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Review

A review of greywater recycling related issues: Challenges and future prospects in Malaysia

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ABSTRACT

To realize Malaysia's vision of becoming a developed country by the year 2020, rapid urbanization and development have taken place in many parts of the country. Despite vast development in Malaysia, the country experiences a myriad of water shortage issues. Therefore, Malaysia needs to carefully manage its freshwater resources to achieve sustainable development. Greywater has proven to be a useful substitute for fresh water for non-potable activities. This paper reviews examples of greywater recycling that have been successfully implemented globally, and identifies constraints of implementing greywater recycling systems for use in Malaysia. Greywater represents 43–70% of total domestic wastewater volume, and reusing greywater for irrigation may have adverse long-term impacts on soil. Greywater should be treated and disinfected before reuse, and can be disinfected via chlorine, UV, or ozone disinfection. Chlorine disinfection is recommended as chlorine is widely available and inexpensive. Malaysia lacks strategies for kick starting greywater recycling projects. To overcome obstacles, Malaysia could establish a moderate treated greywater quality standard (pH 6–9, TSS < 20 mg/L, <5 NTU, $BOD_5 < 20$ mg/L and <10 CFU/100 mL of *E. coli*) for urban reuse and initiate greywater recycling efforts by recycling low strength greywater from ablution activities and bathrooms. Last but not least, researchers and local authorities could work closely to monitor the greywater recycling systems, while the latter could provide subsidies and rebates to financially support the implementation of the greywater recycling system and eventually achieve the goal of water sustainability.

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1. Introduction

To accomplish Malaysia's vision of becoming a developed country by 2020, the country has undergone rapid development in terms of urbanization, industrialization, tourism and communications (Chan, 2005). Nevertheless, these activities have resulted in an increase in water pollution around the regions of the country (Muyibi et al., 2008; Teh et al., 2015), hence limiting the availability of freshwater supplies. Thus, the problem of limited freshwater supplies will be more apparent in densely populated areas with high water demand. Ho (1996) reported that the level of many river beds in Malaysia have risen due to extensive drainage basin development for large-scale projects, resulting in a higher likelihood of flooding and thus reduced volumes of clean water. Despite high rainfall in Malaysia, substantial amounts of freshwater have been lost due to vast urbanization and limited access to clean water sources, hence resulting in water shortages that hinder water sustainability.

To curb water shortages and achieve water sustainability in urban areas, many water sensitive cities have investigated methods for treatment and reuse of wastewater (Hyde, 2013; Po et al., 2003). Greywater is defined as household wastewater generated from kitchen sinks, bathroom sinks, showers and/or baths, and laundry discharges but excludes toilet inputs (Eriksson et al., 2002; Saumya et al., 2015), and can be reused in lieu of freshwater for toilet flushing and irrigation activities. An advantage of recycling greywater is that greywater is a plentiful, alternative source of urban water that is relatively easy to treat as greywater has low concentrations of organic pollutants and pathogens (Revitt et al., 2011): for example, greywater comprises 50–70% of total domestic wastewater despite containing only 30% of the organic fraction and 9–20% of the nutrients (Fountoulakis et al., 2016). Although water sustainability is widely promoted in different regions of the world, the best practices to achieve water sustainability via greywater recycling varies widely, and few attempts have been made to synthesize and evaluate these practices. To bridge this knowledge gap, this paper highlights the experiences of different countries gained from implementation and management of greywater recycling systems. The review also provides a comprehensive evaluation of greywater disinfection technologies and identifies the proper disinfection technology for greywater recycling. Disinfection is a crucial polishing step for partially treated greywater as human exposure to non-disinfected greywater poses a significant health risk when greywater is reused for non-potable activities, such as garden irrigation and toilet flushing. The findings from this review could serve as a decision-making guideline for countries that are exploring the viability of greywater recycling projects, including Malaysia.

Thus, this paper aims to review the following:

1. The current technologies employed for greywater treatment and disinfection,
2. Successful examples of the implementation of greywater treatment systems in other countries,
3. The current scenario of greywater treatment in Malaysia,
4. The challenges and prospects of greywater treatment in Malaysia.

2. Methodology

The authors have used keywords such as, *greywater recycling, greywater treatment, greywater disinfection, greywater reuse, greywater management and water sustainability* to search for journal papers within the aims and scope of this review paper. In order to generate a review paper that covers both diverse treatment technologies and greywater recycling case studies across the globe, the authors have searched for journal papers within the past 22 years (year 1995–2017). Only journal papers that cover experiences from regions that have long since implemented greywater recycling systems and/or regions that have only begun implementing greywater treatment systems were selected. Other than that, the authors have also analyzed how these countries promote and commence greywater recycling.

