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Review

Review of the technological approaches for grey water treatment and reuses

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ABSTRACT

Based on literature review, a non-potable urban grey water reuse standard is proposed and the treatment alternatives and reuse scheme for grey water reuses are evaluated according to grey water characteristics and the proposed standard. The literature review shows that all types of grey water have good biodegradability. The bathroom and the laundry grey water are deficient in both nitrogen and phosphors. The kitchen grey water has a balanced COD: N: P ratio. The review also reveals that physical processes alone are not sufficient to guarantee an adequate reduction of the organics, nutrients and surfactants. The chemical processes can efficiently remove the suspended solids, organic materials and surfactants in the low strength grey water. The combination of aerobic biological process with physical filtration and disinfection is considered to be the most economical and feasible solution for grey water recycling. The MBR appears to be a very attractive solution in collective urban residential buildings.

Contents

1. Introduction

Grey water is defined as the urban wastewater that includes water from baths, showers, hand basins, washing machines, dishwashers and kitchen sinks, but excludes streams from toilets (Jefferson et al., 1999; Otterpohl et al., 1999; Eriksson et al., 2002; Ottoson and Stenström, 2003). Some authors exclude kitchen wastewater from the other grey water streams (Al-Jayyousi, 2003; Christova-Boal et al., 1996; Little, 2002; Wilderer, 2004). Grey water constitutes 50–80% of the total household wastewater (Eriksson et al., 2003; Friedler and Hadari, 2006). Due to the low levels of contaminating pathogens and nitrogen, reuse and recycle of grey water is receiving more and more attention (Li et al., 2003). Numerous studies have been conducted on the treatment of grey water with different technologies which vary in both complexity and performance. However, specific guidelines for grey water reuse are not available or not sufficient and studies on the evaluation of the appropriate technologies for grey water reuse/recycle are scarce. In this study, the treatment alternatives for grey water reuse are examined by reviewing the published literatures and an evaluation and selection procedure of the appropriate techniques for grey water treatments and reuse is proposed.

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2. Characteristics of grey water

2.1. Quantity of grey water

The published literatures indicate that the typical volume of grey water varies from 90 to 120 l/p/d depending on lifestyles, living standards, population structures (age, gender), customs and habits, water installations and the degree of water abundance (Morel and Diener, 2006). However the volume of grey water in low income countries with water shortage and simple forms of water supply can be as low as 20–30 l/p/d (Morel and Diener, 2006).

2.2. Quality of grey water

Grey water is generated as a result of the living habits of the people involved, the products used and the nature of the installation and, therefore, its characteristics are highly variable (Eriksson et al., 2002). Based on literatures reviewing (Li, 2009), the quality ranges of the different grey water are summarized in Table 1. Although there are variations in grey water quality, the analysis of the grey water characteristics by different categories indicates that the kitchen grey water and the laundry grey water are higher in both organics and physical pollutants compared to the bathroom and the mixed grey water. All types of grey waters show good biodegradability in terms of the COD: BOD_5 ratios (Li, 2009). Compared to the suggested COD: N: P ratio of 100:20:1 (Metcalf and Eddy, 1991) for sewage wastewater, bathroom grey water is deficient in both nitrogen and phosphors due to the exclusion of urine and faces. Similar to the bathroom grey water, the laundry grey water and the mixed grey water are also deficient in nitrogen. In some cases, the laundry grey water and the mixed grey water are low in phosphors due to the use of phosphors free detergent. Kitchen grey water contributes the highest levels of organic substance, suspended solids, turbidity and nitrogen. Differing from other grey waters, the kitchen grey water doesn't lack nitrogen and phosphors and has a COD: N: P ratio closes to the suggested ratio by Metcalf and Eddy (1991). Some authors exclude kitchen wastewater from the other streams. However, if grey water is intended to be treated through a biological process, it is suggested that the small amount of kitchen grey water should be collected together with other streams to maintain a optimal COD: N: P ratio. This is because grey water from kitchen sinks and dishwashers contributes most of the biodegradable organic substances and particulate nitrogen. The analysis of the grey water characteristics by different categories also shows that the bathroom and laundry grey water are less contaminated by the micro-organisms compared to the other grey water streams. Due to the presence of the large amount of easily biodegradable organic substances, kitchen grey water is more contaminated by the thermal tolerant coliforms than other grey water streams. Knerr et al. (2008) and Gnirss et al. (2006) has pointed out that mixed grey water has a balance C: N: P ratio as suggested by Metcalf and Eddy (1991).

Table 1
The characteristics of grey water by different categories.

	Bathroom	Laundry	Kitchen	Mixed
pH (−)	6.4–8.1	7.1–10	5.9–7.4	6.3–8.1,
TSS (mg/l)	7–505	68 – 465	134–1300	25–183
Turbidity (NTU)	44–375	50 – 444	298.0	29–375
COD (mg/l)	100–633	231 – 2950	26–2050	100–700
BOD (mg/l)	50–300	48 – 472	536–1460	47–466
TN (mg/l)	3.6–19.4	1.1 – 40.3	11.4–74	1.7–34.3
TP (mg/l)	0.11– >48.8	ND – >171	2.9– >74	0.11–22.8
Total coliforms (CFU/100 ml)	$10–2.4\times10^7$	$200.5–7\times10^5$	$>2.4\times10^8$	$56–8.03\times10^7$
Faecal coliforms (CFU/ 100 ml)	$0–3.4\times10^5$	$50–1.4\times10^3$	–	$0.1–1.5\times10^8$

Table 2
Microbial nutrient requirements and the concentrations present in different grey waters.

