Recycled Vertical Flow Constructed Wetland (RVFCW) - a novel method of recycling greywater for landscape irrigation in small communities and households

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Abstract
The use of greywater for irrigation is becoming increasingly common. Raw greywater is often contaminated and can cause environmental harm and pose health risks. Nevertheless, it is often used without any significant pre-treatment, a practice mistakenly considered safe. The aim of this study was to develop an economically sound, low-tech and easy to maintain treatment system (RVFCW) that will allow safe and sustainable use of greywater for landscape irrigation in small communities and households. RVFCW properties, removal efficiency, hydraulic parameters and feasibility were studied, as well as the environmental effects of the treated greywater, by monitoring a variety of water quality and quantity variables in soils and plants over time. The RVFCW was efficient in removing virtually all of the suspended solids, BOD and about 80% of the COD after 8 hours. Faecal coliforms dropped by 3-4 orders of magnitude from their initial concentration after 8 h, but this was not always enough to meet current regulations for unlimited irrigation. The feasibility analysis indicated return over investment in approximately two years. The study concluded that the RVFCW is a sustainable promising treatment system for greywater use that can be run and maintained by unskilled operators.

Keywords
Greywater; vertical flow constructed wetland; wastewater reuse

INTRODUCTION

The quantity of freshwater available worldwide is declining and there is a pressing need for more efficient use of water. One method of conserving water is by recycling greywater (GW) for irrigation. Greywater is domestic wastewater that includes only wash water (i.e. bath, dish, and laundry water), whereas blackwater consists of toilet water. Due to the substantial difference in their qualities, separating greywater and blackwater will provide for more effective wastewater treatment, allowing a large volume of water to be efficiently recycled (Lindstrom, 2000). This is particularly important in arid zones, were water is scarce and recycling GW for private and public landscape irrigation can reduce potable water use by up to 50% (DHWA, 2002). The use of GW for private garden irrigation is becoming increasingly common. In most countries regulations or specific guidelines for GW reuse are not available, and it is therefore often used without any significant pre-treatment, a practice mistakenly considered safe. In countries such as the USA and Australia, where regulations for the use of GW have been established, they concentrate on issues associated with public health but do not consider potential harmful environmental impacts or pollution (Dixon *et al.*, 1999; DHWA, 2002; ADEQ, 2003). The separation of the toilet stream from domestic wastewater generates effluents which have reduced levels of nitrogen, solids, and organic matter (especially the hardly degradable fraction), but often contain elevated levels of surfactants, oils, boron and salt. The components in GW may alter the soil properties, damage plants and contaminate groundwater (Garland *et al.*, 2000; Gross *et al.*, 2003). A study aimed at applying commercial systems to GW recycling demonstrated that five different commercial systems failed to treat the GW sufficiently for unlimited use. The study suggested that this was either because the treatment was too slight (as the water is considered safe by many), or because it was designed to treat wastewater rather than GW in private houses (Gross *et al.*, 2003).

The aim of this study was to develop an economically sound, low-tech and easy to maintain treatment system that will allow safe and sustainable use of GW for landscape irrigation in small communities and households.

MATERIALS AND METHODS

Recycled vertical flow constructed wetland (RVFCW)

The proposed treatment method is a modification of the vertical flow constructed wetland (VFCW) that was described by IWA (2000), but using a novel set-up. The system is composed of two components: (1) a three-layer bed consisting of planted organic soil over a “filter” with an upper layer of tuff or plastic media and a lower layer of limestone pebbles, and (2) a reservoir located beneath the bed (Fig. 1).

Direct flow of the raw greywater into the root zone prevents bad odors and mosquitoes, and reduces the possibility of human contact and spread of disease. It then trickles down through the filter to the reservoir, enhancing aeration as the water falls from the porous filter to the collecting reservoir, which further prevents development of odours and enhances organic matter degradation and nitrification. The lime pebbles buffer the acidity produced by the nitrification and biodegradation. Recycling the water from the reservoir back to the upper filter, thus diluting the new raw greywater, reduces the risk of organic overload or other damage to the filter, such as excess chlorination. Since the water passes through the filter more than once, the area required to attain a specific water quality is reduced. In small communities and households, the volume of wastewater may change considerably over time from virtually none to several cubic meters a day. The proposed RVFCW is flexible as it recirculates the water and keeps the wetland and filter constantly wet and operating. The recycling rate is determined by the required water quality, the filter dimensions, and the wastewater flow rate.