Content analysis was carried out on the numerous journal papers to screen the most suitable papers with topics within the scope of this review paper. The number of journal papers was then reduced to 109 papers. The materials obtained were organized into three categories to match the scope of this review paper. First, case studies of greywater recycling were reviewed to distinguish the differences in greywater recycling management and treatment processes between developed countries and developing nations. Relevant journal papers were also screened to evaluate a variety of greywater disinfection technologies as greywater disinfection is essential to ensure the end-users' safety. Readers can select a proper disinfection technology based on the water conditions and technical availability. Subsequently, the obstacles that Malaysia faces in commencing greywater recycling projects are also emphasized. Last but not least, the review highlights the future prospects of implementing greywater recycling nation-wide in Malaysia, and incorporates lessons learned from more experienced countries in promoting and managing the greywater recycling process.

3. Greywater generation

Treated greywater may be used as a freshwater substitute for non-potable end-uses, helping to reduce freshwater consumption and overcome water scarcity worldwide (Chen et al., 2012). Studies have shown that 30–50% of potable water can be saved by recycling greywater for garden irrigation and toilet flushing (Prathapar et al., 2005).

The average distribution of household water end-uses in Fig. 1 shows that 1792 families in Malaysia were documented to consume freshwater of approximately 0.226 $m^3/p/d$ (FOMCA, 2010). Malaysian water consumption is much higher relative to its neighbouring countries such as Thailand (0.09 $m^3/p/d$) and Singapore (0.155 $m^3/p/d$) (Choong, 2011; Ho, 1996). Based on Fig. 1, 67% of potable water in Malaysia is used for flushing toilets, showering and laundry washing (FOMCA, 2010; Ho, 1996). The remaining household activities that use potable water are gardening, car washing, outdoor activities, baths and household cleaning, while 15% of water is lost from pipe leakages that normally remain undetected for long periods of time (FOMCA, 2010). 43% of total water use in Malaysia ends up as greywater, and 0.097 $m^3/p/d$ of greywater is generated. In comparison, the United

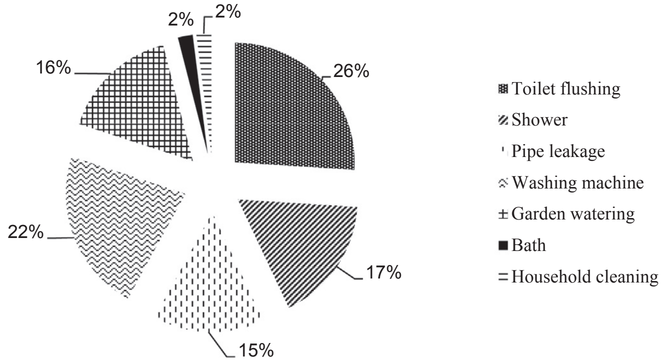

Fig. 1. Average water usage distribution (%) of 1792 families in Malaysia (FOMCA, 2010) where an average of 0.226 m^3/p/d was utilized.

Kingdom (UK) was reported to generate a slightly lower volume of 0.088 m^3/p/d of greywater (Liu et al., 2010).

On the other hand, Fig. 2 shows the water use distribution of 100 households with 3 family members in the UK. Similarly, the overall percentage consumed by toilet flushing, showers, baths, and laundry constitutes 68% of total potable water consumed in UK households, and this water use distribution is similar to the water use distribution in Malaysia (Liu et al., 2010). This is concurrent with the study conducted by Pidou et al. (2007), which indicates that greywater from washbasins, showers, baths, washing machines, and dishwashers represents 44% of total household water demand in UK. Similarly, Chaillou et al. (2011) reported that 50–60% of all water used ends up as greywater. These studies demonstrate the immense potential of greywater that can be reused in places facing water scarcity.

Variation in the greywater end use data was mainly due to differences in the number of people (de Gois et al., 2015) and their age, water usage patterns, weather conditions, daily routines, and the health status of the individuals living within households (Environmental Health Directorate, 2010). For instance, different family lifestyles result in differing greywater production rates: lower greywater volumes are observed during daily working hours (Eriksson and Donner, 2009). Greywater volumes may additionally vary seasonally: higher volumes of bathroom greywater would be generated during hot seasons (e.g. summer) and less in colder seasons (e.g. winter). The large number of factors affecting greywater quantity and quality further emphasize the need to conduct studies on greywater quantity and quality before a treatment system is proposed as knowledge on the average greywater characteristics of a region is necessary to avoid both under and over-design of the treatment system (Jamrah et al., 2008).

4. Treated greywater water quality standards

Despite the advantages of recycling greywater reported worldwide, there is no international standard to control the quality of greywater for reuse purposes (Alkhatib et al., 2006). Countries such as Australia, the United States (USA), the UK, Israel and Canada have developed individual guidelines on the reclaimed greywater quality. The United States Environmental Protection Agency (US EPA) released a guideline in 2004 to encourage states to construct their own standard of reclaimed greywater (Haering et al., 2009). The standards set by these countries are highlighted and these standards can be taken as references for authorities to set up national standards in countries other than Malaysia that wish to recycle greywater.

