Feasibility of a Semi-Batch Vertical-Flow Wetland for Onsite Residential Graywater Treatment

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Abstract

The technical feasibility of graywater treatment, via a semi-batch vertical flow wetland (SB-VFW), was evaluated at a single family home for aboveground water reuse. Graywater treatment was achieved to a quality level that was well within the regulatory compliance limits (e.g., with respect to biochemical oxygen demand (BOD), total suspended solids (TSS) and turbidity) for above ground reuse. System performance over the course of a five-month field study demonstrated that the necessary treatment time was typically ~3 hours for a 300-liter batch. The SB-VFW operated in a stable manner owing to the use of a coconut soil substitute that has high hydraulic conductivity and avoidance of clogging due to excess biofilm growth. The latter was made possible through the use of a bio-based laundry (BBL) detergent which had a lower organic content relative to conventional laundry detergents. The system was able to return to normal operation even after detergent shockloads. Results of the present study are encouraging and suggest that residential level graywater treatment is technically feasible and can thus potentially expand the range of possible water reuse applications.

Keywords: graywater treatment, vertical flow wetland, nonpotable water reuse, biofilm, semi-batch

1 Introduction

Graywater is considered a viable alternative nonpotable water resource for onsite treatment and reuse in residential homes in urban [13] and rural [15] communities. For example, homeowners in California are allowed to collect and treat graywater from bathroom and laundry machines for aboveground non-potable use [16], which account for 32% and 26%, respectively, of the total indoor water consumption [17]. Raw graywater can vary in quality (**Table 1**) particularly with respect to TSS, turbidity and BOD₅. Regulatory requirements for graywater nonpotable reuse (subsurface, aboveground or indoor) vary regionally and among different countries (**Table 2**). For example, treated graywater with high turbidity (<10 NTU) can be reused for aboveground nonpotable water use purposes, including indoor toilet flushing in the United Kingdom, but the turbidity limit for the same type of water uses is <2 NTU in California (**Table 2**). Among the different regions/countries that regulate graywater reuse, California has one of the strictest set of requirements ([16, 18], **Table 2**). These graywater reuse requirements are designed to safeguard public health and minimize odors and other nuisances due to prolonged storage of raw graywater [19]. Various commercial graywater treatment systems using biological treatment processes [20] are available but they are expensive (>\$5,000 for a single family system [21]). Thus, there have been efforts to develop low cost and low maintenance treatment systems using constructed wetlands [22].

Previous studies (**Table 3**) have demonstrated that constructed wetlands are effective in removing BOD₅, total suspended solids (TSS) [23, 24] and turbidity to levels that meet strict aboveground non-potable graywater reuse requirements such as in the USA and Australia (**Table 2**). However, the use of conventional constructed wetlands is limited given the need

for a large deployment area and long treatment time [25]. A viable alternative to conventional constructed wetland for treatment of graywater is the use of a compact semi-batch vertical-flow wetland (SB-VFW) with recirculation (VFWR) [26-28]. The SB-VFW has a smaller footprint and requires shorter treatment time compared to other single-pass vertical flow wetland (SP-VFW) or horizontal-flow wetland designs (**Table 3**).

Table 1. Average reported water quality for graywater originating from laundry and bathroom sources and only from bathroom sources.

Parameters	Graywater Sources	
	laundry + bathroom	Bathroom
Turbidity, NTU	24±8	58±26.2
TDS, mg/L	410*	388*
TSS, mg/L	68±88	47±16
pH	8±2	7.4±0.5
BOD, mg/L	185±73	99±73
COD, mg/L	366±173	221±160
TOC, mg/L	-	38±12.7
NH ₄ -N, mg/L	1*	3.8±4.3
NO ₃ -N, mg/L	24±33	2.1±2.6
TN, mg/L	31±27	7.5±2.5
PO ₄ -P, mg/L	15±23	0.5
TP, mg/L	11*	--
E. Coli, CFU/100mL	--	4x10 ⁶ *
Fecal, CFU/100mL	4x10 ⁴ *	8x10 ⁵ ±2x10 ⁵
Total Coliform, CFU/100mL	4x10 ⁷ ±5x10 ⁷	1x 10 ⁴ ±1x10 ⁵
References	[1-6]	[1, 5-13]

Note: * indicates only one cited literature reported the data

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Table 2. Water quality criteria for aboveground nonpotable graywater reuse in United Kingdom, United States of America and Australia

Standards	Type of reuse	Treatment level equivalent	Water quality criteria
United Kingdom [29]	Sprinkler; Car washing; Toilet flushing; Garden watering; Pressure washing; Washing machine use		<10 NTU of turbidity; pH 5-9.5; < 2 mg/L of residual chlorine; < 0.5 mg/L of residual chlorine for non-spray garden watering; Undetectable residual bromine levels for all spray application and non-spray garden watering
California, USA [30]	Aboveground nonpotable reuse	Disinfected tertiary	Turbidity: 2 NTU (avg.); 5 NTU (max) Total coliform: 2.2 MPN/100 mL (avg.), 23MPN/100 mL (max in 30 days)
Wisconsin, USA [31]	Surface irrigation except food crops; clothes and vehicle washing; air conditioning; soil compaction; dust control; washing aggregate; making concrete	Disinfected tertiary	pH 6–9; ≤ 10 mg/L of BOD ₅ ; ≤ 5 mg/L of TSS; 1.0–10 mg/L of residual chlorine
	Toilet and urinal flushing	Disinfected primary with filtration	pH 6–9; ≤200 mg/L of BOD ₅ ; ≤ 5 mg/L TSS; 0.1–4.0 mg/L of residual chlorine
NSF/ANSI 350R	Restricted indoor and unrestricted outdoor water reuse	Residential capacity ≤ 1,500 GPD	pH 6-9; CBOD ₅ : ≤ 10 mg/L of (avg.), 25 mg/L (max.); TSS: ≤ 10 mg/L (avg.); 30 mg/L (max.) Turbidity: 5 NTU (avg.); 10 NTU (max.) E. coli: 14 MPN/100mL (mean); 240 MPN/100 mL (max.) 0.5 ≤ Storage vessel disinfection ≤ 2.5mg/L
New South Wales, Australia [20]	Toilet flushing; Cold water supply to washing machines; Garden irrigation with local approval	Disinfected Secondary	< 20 mg/L BOD ₅ ; < 20 mg/L TSS; <10 cfu/100ml fecal coliforms
Western Australia, Australia [32]	Toilet flushing Cold water supply to washing machines; Irrigation	Disinfected Tertiary	<10mg/L of BOD; <10mg/L of TSS; <1 MPN/100mL of <i>E. coli</i> <1 pfu/100mL of coliphages; <1 cfu/100mL of clostridia;
Victoria, Australia [33]	Toilet flushing; Cold water supply to washing machines; Surface irrigation, Sub-surface irrigation	Disinfected Tertiary	<10 mg/L of BOD; <10 mg/L of TSS; <10 cfu/100ml of fecal coliforms;

70 **Table 3.** Wetland designs and their reported treatment performance for treatment of graywater