Nutrient	Reported requirements (mg/l)[a]	Real grey water[d] (mg/l)	Real grey water[e] (mg/l)	Real Grey water[f] (mg/l)	Synthetic grey water[g] (mg/l)
N	15[b]	9.68	17.2–47.78	5.00	5.00
P	3[b]	7.53	4.17	1.37	0.047
S	1[b]	23.7	19.00	16.3	17.5
Ca	0.1–1.4	33.8	60.79	47.9	47.0
K	0.8 to >3.0	8.10	11.2–23.28	5.79	3.96
Fe	0.1–0.4	0.36	0.11	0.017	0.009
Mg	0.4–5.0	5.74	6.15	5.29	5.02
Mn	0.01–0.5	0.0121	<0.05	0.04	0.02
Cu	0.01–0.5	0.0618	0.08	0.006	0
Al	0.01–0.5	2.44	0.49	0.003	0
Zn	0.1–0.5	0.0644	0	0.03	0
Mo	0.2–0.5	–	<0.05	0	0
Co	0.1–5.0[c]	0.00136	<0.05	0	0

a: Burgess et al. (1999).
b: Beardsley and Coffey (1985).
c: Sathyanarayana Rao and Srinath (1961).
d: Palmquist and Hanæus (2005).
e: Hernandez et al. (2007).
f & g: Jefferson et al. (2001).

Jefferson et al. (2001) claimed that the deficiency of both macronutrients and trace nutrients in the grey water can limit the treat efficiency of the biological processes. However, Hernandez et al. (2007) and Knerr et al. (2008) concluded that the ratio of COD: BOD_5 in grey water is approximately 0.50 which indicates good potential for biological treatment. They also stated that concentrations of nutrients show no apparent limitation for the growth of micro-organisms. Based on the studies of Palmquist and Hanæus (2005) and Hernandez et al. (2007) (Table 2), it is found out that grey water is high in S, Ca, K and Al and the concentration levels of the trace nutrients are closed to the reported requirements (Burgess et al., 1999). The deficiency of trace nutrients in grey waters reported by Jefferson et al. (2001) was obviously caused by the exclusion of kitchen grey water.

3. Grey water treatments and reuses

3.1. Grey water reuse guidelines

The reclaimed grey water should fulfill four criteria (hygienic safety, aesthetics, environmental tolerance and economical feasibility) for reuse (Nolde, 1999). However, the lack of appropriate water quality standards or guidelines has hampered appropriate grey water reuse (Lazarova et al., 2003). One shall also keep in mind that different reuse applications require different water quality specifications and thus demand different treatments varying from simple processes to more advanced ones. There has been no uniformly enforceable international water reuse guideline to control the quality of the reclaimed wastewater. In many cases, the national water reuse guidelines vary from states to states. There is considerable variation among these guidelines, particularly regarding identifiable values and the limited parameters. The differences observed between published reuse criteria reflect differences in need, applications and social factors (Pidou, 2006). Very few reuse guidelines are particularly made for grey water recycling. Regulations and guidelines for grey water reuse mainly focus on the healthy and environmental impacts and are often established by local authorities. In 2006 the World Health Organization (WHO) released a guideline for grey water reuse for restricted and non-restricted agricultural irrigation. The guideline only outlines the microbiological requirements without considering the other physical and chemical parameters. For restricted irrigation, the

Table 3
Wastewater reuse standard from different countries.

	pH	TSS (mg/l)	TDS (mg/l)	Turbidity (NTU)	BOD_5 (mg/l)	Detergent (anionic) (mg/l)	TN (mg/l)	NH_4-N (mg/l)	TP (mg/l)	Dissolved O_2 (mg/l)	Residual Cl (mg/l)	Total coliform	Faecal coliform	Reuse application
Nolde, 1999, Germany	–	–	–	–	5 mg/l (BOD_7)	–		–	–	>50%	–	<100/ml	<10/ml	Toilet flushing
Ernst et al., 2006, China	6–9	–	<1500	<5	<10	1	–	<10	–		>1 mg/l after 30 min. > 0.2 mg/l at point of use	–	<3/100 ml	Toilet flushing
	6–9	–	<1000	<20	<20	1	–	<20	–	>1	>1 mg/l after 30 min. >0.2 mg/l at point of use	–	<3/100 ml	Irrigation purpose
	6–9	–	>1000	<5	<6	0.5	–	<10	–	–	>1 mg/l after 30 min. >0.2 mg/l at point of use	–	<3/100 ml	Washing purpose
	6–9	–	–	–	<6	0.5	15	<5	<0.5	>1.5	–	–	<10000/ 100 ml	Restricted impoundments and lakes
	6–9	–	–	<5	<6	0.5	15	<5	<0.5	>2	–	–	<500/100 ml	Unrestricted impoundments and lakes
Asano, 2007, USA	6–9	–	–	<2	10	–	–	–	–	–	1 mg/l	–	ND /100 ml	Unrestricted reuses *
	6–9	30	–		30	–	–	–	–	–	1 mg/l	–	<200 / 100 ml	Restricted reuses **
Maeda et al., 1996, Japan	5.8–8.6	–	–	Not unpleasant	≤20	–	–	–	–	–	Retained	≤1000/ml	–	Toilet flushing
	5.8–8.6	–	–	Not unpleasant	≤20	–	–	–	–	–	≥0.4	≤50/ml	–	Landscape irrigation
	5.8–8.6	–	–	≤10	≤10	–	–	–	–	–	–	≤1000/ml	–	Environmental (aesthetic settling)
	5.8–8.6	–	–	≤5	≤3	–	–	–	–	–	–	≤50/ml	–	Environmental (limited public contact)
Australia, Queensland (2003)	–	30	–	–								<100/ 100 ml		

ND: non-detectable *Toilet flushing, landscape irrigation, car washing and agricultural irrigation.
**Irrigation of areas where public access is infrequent and controlled golf courses, cemeteries, residential, greenbelt.

number of the Helminth eggs and the number of E. coli shall be lower than 1 /1 l and 10^5/100 ml respectively (WHO, 2006). For unrestricted irrigation, the number of the Helminth eggs and the number of E. coli shall be lower than 1 /1 l and 10^3/100 ml respectively (WHO, 2006). The German Berliner Senate Office for Construction and Housing has established a grey water reuse guideline, in which parameters like BOD_7, oxygen concentration, total coliform, faecal coliform and pseudomonas aeruginosa are required (Nolde, 1999).

Although most of the published water reuse guidelines are applied for the reclaimed municipal wastewater (Table 3), these guidelines can be used as a basis for the establishment the guideline of grey water recycling. The reviewing of the published wastewater reuse guidelines indicates that parameters like pH, TSS, BOD_5, turbidity, total coliform and fecal coliform shall at least be included for the establishment of a sound grey water reuse guideline. Occasionally, some of the guidelines also contain limits for parameters such as ammonia, phosphors, nitrogen and chlorine residual. The Chinese wastewater reuse guideline is considered to be the very few one, which include additional parameters like TDS, TN, NH_4–N, TP and detergent for wastewater recycling.