Table 1 summarizes and compares the treated greywater standards released by few countries to the drinking water standards in Malaysia. Malaysia does not have water quality standards for treated greywater, and therefore urban reuse guidelines are proposed. As shown in Table 1, pH of the treated greywater should be controlled at pH of 5.0–9.5 as stated by USA, Italy and UK. USA and Israel have more stringent biochemical oxygen demand (BOD_5) discharge requirements while Australia, Italy, the UK and Canada allow discharges with BOD_5 concentrations below 20 mg/L. In addition, chemical oxygen demand (COD) of treated greywater is to be controlled at less than 100 mg/L in Israel and Italy. Italy requires treated effluent to contain less than 15 mg/L total nitrogen and less than 2 mg/L of total phosphorus to minimize the impact of these pollutants on the environment. Therefore, it can be inferred that all countries are very strict on the allowable concentration of organic pollutants in greywater. Monitoring turbidity and total suspended solids (TSS) is crucial in controlling the aesthetic condition of the treated greywater, and most countries impose strict control of turbidity and TSS. In most cases, treated greywater turbidity should not exceed maximum limits of 10 NTU and 30 mg/L for turbidity and TSS respectively.

Most guidelines require pathogenic microorganisms in treated greywater to be at lowest level possible to assure human safety. Based on Table 1, UK and Canada are the least stringent as compared to other countries such as Australia and the USA. A maximum faecal coliform concentration of 1000 CFU/100 mL in treated greywater is allowed for toilet flushing in UK, while a maximum 200 CFU/100 mL is allowed in Canada. In contrast, the

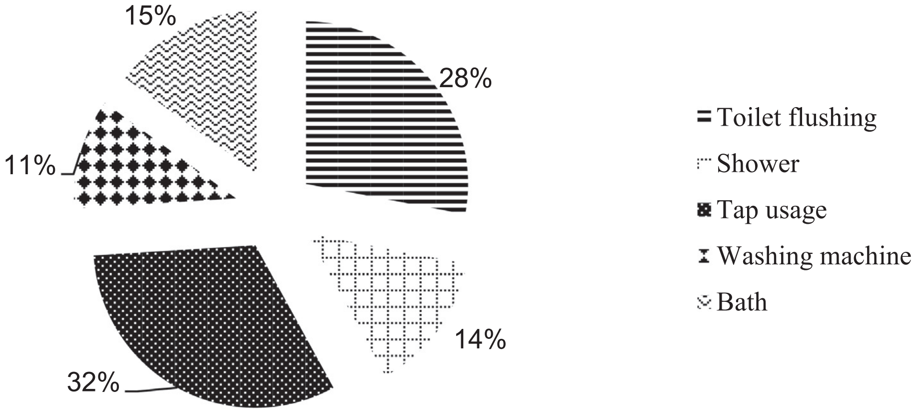

Fig. 2. Average water usage distribution (%) of 100 three-person families in UK (Liu et al., 2010).

Table 1
Treated greywater (for non-potable applications) standard in various countries.

	Unit	Australia	Israel	USA	Italy	New South Wales	UK	Canada
References		Chaillou et al. (2011) Australian Capital Territory (2004)	Chaillou et al. (2011) Ramona et al. (2004)	Couto et al. (2014), Chaillou et al. (2011), US EPA (2004)	Chaillou et al. (2011)	Couto et al. (2014); Leong et al. (2017)	Couto et al. (2014); Environment Agency (2011)	Couto et al. (2014) MHC (2010)
pH	–	–	–	6 to 9	6 to 9.5	–	5 to 9.5	–
TSS	mg/L	<30	<10	–	<10	<20	–	<20
Turbidity	NTU	–		<2	–	2	<10	<5
COD	mg/L	–	<100	–	<100	–	–	
BOD_5	mg/L	<20	<10	<10	<20	<20	–	<20
Total N	mg/L	–	–	–	<15	–	–	
Total P	mg/L	–	–	–	<2	–	–	
Cl_2 residual	mg/L	–	–	>1	–	2	<2	>0.5
E. coli	cfu/100 mL	–	–	–	<10	–	–	–
Thermotolerant coliforms	cfu/100 mL	<10	–	–	–	–	–	–
Faecal coliforms	cfu/100 mL	–	–	N.D	–	<1	1000	<200
Salmonella	cfu/100 mL	–	–	–	N.D	–	–	–
Type of reuse	–	Surface irrigation, toilet flushing, laundry use, car washing	–	Landscape irrigation, toilet flushing, fire protection, commercial air conditioning	–	Toilet flushing	Toilet flushing	Toilet flushing

USA and New South Wales (Australia) allowed non-detectable and less than 1 CFU/100 mL of faecal coliforms in treated greywater respectively. Moreover, Italy monitored treated greywater quality with *Salmonella,* a bacterial indicator. The high toxicity of *Salmonella*, which is responsible for causing typhoid fever and salmonellosis, poses a risk to human health, and thus the presence of *Salmonella* in treated greywater is unacceptable. Hence, other countries may consider including *Salmonella* as part of the bacterial indicators or at least perform *Salmonella* checks on a monthly basis to avoid *Salmonella* outbreaks.