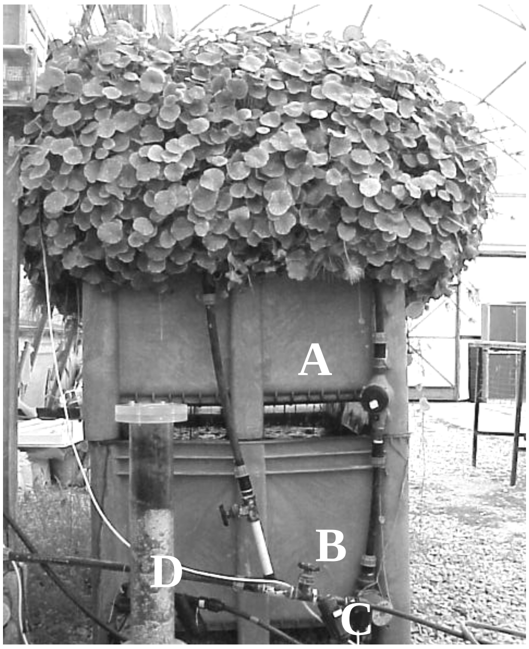

Figure 1. Recycled vertical flow constructed wetland (RVFCW). A. Wetland and Filter tank; B. Reservoir; C. Recycling pump; D. Demonstration of filter media layers (peat, tuff, and lime pebbles in top middle and bottom layers, respectively).

RVFCW performance

The RVFCW properties, removal efficiency and hydraulic parameters were studied in both a short-term study and a 3-month greenhouse study.

Short-term study. After continuous working period of 3 months, the pour volume of the filter section and the treated water reservoir were emptied and a fresh 300 L of GW was introduced to the filter (at the root zone). A sub-sample of the greywater was collected for analysis (Time zero). The

GW was continuously recycled between the reservoir and the filter at a known rate of 390 L h^{-1} determined by a water meter that was attached to the system. Samples of the treated GW were taken immediately after it passed the RVFCW and then after 2, 4, 8, 12, 24, and 48 hours. Samples were analysed for: total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), anionic surfactants, dissolved oxygen (DO), electrical conductivity (EC), pH, 5-day biological oxygen demand (BOD_5), chemical oxygen demand (COD), faecal coliforms (FC), total coliforms, and total boron (B). Water quality analysis followed standard procedures (Standard Methods for the Examination of Water and Wastewater, 1998; Merck, 2000).

Greenhouse study. The RVFCW was used to evaluate the environmental effects of treated GW on plants and soils in comparison with untreated GW and freshwater. Greywater was prepared artificially by mixing ground vegetables, laundry detergent, cooking oil and 10 mL L^{-1} sewage effluent to resemble the GW quality in a nearby farm. Thirty lettuce plants, which are sensitive to water quality, were used as the model plants for each treatment. Plants were grown for 88 days between 15 Feb 02 to 15 May 02 in 5 L pots filled with autoclaved quartz sand, and were drip irrigated twice a day by a computerized irrigation system (~300 mL $plant^{-1}$ day^{-1}). The investigation was concluded once the lettuces started to bud. Water samples of the untreated GW, treated GW and freshwater were collected 3 times a month and analysed for: TSS, TP, TN, total ammonia nitrogen (TAN), nitrite nitrogen (NO_2-N); nitrate nitrogen (NO_3-N), EC, pH, anionic surfactants, BOD_5, COD, B, total coliforms, and FC. Samples were also analysed for minerals (Ca, K, Na, Mg, B) and metals (Fe, Al, Cu, Mn, Zn) by inductively coupled plasma (ICP) and atomic adsorption (AA) once a month. Analysis followed standard procedures (Standard Methods for the Examination of Water and Wastewater, 1998; Merck, 2000) and the quality of the different treatments were statistically analysed by ANOVA ($p<0.05$).