3.2. Establishment of the guideline for grey water reuses

Based on the studies (Maeda et al., 1996; Nolde, 1999; Ernst et al., 2006; Asano, 2007), a non-potable grey water reuse guidelines (Table 4) are proposed for both unrestricted and restricted reuses. Obviously the restricted non-potable reuses have lower water quality requirements, compared to the unrestricted non-potable reuses. This guideline includes parameters like fecal coliform, total coliforms, TSS, Turbidity, BOD_5, detergent, TN and TP.

3.3. Grey water treatment technologies

Technologies applied for grey water treatments include physical, chemical, and biological systems. Most of these technologies are preceded by a solid-liquid separation step as pre-treatment and followed by a disinfection step as post treatment. To avoid the clogging of the subsequent treatment, the pre-treatments such as septic tank, filter bags, screen and filters are applied to reduce the amount of particles and oil and grease. The disinfection step is used to meet the microbiological requirements.

3.4. Physical treatments

The physical treatments include coarse sand and soil filtration and membrane filtration, followed mostly by a disinfection step. The coarse filter alone has limited effect on the removal of the pollutants present in the grey water. March et al. (2004) reported a low strength bath grey water treatment system, which used a nylon sock type filter, followed by a sedimentation step and a disinfection step. The COD, the turbidity, the SS and TN were reduced from 171 mg/l, 20 NTU, 44 mg/l and 11.4 mg/l in the influent to 78 mg/l, 16.5 NTU, 18.6 mg/l and 7.1 mg/l respectively in the effluent. March et al. (2004) claimed that the reclaimed grey water can be used for toilet flushing under controlled working conditions (storage time <48 h and the residual chlorine concentration >1 mg/l in the toilet tank). In the study by Itayama et al. (2004), the COD, the BOD, the SS, the TN and the TP in the kitchen sink grey water were reduced from 271 mg/l, 477 mg/l, 105 mg/l, 20.7 mg/l and 3.8 mg/l in the influent to 40.6 mg/l, 81 mg/l, 23 mg/l, 4.4 mg/l and 0.6 mg/l respectively in the effluent by using a slanted soil filter (The main components of

Table 4
The standards for non-potable grey water reuses and applications.

Categories		Treatments goals	Applications
Recreational impoundments, lakes	Unrestricted reuses	BOD_5: ≤10 mg/l TN: ≤1.0 mg/l TP: ≤0.05 mg/l Turbidity: ≤2 NTU pH: 6–9 Faecal coliform: ≤10/ml Total coliforms ≤100/ml	Ornamental fountains; recreational impoundments, lakes and ponds for swimming
	Restricted reuses	BOD_5: ≤30 mg/l TN: ≤1.0 mg/l TP: ≤0.05 mg/l TSS: ≤30 mg/l pH: 6–9 Faecal coliforms ≤10/ml Total coliforms ≤100/ ml	Lakes and ponds for recreational without body contact
Urban reuses and agricultural irrigation	Unrestricted reuses	BOD_5: ≤10 mg/l Turbidity: ≤2 NTU pH: 6–9 Faecal coliform: ≤10 / ml Total coliforms ≤100/ ml Residual chlorine: ≤1 mg/l	Toilet flushing; laundry; air conditioning, process water; landscape irrigation; fire protection; construction; surface irrigation of food crops and vegetables (consumed uncooked) and street washing
	Restricted reuses	BOD_5: ≤30 mg/l Deterge t (anionic): ≤1 mg/l TSS: ≤30 mg/l pH: 6–9 Faecal coliforms ≤10/ml Total coliforms ≤100/ml Residual chlorine: ≤1 mg/l	Landscape irrigation, where public access is infrequent and controlled; subsurface irrigation of non-food crops and food crops and vegetables (consumed after processing)

the soil are alumina and hydrated silica). The soil treatment system could remove organic pollutants and total phosphors partially. Due to the nitrification and de-nitrification reactions in the soil treatment system, nitrogen was eliminated effectively. Obviously, the soil filter applied in this study can not be regarded as a single filtration but a combination of filtration and biodegradation. The effluents qualities obtained by March et al. (2004) and Itayama et al. (2004) do not meet the reuse standard suggested in this study because the reclaimed grey water remains high in organic load and suspended solids, which can limit the chemical disinfection process and produce disinfection by-products (Al-Jayyousi, 2003). The sand filter combined with activated carbon and disinfection has been reported for grey water treatment, but did not show a significant improvement for the residuals of the suspended solids (48% removal) and turbidity (61% removal). But however, efficient removals of microorganisms were reported (Pidou, 2006).

Birks (1998) reported a medium strength UF membrane grey water treatment system, in which the COD and the BOD were reduced from 451 mg/l and 274 mg/l in the influent to 117 mg/l and 53 mg/l respectively in the effluent. Li et al. (2008) evaluated the performance and suitability of a resource and nutrient oriented decentralized grey water treatment system which uses a submerged spiral wound module. The study revealed that the direct UF membrane filtration system was able to reduce TOC from the influent value of 161 mg/l to 28.6 mg/l in the permeate, corresponding an average elimination rate of 83.4%. In addition, soluble nutrients like ammonia and phosphors can pass through the UF membrane and remain in the permeate. The total nitrogen and total phosphors in the permeate were 16.7 mg/l and 6.7 mg/l respectively. The permeate was low in turbidity (below 1 NTU) and free of suspended solids and E. coli and had an excellent physical appearance. The retentate generated in this system can be treated with black water and kitchen waste in an anaerobic digester at a later stage for producing biogas or compost. Sostar-Turk et al. (2005) investigated the use of a UF membrane (0.05 µm pore size) for the treatment of laundry grey water. The UF membrane decreased the BOD from 195 to 86 mg/l corresponding to a removal of 56%. In terms of organic load, the reclaimed grey water obtained by Sostar-Turk et al. (2005) did not meet the non-potable grey water reuse standards proposed in this study. However, the pore sizes of the membranes play an important role on the treatment performance. For example, Ramon et al. (2004) reported a low strength grey water treatment system with direct nano-filtration membrane, which was able to achieve an organic removal rate of 93%. Sostar-Turk et al. (2005) also reported that the RO membrane after the UF membrane was able to reduce the BOD from 86 to 2 mg/l corresponding to a removal rate of 98%. However, one shall keep in mind that the higher energy consumption and the membrane fouling are often the key factors limiting the economic viability of membrane systems.

