Removal of pollutants by tomato plants during reuse of laundry greywater for irrigation

Rabindra K. Misra[1], Jishiv H. Patel and Venus R. Baxi
Faculty of Engineering and Surveying, Australian Centre for Sustainable Catchments and CRC for Irrigation Futures, University of Southern Queensland, Toowoomba, QLD 4350, Australia
e-mail: misrar@usq.edu.au

Abstract

Laundry greywater is considered as a valuable, reusable water resource for irrigation of household gardens and amenity areas around the world. Public health risks arising from exposure to greywater during irrigation are relatively low compared with other wastewater, but long term use of laundry greywater may lead to accumulation of sodium and surfactants in soil affecting crop productivity and environmental sustainability. In this work, we compared growth, biomass and uptake of several essential nutrients and sodium for a tomato crop using tap water and laundry greywater.

Observations and measurements of growth over a period of nine weeks and sixteen irrigation events indicated no adverse effects of greywater over tap water on growth. Salts and surfactants in greywater had modest influence over soil water retention and evapotranspiration.

Final destructive measurements of plants at flowering indicated similar or significantly higher accumulation of biomass for greywater than tap water irrigated plants. The concentration of P and Na in greywater irrigated plants were 1.4-1.8 times the concentration of tap water irrigated plants. Per cent increase in uptake of P, Na and Fe by greywater over tap water irrigated tomato was 46, 83 and 86, respectively. Since accumulation of sodium in soils from disposal of greywater can be environmentally hazardous, efficient removal of sodium by tomato with reuse of greywater in this study illustrate that plants tolerant to greywater irrigation can reduce soil pollution arising from accumulation of sodium.

Introduction

Greywater is the non-toilet component of household wastewater that originates predominantly from the laundries and bathrooms of residential buildings. Greywater generated from laundry activities in a typical Australian household ranges from 94 to 139 L day^{-1} (Radcliffe 2004) which is equivalent to 20% of the total indoor water use by residents in Queensland (ABS 2000). In many dry regions of the world, greywater is considered as a potentially reusable water resource for irrigation of household lawns and gardens (Al-Jayyousi 2003). However, experimental studies on the interaction of greywater with soils and plants are limited. Diversion of laundry effluent into gardens and lawns (Jeppesen 1996) has become a relatively more common practice in Australia in recent times due to recurring drought and high level of water restriction imposed in various cities and towns. Environmental and public health risks can arise due to

[1] Conference speaker

greywater irrigation from accumulation of environmentally toxic substances in soil and plants and potential transfer of pathogens to humans directly from contact and indirectly via accumulation in food crops. Although public health risks associated with reuse of greywater are well known (Nolde, 1999; Gross et al. 2005), the risks are quite low. However, environmental risks associated with infiltration of greywater into soil during irrigation and the fate of pollutants in greywater and the combined impact of these pollutants on soils, plants and receiving waters are not well known (Eriksson et al., 2003).

Laundry greywater usually contains varying levels of suspended solids, salts, nutrients, organic matter and pathogens (Christova-Boal et al. 1996; Howard et al. 2005). 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. Hence, a portion of these salts (not retained on clothes or on various parts of the washing machine) is expected to be present in the laundry effluent. There are also a variety of suspended solids and sorbed substances (both inorganic and organic matter, and pathogens) released from clothes in laundry effluent. 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. Although there are no reports currently available to indicate how growth and 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 an important component of greywater as they are present as residues of laundry detergents (Smulders 2002). Surfactants have been detected in various wastewaters (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). The ability of surfactants to modify the surface tension of water arises from their tendency to increase the distance between water molecules as they tend to accumulate at the gas-liquid (e.g. air-water) or solid-liquid (e.g. soil-water) interface. The extent to which surfactants can modify the soil-water balance (Kuhnt 1993) and influence water use and plant growth still remains unknown.

Some plants grown in hydroponic systems with added surfactants have exhibited phytotoxic symptoms (Bubenheim et al. 1997; Garland et al. 2000). These latter authors used an anionic surfactant Igepon TC-42 (a linear alkyl taurine sulfonate) for processing of greywater in future, long-duration space missions that elicited toxic response in lettuce but not in wheat due to insufficient degradation of the surfactant by the aquatic microbial community in the rhizosphere (Bubenheim et al. 1997). A more recent study with surfactants commonly found in household and personal care products (Garland et al. 2004) showed rapid degradation of the surfactants in water and moderate phytotoxic responses in wheat. When untreated greywater is used to irrigate plants growing in soil, surfactants may degrade more rapidly in soil due to the presence of a wider range of microbial community in soil than water. However, degradation of surfactants in the presence and absence of other substances found in greywater is not known for soil-plant systems and the effects of the degradation process on water and nutrient availability to plants.

