturation to water content slightly below the moisture content measured during the irrigation experiment (approx. $k_a = 7$). A single calibration equation was developed by combining k_a readings from all TDR sensors to estimate volumetric soil water content (θ, %). The following calibration equation was used to convert k_a readings in the irrigation experiment to θ (%).

$$\theta = 5.613\, k_a^{0.607}. \qquad (r^2 = 0.94, p \leq 0.001) \qquad (1)$$

Prior to irrigation, each type of irrigation water was either freshly prepared (LC and GC treatments) or collected as described before (for TW and GW treatments). The pH and electrical conductivity (EC) of samples of irrigation water was measured before and after each irrigation event with a pH meter (TPS model MC80, Brisbane, Queensland) and EC meter (TPS model MC84, Brisbane, Queensland) fitted with calibrated electrodes using the manufacturer instructions. The ion composition of irrigation water (TW and GW) and drainage water was not determined as it has been recently reported (Misra and Sivongxay, 2009). The concentration of Na in GW is usually >4 times the concentration in TW; however, the soil used in the current study when irrigated with GW tends to retain most sodium (Na) such that the drainage water becomes similar in ionic composition to TW.

Throughout the experiment, plant health was monitored in each of the 20 pots for any obvious symptoms of nutrient deficiency and/or toxicity and insect or disease attack. Plant growth and development was measured periodically following thinning. Length of a specific branch (3rd from the base) of each plant was measured from the node to the branch tip. The length of 2nd leaf from this branch was also measured over time. At harvest, plants were severed close to the soil surface and were sorted into stems, branches and leaves. Leaves of each plant were further sorted into various size classes and a sample of 20% of all leaves of each plant representing various size classes were used for the measurement of leaf area with a LI-3100C leaf area meter (Li-COR Biosciences, Lincoln, Nebraska, USA). Fresh leaf weight and leaf area of sample was used to estimate the total leaf area of the plant for each replicate pot.

The root system of each plant was removed from soil after overnight soaking of each pot in tap water. The whole root system of the plant with some soil attached to the root system was removed first. The remaining soil with roots was washed over a sieve with a 2 mm pore size to reduce root loss during washing. Fresh roots were dried with a paper towel before drying at 55°C for 48 hours in a convection oven to determine dry weight. The dry weight of stems and branches of all plants was also measured in a similar way.

Chemical and statistical analysis

Approximately 25% of each dry component of the plant was combined and were ground to reduce their size to <1 mm. Nitrogen concentration in subsamples of dry matter was measured with Dumas combustion method using a Leco nitrogen analyser (AOAC 1996). The concentrations of P, K, Ca, Mg, S, Na, Fe, Cu, Mn, Zn, Mo and B were measured on separate subsamples following acid digestion (Benton-Jones et al., 1991) using an inductively coupled plasma with optical emission spectroscopy (ICP-OES).

Most data on growth, evapotranspiration (ET) and its components, plant biomass, nutrient concentrations and uptake were analysed using the analysis of variance recommended for randomised block design (Snedecor and Cochran, 1989). Whenever a measured variable was found to be significantly affected by irrigation treatments ($p \leq 0.05$), mean values were compared with an estimate of least significant difference (LSD). On some occasions, when measurements did not include all the five replicates of four irrigation treatments, standard error was used to compare mean values.

Results

During the experiment, tomato plants were irrigated 16 times with various types of irrigation water, viz. tap water (TW), laundry greywater (GW), water with low surfactant concentration (LC) and high concentration of surfactant (HC). The pH and EC of each type of irrigation water was measured before and after irrigation to evaluate their overall chemical quality.

pH and EC of irrigation water

Table 1 shows the variation in pH and EC of irrigation water used for various treatments. As expected, greywater was significantly more alkaline than the other types of water used for irrigation. The pH of various irrigation waters was in the order GW > TW > LC > HC with a maximum difference of slightly above 1 pH unit. Both tap water and greywater contained significantly more dissolved salts than the surfactant solutions (LC and HC) as indicated by EC values (Table 1).

Table 1. Variation in pH and EC of irrigation treatment (Tap water, TW; Greywater, GW; Surfactant solutions of low concentration, LC; and high concentration, HC) before and after irrigation throughout the experiment. Values followed by ± sign indicate standard error, SE (n = 16).