The grey water treatment (including sand filter, membrane filtration and disinfection) reported by Ward (2000) was the only physical process, which was able to achieve non-restricted non-potable reuse standard in terms of the BOD and the turbidity requirements. However, it should stress that the organic strength and the turbidity in the grey water used in Ward's study were extremely low. Funamizu and Kikyo (2007) reported a high strength grey water treatment system by different nano-filtration membranes. 92–98% anionic surfactant (LAS) and 88–92% of nonionic surfactant were rejected by the nano-filtration membranes. The LAS concentrations in the permeate were still higher than the predicted no-effect concentration and further treatments are required.

There were few data available on the removal of micro-organisms by membranes. However, Chiemchaisri et al. (1992) reported that a MBR installed with two types of membranes (pore size 0.1 and 0.03 µm) was able to achieve the same 4 to 6 log removal of the seeded Qβ coliphage at a stable stage although the membrane pore sizes are larger than the size of viruses (25 nm), revealing effective removal of mico-organisms by membranes. Nevertheless, the relative higher residual organic substances in the treated grey water by membrane filtration often promote the re-growth of the micro-organisms in the storage and transportation system. Furthermore, the membrane fouling and its consequences in term of operating and maintenance costs can restrict the widespread application of membrane technologies for grey water treatment. Data on the removal of detergents by physical grey water treatment processes were not available. All in all, physical processes alone are not sufficient for grey water treatments and reuses.

3.5. Chemical treatments

Very few chemical processes were reported for grey water treatments and reuses. The chemical processes applied for grey water treatments include coagulation, photo-catalytic oxidation, ion exchange and granular activated carbon. Lin et al. (2005) reported a combined chemical grey water treatment system, in which electro-coagulation was followed by a disinfection step. The COD, the BOD, the turbidity and the SS in the low strength grey water were reduced from 55 mg/l, 23 mg/l, 43 NTU and 29 mg/l in the influent to 22 mg/l, 9 mg/l, 4 NTU and 9 mg/l respectively in the effluent. The total coliforms were not detected in the reclaimed grey water. The effluent water quality meets the restricted grey water reuse standard proposed in this study. But the raw grey water fed into the treatment plant was low in organic strength.

In a study lead by Pidou et al. (2008), the coagulation processes and the magnetic ion exchange resin process were applied for shower grey water treatment. At optimal conditions, coagulation with aluminium salt reduced the COD, the BOD, the turbidity, TN and $PO4^{3-}$ from 791 mg/l, 205 mg/l, 46.6 NTU, 18 mg/l and 1.66 mg/l in the influent to 287 mg/l, 23 mg/l, 4.28 NTU, 15.7 mg/l and 0.09 mg/l respectively. The total coliforms, the E. coli and the faecal enterococci in the reclaimed grey water are all less than 1/100 ml. Coagulation with ferric salt achieved similar treatment efficiencies as that obtained with aluminium salt. The coagulation processes in Pidou's study in 2008 were able to reduce the BOD concentration to less than 30 mg/l but fail to decrease the turbidity to less than 5 NTU. The COD, BOD, turbidity, TN and $PO4^{3-}$ were decreased by the magnetic ion exchange resin to 272 mg/l, 33 mg/l, 8.14 NTU, 15.3 mg/l and 0.91 mg/l respectively. The total coliforms, the E. coli and the faecal enterococci in the reclaimed grey water are 59/100 ml, 8/100 ml and less than 1/100 ml. The magnetic ion exchange resin process failed to reduce the turbidity and the BOD to the levels required for both unrestricted and restricted reuses. The coagulation process and the magnetic ion exchange resin process have minor effects on the removals of both TN and $PO4^{3-}$. Chang et al. (2007) investigated another flocculation process for grey water treatment. The COD and the anionic surfactant concentration were reduced by 70% and 90% respectively. The study showed that the flocculation process alone is not able to reduce the organic substances to the required reuse standard, thus necessitating the application of biological processes.

A low strength laundry grey water treatment process, combining the coagulation, sand filter and granular activated carbon (GAC) was reported by Sostar-Turk et al. (2005). This grey water treatment process reduced the COD, the BOD and the suspended solids from 280 mg/l, 195 mg/l and 35 mg/l in the influent to 20 mg/l, 10 mg/l and less than 5 mg/l respectively in the effluent and achieved a good treatment performance with the coagulation stage itself achieving 51% of the BOD removal and 100% of the suspended solids removal.

An advanced oxidation process based on photo-catalytic oxidation with titanium dioxide and UV was applied for grey water treatment and a 90% removal of the organics and 6 log removal of the total coliforms were reported (Parsons et al., 2000).

3.6. Biological treatments

Several biological processes, including rotating biological contactor (RBC) (Nolde, 1999; Friedler et al., 2005; Eriksson et al., 2007), sequencing batch reactor (SBR) (Shin et al., 1998; Hernandez et al., 2008), anaerobic sludge blanket (UASB) (Elmitwalli and Otterpohl, 2007; Hernandez et al., 2008), constructed wetland (CW) (Li et al., 2003; Gross et al., 2007) and membrane bioreactors (MBR) (Lesjean and Gnirss, 2006; Liu et al., 2005; Merz et al., 2007), have been applied for grey water treatment. The biological processes were often preceded by a physical pre-treatment step such as sedimentation, usage of septic tanks (Nolde, 1999; Li et al., 2003) or screening (Friedler et al., 2005). Aside from the MBR process, most of the biological processes are followed by a filtration step (for example sand filtration) and /or a disinfection step to meet the non-potable reuse standards.