Country	Graywater sources	Wet-land type	Media	Recir-culation	Mode of operation	Treatment capacity, m ³ /day	Wetland area, m ²	Treatment capacity per area, m ³ /m ² day	HRT, days	Turbidity , % removal (NTU)	Organics, % removal (mg/L)	TSS, % removal (mg/L)	Total coliform, % removed (/100mL)
Sweden (Fittschen & Niemczyn, 1997)	sinks, kitchen, shower, washing machine	HF	Soil, not specified	No	Continuous flow	40	600	0.07	4	-	BOD ₇ : 95.8% (<5); COD: 87% (46)	-	-
Sweden (Schonborn et al., 1997)	sinks, kitchen, shower, washing machine, urinal	VF-HF	Fine grained sand, iron armament pieces, sandy & stony loam	No	Continuous flow	40	38	0.04	-	-	BOD ₅ : 96% (5 mg/L); COD: 91% (27)	-	-
Nepal (Shreshtha et. al, 2001)	Bathroom, shower, washing machines & kitchen sinks	VF	Coarse sand	No	Continuous flow	0.5	6	0.08	-	-	BOD ₅ : 97% (5.2)	97% (2.6)	-
Costa Rica (Dallas & Ho, 2005)	Mixed, not specified	HF	PET	No	Lab, batch	0.01	0.38	0.03	4.2	-	BOD ₅ : 92% (13)	-	Fecal coliform 99.99% (2.1 x10 ³ CFU)
	Mixed, not specified	HF	Crushed rocks	No	Lab, batch	0.01	0.38	0.03	2.5	-	BOD ₅ : 88% (18)	-	Fecal coliform 99% (2.6 x10 ⁵ CFU)
Costa Rica (Dallas et al., 2004)	Mixed, not specified	HF	Crushed rocks	No	Continuous flow	2.5	30	0.08	7.90	98% (2)	BOD ₅ : 99% (3)	-	Fecal coliform: 99.999% (16 CFU)
Israel (Gross et al., 2007; *Sklarz et al., 2009)	Mixed, not specified	VF	Peat, soil & randomly packed plastic media or tuff	Yes	Semi-batch	0.45	0.9	0.5	0.3-0.5	87%* (6*)	BOD ₅ : 100% (0.7); or COD : 81% (157)	98% (3)	Fecal coliform: 99% (2 x10 ⁵ CFU)
Uganda (Katukiza et al., 2014)	Bathroom, shower, laundry & kitchen sinks	VF	Crushed lava rock	No	Batch, single pass	0.22	0.2	1.1	0.06/10 L-batch	-	BOD ₅ : 72% (390); COD: 90% (198); TOC: 69% (277)	93% (80)	99.9% (3.38x10 ⁴ CFU)
Brazil (Paulo et al., 2009)	Laundry, bathroom	HF-VF	Coarse & fine gravel	No	Continuous flow	0.7	7.8	0.09	0.8	95% (13)	BOD ₅ : 95% (22)	92% (9.6)	-

71 Note: Values in brackets are reported average effluent concentration values. HF - a horizontal flow wetland; VF - vertical flow wetlands; HRT - hydraulic retention time.

A typical SB-VFW consists of an upper soil layer and may contain an underlying support layer of gravel, rock or trickling filter media [26-28]. It is noted that the use of siliceous soil in SP-VFWs and SB-VFWs has met with limitations due to relatively low hydraulic conductivity and its tendency to clog [34, 35]. Clogging in SP-VFWs and SB-VFWs is typically exacerbated by excessive biofilm growth stimulated by high organic loading [34, 36]. Severe clogging in VFWs can also lead to anaerobic condition in the soil layer [34] and environmental nuisances such as odor [37]. Thus, management of clogging in SB-VFWs is required to ensure their long term treatment performance [37]. Another challenge in graywater treatment via SB-VFW is that fine silt and clay may leach from the siliceous soil, which in turn can lead to high effluent turbidity (2 – 16 NTU) [38] exceeding regulatory requirements for aboveground reuse (**Table 1**) and impairing disinfection effectiveness [39, 40]. Thus, an alternative design that prevents leaching of soil material would be important for SB-VFW use.

SP-VFWs and SB-VFWs are different from horizontal-flow wetlands since they can nitrify ammonium to nitrite and nitrate. However, SP-VFW do not denitrify nitrite and nitrate to nitrogen gas due to the wetland's aerobic environment [25]. On the other hand, nitrification is limited but denitrification is common in horizontal-flow wetlands due to the limited aerobic conditions [25]. Thus, use of a SP-VFW followed by a horizontal-flow wetland is common in order to achieve complete nitrogen removal [37, 41, 42]. For example, nitrification was reported in a SB-VFW with the reported effluent nitrate-nitrogen at 8.6 mg/L from an influent level of 3 mg/L [27]. Although denitrification in SB-VFWs has not been reported in graywater treatment, denitrification has been documented in SP-VFWs for treatment of domestic wastewater [43]. It was shown that treatment of domestic wastewater with two SP-VFWs in-series enabled denitrification through addition of a carbon source to the influent of the second SP-VFW [43]. Given the above, it is plausible that

nitrification-denitrification could also occur in SB-VFW however such a behavior has not been previously demonstrated.

In the present work, a graywater SB-VFW treatment was developed and a five-month field study was undertaken in order to optimize the treatment approach with the following specific objectives: (a) demonstrate the feasibility of achieving water quality (e.g., BOD₅, TOC and turbidity) for permitted aboveground non-potable reuse (**Table 2**), (b) decrease the required batch treatment time using a reasonably small treatment system, (c) eliminate leaching of siliceous soil material by using coconut coir soil substitute that has high hydraulic conductivity, (d) assess the potential for simultaneous nitrification and denitrification, and (e) evaluate treatment effectiveness when using a bio-based laundry detergent with the goal of reducing graywater organic content and avoiding excessive biofilm growth.

2 Materials and methods

2.1 Materials and graywater sources

The performance of the graywater treatment system (described in **Section 2.2**) was evaluated for treatment of bathroom, showers, handwashing sinks and laundry waters. Two types of detergents were evaluated for clothes washing: (a) a United States Department of Agriculture certified bio-based laundry (BBL) detergent, (b) a conventional non-bio-based laundry (non-BBL) detergent. The BBL detergent was reported to be less toxic to graywater effluent microbial community compared to the non-BBL detergent [44]. The non-BBL detergent contained 22 organic compounds; while the BBL detergent contained 16 ingredients, seven of which were organic compounds and nine were inorganic compounds. The total organic carbon (TOC) content for the BBL and non-BBL detergents were determined (**Section 2.3**) to be ~72 mg-TOC/g-detergent and ~150 mg-TOC/g-detergent, respectively.

2.2 Graywater treatment system

Onsite residential graywater treatment and reuse was evaluated over a five-month study with an automated SB-VFW system (**Fig. 1**) deployed in a single-family home. The wetland (top) and reservoir (bottom) units had dimensions of 1.1 m (L) x 0.7 m (W) x 0.7 m (H). The wetland unit consisted of a bottom plastic container, with large holes bored through the bottom, for housing a coconut coir soil substitute layer (the “soil” layer) placed above a layer of cross-flow media (CFM). The soil layer, which was compartmentalized using fabric containers (SmartPots, Oklahoma City, OK), served as the medium for soil microbial community and for plant growth. A number of ordinary garden plants, along with wetland plant species (*Carex spissa* and *Phyla nodiflora*), were planted in the wetland. Household garden plant species included *Aeonium purpureum* and *Crassula ovate*, *Equisetum hyemale*, *Nasturtium*, *Narcissus impatiens*, *Anigozanthos*, and *Colocasia*. The viability of the plants was assessed based on their overall appearance, e.g. leaf greenness and ability to produce flowers for flowering plants. CFM installed below the soil layer had a specific surface area of 226 m²/m³ (AccuPac Cross Flow Media, Brentwood Industries, Reading, PA). The CFM provided structural support for the soil layer with its open channel configuration enabling significant aeration while avoiding channel clogging. Dripping water from the wetland unit was captured by the reservoir below (the bottom reservoir), from which water was recirculated to the wetland during the treatment period.