Treatments	pH			EC (µS cm^{-1})		
	Before irrigation	After irrigation	Mean	Before irrigation	After irrigation	Mean
TW	6.86 ± 0.06	6.79 ± 0.09	6.83	477.6 ± 3.1	491.7 ± 2.5	484.7
GW	8.15 ± 0.12	7.92 ± 0.11	8.04	653.3 ± 3.1	665.4 ± 8.8	659.4
LC	7.80 ± 0.14	7.88 ± 0.91	7.84	10.0 ± 0.2	10.4 ± 0.2	10.2
HC	7.31 ± 0.12	7.19 ± 0.10	7.25	62.8 ± 3.1	64.9 ± 3.2	63.9

A comparison of EC for LC and HC treatments indicated a six-fold increase in EC with a ten-fold increase in the surfactant concentration. EC for TW and GW was approx. 48-65 times higher than the EC of water containing low surfactant concentration (LC). Low salt levels (low EC) found for surfactant solutions in this experiment was due to the use of distilled water in making these solutions. Since anionic surfactants used in our experiments (sodium alkylbenzene sulfonate) are salts of strong bases and weak acids, their solutions are slightly alkaline, but their contribution towards the salinity of irrigation water was low.

Components of water balance and water use

The amount of water retained within soil for 12 irrigation events is shown in Fig. 1 and variation in volumetric soil water content (θ) over time in Fig. 2. All irrigation treatments commenced with the first irrigation at 4 days before planting. However, all pots were irrigated inadvertently with tap water 2 days after planting (DAP) that caused some delay to the 2nd irrigation given at 8 DAP. Pot weights also could not be obtained for the irrigation at 23 DAP. Although these data are omitted from Fig. 1, values of θ for all irrigation events can be seen in Fig. 2. Soil water content oscillated from slightly above nominal field capacity (ψ = -10 kPa) to well below nominal wilting point (ψ = -1500 kPa). Statistical analysis for irrigation treatment effects on values of θ was not made because these were limited to two replicate pots only.

Water retained during a given irrigation is a function of water deficit present in the soil at the time of irrigation (arising from ET losses from the previous irrigation) and the water that could be retained by the soil following an irrigation and drainage. Significant effects of irrigation treatments were detected for 3 of the 16 irrigation events analysed. Statistical effects of the irrigation treatments were evident during the early period of plant growth when soil water deficit was modest and soil water content remained above the nominal wilting point.

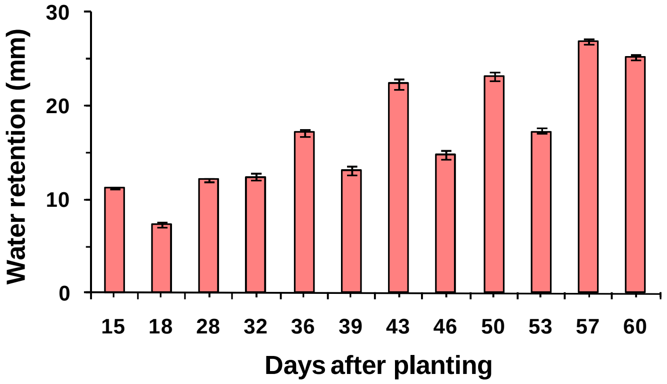

Fig. 1. Variation in soil water retention following irrigation and drainage for various irrigation treatments (TW, GW, LC and HC) during the experiment with tomato plants. Vertical bars over mean values indicate standard errors ($n = 20$).