Friedler et al. (2005) studied a low strength grey water treatment system, which combined RBC, sand filtration and chlorination. The RBC step was preceded by a fine screen for the removal of gross solids and hairs larger than 1 mm and followed by a sedimentation step in a sedimentation basin to separate sludge from the effluent. The TSS, Turbidity, COD, BOD and faecal coliform were reduced from 43 mg/l, 33 NTU, 158 mg/l, 59 mg/l and 5.6×10^5/100 ml in the influent to 16 mg/l, 1.9 NTU, 46 mg/l, 6.6 mg/l and 9.7×10^3/100 ml respectively in the effluent of the sedimentation basin. The sand filtration step, acting as a polishing stage, further reduced the TSS, turbidity, COD and BOD to 7.9 mg/l, 0.61 NTU, 40 mg/l and 2.3 mg/l respectively. Astonishingly, the faecal coliform level increased from 9.7×10^3/100 ml to 5.2×10^4/100 ml after the sand filtration, demanding a disinfection step thereafter. The faecal coliform level was reduced to 0.1/100 ml by the disinfection step in the final effluent. The pilot plant successfully reduced the TP, TKN, ammonia and organic nitrogen from 4.8 mg/l, 8.1 mg/l, 4.9 mg/l and 3.2 mg/l in the influent to 2 mg/l, 1 mg/l, 0.16 mg/l and 0.97 mg/l respectively in the final effluent. Effluent from this pilot grey water treatment plant met the non-restricted non-potable water reuse standard proposed in this study. Nolde (1999) also studied a RBC grey water treatment system. The process comprises a sedimentation tank followed by a four-stage RBC and a final UV disinfection stage. The BOD_7 was reduced from the influent value of 50–250 mg/l to below 5 mg/l by the biological step. After the UV disinfection step, bacteriological effluent quality mostly meets water reuse standards. Similarly, Eriksson et al. (2007) reported a pilot RBC low strength pilot grey water treatment plant. The grey water plant treats effluents from showers and hand basins from bathrooms in 84 apartments and the treated water is utilized for toilet flushing. The plant consists of a primary settling tank which is also used for equalising the flow, biological treatment with 3 rotating biological contactors (RBC) in series, followed by secondary settling, a sand filter and UV treatment. The treated water is kept in two storage tanks. The pilot grey water treatment plant was able to reduced the COD, the BOD, the TOC, the NH_4–N and the ortho-phosphate from 142 mg/l, 93 mg/l, 72 mg/l 5.2 mg/l and 0.66 mg/l in the influent to 25 mg/l, 6 mg/l, 13 mg/l, 0.031 mg/l and 0.26 mg/l in the final effluent respectively. Surprisingly the COD, the BOD and the TOC were increased from 20 mg/l, 1.6 mg/l and 0.5 mg/l in the effluent of the sand filter to 25 mg/l, 6 mg/l and 13 mg/l in the final effluent respectively. However, the study from Eriksson et al. (2007) also showed that the BOD can be reduced by the RBC step to below 5 mg/l. Eriksson et al. (2007) also the examined the removal efficiencies of 5 selected trace organic substances by the pilot grey water treatment plant. Their study showed that the five selected paraben biocides (methyl-, ethyl-, propyl-, butyl-, and iso-butyl-esters of parahydroxy benzoic acid) can be removed effectively by the treatment plant, showing that the micro-organisms has adapted to the parabens as a carbon source for their growth. The removal efficiencies of the selected biocides ranged from 87% to 99%, which were even higher than the removal efficiencies of the composite parameters (COD, BOD and TOC).

A sequencing batch reactor (SBR) was operated for a high strength grey water treatment (Hernandez et al., 2008). The sludge retention time and hydraulic retention time were set as 15 days and 11.7 h respectively. The COD, TP, TN and ammonia was reduced from 830 mg/l, 7.7 mg/l, 53.6 mg/l and 1.2 mg/l in the influent to 91 mg/l, 6.5 mg/l, 34.4 mg/l and 0.41 mg/l respectively in the effluent. Another sequencing batch reactor (SBR) was operated for a high strength grey water treatment (Hernandez et al., 2008). During this period, the sludge retention time was increased to 378 days and the hydraulic retention time was reduced to 5.9 hours. The COD, TP, TN

Table 5
Physical processes for grey water treatment.

Reference	Process	TSS		Turbidity		COD		BOD		TN		TP		Total coliform		Faecal coliform	
		(mg/l)		(NTU)		(mg/l)		(mg/l)		(mg/l)		(mg/l)		(cfu/100 ml)		(cfu/100 ml)	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Gerba et al. (1995)	Cartridge filter	19	8 V	21	7 X	–	–	–	–	–	–	–	–	2×10^8	2×10^6 X	–	–
Ward (2000)*	Sand filter + Membrane + Disinfection	–	–	18	0 V	65	18	23	8 V	–	–	–	–	–	–	–	–
Brewer et al. (2000)*	Filtration + Disinfection	–	–	21	7 X	157	47	–	–	–	–	–	–	2×10^5	13 V	–	–
CHMC (2002)*	Screening + Sedimentation + Multi-media filter + Ozonation	67	21 V	82	26 X	–	–	130	–	–	–	–	–	–	–	–	–
Hills et al. (2003)*	Coarse filtration + Disinfection		35		40 X		166		40 X						ND V		
March et al. (2004)	Screening + Sedimentation + Disinfection	44	19 V	20	17 X	171	78	–	–	11.4	7.1	–	–	–	–	–	–
Itayama et al. (2004)	Soil filter	105	23 V	–	–	271	40.6	477	81 X	20.7	4.4	3.8	0.6	–	–	–	–
Ramon et al. (2004)	UF membranes (400 kDa)	–	–	18	1.4 V	146	80	–	–	–	–	–	–	–	–	–	–
	UF membranes (200 kDa)	–	–	17	1 V	146	74	–	–	–	–	–	–	–	–	–	–
	UF membranes (30 kDa)	–	–	24	0.8 V	165	51	–	–	–	–	–	–	–	–	–	–
Sostar-Turk et al. (2005)	UF membrane	35	18 V	–	–	280	130	195	86 X	–	–	–	–	–	–	–	–
	NF membrane	28	0 V	30	1 V	226	15	–	–	–	–	–	–	–	–	–	–
	RO membrane	18	0** V	–	–	130	3	86	2 V	–	–	–	–	–	–	–	–
Prathapar et al. (2006)	Filtration + Activated carbon + Sand filter + Disinfection	9	4 V	13	6 X	51	35	–	–	–	–	–	–	>200	0 V	–	–
Birks (1998)	UF membrane	–	–	–	–	451	117	274	53 X	–	–	–	–	–	–	–	–