Strict urban water quality standards are necessary to ensure that treated greywater has low organic and pathogenic content. However, the final end-use of treated greywater is the main criterion in determining the appropriate water quality standard for treated greywater discharge in Malaysia. Reclaimed greywater does not need to be treated to drinking water quality standards if it is not intended for human consumption. Hence, the reclaimed water could be treated to an acceptable level with TSS <20 mg/L, $BOD_5 <$ 20 mg/L, pH between 6 and 9, and turbidity <5 NTU for non-potable end uses. The turbidity and TSS levels recommended ensure the aesthetics of the treated water. Nevertheless, due to the potential of bacterial and viral re-growth that would eventually lead to risks towards human health, the treated greywater should contain a maximum concentration of <10 CFU/100 mL of *Escherichia coli (E. coli).*

5. Greywater treatment and disinfection technologies

Since the degree of greywater treatment required depends on the “fit-for-purpose” application of reclaimed greywater, greywater treatment techniques can vary widely between sites (de Koning et al., 2008). Light greywater can be reused after sand filtration without any further treatment for outdoor garden irrigation (Allen et al., 2010), though effluent from this simple filtration and diversion system is unsuitable for irrigation with spraying (Eriksson et al., 2002; Finley, 2008). Additionally, potential ground water contamination, soil contamination and adverse changes in soil properties could occur due to the presence of pathogenic bacteria, salinity, and elevated pH and boron levels in greywater reused for irrigation (Finley, 2008; Gross et al., 2005). Spraying untreated greywater that contains pathogenic bacteria for irrigation purposes would potentially lead to illnesses, as there is a risk of inhaling or of direct skin contact with pathogenic bacteria. Hence, treated greywater should be properly treated before reuse, especially for food crops watering, fields irrigation and household usage.

Other than simple diversion systems, greywater recycling systems may consist of a complex combination of treatments (Pidou et al., 2007; Waskom and Kallenberger, 2003). Prior to entering the main treatment process, raw greywater normally enters a screening process, followed by sedimentation to remove coarse particles and suspended solids. Subsequently, the greywater is directed to the main treatment process involving either biological, chemical, physical or extensive treatment units, before disinfection (Alkhatib et al., 2006). Fig. 3 illustrates the flow diagram of a typical greywater treatment system.

Common biological treatment methods include rotary biological contactors (RBC) (Pidou et al., 2007), biological aerated filters (BAF) (Al-Jayyousi, 2003), sequencing batch reactors (SBR) (Ghaitidak and Yadav, 2013) and aerated bio-reactors (Pidou et al., 2007). For chemical treatment, electro-coagulant, photo-catalysis and conventional coagulants are some of the most common techniques (Pidou et al., 2007). Membrane bio-reactors (MBR) (Atanasova et al., 2017) and sand bed filters (Chaillou et al., 2011) are common physical treatment methods while extensive treatment methods, such as reed beds (Pidou et al., 2007), ponds (de Koning et al., 2008) and wetlands (Mah et al., 2009; Saumya et al., 2015) usually require large areas.

In recent years, the development of greywater recycling systems has evolved from conventional treatment technologies into more environmentally friendly treatment techniques. Membranes for greywater treatment may be fabricated from food wastes and biodegradable materials: Oh et al. (2016) has utilized chitosan and alginate to fabricate a polyelectrolyte bi-layer membrane (PCBM). The study showed that the membrane can remove pollutants with a size of 2.71 kDa, and produces treated greywater effluent with <2 NTU, < 20 ppm TSS and <100 ppm COD. The biodegradable PCBM membrane provides a greener treatment material for greywater treatment (Oh et al., 2016). Other than that, green walls or vegetated walls, are another recent application in greywater recycling. This treatment system is similar to reed beds, in which greywater is filtered through plants in pots filled with a combination of granular medias such as vermiculite, river sand, growstone, expanded clay, fytofoam, coco air and perlite (Prodanovic et al., 2017). The media for the plants act as adsorbents to the pollutants in greywater,

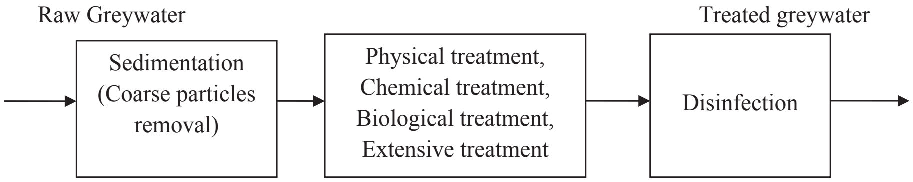

Fig. 3. Flow of greywater treatment.

while the nutrients in greywater, such as nitrogen and phosphorous, are used to support the plants growing on the media (Fowdar et al., 2017; Prodanovic et al., 2017). Green walls are an attractive method of recycling greywater as green walls have low treatment footprints and small space requirements relative to the conventional reed bed treatment method (Masi et al., 2016). However, the major drawbacks of this system include both the high water demand imposed by the plants, which makes green walls unsuitable for arid regions, and the fluctuating adsorption efficiency due to the variation in the size and properties of the adsorption media. In addition to that, such a system is not suitable for the application of high strength greywater as treatment efficiency is limited by the adsorption capacity of planting media and low retention time of greywater. Moreover, a disinfection unit is required since green walls cannot disinfect greywater.