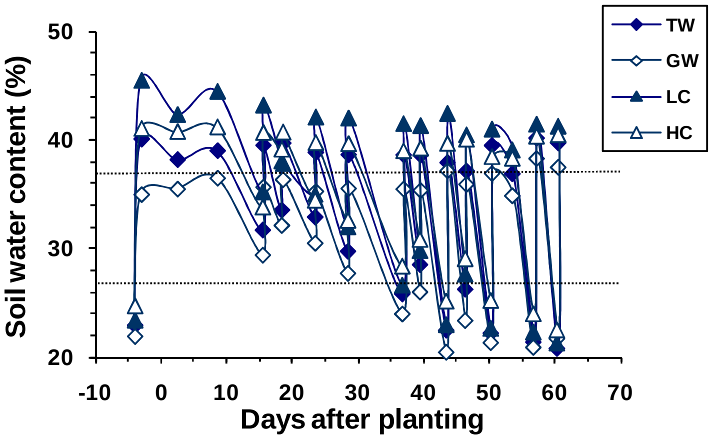

Fig. 2. Variation in volumetric soil water content during the irrigation experiment with four treatments (TW, GW, LC and HC) given to tomato plants. Top and bottom lines superimposed over the soil water content indicate water retained at -10 and -1500 kPa, respectively. Average standard errors of mean values for 2 replicate pots (not shown for clarity) ranged from 0.8-3.1% for LC and TW treatments, respectively.

Mean values of water retention for these irrigation events are shown in Table 2. Soil treated with HC and GW treatments retained lower quantity of water than TW and LC treatments for the first two irrigation events. On the third occasion, water retention for the soil receiving HC treatment was lower than the other treatments. As plant growth remained similar in all pots (details given later), it may appear that irrigation water containing high concentration of surfactants and/or combined with other pollutants (as in GW) can reduce soil water retention. The data in Fig. 2 also showed soil water content (θ) to remain in the order GW < TW < HC < LC following irrigation.

Soil water deficit due to ET losses was high during the late vegetative growth phase of tomato (40 DAP onward, Fig. 2). As our experiment focussed to examine the effects of different types of irrigation water on ET, ET data were not corrected for plant biomass accumulated during the measurement period. Values of ET, averaged over all treatments, are shown in Fig. 3 along with the reference ET (ET_0, estimated with the FAO-56 method) for the corresponding period to indicate the magnitude of atmospheric demand. ET from all irrigation treatments were similar or exceeded the reference ET shortly after 39 DAP. However, any significant effect of irrigation treatments on ET was observed only once at 50-53 DAP ($p = 0.03$, LSD = 1.3 mm). At that time, ET (in mm) was in the order GW $(19.5)^{a}$ = TW $(19.5)^{a}$ ≥ LC $(18.1)^{ab}$ ≥ HC $(17.8)^{b}$, where different superscripts indicate significant difference > LSD. These data indicate that plant water use with greywater and tap water was similar but reduced only when surfactants were present at high concentration.

Table 2. Effects of irrigation treatments on soil water retained following irrigation and drainage. Different superscript letter(s) near mean values under various irrigation treatments on a specific day after planting (DAP) are significantly different at *p*≤0.05 when the difference exceeds the least significant difference (LSD).

Irrigation at DAP	Water retained from irrigation (mm)				LSD
	TW	GW	LC	HC	
-4	22.6^a	21.1^b	22.5^a	21.3^b	1.0
28	12.6^a	11.7^b	12.6^a	11.9^{ab}	0.8
36	18.3^a	17.7^a	17.7^a	15.5^b	2.0

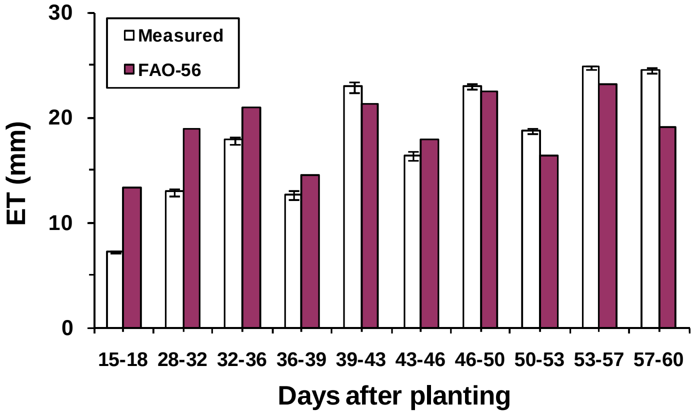

Fig. 3. Variation in evapotranspiration (ET) during successive irrigation cycles of various irrigation treatments given to tomato plants. Reference ET estimated with the FAO-56 method for the corresponding period is shown. Vertical bars over mean values indicate standard errors (*n* = 20).