Graywater, which was recirculated from the bottom reservoir, was distributed over the wetland using a gravity-driven flow distribution system. The distribution system consisted of partially filled enclosed conduits with holes at the bottom (installed just above the soil layer), which were arranged to facilitate even flow distribution over the wetland. Uniformity of the flow distribution was verified by determining the local flow rate at the different locations beneath the wetland unit. The enclosed conduits also served to avoid direct human contact with graywater and reduce water

143 loss due to evaporation. The recirculation flow rate was measured by an inline paddlewheel flow
 144 meter (GF Signet P51530-P0, El Monte, CA) connected to a powered transmitter/totalizer (GF
 145 Signet 3-8550-2, El Monte CA).

Figure 1. Schematic diagram of the graywater treatment system. The upper wetland unit consists of a soil layer and a cross-flow media (CFM). Graywater intake (pump 1), recirculation (pump 2) and discharge (pump 3) are controlled by three different submerged pumps.

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147 Automated system operation was enabled by a low-cost irrigation controller for operation of
 148 the system pumps for water inflow to the SB-VFW, recirculation within the SB-VFW system and
 149 water outflow for reuse (**Fig. 1**). Graywater was pumped from the collection tank to the SB-VFW
 150 system using a submerged sump pump having a maximum pumping flow delivery of up to 3,400
 151 L/hr (Little Giant 5-ASP, Fort Wayne, IN) that was installed inside the collection tank. A small

fountain pump (100 W) (Laguna Maxflow 2400, Mansfield, MA) submerged in the bottom SB-VFW reservoir was used for graywater recirculation. A third sump pump (Little Giant 5-ASP, Fort Wayne, IN) in the bottom reservoir served for pumping the treated effluent for irrigation. In principle, a single pump could be used for both recirculation and for outflow (e.g. irrigation); however, for the purpose of the present study, two pumps were used to simplify the operational control.

The SB-VFW system was designed to operate in a semi-batch mode given the intermittent generation of graywater. A collection tank of 300 L storage capacity was used for collecting and storing raw graywater between treatment cycles. Raw graywater entered the collection tank by gravity feed and was first filtered through a nylon filter fitted over the inlet pipe in order to protect the sump pump from being damaged by hair and other stringy substances. Once filled, raw graywater was pumped from the collection tank to the wetland feed distribution system with graywater recirculating (through the wetland unit) until the treated graywater effluent discharge.

2.3 Analytical methods

The SB-VFW system treatment effectiveness was evaluated based on water quality analysis of the influent and treated effluent. Grab samples were collected directly from the mid-water column of the collection tank (influent) and the reservoir of the SB-VFW system (effluent) using two auto-samplers (Hach Sigma MAX900, Loveland, CO). For each experiment, influent samples were collected just prior to pumping the graywater into the SB-VFW system, Grab effluent samples from the SB-VFW system were collected for evaluation over a 24-hour period at times of 0, 0.5, 1, 2, 3, 8 and 24 hours. Collected samples were kept in a cooler ($< 4^{\circ}\text{C}$) before transporting back to the laboratory for water quality analysis. It is noted that all the reported water quality data are provided as average values over the different operational periods unless specified otherwise.

Water quality of the treated graywater was evaluated with respect to the SB-VFW system's ability to remove organics (TOC, five-day biochemical oxygen demand (BOD₅), and chemical oxygen demand (COD)), TSS and turbidity to levels that would meet the aboveground nonpotable water reuse requirements (**Table 1**). System performance was also assessed with respect to removal of ammonium-nitrogen (NH₄-N) and Nitrate-Nitrogen (NO₃-N). The study consisted of two phases. Phase I focused on evaluating the long-term treatment performance of the SB-VFW system for graywater that contained BBL detergent from clothes washing daily. Additionally, detergent shockload tests were performed in two consecutive days to evaluate the impact of sudden increase in organics and turbidity on treatment performance. On the first day of the detergent shockload test, 160 g of BBL detergent was added into the 300 L graywater collection tank containing the raw graywater, followed by manual mechanical mixing prior to taking a grab sample for analysis. The raw graywater was then pumped into the treatment system and the recirculation commenced. On the next day, 80 g of BBL detergent was added into 300 L of raw graywater and a grab sample was collected for analysis. Effluent samples were collected at 0, 0.5, 1, 2, 3, 8 and 24 hours and analyzed for turbidity and organics for each day of the detergent shockload tests. During Phase II, non-BBL detergent was used by the residents. Water sampling and laboratory analysis protocols in Phase II were identical to those used in Phase I. Detergent shockload was not conducted during Phase II because of rapid deterioration of treatment performance during the first month after commencing with the treatment of non-BBL graywater.

Total organic carbon (TOC) and dissolved organic carbon (DOC) were determined using Standard Methods 5310C (Aurora 1030D TOC Analyzer, OI Analytical, College Station, TX). Samples for DOC analysis were prepared by water samples filtration through 0.8 µm filters (MCE with modified acrylic housing, Millipore Millex Sterile Syringe Filters, EMD Millipore, Billerica, MA). In order to determine the biodegradable portion of the TOC in the influent and effluent

streams, five-day seeded TOC tests [45] were conducted. For both cases, 300-mL volume samples were placed in amber bottles and kept in the dark at room temperature (22°C). In the five-day test, the influent was seeded with 1mL of the effluent. It is noted that the effluent was not added to the influent sample in the non-seeded biodegradable TOC test, and the effluent samples were not seeded. All samples were aerated daily (during the test period). The difference in TOC before and after the above tests represented the level of non-biodegradable organics.

Turbidity (USEPA Method 180.1; 2020 Portable Turbidity Meter, LaMotte, Chestertown, ML) was used as the primary monitoring parameter to assess reduction in suspended particles/colloidal matter. Other monitored inorganic water quality parameters included pH, conductivity (Oakton CON 11 Economy Meter, Vernon Hills, IL), temperature, total inorganic carbon (Standard Methods 5310C; Aurora 1030D TOC Analyzer, OI Analytical, College Station, TX), particle size (AccuSizer 780, Santa Barbara, CA), ammonium (Hach Method 10205, Loveland, CO), nitrate (Hach Method 10206, Loveland, CO), phosphate (Hach Methods 10209 and 10210, Loveland, CO), and dissolved oxygen (Dissolve Oxygen Tracer PocketTester, LaMotte, Chestertown, ML). While TOC and DOC were the primary parameters for monitoring organic concentrations, BOD₅ and COD were calculated by establishing the relationships between TOC and COD (COD:TOC ratio) and BOD₅ and COD (BOD:COD ratio) using three batches of samples. COD was calculated from the TOC using an influent COD:TOC ratio of 4.40, an effluent (after 3 hours treatment) COD:TOC ratio of 2.22 based on previous observations (Yu et al., 2014). The estimated COD was then used for calculating BOD₅. Influent and effluent (after 3 hours treatment) BOD₅:COD ratios were 0.31 and 0.16, respectively.