Undisturbed 5 cm soil cores were taken monthly from 7 pots of each treatment and analysed for: pH, organic carbon (OC), total kjeldahl nitrogen (TKN), minerals and metals (Soil and Plants Analysis Council, 1999). For the FC count 5 undisturbed cores (~6 g wet weight from depths of 5 cm) of each treatment were put into sterile tubes. Pyrophosphate buffer (6 mL) was added and samples were shaken for an hour. The supernatant was used for FC count on TBX agar plates (Merck, 2000).

The plants from these pots were tested for wet and dry weight, leaf weight, surface area, number of leaves, minerals and metals.

Feasibility analysis

A case study feasibility analysis on the RVFCW was conducted for a 5-person household, watering a 150-m^2 garden in the Negev desert over a year. The construction and maintenance expenses were recorded. The GW reclaimed for irrigation was recorded with a water meter and compared with the water consumption of the family.

RESULTS AND DISCUSSION

RVFCW performance

Short term study. The initial GW quality was similar to the one presented in Table 1. The RVFCW was efficient at removing virtually all the suspended solids, BOD_5 and about 80% of the COD after 8 hours (Figure 2). Total nitrogen and total phosphorus were also significantly reduced after 8 h (75% and 60%, respectively). Faecal coliforms dropped by 3-4 orders of magnitude from their initial concentration after 8 h, but were still higher than the Israeli standard for unlimited irrigation of less than 1 CFU 100 mL^{-1} (Halperin and Aloni, 2003). Complete anionic surfactant removal occurred after 24 h and about 50% of the B was removed, mainly by adsorption to the peat (Figure 3). The plants and other filter bed layers accumulated negligible amounts of B (Shmueli, 2004). It might be possible to increase B removal by introducing plants that are known to accumulate B such as reed (*Phragmites australis*), duckweeds (*Lemna* spp.), and mare's tail (*Hippuris bulgaris*) (Raskin *et al.*, 1997; Meaguer, 2000; Del Campo, 2003). The EC and pH were similar to their initial values and in acceptable ranges for irrigation (data not shown). These results suggest that GW recycling of 8 - 12 h was sufficient to produce high quality water for landscape irrigation. If surface irrigation is used a disinfection method should be considered.