Plant growth and biomass

Although elongation of leaf, branch and stem (plant height) was measured on 9-10 occasions throughout the growth period, these were not significantly influenced by the irrigation treatments. Temporal variation in plant height and elongation of selected leaf and branch are shown in Fig. 4. These data indicate that plant-to-plant variation in growth was small (small SE in Fig. 4) and was unaffected by irrigation treatments. Temporal variation in plant height (Fig. 4) and number of leaves per plant (data not shown) was mostly exponential until harvest time at flowering which indicates that resources were not limiting plant growth. However, variation in leaf and branch elongation was exponential for a brief period and became asymptotic with age. There was a change in the growth and elongation rates of tomato (as seen from the change in the slope of the plant height data in Fig. 4) around 43 DAP that corresponded with an increase in ET above ET_0 at 39-43 DAP (Fig. 3) and increased soil water deficit around similar time (Fig. 2).

Although cumulative growth was unaffected by irrigation treatments, most components of plant biomass and leaf area at harvest were significantly affected by irrigation treatments ($p<0.05$), except root biomass. Greywater irrigated tomato plants had similar or higher leaf and stem biomass than tap water irrigated plants (Fig. 5). Significant reduction in various components of plant biomass and total biomass occurred for plants irrigated with surfactant solutions, especially at high concentrations (HC). Biomass and its components were mostly in the order GW ≥ TW > LC ≥ HC. Although root biomass was unaffected by irrigation treatments, root shoot ratio was significantly higher for plants irrigated with HC (Fig. 6). This indicates that irrigation with surfactants may have exposed tomato plants to nutrient and/or water stress within the root zone. However, when surfactants are combined with salts or nutrients, as in greywater, plant growth responses were favourable. This view is well supported by significantly higher ($p < 0.001$) leaf area observed for greywater irrigated plants over other irrigation treatments (Fig. 6).

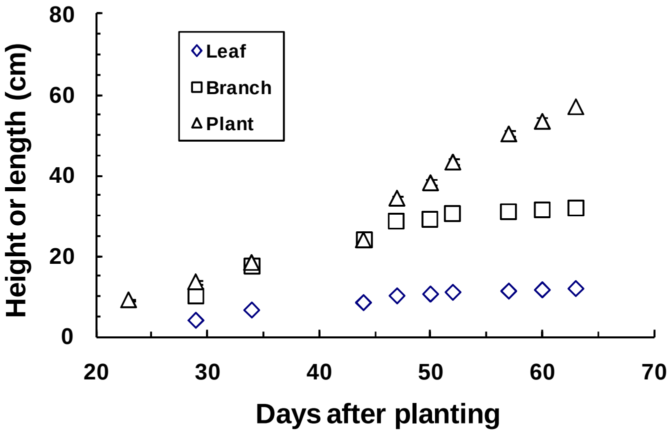

Fig. 4. Temporal variation in lengths of leaf and branch, and height of tomato plants with little or no effects of irrigation treatments used. Vertical bars over symbols (occasionally smaller than the size of symbol) denote standard errors ($n = 20$).

Nutrient concentration and uptake

Irrigation treatments had significant influence ($p \leq 0.05$) over the concentration of four nutrient elements (P, Fe, Zn and Na) out of twelve essential nutrient elements (N, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn, Mo and B) and Na (considered as a beneficial nutrient for plants) measured for the whole-plant. Table 3 shows the level (probability) of significance for the concentrations of those nutrients affected by irrigation treatments and mean concentration of those nutrients which were not affected significantly by irrigation treatments. As shown in Table 4, GW irrigated plants had the highest concentration of P, Na and Fe which were 39-85% greater than TW irrigated plants. The concentrations of Fe and Zn were also significantly higher with greywater or surfactant solutions compared with the tap water irrigated plants. These results suggest that substantial plant removal of these nutrients is possible with GW irrigation.