Biofilm growth on the CFM surfaces was evaluated using clear polyvinyl film sampling coupons that were attached to the bottom of the wetland unit. These coupons were sampled after three months of treating BBL graywater, and after a month of treating non-BBL graywater. The

biofilm sample coupons were stained using gram stain (Gram Stain Advanced, Hardy Diagnostics, Santa Maria, CA), air dried, and cover-slipped in Prolong Gold (Life Technologies, Carlsbad, CA) before imaging on an Zeiss Imager D1 microscope with AxioCam ICc 1 color camera, and processed using the Axiovision Software (Zeiss Microscopy GmbH, Oberkochen, Germany).

3 Results and Discussions

3.1 Influent and effluent water quality

Raw graywater that contained laundry water generated from clothes washing using the BBL (“BBL graywater”) or non-BBL (“non-BBL graywater”) detergents had organics, total suspended solids (TSS) and turbidity concentrations exceeding the water quality requirements for aboveground water reuse (**Table 2**). Continuous field operation of the SB-VFW system for the BBL and non-BBL graywater over 3.5 and 1.5 months, respectively, demonstrated that average treated water quality (**Table 4**) complied with the aboveground graywater reuse standards (**Table 2**). Significant turbidity removal was achieved with average effluent turbidity of 0.3 NTU for BBL graywater (relative to ~22 NTU for the raw BBL graywater) after three hours of treatment, and 0.1 NTU for non-BBL graywater (relative to ~30 NTU for the raw non-BBL graywater) after 24 hours of treatment. Such effluent levels were well below even the most stringent turbidity requirement of <2 NTU for aboveground graywater reuse in California (**Table 1**).

The BBL and non-BBL graywater effluent had low BOD₅ of 0.5 mg/L and 2.8 mg/L (representing reduction of >97% relative to both influent types), respectively, and TSS of < 1 mg/L for both effluents (representing reduction of >97% and >95% relative to the influent graywater); the above treatment performance was also well within the BOD₅ and TSS requirements for aboveground graywater reuse in Australia and Wisconsin (**Table 1**). Raw BBL and non-BBL graywater pH was 6.8 (relative to tap water pH of 6.4) and decreased to 6.6 after 24 hours of

treatment. The slightly higher raw graywater pH was likely due to the use of detergents containing alkalis (e.g., sodium bicarbonate and sodium citrate in BBL detergent, and monoethanolamine citrate in non-BBL detergent), which increases surface charge of fabric and soil particles to enhance cleaning performance [46]. The slight reduction of graywater effluent pH after treatment could be due to alkalis reduction due to biodegradation of organic alkalis, such as citrate, or other physio-biochemical reactions that neutralize inorganic alkalis such as sodium bicarbonate and carbonate. The raw BBL and non-BBL graywater TDS levels were 337 mg/L (53% higher than tap water) and 295 mg/L (34% above tap water) and increased slightly (by 3% and 6%, respectively) after treatment (**Table 4**). Such slight increase in TDS post treatment, although within experimental variability, could also be the result of dissolution of divalent salt precipitate (e.g., calcium

Table 4. Water quality of influent (raw) and treated (effluent) BBL and non-BBL graywater

	BBL Graywater		Non-BBL graywater	
	Raw graywater ^(a)	Effluent after 3-hr ^(a) treatment	Raw graywater ^(b)	Effluent after 24-hr treatment ^(b)
pH	6.8	6.6	6.8	6.6 ± 0.1
TDS, mg/L	337 ± 28	347 ± 26	295 ± 7	313 ± 12
DO, mg/L	1.6 ± 0.4	4.9 ± 1.3	2.5 ± 1.8	7.0 ± 1.3
Temp, C	21.4 ± 1.2	22.0 ± 1.0	20.1 ± 2.6	17.4 ± 2.6
Turbidity, NTU	21.6 ± 12.7	0.3 ± 0.3	29.8 ± 13.1	0.5 ± 0.1
TSS, mg/L	23.5 ± 9.3	<1	35.3 ± 1.3	< 1
TOC, mg/L	31.5 ± 8.9	6.2 ± 1.0	101.2 ± 22.0	8.0 ± 1.1
Total inorganic carbon (TIC), mg/L	29.4 ± 5.4	30.5 ± 6.3	21.1 ± 6.6	20.0 ± 8.0
DOC, mg/L	24.6 ± 7.7	5.6 ± 0.9	87.8 ± 17.5	7.7 ± 1.3
bDOC, mg/L	20.4 ± 7.7	1.4 ± 0.8	80.1 ± 15.5	2.5 ± 1.1
DIC, mg/L	28.6 ± 4.6	27.4 ± 5.7	19.0 ± 6.3	18.2 ± 7.8
Particulate TOC, mg/L	7.7 ± 2.7	0.5 ± 0.3	13.4 ± 4.6	0.4 ± 0.3
COD ^a , mg/L	128 ± 46	6.0 ± 4.7	490 ± 112	17.4 ± 5.7
BOD ^b , mg/L	40 ± 14	< 1	152 ± 36	2.8 ± 2.2
NH ₄ -N, mg/L	5.30 ± 1.95	1.70 ± 0.82	2.24 ± 0.39	0.10 ± 0.02
NO ₃ -N, mg/L	0.12 ± 0.05	2.47 ± 1.52	0.21 ± 0.03	0.13 ± 0.03
PO ₄ -P, mg/L	3.89 ± 0.73	2.44 ± 0.24	4.00 ± 0.80	2.13 ± 0.47

^a COD was calculated from the TOC using an influent COD:TOC ratio of 4.40, an effluent COD:TOC ratio of 2.22 based on three selected observations from three separate treatment cycles (or days) collected in the same week (**Section 2.3**). Influent and effluent BOD:COD ratios were 0.31 and 0.16, respectively. N - number treatment cycles (i.e., days); ^(b) average for 25 batches; ^(c) average for five batches. Note: Samples from two separate treatment cycles (i.e., days) were collected twice weekly and once per week when treating BBL and non-BBL graywater, respectively.

carbonate in the raw graywater) during recirculation in which the pH decreased relative to the raw graywater. It is also noted that the non-BBL graywater part of the study was commenced after 3.5 months operation with the BBL graywater. Therefore, it is possible that the non-BBL treated graywater effluent TDS was skewed to higher level than the influent due to slow release of sodium and/or calcium salts that may have accumulated in the soil matrix. Irrespective of the above, it is stressed that the treated effluent TDS for both types of graywater was well below the maximum recommended level (i.e. 1,000 mg/L for irrigation [47]).

Figure 2. Average bDOC (a) and turbidity (b) removal of BBL (25 treatment cycles) and non-BBL (four treatment cycles) graywater indicates that the SB-VFW system was effective in removing both turbidity and bDOC. Error bars represents one standard deviation of the data set.