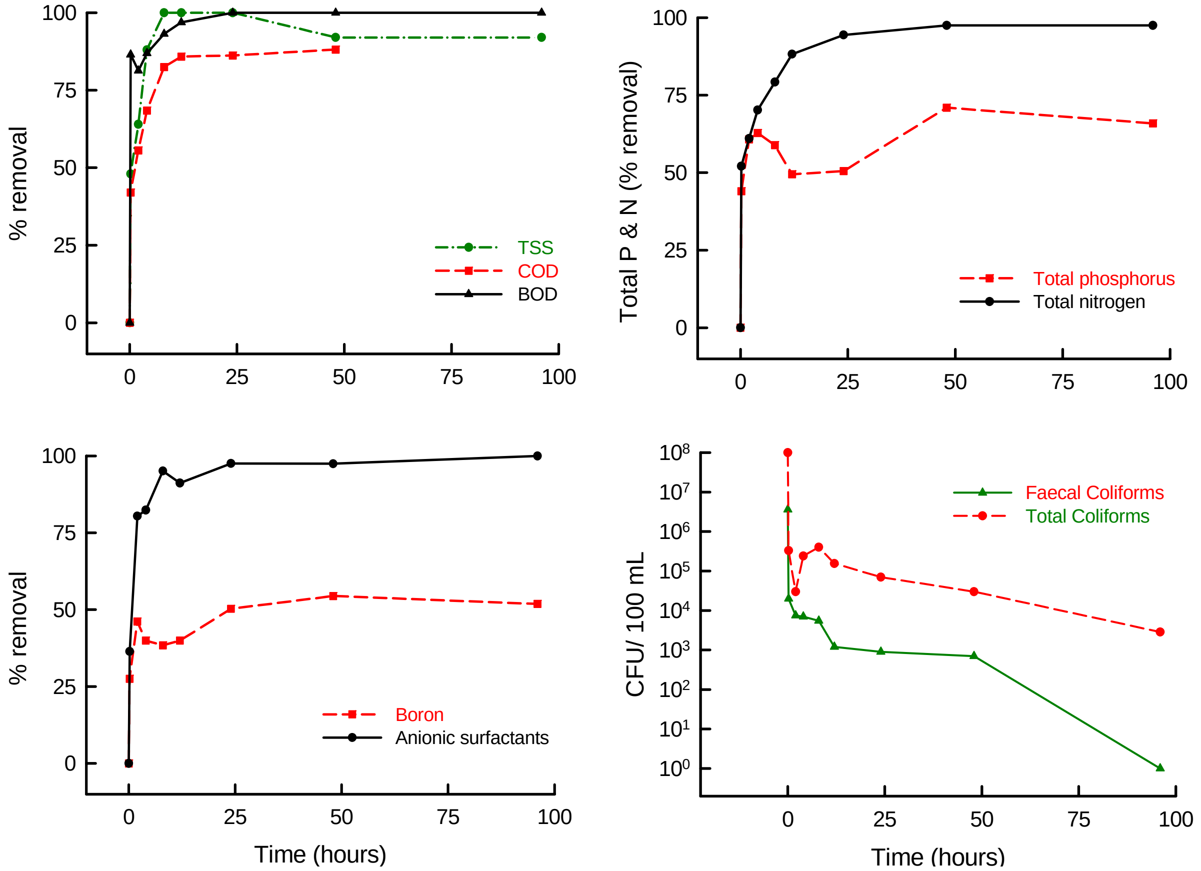

Figure 2. Percent removal of: total suspended solids (TSS), 5-day biological oxygen demand (BOD_5), chemical oxygen demand (COD), total phosphorus, total nitrogen, boron, faecal you coliforms (FC) and total coliforms (TC) over time by a RVFCW. The greywater was recycled through the filter continuously at a rate of 390 L h^{-1}.

Greenhouse study. The experimental set-up was designed to test the performance of the RVFCW over a longer period of time and to emphasize the different effects of treated greywater compared to freshwater and untreated GW on the soil and plants. In addition, the experiment was used to compare the "fertilization properties" of the different sources. The average water quality of the different sources is summarized in Table1.

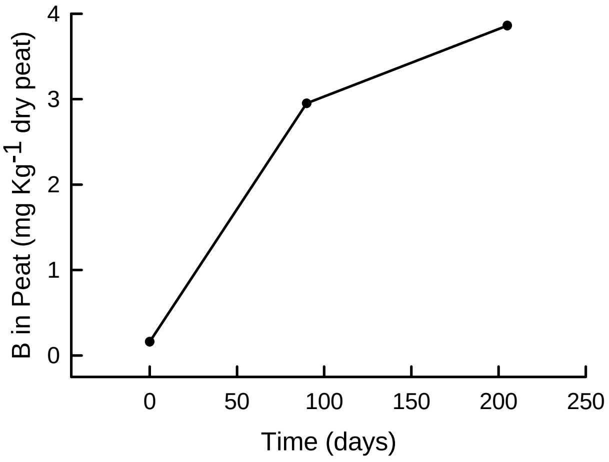

Figure 3. Accumulation of B in the peat layer of the RVFCW over time.

Table 1. Average concentrations ± standard errors (SE) and the ranges of the greywater (GW), treated GW, and freshwater used to irrigate lettuce plants. The GW was treated with RVFCW and the mean % removal demonstrates its performance. Samples were taken twice a month between March and May 2002 (n = 6), and results are in mg L^{-1} unless stated otherwise.