*: Referenced from Pidou (2006).
**: Referenced in Pidou (2006), the BOD_5 was changed from 8 mg/l to 0 mg/l.
V: Meet the reuse guideline.
X: Fail to meet the reuse guideline.

and ammonia was reduced from 827 mg/l, 8.5 mg/l, 29.9 mg/l and 0.8 mg/l in the influent to 100 mg/l, 5.8 mg/l, 26.5 mg/l and 0.44 mg/l respectively in the effluent. The organic nitrogen in the effluents accounts for 90% and 74% of the TN, indicating that the transformation of particulate organic nitrogen to ammonia during the aerobic treatment was very limited. This study also revealed that 97% of anionic surfactants were eliminated by the aerobic degradation.

In the study lead by Elmitwalli et al. (2007), a UASB was operated at ambient temperature for mixed grey water treatment. The study showed that the continuous operations at HRT of 20, 12, and 8 h reduced 31–41% of total COD, 24–36% of TN and 10–24% of TP respectively. Hernandez et al. (2008) also reported a UASB grey water treatment system at an operating temperature of 35 °C. Hernandez et al. (2008) concluded that around 50% of total COD and 24% of the anionic surfactants can be eliminated by the UASB system at HRT of 7.0 and 12.5 h.

The constructed wetland has been considered as the most environmentally friendly and costs effective technology for grey water treatment. In the study led by Gross et al. (2007), a recycled vertical flow constructed wetland was applied for a high strength mixed grey water treatment. The TSS, BOD_5, COD, TN, TP, anionic surfactants, boron and faecal coliform were reduced from 158 mg/l, 466 mg/l, 839 mg/l, 34.3 mg/l, 22.8 mg/l, 7.9 mg/l, 1.6 mg/l and 5×10^7/100 ml in the influent to 3 mg/l, 0.7 mg/l, 157 mg/l, 10.8 mg/l, 6.6 mg/l, 0.6 mg/l, 0.6 mg/l and 2×10^5/100 ml respectively in the effluent. The constructed wetland reported in the literature showed good treatment performance to treat grey water. Indeed, an average BOD residual of 17 mg/l was observed including more than half of the schemes with a residual concentration below 10 mg/l. Similarly, average residual concentration of 8 NTU for turbidity and 13 mg/l for suspended solids were reported.

The membrane bioreactor (MBR) combines biodegradation with membrane filtration for solid liquid separation. The MBR has been regarded as an innovative technology for grey water treatment due to its process stability and its ability to remove pathogens. Liu et al. (2005) reported a submerged MBR from Mitsubishi Rayon (polyethylene, pore size 0.4 µm) for low strength bath grey water treatment. This study revealed that the COD was reduced from the influent value of 130–322 to 18 mg/l on average in permeate. NH_4–N concentration was reported to have decreased from 0.6–1.0 mg/l in influent to less than 0.5 mg/l in the effluent. BOD_5 was reduced from the influent value of 99–221 mg/l to less than 5 mg/l in the permeate. Anionic surfactants (AS) were reduced from 3.5–8.9 mg/l in the influent to less than 0.5 mg/l in the effluent. The effluent was colorless and odorless and free of SS and faecal coliform concentrations were below the determination threshold. This study demonstrated that biological degradation removed most of the pollutants and membrane separation further eliminated the rest of the pollutants, thus ensuring a stable and excellent effluent water quality. Permeate flux achieved in study was less than 15 l/m^2.h. In the study lead by Lesjean and Gnirss (2006), a submerged plate and frame MBR grey water (including kitchen grey water) treatment unit was operated under low SRT (down to 4 d) and low HRT (set as 2 h) condition. The COD was reduced from the influent value of 493 mg/l to 24 mg/l in permeate and the elimination rate was greater than 85%. Nitrogen was decreased from 21 mg/l to 10 mg/l, but its elimination rate was not consistent (ranging from 20 to 80%). Phosphors was reduced by around 50%, decreasing from the influent value of 7.4 mg/l to 3.5 mg/l in effluent. SS in permeate was reported to be less than 1 mg/l during the whole observation period. The stable permeate flux achieved in this study was 7 l/m^2.h. Merz et al. (2007) studied a submerged MBR from Zeno (membrane pore size, 01 µm) for low strength grey water from a sports and leisure club. The turbidity, COD, BOD_5, TKN, ammonia, TP, LAS and faecal coliforms were reduced from 29 NTU, 109 mg/l, 59 mg/l, 15.2 mg/l, 11.8 mg/l, 1.6 mg/l, 299 µg/l and 1.4× 105/100 ml in the influent to 0.5 mg/l, 15 mg/l, 5 mg/l, 5.7 mg/l, 3.3 mg/l, 1.3 mg/l, 10 µg/l and 68 /100 ml respectively in the effluent. The effluent was free of colour and odourless. The detection of the faecal coliforms in the permeate was probably caused by the accidental contamination in the distribution system. The stable permeate flux obtained in this study ranged from 8 to 10 l/m^2 h.

3.7. Selection of appropriate technologies for grey water treatments and reuses

The characterisation of grey water reveals that the grey water shall be treated to a higher standard before reusing to avoid the health risk and negative aesthetic and environmental effects. The major target of grey water reclamation and reuses is to reduce the suspended solids, the organic strength and the micro-organisms due to its relationship with the aesthetic and health characteristics of the product water and directly through legislative requirements.