The aim of this study was to evaluate the reuse potential of laundry greywater by comparing growth, water and nutrient use of tomato (*Lycopersicon esculentum* Mill. cv. Grosse Lisse) plants irrigated with laundry greywater and tap water.

Materials and Methods

We conducted a glasshouse experiment 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) 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 retained at water potentials (ψ) of -10 and at -1500 kPa were 36.5 and 27.0%, respectively. The pH and EC of the soil at a soil-water ratio of 1:5 were 6.35 and 30.7 $\mu S\ cm^{-1}$, respectively; and CEC 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

The full experiment consisted of four irrigation treatments and five replicates of each treatment following a randomised block design. This work focuses on only two of the four treatments as detailed below.

Tap water (TW) – sampled from a designated tap in an adjacent laboratory and Greywater (GW) – laundry greywater as detailed below.

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), all laundry greywater collected was used to irrigate GW designated pots within 4 h of collection.

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 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 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 2 replicates of each 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 (%).

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

Throughout the experiment, plant health was monitored in each pot 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 analysis

Prior to the irrigation experiment, laundry greywater was initially sampled from two washes to determine the surfactant concentration with the MBAS (Methylene Blue Active Substance) method (Method 5540C, APHA, 2005).

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 reported in a separate experiment by Misra and Sivongxay (2009).

After harvesting and drying of plant samples, approx. 25% by weight of various components of the plant biomass (leaf, stem and root) were combined and then ground to reduce their size to <1 mm. Nitrogen concentration in subsamples of the combined 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).

Results and Discussion

Quality of irrigation water

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

Table 1. Chemical properties of tap water and laundry greywater used for irrigation. Variation in pH of TW and GW over time of the experiment is indicated by standard error, SE (n = 16) after the ± sign. Anionic surfactant concentration is shown for laundry greywater only. Data on ion concentration (Na, Ca, Mg and K) are from Misra and Sivongxay (2009).

Parameters	Mean value	
	Tap water	Greywater
pH (before irrigation)	6.86 ± 0.06	8.15 ± 0.12
pH (after irrigation)	6.79 ± 0.09	7.92 ± 0.11
Mean pH	6.83	8.04
EC ($\mu S\ cm^{-1}$) - before irrigation	477.6 ± 3.1	653.3 ± 3.1
EC ($\mu S\ cm^{-1}$) - before irrigation	491.7 ± 2.5	665.4 ± 8.8
Mean EC ($\mu S\ cm^{-1}$)	484.7	659.4
Na concentration ($mmol_c\ L^{-1}$)	1.48	5.74
Ca concentration ($mmol_c\ L^{-1}$)	1.05	0.11
Mg concentration ($mmol_c\ L^{-1}$)	1.32	0.33
K concentration ($mmol_c\ L^{-1}$)	0.12	0.15
SAR	1.36	12.32
Surfactant concentration ($mg\ L^{-1}$)	unknown	15.48

Table 1 shows the variation in pH and EC of irrigation water used for various treatments. Greywater was significantly more alkaline (>1 pH unit) and more saline (1.4 times EC) than the tap water. The surfactant concentration in laundry greywater was 15.5 mg L^{-1}. The tap water was not expected to contain any surfactants. As reported earlier (Misra and Sivongxay, 2009) greywater contained significantly higher levels of Na and low levels of Ca and Mg which contributed to a ten-fold increase in Sodium Adsorption Ratio (SAR). SAR is an indicator of the relative concentrations (in mmole charge per litre, $mmol_c\ L^{-1}$) of sodium to the combined concentrations of calcium and magnesium as it is expressed as

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{\frac{1}{2}\left([\mathrm{Ca}^{2+}]+[\mathrm{Mg}^{2+}]\right)}}\,. \qquad (2)$$

The pH, EC and SAR values shown in Table 1 is not expected to have any restriction for its use for agriculture crops in terms of salinity and infiltration problems (Ayers and Westcot, 1985), although public health hazards need some consideration. Recent research shows that health risks arising from pathogenic contamination of food crops irrigated with greywater is relatively small (Jackson et al., 2006; Finley et al., 2009). However, environmental concerns with land disposal of greywater may pose problems if salts and other pollutants in the irrigation water do not degrade rapidly in soil (Misra and Sivongxay, 2009). Potential of sodium accumulation in soil from long-term use of greywater can be avoided if plants are able to remove excess sodium from greywater.