Analysis	**GW**	**Treated GW**	**Mean % removal**	**Freshwater**	**Standards**[1]
TSS	158 ± 30 85 - 285	3 ± 1 0 - 6	98.1	------	10
BOD$_5$	466 ± 66 280 - 688	0.7 ± 0.3 0 - 1.5	99.8	0.5 ± 0.1 0.4 – 0.6	10
COD	839 ± 47 702 - 984	157 ± 62 60 - 220	81.3	----	
TP	22.8 ± 1.8 17.2 - 27	6.6 ± 1.1 3.5 - 10.2	71.1	0.08 ± 0.00 0.02 – 0.13	
TN	34.3 ± 2.6 25.0 - 45.2	10.8 ± 3.4 1.4 - 21.0	68.5	5.7 ± 1.5 4 – 7.3	8*
Total ammonia nitrogen (TAN)	0.3 ± 0.1 0.1 - 0.5	0.9 ± 0.7 0.0 - 4.5	----	0.1 ± 0.1 0 – 0.2	2*
NO_2-N	0.3 ± 0.2 0.0 – 1.0	0.2 ± 0.2 0.0 - 0.9	----	< 0.05	
NO_3-N	3.0 ± 1.3 0.0 – 5.8	8.6 ± 4.3 0.0 - 23.5	----	4.9 ± 0.7 4.1 – 5.7	
EC dS m^{-1}	1.2 ± 0.0 1.0 - 1.3	1.3 ± 0.0 1.1 - 1.4	-8.3	1.2 ± 0.1 1.2 – 1.3	
pH	6.5 ± 0.1 0.0 - 7.0	7.6 ± 0.2 7.0 – 8.0	----	7.6 ± 0.3 7.1 – 8.8	
Anionic surfactants	7.9 ± 1.7 4.7 – 15.6	0.6 ± 0.1 0.4 - 1.3	92.4	----	
Boron	1.6 ± 0.1 1.4 – 1.7	0.6 ± 0.1 0.4 – 0.8	65	0.3 ± 0.03	0.5*
FC CFU 100 mL^{-1}	$5\text{x}10^7 \pm 2\text{x}10^7$ $9\text{x}10^4 – 1\text{x}10^8$	$2\text{x}10^5 \pm 1\text{x}10^5$ $3\text{x}10^2 – 7\text{x}10^5$	99.5	<1	<1

[1] Standards = current Israeli standards for unlimited irrigation (Halperin and Aloni, 2003).

* Standards from the Israeli water law (1975) for unlimited use (except drinking).

It was noticeable that untreated GW did not meet current standards for unlimited irrigation. The TSS was 158 mg L^{-1}, BOD$_5$ 466 mg L^{-1} and the FC over 10^7 CFU 100 mL^{-1}. The RVFCW treatment system was evaluated by two parameters: a) its ability to remove variables of environmental and health concern and b) whether the output water met current Israeli standards for unlimited irrigation (Table 1). Analysis of minerals and metals did not yield significant differences ($p<0.05$) between the sources (data not shown). The treated GW met the current standard except with regards to the FC count, which was in the range of 10^5 CFU 100 mL^{-1}. Results were similar in pattern to the short-term study. Although there was a significant decrease in FC in the treated GW, in its present form it must first be disinfected prior to surface irrigation, or used in a subsurface irrigation system. As expected no FC were found in the freshwater. In the soils that were irrigated with treated GW an average of 2 CFU g soil^{-1} were found and about 10^4 CFU g soil^{-1} in the soils that were irrigated with raw GW (Table 2). The reduction in FC during their transit through the unsaturated soil profile is due to three primary processes: a) adsorption to soil particles, b) filtering of aggregate lumps, and

c) inactivation (die-off) due to chemical reactions and microbial antagonism within the soil (Feachem *et al.*, 1983). In most soils with a range of temperatures of 20-30 ^{o}C the reduction is several-fold within the first few days and does not usually exceed 20 days (Feachem *et al.*, 1983; Spackman *et al.*, 2003). Soil OC, TN and EC accumulated in the soils in correlation to their concentrations in the irrigation water (Tables 1, 2).

Table 2. Average ± standard errors concentrations of organic carbon (OC), total nitrogen (TN), pH, electrical conductivity (EC), and faecal coliform count (FC) in sandy soil following 3 months irrigation with freshwater, greywater (GW) and treated GW.