On the other hand, greywater should not be stored for more than 48 h since the resulting exponential bacterial growth and depletion of dissolved oxygen contributes to odour and colour (i.e. aesthetic) issues and increases human health risks (Alkhatib et al., 2006; Dixon et al., 2000). Selection of an appropriate disinfection technology is crucial to ensure the hygiene of reclaimed greywater for activities that may potentially involve direct skin contact and for activities requiring overnight storage, such as toilet flushing and irrigation of food crops (Gulyas et al., 2009; US EPA, 2004).

Table 2 tabulates the disinfection technologies available in literature that are capable of eradicating pathogenic bacteria. Table 2 shows that greywater contains a large variety of bacteria, protozoans, and viruses, and many of these are pathogenic, thereby resulting in illness. Greywater contains skin and mucous pathogens *Staphylococcus aureus* and *Pseudomonas aeruginosa* (Casanova et al., 2001; Gilboa and Friedler, 2008; Winward et al., 2009) respiratory pathogens such as *Legionella pneumophila* (Birks et al., 2004), and enteric pathogens which reside in intestines such as *Cryptosporidium* and *Giardia* (Birks and Hills, 2007). In contrast to bacteria, viruses, such as F-RNA bacteriophages, are often found only in greywater sourced from infected people (Dixon et al., 2000; Gilboa and Friedler, 2008), which may imply a high health risk when greywater is reused in communal or multi-storey buildings. A potential measure against this is to ensure that the disinfectant contains a coloured dye as a rapid visual test to check if the dosing system is operational (Brewer et al., 2001).

The disinfection unit could be as simple as utilizing sunlight and polyethylene terephthalate (PET) bottles to disinfect greywater. Pansonato et al. (2011) showed that *E. coli* and total coliforms can be disinfected by sunlight. A continuous greywater recycling system showed a higher removal rate as compared to the batch system: by exposing a continuous flow of untreated greywater containing 2.0×10^4–6.6×10^5 MPN/100 mL of *E. coli* and 8.2×10^6–8.7×10^8 MPN/100 mL of total coliforms under the sunlight for 24 h, the treated greywater was found to have non-detectable *E. coli* and <1–3.7×10^1 MPN/100 mL of total coliforms. In addition, filtration using coarse materials, such as lime pebbles and zeolite, was also used to disinfect greywater (Ammari et al., 2014). Through recirculating the greywater in the system, 90% of total coliforms and up to 99.5% of *E. coli* was eradicated. Despite the low cost and simplicity of this technology, the long disinfection duration of 24 h and weather dependency make this disinfection method unsuitable for widespread, commercial application. A rapid disinfection technology such as membrane technology that is independent of weather would be favourable to speed up the recycling process and ensure that the treated greywater is consistently free of pathogens.

UV light disinfection is another disinfection technology for eradicating bacteria in greywater. UV irradiation is characterized in terms of energy per surface area (mJ/cm^2) or average UV intensity (mW/cm^2). The volume of the greywater in these systems could vary from 0.036 to 2.16 m^3/d (do Couto et al., 2013). The same study showed that a UV dose of 114 mW/cm^2 removed 100% of *E. coli* from 80% of anaerobically treated greywater samples, while the remaining 20% of samples had *E. coli* concentrations below 1 MPN/100 mL. However, as shown in Table 2, Friedler and Gilboa (2010) showed trace amounts of heterotrophic plate counts (HPC), faecal coliforms, *Staphylococcus aureus,* and *Pseudomonas aeruginosa* in disinfected, aerobically treated greywater, with UV doses varying between 69 and 439 mW s/cm^2. This study showed that some bacteria (e.g. faecal coliforms and HPC) had higher resistance to UV irradiation than others (e.g. *Pseudomonas aeruginosa*). Thus, depending on the condition of the treatment system, UV light contact time and light intensity of the UV light sources require further optimization to obtain complete removal of bacteria to ensure that greywater can be reused safely.