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.

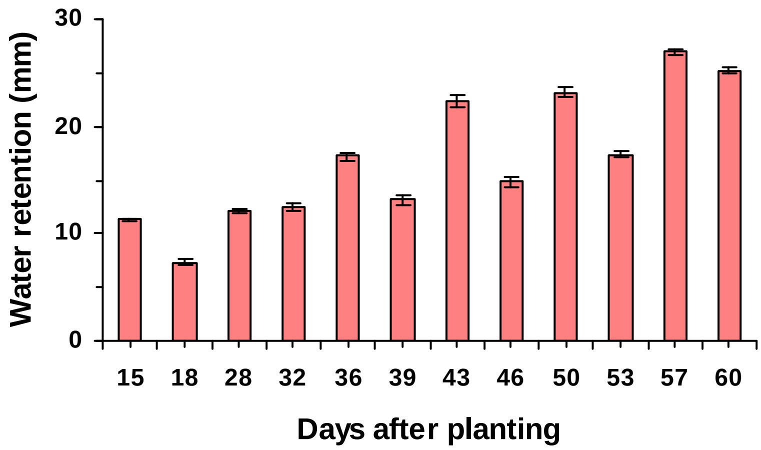

Figure 1. Variation in soil water retention following irrigation and drainage for various irrigation treatments during the experiment with tomato plants. Vertical bars over mean values indicate standard errors (n = 20).

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 treatment on water retention were detected for 2 of the 16 irrigation events analysed. On both occasions, greywater irrigated pots retained significantly lower (~ 1 mm) water than the tap water irrigated plants. 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 on most occasions following irrigation. Reduced soil water retention could be due to the presence of surfactants as these tend to influence capillary rise (Shafran et al., 2005). Capillary rise is expected to relate to the pore size distribution of soil and the surface tension of the fluid which are important for retention and movement of soil water (Hillel, 2004). Recent studies show that anionic surfactants (similar to the type 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). Thus, some adverse impacts of greywater on water retention are expected albeit less frequently as our results suggest.

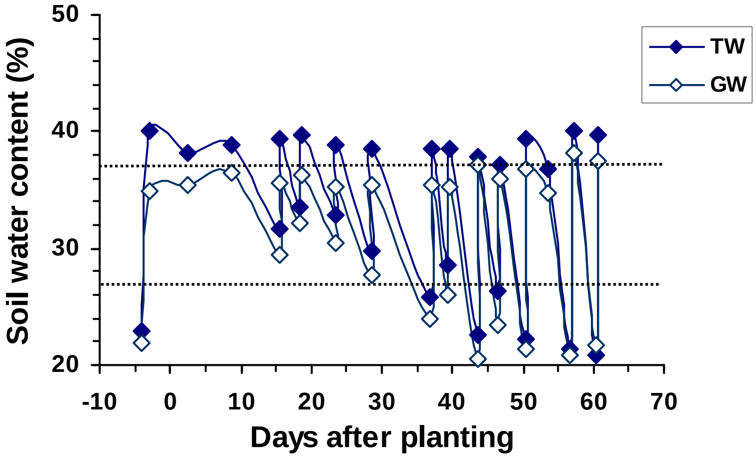

Figure 2. Variation in volumetric soil water content for tap water (TW) and greywater (GW) treatments under tomato plants. Top and bottom lines superimposed over the soil water content indicate water retained at -10 and -1500 kPa, respectively. Standard errors of mean values have not been shown for clarity.

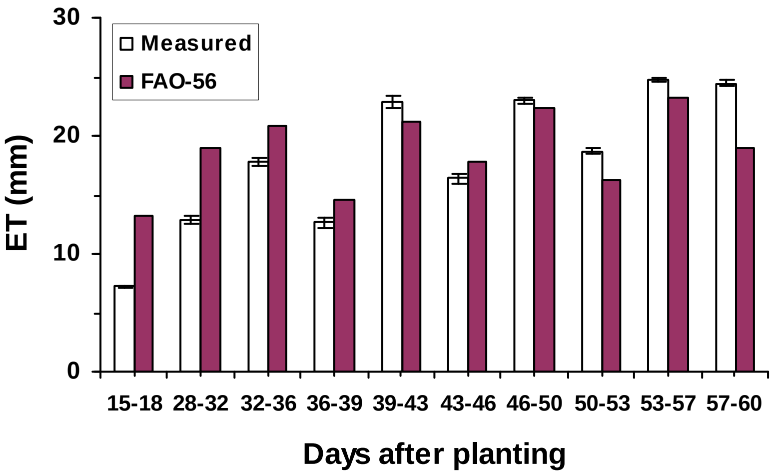

Figure 3. Variation in evapotranspiration (ET) during successive irrigation cycles of TW and GW given to tomato plants. Reference ET estimated with the FAO-56 method for the corresponding period is shown. Vertical bars over mean values indicate standard errors (n = 20).