Source	OC (% dry soil)	TN (mg Kg dry soil^{-1})	pH	FC (CFU g dry soil^{-1})
GW	0.29 ± 0.02	385 ± 35	8.2	$3.1x\ 10^{4} \pm 6.0 \times 10^{4}$
Treated GW	0.26 ± 0.01	176 ± 18	8.5	$4.0x\ 10^{3} \pm 2.0 \times 10^{3}$
Freshwater	0.22 ± 0.01	70 ± 7	8.6	<1

Limited nutrient source (P and N) in the freshwater and treated GW as compared to the raw GW (Table 1) resulted in retarded growth in these treatments as demonstrated by the leaf surface area (Figure 4). Similarly, the leaf weight and number per lettuce head were smaller in these treatments (data not shown). Nevertheless, in the GW irrigated plants brown patches (chlorosis) developed on the tip of the leaves (Figure 5). This was caused by the elevated salinity and B levels in the plant's leaves (Table 3), which was correlative to their concentrations in the irrigation waters (Table1).

Figure 5. Chlorosis of lettuce leaves due to elevated salinity and boron accumulation.

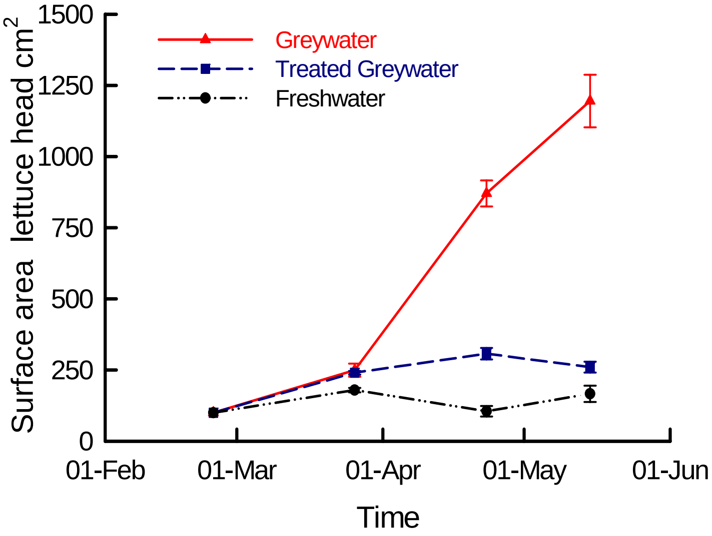

Figure 4. Average surface area ± standard errors over time of lettuces that were irrigated with freshwater, treated GW and raw greywater for three months.

Table 3. Average concentration of boron (B) and chloride (Cl^{-}) in the lettuce leaves of the different treatments, after 3 months of irrigation (n = 6). ^{a,b} indicate statistical significance ($p<0.05$).

Irrigation source	Cl^{-} in leaves (mg Kg dry soil $^{-1}$)	B in leaves (mg Kg dry soil^{-1})
Greywater	126.8 ^{a}	0.54 ^{a}
Treated GW	83.9 ^{b}	0.21 ^{b}
Freshwater	64.7 ^{b}	0.21 ^{b}
Initial concentrations	39.0	0.2

Feasibility analysis

Analysis of the water meters revealed that the annual water consumption of the 5-person family in the Negev desert was 465 m^3. The net volume for irrigation was 210 m^3 (45% of the consumption), which was composed of treated GW originating from the showers and sinks (120 m^3), except the kitchen effluent, and about 90 m^3 of laundry effluent (Table 4).

Table 4. Overall consumption and reclaimed greywater from 5-person household located in the Negev Desert in the year 2003.

Water meters	Annual Volume (m^3)
Overall consumption	465
Showers and sinks	120
Laundry effluents	90

The outcome of the analysis was that all irrigation needs can be supplied by reusing GW. The reuse of GW for irrigation saved on average about US$ 20 per month (based on water cost of $US 1.1 m^3), which indicates a return over investment (ROI) in approximately 4 years according to existing manufacturing costs (US$ 600 per system) and annual maintenance of about US$ 100 $year^{-1}$. This is expected to decrease when manufactured on line. Such an ROI is very attractive for the private sector.