Chlorination is the one of the most common disinfection methods in Malaysia as chlorine is widely available, inexpensive, and is relatively simple to dose when compared against other disinfection methods (Yee et al., 2008). The major advantage of utilizing chlorine for greywater disinfection is the lengthening of treated greywater storage time, as unlike UV or ozone, chlorine leaves a residual which prevents bacterial regrowth. Chlorine doses are expressed in concentration of disinfectant (mg/L), C, and contact time (min), t, and this is denoted by CT. The efficacy of chlorine disinfection is inversely proportional to the particle size of suspended solids (Winward et al., 2008), independent of the concentration of organics in chlorinated greywater samples with a fixed free chlorine concentration (Winward et al., 2008), and the decay of residual chlorine can be slowed with the addition of ammonia to form chloramines (March et al., 2004; March and Gual, 2009). The microorganisms most resistant to chlorination are protozoans *Cryptosporidium* and *Giardia* and poliovirus type 3 (Gehr et al., 2003). Chlorine can be supplied to water in the form of sodium hypochlorite, calcium hypochlorite, or chlorine gas, although transporting and storing the former two are easier. Appropriate hypochlorite concentration and hydraulic retention time (HRT) are crucial factors in obtaining good disinfection rates in chlorination systems. 1 mg/L of hypochlorite with the HRT of 6 h completely removed faecal coliforms and *Staphylococcus aureus* (Friedler et al., 2011), and similarly, a dose of 1 mL/L of H_2O_2 added to aerobically treated greywater was sufficient to prevent microbial regrowth for up to 3 days of storage (Teh et al., 2015). On the other hand, Ronen et al. (2010) investigated the disinfection rate using hydrogen peroxide plus (HPP). 99% of total coliforms were removed using HPP concentration of 125 mg/L with a retention time of 35 min.

Table 2
Disinfection technologies and the microorganism indicator in greywater.[a]

	Operating conditions	Influent						Effluent						Removal efficiency	References
		E. C[b]	T.C[c]	HPC[d]	F.C[e]	*S.A*[f].	*P.A*[g]	*E. C*[b]	T.C[c]	HPC[d]	F.C[e]	*S.A*[f].	*P.A*[g]		
UV light disinfection	UV: $\lambda = 254$ nm; lamp intensity: 250 m J cm^{-2}; Greywater flow rate: 2.4 m^3/d	4.64×10^0	–	–	–	1.58×10^2	1.58×10^2	N.D	–	–	–	1.26×10^1	2.00×10^1	–	Benami et al. (2015)
UV light disinfection	UV: $\lambda = 254$ nm; lamp intensity: 2.8 mV s cm^{-2}; Greywater flow rate: 0.036 m^3/d –2.16 m^3/d	–	–	–	–	–	–	–	–	–	–	–	–	100% *E.coli*	do Couto et al. (2013)
UV light disinfection	UV: 36 W; lamp intensity: 69m W cm^{-2}; Greywater flow rate: 0.28 m^3/d	–	–	1.8×10^5	3.8×10^1	2.4×10^1	5.3×10^3	–	–	$> 10^5$	<10	<10	$> 10^3$	–	Friedler and Gilboa (2010); Friedler et al. (2011)
Recirculated vertical flow bioreactor	Filters: Layers of diameter 1.5 cm and 3–4 cm lime pebbles, 0–6 mm and 3–6 mm zeolites	3.10×10^4–4.1×10^5	6.2×10^4–3.85×10^6	–	–	–	–	–	–	–	–	–	–	Up to 90% total coliforms; Up to 99.5% *E. coli*	Ammari et al. (2014)
Photocatalytic Photon-fenton	UV: $\lambda = 254$ nm, 150 ppm H_2O_2/UV	–	–	–	–	–	4.7×10^4 MPN/100 mL	–	–	–	–	–	0	–	Teodoro et al. (2014)
Solar disinfection (SODIS)	Solar: 518 W/m^2, Batch system of HRT: 24 h	2.0×10^4–-6.6×10^5 MPN/100 mL	$8.2 \times 10^{\ 6}$ -8.7×10^8 MPN/100 mL	–	–	–	–	5.29×10^4–1.48×10^2 MPN/100 mL	Not reported	–	–	–	–	–	Pansonato et al. (2011)
Solar disinfection (SODIS)	Solar: 518 W/m^2, Continuous system of 24 h	N.D	5.4×10^1–1.2×10^2 MPN/100 mL	–	–	–	–	N.D	<1–3.7×10^1 MPN/100 mL	–	–	–	–	–	Pansonato et al. (2011)
Chlorination	Hypochlorite: 0.5 mg/L, HRT: 0.5 h	–	–	1.1×10^6	1.5×10^2	9.8	3.8×10^2	–	–	5.8×10^2	2.1	1×10^{-1}	4×10^1	–	Friedler et al. (2011)
	Hypochlorite: 0.5 mg/L, HRT: 3 h	–	–	1.1×10^6	1.5×10^2	9.8	3.8×10^2	–	–	7.2×10^2	0.8×10^{-1}	4×10^{-1}	2.9×10^1	–	Friedler et al. (2011)
	Hypochlorite: 0.5 mg/L, HRT: 6 h	–	–	1.1×10^6	1.5×10^2	9.8	3.8×10^2	–	–	4.4×10^2	3×10^{-1}	0	3.1×10^1	–	Friedler et al. (2011)
Chlorination	Hypochlorite: 1 mg/L, HRT: 0.5 h	–	–	1.1×10^6	1.5×10^2	9.8	3.8×10^2	–	–	5.6×10^2	2	0	1.8×10^1	–	Friedler et al. (2011)
	Hypochlorite: 1 mg/L, HRT: 3 h	–	–	1.1×10^6	1.5×10^2	9.8	3.8×10^2	–	–	3.8×10^2	3×10^{-1}	1×10^{-1}	8	–	Friedler et al. (2011)
	Hypochlorite: 1 mg/L, HRT: 6 h	–	–	1.1×10^6	1.5×10^2	9.8	3.8×10^2	–	–	1.5×10^{-2}	0	0	3.6	–	Friedler et al. (2011)
	Hypochlorite: 5–10 mg/L, HRT = 36 s	4.64×10^0	–	–	–	1.58×10^2	1.58×10^2	N.D	–	–	–	3.98×10^0	1.58×10^0	–	Benami et al. (2015)
Hydrogen peroxide plus (HPP)	Concentration: 125 mg/L, contact time: 35 min	–	–	–	9×10^1–3×10^5	–	–	–	–	–	–	–	–	99% Faecal coliform	Ronen et al. (2010)
Hydrogen peroxide	Concentration: 1 mL/L greywater	–	8.13 log		–	–	–	–	6.60 log	–	–	–	–	96.99%	Teh et al. (2015)