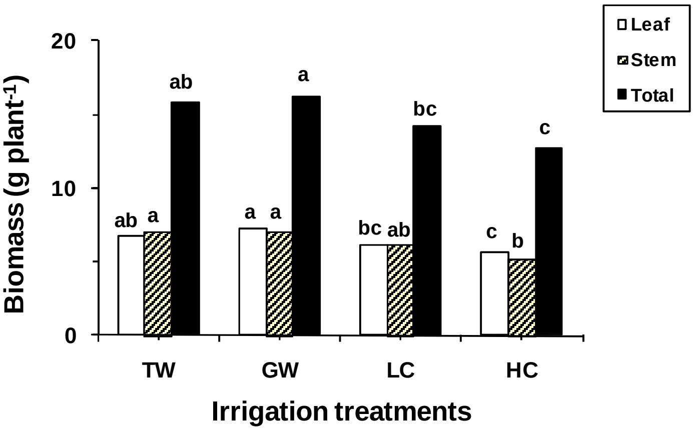

Fig. 5. Variation in total plant biomass and its components (leaf and stem) for tomato as affected by various irrigation treatments used. For a specific biomass component, similar letter(s) over the set of four treatments (TW, GW, LC and HC) indicate that the differences between mean values are less than the least significant difference (LSD). LSD values for leaf, stem and total biomass were 0.68, 0.98 and 1.71 g plant^{-1}, respectively.

The effects of irrigation treatments on uptake of various nutrients are given in Table 3 with mean values for uptake of specific nutrients not influenced significantly by irrigation treatments. Nutrient uptake was estimated as the product of nutrient concentration and biomass. For the uptake of P, K, Ca, Mg, Na, Fe and B, which were significantly influenced by irrigation treatments, are given in Table 5. Once again, uptake of these seven nutrients was significantly higher when plants were irrigated with greywater (GW) and lower when irrigated with surfactant solutions (LC or HC) than irrigated with tap water, TW (Table 5). Greywater irrigated plants accumulated relatively similar quantity of B, but substantially greater quantity of Na (83%) and Fe (86%) compared with TW irrigated plants. Uptake of these seven nutrients by tomato was generally in the order GW≥TW>HC≥LC.

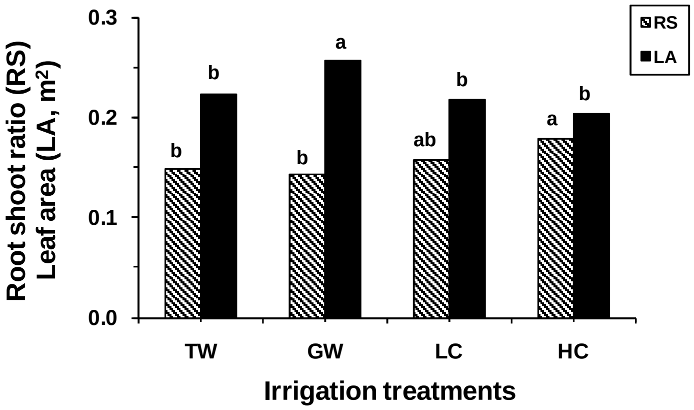

Fig. 6. Variation in root-shoot ratio (RS) and leaf area (LA) of tomato with various irrigation treatments. For a biomass component, similar letter(s) over the set of four treatments (TW, GW, LC and HC) indicate that the differences between mean values are less than the least significant difference (LSD). LSD values for both RS and LA (m^2) were 0.02.

Discussion

For irrigation of residential urban areas, water quality guidelines developed for agricultural use are difficult to apply to greywater as it is a wastewater requiring consideration of public health hazards (Ayers and Westcot, 1985). Reuse of untreated greywater for irrigation is considered hazardous due to the potential risk of infection from direct human exposure (Jeppesen, 1996). However, recent reports (Jackson et al., 2006; Finley et al., 2009) suggest that public health risks arising from pathogenic contamination of food crops irrigated with greywater are relatively small. Since our research focuses on the environmental impacts of reusing greywater to irrigate crops, we discuss the sensitivity of tomato to greywater and surfactants with implication to other soils and plants.

Table 3. Summary of the effects of irrigation treatments on nutrient concentration and uptake by tomato plants at harvest. Mean concentration or uptake values are shown only for nutrients which are not significantly (NS) affected by irrigation treatments (*p*>0.05).