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, but without any significant effects of irrigation treatments on ET.

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) 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 plotted 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).

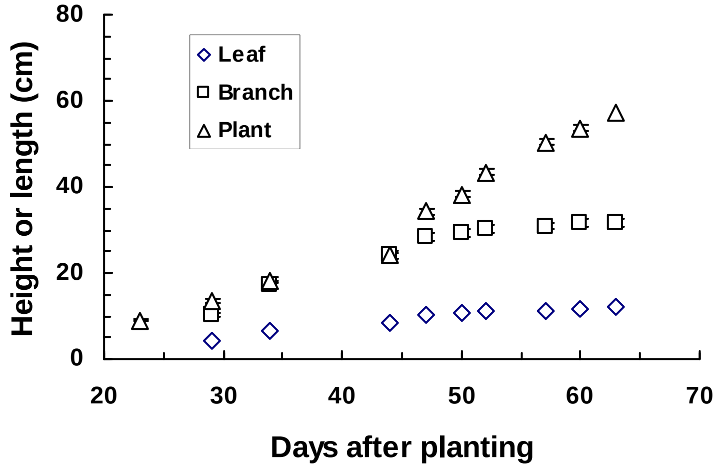

Figure 4. Temporal variation in lengths of leaf and branch, and height of tomato plants with little or no effects of irrigation treatments used. Vertical bars over symbols (occasionally smaller than the size of symbol) denote standard errors (*n* = 20).

At harvest, components of plant biomass were mostly in the order GW > TW, although significant differences were not observed. This indicates that when surfactants are present with other salts or nutrients, as in greywater, plant growth responses were favourable.

Nutrient and pollutant removal by tomato

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. As shown in Table 3, GW irrigated plants had significantly higher concentration of P (1.4 times), Na (1.8 times), Fe (1.85 times) and Zn (1.2 times) than TW irrigated plants. These results suggest that substantial plant removal of these nutrients is possible with GW irrigation. Greywater irrigated plants removed slightly greater quantity of P (46%), but substantially greater quantity of Na and Fe (83-86%) compared with TW irrigated plants (Table 4).

Table 3. Effects of irrigation treatments on the nutrient concentrations of tomato plants. Mean values for a given nutrient followed by the same superscript letter(s) are not significantly different at $p \leq 0.05$.

Nutrients	Irrigation treatments	
	TW	GW
P (%)	0.154^{b}	0.214^{a}
Na (%)	0.182^{b}	0.326^{a}
Fe (g kg^{-1})	0.802^{b}	1.480^{a}
Zn (g kg^{-1})	0.076^{b}	0.090^{a}

Table 4. Effects of irrigation treatments on the nutrient uptake of tomato plants at harvest. Mean values for a given nutrient followed by the same superscript letter(s) are not significantly different at $p \leq 0.05$.

Nutrients	Irrigation treatments	
	TW	GW
P (g $plant^{-1}$)	0.024^{b}	0.035^{a}
Na (g $plant^{-1}$)	0.029^{b}	0.053^{a}
Fe (mg $plant^{-1}$)	12.893^{b}	23.980^{a}

As greywater is a wastewater containing various types of dissolved and suspended substances, plant growth could be reduced due to inhospitable pH, excess salts, deficiency or toxicity of nutrients and pollutants (e.g. surfactants). 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 reported for greywater (Table 1) is also known 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 greywater may not persist in soils long enough to affect plant growth adversely.

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 3 and elevated levels of uptake in Table 4 suggest that nutrient uptake ability of tomato was not adversely affected by using greywater 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 (Table 5).

Table 5. A comparison of nutrient concentration in tomato plants found in this study with concentration ranges considered adequate for plant growth.