Electro-coagulation + disinfection	1 M NaCl, 1 M H_2SO_4, system conductivity: 500–600 μS/cm, effective electrode area: 1000 cm^2, contact time: 70 s, Greywater flowrate: 1.2–1.4 m^3/hr,	3.5×10^2–5.6×10^2	–	–	–	–	–	N.D	–	–	–	–	–	–	Lin et al. (2005)
Ultrafiltration and Reverse Osmosis membrane	5 m^3/hr hand basin greywater (mixed with 11.7 m^3/hr groundwater and 4.2 m^3/hr rainwater)	10^5 to 10^6	–	–	–	–	–	N.D	–	–	–	–	–	–	Birks et al. (2004)

[a] In CFU/100 mL, otherwise stated.
[b] *Escherichia coli.*
[c] Total coliforms.
[d] Heterotrophic plate counts.
[e] Faecal coliform.
[f] *Staphylococcus aureus.*
[g] *Pseudomonas aeruginosa.*

Despite the ease in operating the chemical disinfection units dosing hypochlorite and/or HPP, optimization of the disinfectants' concentration and HRT is essential. Optimization prevents low disinfection efficiencies due to under-dosage of disinfectants, and prevents over-dosage of disinfectants that could lead to the formation of harmful disinfection by-products (Li et al., 2008) with other pollutants in greywater. Hence, it is difficult to obtain a suitable disinfectant dosing rate that can address the wide variation and concentration of pathogens in greywater. There is a need to develop an alternative disinfection method that is easy to operate, cost effective, and does not produce harmful by-products unlike chlorine disinfection.

Ozone is the most efficient disinfectant available, with lower CT values than chlorine or bromine. For instance, chlorine doses for wastewater applications can range between 60 and 900 mg min/L (Winward, 2007). Similarly, Friedler et al. (2011) showed that 30 mg min/L of chlorine reduced influent faecal coliform concentration by 1.9 $\log_{10}$ units, while Beck et al. (2013) found that 45–68 mg min/L of chlorine reduced up to 3.5 $\log_{10}$ reduction of total coliforms. In contrast, ozone required 0.4–4.3 mg min/L to inactivate 2 $\log_{10}$ units of total coliforms (Beck et al., 2013). The key issue with ozone is the lack of residual disinfectant: unlike chlorine, there is a risk of microbial regrowth after ozone disinfection. Despite this, several studies have reported that faecal coliforms do not exhibit any regrowth over a period of 6 h with chlorine residuals of 1 and 0.5 mg/L after 30 min of contact time, and similarly, no regrowth over a period of 6 h when 19 mJ/cm^2 of UV irradiation was used (Friedler et al., 2011). Furthermore, Beck et al. (2013) found no regrowth of *E. coli* over a period of 15 days after disinfection with 288 mg min/L of free chlorine, 1 mg/L of ozone, or 10 mJ/cm^2 of UV irradiation.

Electro-coagulation is an advanced disinfection technology that involves application of an electrolysis cell (Bani-Melhem and Smith, 2012; Vakil et al., 2014). Lin et al. (2005) investigated the effect of applied voltage on the treatment efficiency of greywater. Greywater influent contained 3.5×10^2–5.6×10^2 CFU/100 mL of *E. coli*, and treated greywater effluent from electro-coagulation treatment coupled with the flotation process contained non-detectable *E. coli*. However, it was reported by Lin et al. (2005) that the treatment efficiency of the system was reduced due to the presence of dissolved pollutants in the greywater. Hence, the disinfection rate of such a system might be reduced when higher concentrations of dissolved contaminants are present in greywater.