The treatment time required for reaching the target effluent quality for aboveground nonpotable water reuse (**Table 2; Fig. 2**) for BBL and non-BBL graywater were 3 and 24 hours,

268 respectively. The above performance difference was attributed to the lower TOC level in the raw
 269 BBL graywater (~32 mg/L) with 22% of the TOC in particulate form. The biodegradable dissolved
 270 organic carbon (bDOC) in the raw BBL graywater was at ~20.4 mg/L bDOC, which was ~64% of
 271 the total TOC, and declined by 93% after 3 hours of treatment. On the other hand, the raw non-
 272 BBL graywater TOC was 101 mg/L with 14% of the TOC in particulate form, while the remaining
 273 being in dissolved form. Raw non-BBL graywater bDOC was 80 mg/L (~80% of the TOC), and
 274 was reduced by 99% after 24 hours of treatment (**Fig. 2a**). High TOC in the raw non-BBL
 275 graywater was attributed to both its high TOC content (150 mg TOC/g-detergent relative to 71 mg
 276 TOC/g-detergent for the BBL detergent) and its higher (recommended) detergent dosage. The
 277 manufacturer recommended laundry dosage for the non-BBL detergent are ~44 g-
 278 detergent/normal-load and ~64 g/heavy-load as compared to ~19 g-detergent/normal-load and ~38
 279 g-detergent/heavy-load for BBL detergent, which led to the higher non-BBL graywater TOC.

Figure 3. Correlation of particulate TOC (i.e. total TOC - DOC) with graywater turbidity suggesting that graywater turbidity was possibly of mostly organic origin. The data set comprised of 25 and 4 of 24-hour treatment cycles of BBL and non-BBL graywater batches, respectively, collected over a period of five-months. The R^2 values for the BBL and non-BBL graywater linear correlations were 0.72 and 0.67, respectively.

The raw graywater turbidity correlated linearly with the total organic carbon associated with particulate organics (i.e. TOC minus DOC, represented as particulate TOC) as shown in **Fig. 3**. The SB-VFW was effective for turbidity removal of up to 99% (from 30 NTU to 0.3 NTU) within three hours of treatment. Coincidentally, the time required for 93% bDOC removal was achieved in after three hour of treatment. A similar level of turbidity removal (~98%) was achieved for the non-BBL graywater within ~8 hours (to 0.5 NTU, **Fig. 2b**), along with 90% bDOC (to 8 mg/L bDOC) over the same period with further removal to 97% bDOC (to ~2.5 mg/L) at 24 hours.

The bDOC degradation kinetics for the non-BBL relative to the BBL graywater for the SB-VFW system can be analyzed using a simple model that considers the hydraulic retention time in the wetland, wetland bed thickness, wetland area and removal rate constant [48]. Accordingly, the bDOC level can be expressed as

$$C_{eff} = C_{i,gr} \cdot \exp \left[-\frac{t}{\theta} \left[1 - \exp \left(-k \frac{A \varepsilon L}{Q} \right) \right] \right] \quad (5)$$

where C_{eff} is the effluent bDOC (mg/L), $C_{i,gr}$ is the influent bDOC, θ is hydraulic retention time in the wetland (i.e., the ratio V_R/Q , $\theta = 0.53$ hr); V_R is the reservoir volume ($V_R = 0.3$ m³; L wetland bed thickness ($L = 0.12$ m); A is the wetland area ($A = 0.68$ m²), Q is the graywater recirculation flow rate ($Q = 0.58$ m³/hr), ε is the wetland porosity ($\varepsilon = 0.9$), k is the removal rate constant (hr⁻¹) and t is time (hr). The bDOC removal rate constants for BBL and non-BBL graywater being 4.0 hr⁻¹ and 1.5 hr⁻¹, respectively, were determined from fitting Eq. 5 to the bDOC data (**Fig. 2**). It is noted that the faster bDOC removal kinetics for BBL graywater could be, in part, due to the greater biomass availability in the SB-VFW in comparison to that which could be achieved with the BBL graywater of lower content of degradable organics. The above results and improved treated effluent quality for BBL graywater, relative to non-BBL graywater, suggests that use of BBL detergent would be preferable when considering residential graywater treatment and reuse.

3.2 VFWR system characterization and long-term treatment of BBL

graywater

The SB-VFW wetland unit acted as a packed-bed filter that captured particulates and provided surface area for biofilm growth. Thin slimy (“biofilm”) layers were observed on the CFM surface and plastic coupon samples just underneath the soil layer. Microscope biofilm images revealed a rich collection of diverse organisms (**Fig. 4**). The role of the CFM layer on bDOC and turbidity removal was evaluated by removing it from the SB-VFW system for 14 days. The effluent bDOC levels after three hours of BBL graywater treatment with and without the CFM, were both ~1.3 mg/L (**Table 5**). Similarly, effluent turbidity after three hours of treatment were ~0.3 NTU and 0.2 NTU with and without the CFM, respectively (**Table 5**). Turbidity and bDOC removal in the above

Figure 4. Microscopic biofilm images (from the plastic media) during BBL graywater treatment. a) protozoa and algae, b) fungi, c) protozoa and bacteria, d) protozoa, e) algae cluster, f) algae. The presence of protozoa suggests aerobic environment in the plastic media. Scale bars represent

tests indicated that the CFM did not affect organics or turbidity removal. The CFM, however, enabled aeration enhancement during treatment (**Fig. 5**) as evident by the higher DO level (~6 mg/L) relative to the case without the CFM (~4 mg/L). High DO (e.g. > 6 mg/L) has been reported to enhance biodegradation of organics [49] as well as nitrification (> 5 mg/L DO) [50].

Furthermore, higher DO concentration allowed for greater oxygen diffusion into the biofilm, thereby enhancing organic degradation by the biofilm [51].

Table 5. Effluent bDOC and turbidity achieved by the wetland with and without the use of cross flow media

Parameters	Treatment time, hours	With CFM ^(a)	Without CFM ^(b)
bDOC, mg/L	3	1.3 ± 0.8	1.3 ± 1.2
	8	0.3 ± 0.2	0.2 ± 0.2
Turbidity, NTU	3	0.3 ± 0.1	0.2 ± 0.1
	8	<0.1	<0.1

^(a) 10 graywater batches treated over a period of five weeks; ^(b) 3 graywater batches treated during the same one week period

Figure 5. Dissolved oxygen level achieved for graywater treatment with and without the CFM over a period of 4 and 2 weeks of treatment, respectively.

Particle size analysis revealed that the soil layer provided effective removal of particles from non-BBL graywater. The SB-VFW system was effective in removing large particles and achieved ~88% size reduction (i.e. from 56 μm to 6 μm) within the first hour of treatment (**Fig. 6**). Further reduction of particle size to 3.8 μm and 67% reduction of effluent particle concentration (down to ~5,800 particles/mL) was achieved after three hours of treatment (**Fig. 6**). Over the same

treatment period, the effluent bDOC of ~ 1 mg/L was attained indicating that a limited source of organics was available for the microorganisms in the SB-VFW system. It has been shown that low organic content stimulates extracellular polymer substance (EPS) excretion by microorganisms, which would promote bioflocculation to form larger suspended particles in the water phase [52]. The presence of larger aggregates, as a result of bioflocculation, is indeed suggested by the suspended matter size increase (e.g. from $3.8 \mu\text{m}$ to $44 \mu\text{m}$) and particle concentration decrease (e.g. from $\sim 5,800$ particles/mL to $2,000/\text{ml}$ after 24 hours of treatment), which are consistent with other biological treatment systems [53].