CONCLUSIONS

Using raw greywater for irrigation is becoming increasingly common and may cause environmental harm and pose public health risks. In most countries regulations or specific guidelines for GW reuse are not available or not sufficient, as they consider health risks while ignoring environmental risks. Greywater is therefore often used without any significant pre-treatment, a practice mistakenly considered safe. We believe that proper standards, their enforcement and education are necessary to resolve these potential risks as well as the development of specific GW treatment systems. The latter should be developed to meet current guidelines for unlimited irrigation. The suggested RVFCW is a promising low-cost low-tech treatment system with low running costs that can be run and maintained by unskilled operators. Hence, it can sufficiently treat GW to meet current standards for unlimited irrigation, except for the complete removal of FC, which can be achieved by the introduction of a small disinfection unit. Subsurface irrigation can also be used to mitigate this problem.

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REFERENCES

Arizona Department of Environmental Quality (ADEQ) (2003). *Using Greywater at Home,* Publication No. C 01-06, Arizona Department of Environmental Quality, Phoenix, AZ, USA.

Department of Health Western Australia (DHWA) (2002). *Draft Guidelines for the Reuse of Greywater in Western Australia*. Department of Health, Perth, Australia, p. 37.

Del-Campo, C. M., and Oron G. 2002. Boron removal from water and accumulation by duckweed, *lemna gibba*. Proceedings of 8th international conference on wetland systems for water pollution control. Arusha, Tanzania, 627-633.

Dixon A. M., Butler D., and Fewkes A. (1999). Guidelines for graywater re-use: health issues. *J. of the Chartered Institution of Water and Environmental Management*, **13**, 322-326.

Feachem R. G., Bradley D. J., Garelick H. and Mara D. D. (1983). *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management.* John Wiley & Sons, Chichester.

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 Research* **34**, 3075-3086.

Gross A., Shmueli O., Weil A., Oron G. and Ronen Z. (2003). Reuse of greywater for landscape irrigation in small communities and households. (In Hebrew) *Water and Irrigation* **437**, 29-39.

Halperin R. and Aloni U. (2003). *Standards for Treated Wastewater Reuse in the City, for Recreation and in Industry.* (in Hebrew) Ministry of Health, Jerusalem, Israel, p.15.

IWA, specialist group on use of macrophytes in water pollution control (2000). *Constructed Wetlands for Pollution Control.* IWA Publishing, London.

Lindstrom C. R. (2000). Graywater: facts about graywater - what it is, how to treat it, when and where to use it. Cambridge ,USA. Electronic manuscript www.graywater.com.

Meaguer, R.B. (2000). Phytoremediation of toxic elemental and organic pollutants. *Current Opinion in Plant Biology* **3,** 153-162.

Merck (2000). *Microbiology Manual.* Laboratory products division, Merck, Darmstadt, Germany.

Raskyn, I., Smith, R., and Salt, D. (1997). Phytoremediation of metals: using plants to remove pollutants from the environment. *Current Opinion in Biotechnology* **8**, 22-226.

Shmueli, O. (2004). *Reuse of graywater for irrigation - Environmental and health risks associated with it's use*. MSc thesis, Environmental Engineering Unit, Ben-Gurion University of the Negev.

Soil and Plants Analysis Council. (1999). *Soil Analysis Handbook of Reference Methods*. CRC Press LLC, Boca Raton, Florida.

Spackman R., Entry J. A., Sojka R. E. and Ellsworth J. W. (2003). Polyacrylamide for coliform bacteria removal from agricultural wastewater. *Journal of Soil and Water Conservation* **58**(5), 276-283

Standard Methods for the Examination of Water and Wastewater (1998). 20th edn, American Public Health Association/ American Water Works Association/ Water Environment Federation, Washington DC, USA.

Water law (1975). *Water Standards (surface water quality).* (In Hebrew) The State of Israel, Jerusalem.