Nutrients	Level of significance (*p*)		Mean values	
	Concentration	Uptake	Concentration	Uptake
N	0.159 NS	0.215 NS	2.985%	0.215 g plant^{-1}
P	0.004	0.001	-	-
K	0.743 NS	0.025	2.826%	-
Ca	0.186 NS	0.004	1.953%	-
Mg	0.436 NS	0.050	1.013%	-
S	0.652 NS	0.318 NS	0.303%	0.044 g plant^{-1}
Na	<0.001	<0.001	-	-
Fe	0.013	0.012	-	-
Cu	0.174 NS	0.279 NS	22.8 mg kg^{-1}	0.334 mg plant^{-1}
Mn	0.166 NS	0.833 NS	171.5 mg kg^{-1}	2.502 mg plant^{-1}
Zn	0.034	0.144 NS	-	1.303 mg plant^{-1}
Mo	0.066 NS	0.071 NS	0.161 mg kg^{-1}	0.002 mg plant^{-1}
B	0.166 NS	0.009	23.0 mg kg^{-1}	-

Table 4. Effects of irrigation treatments on the nutrient concentrations of tomato plants. For a specific nutrient, same superscript letter(s) near the mean value for an irrigation treatment indicate that it is not significantly different from the mean value of another irrigation treatment unless the difference in mean value exceeds the least significant difference (LSD).

Nutrients	Irrigation treatments				LSD
	TW	GW	LC	HC	
P (%)	0.154^{b}	0.214^{a}	0.150^{b}	0.142^{b}	0.037
Na (%)	0.182^{b}	0.326^{a}	0.124^{bc}	0.115^{c}	0.063
Fe (g kg^{-1})	0.802^{b}	1.480^{a}	1.572^{a}	0.708^{b}	0.591
Zn (g kg^{-1})	0.076^{c}	0.090^{ab}	0.086^{bc}	0.106^{a}	0.019

Table 5. Effects of irrigation treatments on the nutrient uptake of tomato plants at harvest. For a given nutrient, same superscript letter(s) near the mean values of various irrigation treatments indicate that the difference in uptake for those treatments are not significantly different unless they exceed the least significant difference (LSD) for that nutrient.

Nutrients	Irrigation treatments				LSD
	TW	GW	LC	HC	
P (g plant^{-1})	0.024^{b}	0.035^{a}	0.021^{b}	0.018^{b}	0.007
K (g plant^{-1})	0.424^{a}	0.464^{a}	0.392^{b}	0.372^{b}	0.059
Ca (g plant^{-1})	0.292^{ab}	0.322^{a}	0.265^{b}	0.266^{b}	0.030
Mg (g plant^{-1})	0.152^{ab}	0.167^{a}	0.135^{b}	0.139^{b}	0.024
Na (g plant^{-1})	0.029^{b}	0.053^{a}	0.018^{bc}	0.015^{c}	0.011
Fe (mg plant^{-1})	12.893^{bc}	23.980^{a}	22.129^{ab}	9.040^{c}	9.327
B (mg plant^{-1})	0.370^{a}	0.393^{a}	0.353^{a}	0.249^{b}	0.079

Effects of greywater and surfactants on water use

Recent studies show that anionic surfactants (similar to the type used in this study and likely to be present in greywater) cause a greater reduction in capillary rise than the deionised water (Abu-Zreig et al., 2003) or freshwater (Wiel-Shafran et al., 2006). This is consistent with our experimental results which showed reduced soil water retention on several occasions when tomato was continuously irrigated with surfactant solutions and laundry greywater (Figs. 1 and 2). However, ET was affected by irrigation treatments only on one occasion (Fig. 3) and ET losses were highest with GW irrigation and lowest with solutions of high surfactant concentration (HC). Overall, lack of persistent, adverse impacts of surfactant-rich irrigation water and greywater on water retention and ET observed in our study indicates that surfactants and other pollutants present in greywater may only have a modest effect on water use by tomato over short periods. Since surfactants are used in numerous agricultural and household products, it was not possible in this study to determine if the soil was free from surfactant residues from past applications.