Nutrients	Adequate concentration range		
	Tomato[1]	All plants[2]	This study
N (%)	5.0-6.0	0.5-5.0	2.4-3.5
P (%)	0.4-0.9	0.5-5.0	0.12-0.26
K (%)	3.8-6.0	0.5-5.0	2.19-3.63
Ca (%)	1.5-2.5	0.5-5.0	1.62-2.48
Mg (%)	0.4-0.6	0.5-5.0	0.72-1.28
S (%)	1.25	0.5-5.0	0.17-0.39
Na (%)	0.1-0.4	NA	0.014-0.4
Fe (g kg^{-1})	0.06-0.3	0.025-0.3	0.56-2.4
Cu (g kg^{-1})	0.005-0.015	0.004-0.015	0.013-0.034
Zn (g kg^{-1})	0.03-0.1	0.01-0.10	0.07-0.13
Mn (g kg^{-1})	0.05-0.25	0.025-0.3	0.12-0.23
B (g kg^{-1})	0.03-0.1	0.01-0.10	0.011-0.03
Mo (g kg^{-1})	0.0006	0.0001-0.005	0.0001-0.001

[1]Adequate at early flowering growth stage, Huett et al. (1997)
[2]Source: Liphadzi and Kirkham (2006)
NA: Not available

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 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 for irrigation indicates that reduced quality of greywater with high pH and EC compared to tap water did not affect plant growth continuously over time. On a few occasions, soil water retention following irrigation was reduced significantly when plants were irrigated with GW. 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. Irrigation treatments significantly influenced the concentration and uptake of four nutrients (P, Fe, Zn and Na) with a general trend of GW > TW. 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 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 plants are managed well to maintain growth and the selected plant is able to remove pollutants (Na and metals) from greywater irrigated soils without adversely affected by surfactant residues and other pollutants in soil and water. Further research is required with a range of soils, plant species and various types of greywater to determine the feasibility of widespread use of laundry greywater for irrigation.

Acknowledgments

We thank Prof. Mark Sutherland of University of Southern Queensland for access to the glasshouse.

References

ABS (2000). Water Account Australia 2000-01, Cat. No. 4610.0. Australian Bureau of Statistics, Canberra.

Abu-Zreig, M., Rudra, R.P. and Dickinson, W.T. (2003). Effect of application of surfactants on hydraulic properties of soils. Biosys. Eng. 84, 363-372.

Al-Jayyousi, O.R. (2003). Greywater reuse: towards sustainable water management. Desalination 156, 181-192.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Crop evapotranspiration - guidelines for computing crop water requirements. FAO Technical Paper 56. Food and Agriculture Organisation of the United Nations, Rome.

AOAC (1996). Official methods of analysis of AOAC international. 16th edition, AOAC International, Arlington, VA, USA.

APHA (2005). 5540 C. Anionic surfactants as MBAS. In: American Public Health Association (Ed.), Standard Methods for the Examination of Water and Wastewater, 21st ed., Washington DC, pp. 5-50 to 5-55.

Ayers, R.S. and Westcot, D.W. (1985). Water quality for agriculture. FAO Irrigation and Drainage Paper 29, Food and Agriculture Organization of the United Nations, Rome.

Beckmann, G.G., Thompson, C.H. and Hubble, G.D. (1974). Genesis of red and black soils on basalt on the Darling Downs, Queensland, Australia. J. Soil Sci. 25, 265-281.

Benton Jones, J.Jr, Wolf, B. and Mills, H.A. (1991). Plant analysis handbook. Micro-Macro Publishing Inc., Georgia, USA.

Brunner, P.H., Capri, S., Marcomini, A. and Giger, W. (1988). Occurrence and behaviour of linear alkylbenzenesulphonates, nonylphenol, nonylphenol mono-and nonylphenol diethoxylates in sewage and sewage sludge treatment. Water Res. 22, 1465–1472.

Bubenheim, D., Wignarajah, K., Berry, W. and Wydeven, T. (1997). Phytotoxic effects of gray water due to surfactants. J. Am. Soc. Hort. Sci. 122, 792-796.

Christova-Boal, D., Eden, R.E. and McFarlane, S. (1996). An investigation into greywater reuse for urban residential properties. Desalination 106, 391-397.

Eriksson, E., Auffarth, K., Eilersen, A.M., Henze, M. and Ledin, A. (2003). Household chemicals and personal care products as sources for xenobiotic organic compounds in grey wastewater. Water SA 29, 135-146.

Field, J.A., Barber, L.B., Thurman, E.M., Moore, B.L., Lawrence, D.L. and Peake, D.A. (1992). Fate of alkylbenzenesulfonates and dialkyltetrasulfonates in sewage-contaminated groundwater. Environ. Sci. Technol. 26, 1140-1148.