A literature review of the reported physical processes for grey water treatment and reuses is summed up in Table 5. Obviously, coarse filtration and soil filtration alone are not able to reduce the physical, chemical and microbiological parameters to the values required by the non-potable reuse guideline. The micro filtration and the ultra filtration membrane provide a limited removal of the dissolved organics but an excellent removal of the suspended solids, turbidity and pathogens. Removal efficiencies up to 100% for the turbidity and the suspended solids have been reported by Ahn et al. (1998), and Ramon et al. (2004). Based on Birks (1998) and Sostar-Turk et al. (2005), the UF membrane filtration process is not able to reduce the BOD_5 to the values required in both restricted and non-restricted non-potable reuse standards. The residual organics in the reclaimed water can cause biological re-growth in the storage and distribution systems,

Table 6
Chemical processes for grey water treatment.

Reference	Process	TSS		Turbidity		COD		BOD		TN		TP		Total coliform		Faecal coliform	
		(mg/l)		(NTU)		(mg/l)		(mg/l)		(mg/l)		(mg/l)		(cfu/100 ml)		(cfu/ 100 ml)	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Lin et al. (2005)	Electro-coagulation + Disinfection	29	9 V	43	4 X	52	22	23	9 V	–	–	–	–	2×10^8	2×10^6 X	–	–
Sostar-Turk et al. (2005)	Coagulation + Sand filter + GAC	35	<5 V	–	–	280	20	195	10 V	–	–	–	–	–	–	–	–
Pidou et al. (2008)	Coagulation with aluminium salt	–	–	46.6	4.28 X	791	287	205	23 V	18	15.7	1.66	0.09	–	<1 V	–	–
Pidou et al. (2008)	Magnetic ion exchange resin	–	–	46.6	8.14 X	791	272	205	33 X	18	15.3	1.66	0.91	–	<59 V	–	–

V: Meet the reuse guideline.
X: Fail to meet the reuse guideline.

Table 7
Biological processes for grey water treatment.

Reference	Process	TSS (mg/l)		Turbidity (NTU)		COD (mg/l)		BOD (mg/l)		TN (mg/l)		TP (mg/l)		Total coliform (cfu/100 ml)		Faecal coliform (cfu/100 ml)	
		In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
Nolde (1999)	Sedimentation + RBC + UV disinfection	–	–	–	–	100–430	–	50–250 BOD_7	<5 BOD_7 V	5–10	–	0.2–0.6	–	10^4–10^8	<10^3	10–10^8	<10^2 V
Nolde (1999)	Fuidized-bed reactor + UV disinfection	–	–	–	–	113–633	–	70–300 BOD_7	<5 BOD_7 V	–	–	–	–	10^3–10^5	<10^4	10–10^3	<10^3 V
Friedler et al. (2005)	Screen + RBC + sand filtration filtration + chlorination	43	7.9 V	33	0.61 V	158	40	59	2.3 V	–	–	4.8	2	–	–	5.6×10^5	0.1 V
Liu et al. (2005)	MBR	–	ND V	–	–	130–322	18	99–221	<5 V	–	–	–	–	–	–	–	ND V
Lesjean and Gnirss (2006)	MBR		<1 V			493	24			21*	10*	7.4	3.5				
Merz et al. (2007)	MBR	–	–	29	0.5 V	109	15	59	4 V	15.2	5.7	1.6	1.3	–	–	1.4×10^5	68 V
Elmitwalli et al. (2007)	UASB	–	–	–	–	681	469.9	–	–	27.1&	20.6&	9.9	7.5	–	–	–	–
		–	–	–	–	647	381.7	–	–	27.1&	20.6&	9.7	7.6	–	–	–	–
		–	–	–	–	682	456.9	–	–	27.3&	24.0&	9.9	8.9	–	–	–	–
Gross et al. (2007)	Constructed wetland	158	3 V	–	–	839	157	466	0.7 V	34.3	10.8	22.8	6.6	–	–	5 X 10^7	2 X 10^5 X
Hernandez et al. (2008)	SBR, SRT = 378 d HRT = 5.9 h	–	–	–	–	827	100	–	–	29.9	26.5	8.5	5.8	–	–	–	–

*: TN was calculated as the summation of TKN and NO_3–N.
&: TKN.
V: Meet the reuse guideline.
X: Fail to meet the reuse guideline.

limit the chemical disinfection effect and produce disinfection by-products. Therefore, physical processes are not recommended for grey water recycling. However, physical processes such as sand filtration and membrane filtration can be applied as post-treatments for polishing purposes.

The literature review of the chemical processes for grey water treatment and reuses is shown in Table 6. In comparison with the physical processes, the chemical processes are able to reduce organic substance and turbidity in grey water to certain degree but not sufficient to meet the non-potable reuse standards especially for high strength grey water. The chemical processes reported by Lin et al. (2005), Sostar-Turk et al. (2005) and Pidou et al. (2008) all failed to meet the turbidity value of less than 2 NTU. Based on the limited literatures on the grey water treatment with chemical processes, it was found out that the chemical processes, such as coagulation, followed by a filtration and/or disinfection stage, are able to reduce the suspended solids, organic substances and surfactants in the low strength grey water to an acceptable level to meet the non-potable urban reuses (Lin et al., 2005; Sostar-Turk et al., 2005; Chang et al., 2007; Pidou et al., 2008). However, for the medium and high strength grey water, the reclaimed water after the chemical processes is not always able to meet the required reuse standards in all situations unless they are combined with other processes (Lin et al., 2005; Sostar-Turk et al., 2005; Chang et al., 2007; Pidou et al., 2008). The effluent from the chemical processes can be either polished by a sand filtration stage to meet the restricted non-potable urban reuse standard or further treated by a membrane filtration stage to reach the non-restricted reuse standard. The effluent from the sand filtration stage shall be disinfected to meet the non-restricted reuse standard. Chemical solutions are especially attractive for the single household low strength grey water treatment system as the variability in strength and flow of the grey water did not affect their treatment performance (Pidou et al., 2008).