Figure 6. Effluent mean particle size and particle number concentrations during treatment of BBL graywater (one-week operation).

The aerobic environment in the SB-VFW allowed for nitrification to take place, which was indicated by ammonium-nitrogen ($\text{NH}_4\text{-N}$) removal and nitrate-nitrogen ($\text{NO}_3\text{-N}$) production during the 24-hour treatment cycle (**Fig. 7**). For example, the raw BBL graywater contained 5.2 ± 2.0 mg/L $\text{NH}_4\text{-N}$, which was reduced to 0.1 ± 0.1 mg/L after eight hours of treatment. Simultaneously, $\text{NO}_3\text{-N}$ was undetected in the influent, but increased to $\sim 2.5 \pm 1.5$ mg/L and

344 $\sim 5.9 \pm 1.4$ mg/L after three- and 24- hour of treatment, respectively (**Fig. 7**). The continual increase
 345 of $\text{NO}_3\text{-N}$ indicates that denitrification did not take place. However, denitrification was observed
 346 only at higher organic loading during two BBL detergent shockload events where TOC was
 347 increased from the normal average of 32 ± 8.9 mg/L to 84 ± 1.5 mg/L and 45 ± 0.9 mg/L, with
 348 $\text{NO}_3\text{-N}$ remaining < 0.1 mg/L during those two 24-hour treatment cycles. Nitrification also took
 349 place during the detergent shockloading events with $\text{NH}_4\text{-N}$ being reduced from 2.6 mg/L to < 0.1
 350 mg/L within the first three hours and maintaining at the same above level over the 24 hour
 351 treatment period. Nitrification-denitrification during the detergent shockloading tests suggests that
 352 aerobic and anoxic environments co-existed in the soil layer of the SB-VFW system while
 353 sufficient carbon source and an anoxic environment enabled denitrification.

Figure 7. Change in $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ levels for: (a) treatment of BBL graywater batch spiked with BBL detergent (i.e., average over two shockload events), (b) treatment of a new BBL graywater batch after discharge of detergents spiked graywater treated in (a), and (c) normal BBL graywater treatment operation (three weeks average) prior to laundry detergent shockload events.

Figure 8. The impact of (a) TOC and (b) turbidity removal by the treatment system during BBL detergent shockload tests (Day 1: detergent shockload (160g BBL detergent added into 300 L raw BBL graywater) and Day 2: detergent shockload (80g BBL detergent added into 300 L raw BBL graywater), immediately after detergent shockload tests (Day 3: normal load) and the average normal load water quality.

354

355 The SB-VFW system remained effective with respect to turbidity removal but TOC removal

356 required longer treatment time than usual during two sequential detergent shockloading tests. On

357 the first day of the detergent shockload test, the SB-VFW system achieved ~61% TOC removal

358 from raw BBL graywater (84 mg/L TOC) within the first half-hour (**Fig. 8a**). Turbidity removal

359 of 86% was achieved (from 82 to 11 NTU) for the same treatment period (**Fig. 8b**); and reached

360 removal of 99.6% and was below detection after 8 and 24 hours of treatment, respectively (**Fig.**

8b). On the second day of the detergent shockload test, the SB-VFW system produced effluent with turbidity of < 1 NTU (0.8 NTU) after three hours of treatment, and TOC of 6.8 mg/L after 24-hour of treatment (**Fig. 8**). SB-VFW treatment of a new BBL graywater batch immediately after the two-day detergent shockload tests was again at a high treatment efficiency (**Fig. 8**, e.g. ~ 0.3 mg/L bDOC and 0.2 NTU turbidity) with 3-hour of treatment. The above observations suggest that the SB-VFW is resilience to detergent shockloads and thus indicates that the system can handles fluctuation in TOC and turbidity levels.

3.3 Organic loading and clogging of the VFW system

The SB-VFW system operated in a stable manner, without clogging during the three month of daily BBL graywater treatment at a recirculation flow rate of 9.5 L/min (or 46 turnovers/24-hour). During the operation of the system, the soil hydraulic conductivity was invariant (~1.5 cm/min). High organic content is known to enhance biomass growth and may also affect the hydraulic conductivity of the soil layer (Zhao et al., 2009). Accordingly, in order to further evaluate the importance of controlling organic loadings in the raw graywater when using the SB-VFW system, the residents were asked to switch from using the non-BBL detergent to the BBL detergent, which contained a lower level of organics (by a factor of ~2.5 times). After the switch from treating BBL graywater to non-BBL graywater, the hydraulic conductivity of the SB-VFW system remained (for nearly 22 days; **Fig. 9a**) at about 1.5 cm/min as during the previous 3.5 months of treating BBL graywater. The treatment system achieved 66% bDOC removal (e.g. from 90 mg/L to 32 mg/L bDOC) within the first 30 minutes of treatment (**Fig. 9a**) and further removed of up to 84% after three hours of treatment. The effluent bDOC was at 2 mg/L, achieving 98% removal after 24 hours (**Fig. 9a**). Progressive reduction in bDOC removal was observed when the non-BBL graywater was treated for extended period, only attaining 82% of bDOC removal (32 mg/L) (**Fig.**

9a) for a 24-hour batch after 34 days of operation. Turbidity removal by the SB-VFW remained effective, during the first 22 days of treating non-BBL (attaining treated graywater turbidity of <1 NTU and below detection limit after eight and 24 hours of treatment, respectively (**Fig. 9b**)). Progressive wetland soil clogging eventually resulted in significant loss of hydraulic conductivity, and by day 34, water overflow from the wetland into the bottom reservoir resulted in marked increase in effluent turbidity and bDOC. The above system behavior is consistent with other reported studies in which it was reported that soil clogging can be a concern at high graywater loading of organics and turbidity, as well as with detergents of high organic content [34, 35].

Figure 9. (a) bDOC, and b) turbidity treatment performance change during the one month of treating non-BBL containing graywater.

Reduction of the soil hydraulic conductivity after treating non-BBL graywater for over a month was likely due to excess biomass growth stimulated by the organic rich non-BBL graywater. Increase biomass was evident as a biofilm growth (~2 mm) on the CFM surfaces (**Section 3.2**) was observed when treating non-BBL graywater. In contrast, a thinner biofilm layer of <1 mm (**Fig. 5**) was observed when treating BBL graywater. The thick biofilm encountered when treating the organic-rich non-BBL graywater suggests that this type of graywater was capable of supporting greater biomass growth (**Fig. 10**). Excessive biomass growth can lead to reduction in soil porosity and thus its hydraulic conductivity, and eventually clogging in the SP-VFWs soil [35].

Figure 10. Microscopic images of biofilm collected from the plastic media when the treatment system was treating non-BBL graywater. a) a cluster of algae, b) algae, c) fungi, d) clusters of algae and protozoa, e) algae and protozoa, d) eukaryotic microorganisms, h) algae and protozoa, i) protozoa, j) protozoa. Protozoa were found in large number in the biofilm indicating that there was plentiful of bacteria for protozoa to forage on. Scale bars are 10 μ m.