Plant growth response to nutrients and surfactants in irrigation water

As greywater is a wastewater containing various types of dissolved and suspended substances, plant growth may be reduced due to inhospitable pH, excess salts, deficiency or toxicity of nutrients and pollutants (e.g. surfactants). Although greywater was alkaline with a pH > 8 (Table 1) that exceeded the pH of other types of water by 0.5-1 pH units, growth of tomato remained unaffected over 9 weeks (Fig. 4). Biomass at harvest indicated similar or higher plant biomass (Fig. 5) and leaf area (Fig. 6) for tomato irrigated with laundry greywater (GW) compared to tap water (TW). In contrast, irrigation with surfactant solutions (LC and HC) caused a modest decrease in various components of biomass and leaf area without any visible toxic or deficiency response in the plant. In hydroponic systems, some plants (e.g. lettuce) have been reported to be quite susceptible to surfactant toxicity (Bubenheim et al., 1997) but not wheat (Garland et al., 2000, 2004). Chlorosis in lettuce has been also reported with greywater irrigation (Wiel-Shfran et al., 2006). Since in our experiment, plant parts (leaf or root) did not come in direct contact with surfactant solutions or greywater except via soil, no toxic responses were observed. The anionic surfactant used in our experiment is known to have a lower capacity to remain adsorbed in soil than various mixed types of surfactants commonly used in the formulation of detergents (Rao and He, 2006). Anionic surfactants also tend to degrade rapidly in soil (Küchler and Schnaak 1997) with little or no risk to soil biota (Scott and Jones, 2000). Thus, anionic surfactants present in irrigation water may not persist in soils long enough to affect plant growth adversely.

Nutrient and pollutant removal by plants

On the basis of relative salt tolerance of crops, tomato is considered as moderately sensitive to salts (Ayers and Westcot, 1985; Maas, 1990). Elevated concentrations of specific nutrients (P, Na, Fe and Zn) for laundry greywater irrigated plants in Table 4 and elevated levels of uptake of P, K, Ca, Mg, Na, Fe and B in Table 5 suggest that nutrient uptake ability of tomato was not adversely affected by using greywater or surfactant solutions for irrigation. Although nutrient concentration was not measured in the soil solution in our experiment (as all plants received fertilizer at the time of planting), continuous measurements of plant growth and visual assessment of toxicity and deficiency symptoms suggest that repeated irrigation with greywater may not contribute to unusually high or low nutrient concentration in the root zone of plants for a sustained period to cause decline in plant growth. For further examination of any association of nutrient deficiency or toxicity arising from irrigation treatments used in our study, nutrient concentration data in our study has been compared with the data typical for tomato and other plants (Huett et al., 1997; Liphadzi and Kirkham, 2006). These comparisons show that tomato plants in our study may have been deficient in major nutrients (N, P, K, Ca, Mg and S) that would require additional fertilizer application. The concentrations of Na, Mn, B and Mo in tomato plants in our study were within the range considered adequate. However, the concentration of Cu and Zn was slightly above the adequate range. The concentration of Fe in the plant was beyond the upper limit of adequate concentration reported for all plants. Since the soil used in our experiment is a Ferrosol that is derived from iron oxide minerals, excess concentration of Fe found for plants from all irrigation treatments may have originated from soil rather than from greywater or surfactants.

Conclusions

Our experimental evaluation of the reuse potential of laundry greywater and surfactant solutions as irrigation water indicate that reduced quality of greywater with high pH and EC compared to other types of irrigation water did not affect plant growth continuously over time, except at the time of harvest. On a few occasions, soil water retention following irrigation was reduced significantly when plants were irrigated with GW or surfactant solutions. Water use measured as evapotranspiration (ET) was affected even to a lesser extent than water retention. ET of GW irrigated plants was similar to those receiving TW, but was significantly higher than the plants receiving HC treatment. At harvest, various components of plant biomass and leaf area for GW irrigated plants were similar or significantly higher than TW irrigated plants following the trend of GW ≥ TW > LC ≥ HC. Irrigation treatments significantly influenced the concentration of four nutrients (P, Fe, Zn and Na) and uptake of seven nutrients (P, K, Ca, Mg, Na, Fe and B) with nutrient uptake following the trend GW ≥ TW > HC ≥ LC. GW irrigated plants had the highest concentration of P, Na and Fe which were 39-85% higher than the TW irrigated plants. Compared with tap water irrigated plants, greywater irrigated plants removed an additional 6% B, but substantially greater quantity of Na (83%) and Fe (86%). Our results suggest that laundry greywater has good potential for irrigation of household gardens and lawns if the selected plant is able to remove pollutants (Na and metals) from greywater irrigated soils without adversely affected by surfactant residues and other pollutants. However, further research is needed to determine if hyper accumulation of these nutrients in tomato has any adverse effect on human nutrition that may limit widespread use of laundry greywater in various soils and plants.

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