A literature review of the biological processes for grey water treatment and reuses is shown in Table 7. Table 7 reveals that aerobic biological processes are able to achieve excellent organic and turbidity removals. The poor removal efficiencies of both organic substances and surfactants make anaerobic processes unsuitable for grey water recycling, though biogas production is an advantage. The aerobic biological grey water treatment processes including constructed wetland can achieve satisfactory performances with regard to the removal of the biodegradable organic substances. After aerobic biological grey water treatment processes, most of the biodegradable organic substances are removed and consequently the re-growth of micro-organisms and odour problems are avoided, making the treated grey water more stable for storage over longer periods. Hence, medium to high strength grey water are suggested to be treated by biological processes. However, poor removal of micro-organisms, suspended solids and turbidity were observed, which demands a final filtration and/or a disinfection step to meet the proposed urban reuse standard. The combination of aerobic biological processes with physical filtration and/or disinfection is considered to be the most economical and feasible solution for grey water recycling. Friedler and Hadari (2006) concluded that the RBC based system will become economically feasible when the building size reach seven storeys (28 flats).

In term of treatment performance and operating and maintenance costs, the constructed wetland can be regarded as the most environmentally friendly and cost effective technology for grey water treatment and reuses. However, it requires a large space and, therefore, it is not suitable to be applied in the urban areas.

The MBR is the only technology being able to achieve satisfactory removal efficiencies of organic substances, surfactants and microbial contaminations without a post filtration and disinfection step. The qualities of the MBR effluent meet the most stringent non-potable urban reuse standards (Pidou, 2006). Due to the excellent and stable effluent quality, high organic loading rate, compact structure as well as low excess sludge production, the MBR appears to be an attractive technical solution for grey water recycling, particularly in collective urban residential buildings (Lazarova et al., 2003). Friedler and Hadari (2006) found out that the on-site MBR based grey water treatment system has proven to be economically realistic and feasible when the building size exceeds 37 storeys (148 flats). Lazarova et al. (2003) estimated that the annual capital and operational costs of MBR grey water treatment system can drop to 1.7 €/m3 for installations serving more than 500 inhabitants.

The detail analysis of the various physical grey water treatment processes lead to the conclusion that physical processes alone are insufficient to guarantee an adequate reduction of the organics, nutrients and surfactants except in situations where the organic strength is extremely low. Based on the characteristics of the influent grey water and requirement of quality, the appropriate alternatives for grey water treatment and recycling are given in Fig. 1. As it is shown in Fig. 1, grey water shall be equalized in a storage tank to cope with the variability in influent and the larger particles, hair, oil and grease shall be removed before feeding it into the followed treatment processes. Fig. 1 implies that chemical solutions, such as coagulation and ion exchange followed by membrane filtration can be applied for the treatment of the low strength grey water to meet the requirements of the unrestricted non-potable urban reuses. Alternatively, effluent from the chemical processes can be further polished by the sand filtration to meet the less stringent requirements of the restricted non-potable urban reuses. After the disinfection of the effluent of the sand filtration step, the quality of the reclaimed grey water can meet the standard of the unrestricted non-potable urban reuses. For medium and high strength grey water, the appropriate biological processes, such as RBC and SBR can be used to remove the organic substances in grey water. Through the investigation of the treatment efficiencies of the existing biological grey water treatment processes, the BOD_5 in the grey water can be reduced to less than 10 mg/l, which meets the most stringent non-restricted reuse standard proposed in this paper. A final membrane filtration or a sand filtration step followed by a disinfection step can be applied to meet the

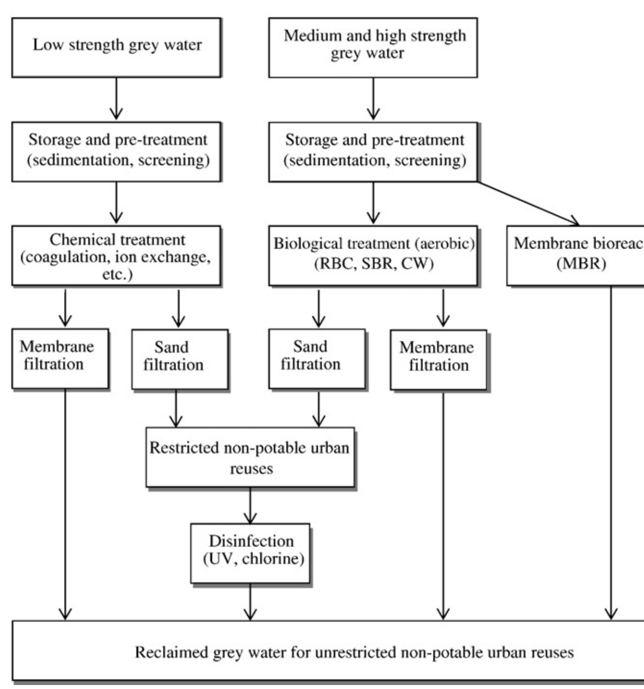

Fig. 1. The grey water recycling schemes for non-potable urban reuses.

requirements for micro-organisms, suspended solids and turbidity. The medium and high strength grey water can also be treated by the MBR to meet the unrestricted non-potable urban reuse standards.

4. Conclusions

Based on literatures review, a non-potable urban grey water treatment and reuse scheme is proposed in this study. The reuses of the reclaimed grey water in urban areas are based on the grey water characteristics and the proposed standards. The following conclusions can be withdrawn from the literature research:

1. All types of grey water show good biodegradability in terms of the COD: BOD_5 ratios. The bathroom and the laundry grey water are deficient in both nitrogen and phosphors. The kitchen grey water has a balanced COD: N: P ratio. If grey water is intended to be treated through a biological process, it is suggested that kitchen grey water shall be mixed with other streams to avoid the deficiency of both macronutrients and trace nutrients.
2. The grey water reuse guideline proposed in this paper was used as a standard to evaluate the treatment efficiencies of the reported grey water treatment.
3. The physical processes alone are not sufficient to guarantee an adequate reduction of the organics, nutrients and surfactants. Therefore, it is not recommended for grey water recycling.
4. The chemical processes can efficiently remove the suspended solids, organic materials and surfactants in the low strength grey water.
5. Due to the poor removal efficiencies of both organic substances and surfactants, anaerobic processes are not recommended for the grey water treatment.
6. The aerobic biological processes, such as RBC and SBR can be applied for medium and high strength grey water treatment. The combination of aerobic biological process with physical filtration and disinfection is considered to be the most economical and feasible solution for grey water recycling.
7. The MBR appears to be a very attractive solution for medium and high strength grey water recycling, particularly in collective urban residential buildings serving more than 500 inhabitants.

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