Figure 11. The biomass growth phase diagram for the SB-VFW system adapted from a typical biological batch reactor [14]. The cycle of non-BBL graywater is shown to only overlap with the lag, exponential growth and stationary phases; while the non-BBL graywater treatment cycle is shown to overlap with the above three phases in addition to the decay phase.

The SB-VFW system is a batch treatment process, and thus the relationship between biomass growth and organic concentration in the SB-VFW system can be conceptualized by a typical biological batch reactor biomass growth behavior as depicted in **Fig. 11**. In a typical biological batch reactor, biomass growth occurs in the presence of organics while biomass reduction takes place when undergoing endogenous decay under low organic conditions (**Fig. 11**) [14]. In the present system, when BBL graywater was treated, the bDOC of the recirculating water was already at ~ 1 mg/L after 3 hours of treatment, which means that water of low organic content was recirculated in the SB-VFW system for approximately 21 hours during the 24-hour treatment cycle (**Fig. 2a**). Recirculation of water of low organic concentration beyond 3-hours after complete removal of organics allowed for endogenous biomass decay (**Fig. 11**). When non-BBL graywater was treated, however, the bDOC concentration remained relatively high (reduced to ~ 2 mg/L

bDOC after 24 hours of treatment) even for a 24-hour of treatment cycle (**Fig. 2a**). Therefore, it is reasonable to expect that the biomass growth was only at the stationary phase when a fresh batch of raw graywater recharged into the SB-VFW system.

In order to illustrate the importance of endogenous decay, a hypothetical treatment cycle of the SB-VFW system, for the BBL and non-BBL, is presented in **Fig. 11**. Results of the present study suggest that in the non-BBL treatment cycle, there was relatively abundance of organics at the end of the 24-hour treatment cycle, which permitted the biomass to undergo the lag, exponential growth and the stationary phases before the next treatment cycle began. An absence of an endogenous decay phase in the non-BBL graywater treatment cycle would mean that the biomass would continue growing and accumulating after each treatment cycle. It is hypothesized that the above would explain the gradual clogging of the wetland (soil layer). The resulting hydraulic conductivity reduction would then necessitate lowering of the recirculation flow rate to avoid excessive ponding and possible overflowing of water from the top wetland section (**Fig. 1**). In contrast, in the treatment of BBL graywater, the organics were significantly depleted for a given batch within 3 hours of treatment with bDOC reduced to achieve ~ 1 mg/L (**Fig. 2**). As a result, the biomass is likely to have undergone an extended endogenous decay phase during the remaining 24-hour treatment cycle. It is argued here that the endogenous biomass decay phase is crucial for maintaining a stable biomass (i.e. prevent excessive growth) in the soil layer. The above arguments and higher performance of the SB-VFW for treatment of BBL relative to non-BBL graywater suggest that the use of detergents that are lean in organics would be more suitable if one's goal is to effectively treat graywater for aboveground onsite reuse. For graywater that is high in organics, a thicker soil layer or longer treatment time would be necessary in order to promote sufficient endogenous biomass decay to avoid overgrowth of biomass that would then clog the soil layer. However, the above options would result in higher system footprint and possibly increased odor

and other nuisance due to longer raw graywater storage time, as well as larger storage volume. On the other hand, for treatment of graywater with low organic concentrations, a smaller treatment system could also be devised to provide sufficient treatment.

4 Conclusions

The feasibility of residential graywater treatment via a semi-batch vertical flow wetland (SB-VFW) with recirculation was evaluated in a 5-month field study. The study demonstrated the following:

- 1) Treatment of graywater, from showers, sinks and laundry, in the SB-VFW which contained a coconut coir soil substitute was achieved to a level that meets the strict water quality requirements (with respect to BOD₅, TOC and turbidity) for above ground non-potable reuse;
- 2) Treatment time of about three hours was typically sufficient for batches of up to ~ 300 liters in a small footprint SB-VFW system.
- 3) System performance was stable when a bio-based laundry detergent was utilized owing to its lower organic content relative to typical non-bio-based detergents. Clogging of the wetland soil medium due to biofilm overgrowth was avoided when treating graywater of low organic loading (e.g., when utilizing a bio-based detergent) owing to the formation of a stable biofilm exists in the wetland. However, at higher organic loading rates or with detergents of higher organic content, clogging may be a concern.

Results of the present study suggest that there is merit in exploring the use of compact SB-VFW systems for increasing graywater reuse in urban environments, as well as possibly for deployment as a polishing process for certain industrial water treatment applications.

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References

1. Surendran, S. and A.D. Wheatley, *Grey-Water Reclamation for Non-Potable Re-Use*. Water and Environment Journal, 1998. **12**(6): p. 406-413.
2. Andersen, M., et al., *Pilot-scale testing membrane bioreactor for wastewater reclamation in industrial laundry*. Water science and technology : a journal of the International Association on Water Pollution Research, 2002. **46**(4-5): p. 4-5.
3. Sostar-Turk, S., I. Petrinic, and M. Simoncic, *Laundry wastewater treatment using coagulation and membrane filtration*. Resources Conservation and Recycling, 2005. **44**(2): p. 185-196.
4. Friedler, E., *Quality of individual domestic greywater streams and its implication for on-site treatment and reuse possibilities*. Environmental technology, 2004. **25**(9): p. 997-1008.
5. Friedler, E., R. Kovalio, and A. Ben-Zvi, *Comparative study of the microbial quality of greywater treated by three on-site treatment systems*. Environmental technology, 2006. **27**(6): p. 653-663.
6. Gilboa, Y. and E. Friedler, *UV disinfection of RBC-treated light greywater effluent: Kinetics, survival and regrowth of selected microorganisms*. Water Research, 2008. **42**(4-5): p. 1043-1050.
7. Nolde, E., *Greywater reuse systems for toilet flushing in multi-storey buildings - over ten years experience in Berlin*. Urban Water, 2000. **1**(4): p. 275-284.
8. Friedler, E., et al., *On-site greywater treatment and reuse in multi-storey buildings*. 2005. **51**(10): p. 187-194.
9. Lamine, M., D. Samaali, and A. Ghrabi, *Greywater treatment in a submerged membrane bioreactor with gravitational filtration*. Desalination and Water Treatment, 2012. **46**(1-3): p. 182-187.
10. Hourlier, F., et al., *Membrane process treatment for greywater recycling: Investigations on direct tubular nanofiltration*. Water Sci. Technol. Water Science and Technology, 2010. **62**(7): p. 1544-1550.