Finley, S., Barrington, S. and Lyew, D. (2009). Reuse of domestic greywater for irrigation of food crops. Water Air Soil Pollut. 199, 235-245.

Garland, J.L., Levine, L.H., Yorio, N.C., Adams, J.L. and Cook, K.L. (2000). Graywater processing in recirculating hydroponic systems: phytotoxicity, surfactant degradation, and bacterial dynamics. Water Res. 34, 3075-3086.

Garland, J.L., Levine, L.H., Yorio, N.C. and Hummerick, M.E. (2004). Response of graywater recycling systems based on hydroponic plant growth to three classes of surfactants. Water Res. 38, 1952-1962.

Gross, A., Azulai, N., Oron, G., Ronen, Z., Arnold, M. and Nejidat, A. (2005). Environmental impact and health risks associated with greywater irrigation: a case study. Water Sci. Technol. 52, 161-169.

Hillel, D. (2004). Introduction to Environmental Soil Physics. Elsevier Academic Press, New York.

Howard, E., Misra, R.K., Loch, R. and Le-Minh, N. (2005). Laundry grey water potential impact on Toowoomba soils - final report. National Centre for Engineering in Agriculture Publication 1001420/2, USQ, Toowoomba, Australia, http://eprints.usq.edu.au/641/>, (viewed 19.2.08).

Huett, D.O., Maier, N.A., Sparrow, L.A. and Piggott, T.J. (1997). Vegetables. In: Reuter, D.J., Robinson, J.B. (Eds.), Plant analysis: an interpretation manual. CSIRO Publishing, Collingwood, Victoria, pp. 385-464.

Isbell, R.F. (1996). The Australian Soil Classification. CSIRO Publishing, Collingwood, Victoria.

Jackson, S., Rodda, N. and Salukazana, L. (2006). Microbiological assessment of food crops irrigated with domestic greywater. Water SA 32, 700-704.

Jeffrey, S.J., Carter, J.O., Moodie, K.M. and Beswick, A.R. (2001). Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software 16, 309-330.

Jeppesen, B. (1996). Domestic greywater re-use: Australia's challenge for the future. Desalination 106, 311-315.

Jones, E. and Childers, R. (2001). Contemporary college physics, 2001 updated 3rd edition. McGraw Hill, Boston, USA.

Küchler, T. and Schnaak, W. (1997). Behaviour of Linear Alkylbenzene Sulphonates (LAS) in sandy soils with low amounts of organic matter. Chemosphere 35, 153-167.

Kuhnt, G. (1993). Behaviour and fate of surfactants in soil. Environ. Toxic. Chem. 12, 1813-1820.

Liphadzi, M.S. and Kirkham, M.B. (2006). Physiological effects of heavy metals on plant growth and function. In: Huang, B. (Ed.), Plant-environment interactions, 3rd edition. CRC/Taylor & Francis, Boca Raton, pp. 243-269.

Maas, E.V. (1990). Crop salt tolerance. In: Tanji, K.K. (Ed.) Agriculture Salinity Assessment and Management. American Society of Civil Engineers, New York, pp. 262-304.

Misra, R.K. and Sivongxay, A. (2009). Reuse of laundry greywater as affected by its interaction with saturated soil. J. Hydrol. 366, 55-61.

Nolde, E. (1999). Greywater recycling systems in Germany - results, experiences and guidelines. Water Sci. Tech. 51, 203-210.

QDNRM (2008). NRM enhanced meteorological datasets. Queensland Government Department of Natural Resources and Mines, www.nrm.qld.gov.au/silo/>, (viewed 15.5.08).

Radcliffe, J.C. (2004). Water recycling in Australia. Australian Academy of Technological Sciences and Engineering, Parkville, Victoria.

Scott, M.J. and Jones, M.N. (2000). The biodegradation of surfactants in the environment. Biochim. Biophysic. Acta 1508, 235-251.

Shafran, A.W., Gross, A., Ronen, Z., Weisbrod, N. and Adar, E. (2005). Effects of surfactants originating from reuse of greywater on capillary rise in the soil. Water Sci. Tech. 52, 157-166.

Smulders, E. (2002). Laundry Detergents. Wiley-VCH Verlag GmbH, Weinheim, FRG.

Wiel-Shafran, A., Ronen, Z., Weisbrod, N., Adar, E. and Gross, A. (2006). Potential changes in soil properties following irrigation with surfactant-rich greywater. Ecol. Eng. 26, 348-354.