11. Ronen, Z., A. Guerrero, and A. Gross, *Greywater disinfection with the environmentally friendly Hydrogen Peroxide Plus (HPP)*. Chemosphere, 2010. **78**(1): p. 61-65.
12. Pidou, M., et al., *Chemical solutions for greywater recycling*. Chemosphere, 2008. **71**(1): p. 147-155.
13. Zhang, D., et al., *Decentralized water management: rainwater harvesting and greywater reuse in an urban area of Beijing, China*. Urban Water Journal, 2009. **6**(5): p. 375-385.
14. Metcalf & Eddy., et al., *Wastewater engineering : treatment and reuse*. 4th ed. McGraw-Hill series in civil and environmental engineering. 2004, New York London: McGraw-Hill. xxviii, 1819 p.
15. Al-Jayyousi, O., *Focused environmental assessment of greywater reuse in Jordan*. Environmental engineering and policy, 2002. **3**(1): p. 67-73.
16. Yu, Z.L.T., et al., *Critical review: regulatory incentives and impediments for onsite graywater reuse in the United States*. J. of Water and Environment Research, 2013. **85**(7): p. 650-662.
17. DeOreo, W.B., *Analysis of water use in new single family homes*. 2011, Aquacraft Water Engineering & Management.
18. Boyjoo, Y., V.K. Pareek, and M. Ang, *A review of greywater characteristics and treatment processes*. Water Science & Technology, 2013. **67**(7): p. 1403-1424.
19. Dixon, A., et al., *Measurement and modelling of quality changes in stored untreated grey water*. Urban Water, 2000. **1**(4): p. 293-306.
20. NSW Health Dept. *Greywater Treatment Systems: Register - Certificates of Accreditation*. 2011 [cited 2011 June 2011]; Available from: <http://www.health.nsw.gov.au/publichealth/environment/water/accreditations/gts.asp>.
21. EMRC, *Reuse of greywater in Western Australia*. 2011, Eastern Metropolitan Regional Council Belmont, , Western Australia.
22. Hoffmann, H., et al., *Technology Review of Constructed Wetlands: Surface Flow Constructed Wetlands for Greywater and Domestic Wastewater Treatment*. 2011, GIZ Sustainable Sanitation ecosan: Eschborn.
23. Niemczynowicz, J. and I. Fittschen, *Experiences with dry sanitation and greywater treatment in the ecovillage Toarp, Sweden*. Water Science & Technology, 1997. **35**(9).
24. Shrestha, R.R., et al., *Application of constructed wetlands for wastewater treatment in Nepal*. Water Science and Technology, 2001. **44**(11-12): p. 11-12.
25. Kadlec, R.H. and S.D. Wallace, *Treatment wetlands*. 2nd ed. 2009, Boca Raton, FL: CRC Press. 1016 p.
26. Lemon, E., et al. *SWAMP pilot scale wetlands: Design and performance, Niagara-on-the-Lake, Ontario, Canada*. in *Constructed Wetlands in Cold Climates: Design, Operation, Performance Symposium*. 1996. The Friends of St. George.
27. Gross, A., et al., *Recycled vertical flow constructed wetland (RVFCW)--a novel method of recycling greywater for irrigation in small communities and households*. Chemosphere, 2007. **66**(5): p. 916-923.
28. IWA, *Constructed wetlands for pollution control : processes, performance, design and operation*. 2000, London: IWA Publishing.
29. Environment Agency, U., *Greywater for domestic users: an information guide*, U.K. Environment Agency, Editor. 2011: Bristol
30. California Building Standards Commission, *2010 California Plumbing Code*, in 24, C.B.S. Commission, Editor. 2010, International Association of Plumbing and Mechanical Officials: CA, USA.

31. Wisconsin Department of Commerce, *Design, Construction, Installation, Supervision, Maintenance and Inspection of Plumbing*, W.D.o. Commerce, Editor., Wisconsin Department of Commerce Wisconsin. p. 63.
32. DOH WA, *Code of practice for the reuse of greywater in Western Australia 2010*, W.A. Department of Health, Editor. 2010, Government of Western Australia
33. EPA Victoria, *Code of Practice Onsite Wastewater Management*, V. Environmental Protection Agency, Australia Editor. 2013, EPA Victoria: Carlton.
34. Platzer, C. and K. Mauch, *Soil clogging in vertical flow reed beds - mechanisms, parameters, consequences and solutions?* Water Science and Technology, 1997. **35**(5): p. 175-181.
35. Zhao, L., W. Zhu, and W. Tong, *Clogging processes caused by biofilm growth and organic particle accumulation in lab-scale vertical flow constructed wetlands*. Journal of Environmental Sciences, 2009. **21**(6): p. 750-757.
36. Leverenz, H.L., G. Tchobanoglous, and J.L. Darby, *Clogging in intermittently dosed sand filters used for wastewater treatment*. Water Research, 2009. **43**(3): p. 695-705.
37. Cooper, P., *What can we learn from old wetlands? Lessons that have been learned and some that may have been forgotten over the past 20 years*. Desalination, 2009. **246**(1-3): p. 11-26.
38. Sklarz, M.Y., et al., *A recirculating vertical flow constructed wetland for the treatment of domestic wastewater*. Desalination, 2009. **246**(1-3): p. 617-624.
39. Winward, G.P., et al., *Chlorine disinfection of grey water for reuse: Effect of organics and particles*. Water Research, 2008. **42**(1-2): p. 483-491.
40. Winward, G.P., et al., *Ultraviolet (UV) disinfection of grey water: Particle size effects*. Environmental technology, 2008. **29**(2): p. 235-244.
41. Zhang, D.Q., et al., *Application of constructed wetlands for wastewater treatment in developing countries – A review of recent developments (2000–2013)*. Journal of Environmental Management, 2014. **141**(0): p. 116-131.
42. Leverenz, H.L., et al., *Anoxic treatment wetlands for denitrification*. Ecological Engineering, 2010. **36**(11): p. 1544-1551.
43. Laber, J., R. Perfler, and R. Haberl, *Two strategies for advanced nitrogen elimination in vertical flow constructed wetlands*. Water Science and Technology, 1997. **35**(5): p. 71-77.
44. Pickering, K.D., et al., *Alternative Water Processor Test Development*. American Institute of Aeronautics and Astronautics, 2013.
45. Khan, E., et al., *Biodegradable dissolved organic carbon for indicating wastewater reclamation plant performance and treated wastewater quality*. Water Environment Research, 1998. **70**(5): p. 1033-1040.
46. Bajpai, D. and V. Tyagi, *Laundry detergents: an overview*. Journal of Oleo Science, 2007. **56**(7): p. 327-340.
47. USEPA, *2012 Guidelines for Water Reuse*, U.S.E.P. Agency, Editor. 2012, U.S. Environmental Protection Agency Washington, D.C. .
48. Yu, Z.L.T., et al., *Performance and economic evaluation of a modular vertical-flow wetland for onsite residential graywater recycling*. Journal of Environmental Management (submitted on Aug 1, 2014), 2014.
49. Chapman, T.D., L.C. Matsch, and E.H. Zander, *Effect of High Dissolved Oxygen Concentration in Activated Sludge Systems*. Journal (Water Pollution Control Federation), 1976. **48**(11): p. 2486-2510.

- 597 50. Stenstrom, M.K. and R.A. Poduska, *The effect of dissolved oxygen concentration on*
598 *nitrification*. Water Research, 1980. **14**(6): p. 643-649.
- 599 51. Costerton, J.W., et al., *Microbial biofilms*. Annual Reviews in Microbiology, 1995. **49**(1):
600 p. 711-745.
- 601 52. Sheng, G.-P., H.-Q. Yu, and X.-Y. Li, *Extracellular polymeric substances (EPS) of*
602 *microbial aggregates in biological wastewater treatment systems: A review*.
603 Biotechnology Advances, 2010. **28**(6): p. 882-894.
- 604 53. Leu, S.-Y., L. Chan, and M.K. Stenstrom, *Toward Long Solids Retention Time of*
605 *Activated Sludge Processes: Benefits in Energy Saving, Effluent Quality, and Stability*.
606 Water Environment Research, 2012. **84**(1): p. 42-53.

607