Hence, to overcome the restrictions of the disinfection techniques mentioned above, an inert and rapid disinfection technique would be preferable. Complete removal of 10^5 CFU/100 mL–10^6 CFU/100 mL of *E. coli* in greywater influent was achieved via ultrafiltration and reverse osmosis membranes in series in a commercial scale treatment facility in the UK (Birks et al., 2004). The membrane filtration system is relatively inert as compared to other treatment techniques, which makes it easier to control and manage. On top of that, the capability of the membrane system to handle large volumes of wastewater in a small and compact area is another benefit. Membrane systems may also eliminate fluctuating disinfection efficiencies due to the wide variation of the pollutants in untreated influent greywater.

6. Lessons learned from greywater recycling case studies worldwide

Greywater recycling is widely practised worldwide, especially in developed nations such as the USA, the UK, Australia, Japan, and

Germany. Recently, some developing countries have begun adopting greywater recycling to reduce freshwater consumption and curb water shortage (Mah et al., 2009; Mandal et al., 2011). The experience of these countries in greywater recycling is crucial to provide insights for those who are developing greywater recycling systems. The following sections analyze different case studies of greywater recycling around the world.

6.1. Developed countries

The USA has used treated greywater for toilet flushing and irrigation since 1925 (Christova-Boal, 1995). The first greywater recycling system was constructed in the Grand Canyon to reclaim greywater from tourist facilities. According to Christova-Boal (1995), greywater treatment and recycling units were illegal in the USA prior to 1989. The Santa Barbara County took the initiative to legalize greywater reclamation by introducing greywater regulations. Subsequently in May 1991, a major drought in California triggered public interest in greywater recycling (Dixon et al., 1999). The Santa Barbara County's initiative, coupled with drought, caused 11 counties in California to legalize greywater reuse in 1992. Other than California, the reuse of reclaimed greywater has also been implemented in Florida for more than 40 years (Parsons, 2009). In Florida, a separate purple pipeline is in place to carry the reclaimed greywater to avoid accidental cross-connection of drinking water pipelines to reclaimed greywater pipelines. Under the guidelines, drinking and continuous contact of reclaimed greywater is prohibited, although reclaimed greywater may be reused for landscape irrigation without spraying, filling of decorative ponds and lakes, cooling towers, and irrigation of non-raw-eaten food crops (Parsons, 2009). US EPA (2012) showed that USA has successfully reclaimed approximately 16.43 billion m^3 of water, and will expect to achieve higher water reclamation volumes in the future. The successful reclamation of greywater in USA proved that greywater recycling systems save water and reduce the stress of water scarcity.

Dixon et al. (1999) reported that apartments, municipal buildings and office buildings in the cities of Japan have long implemented greywater recycling units due to potable water shortages. Common greywater treatment units in Japan consist mainly of aerobic treatment or membrane filtration followed by disinfection (Christova-Boal, 1995; Ogoshi et al., 2001). The greywater generated in these buildings are used to flush toilets and to fill artificial ponds or fountains (Asano et al., 1996; Christova-Boal, 1995). A statistical report in 1997 showed that Japan has successfully reclaimed a total of 206 million m^3 per annum with the implementation of greywater recycling systems (Ogoshi et al., 2001).

Australia, especially south-eastern Australia, was reported to face fresh water shortages as a result of population growth, urbanization, and climate change (Ryan et al., 2009). Australia has developed several approaches to reduce freshwater consumption, and one such approach is to recycle greywater (Pham et al., 2011). Reclaimed greywater is now commonly used in Australia for most daily non-potable activities (e.g. toilet flushing and garden irrigation) except for clothes washing in households, and also for industrial uses and irrigation purposes (Pham et al., 2011). Sydney has successfully reused 25 million m^3 of water annually through the implementation of greywater recycling systems (Sydney Water, 2009). While most of the research focuses on reducing potential health risks of greywater reuse, a recent publication by Turner et al. (2013) discusses the potential environmental risks of reusing greywater for irrigation, such as soil contamination due to excessive pollutants present in greywater. Turner et al. (2013) concludes that there is limited influence to the soil environment when irrigating with greywater. Rather, the irrigation using greywater curbs the high volume of freshwater consumption for irrigation and the greywater provides nutrients for the crops or plants. Therefore, with proper management of the greywater irrigation system, reusing greywater for irrigation can fulfil the three pillars of sustainability: ecological, economical, and social aspects.

In Berlin, Germany, Nolde (2000) recorded two greywater reclamation and treatment systems installed in two buildings. A four-stage RBC treated greywater sourced from the shower, hand basins, and bath tubs of 70 people, whereas a two-stage fluidized bed reactor treated greywater sourced from the shower and bathtubs of two people. Both of the systems were installed jointly with sedimentation, organic matter removal, and disinfection processes to optimize pollutant removal and reduce the potential health risks of raw greywater. Nolde (2000) suggested that extensive biological treatment of greywater is necessary to meet mandatory water quality standards and to ensure the technical feasibility of the process. The two systems successfully treated the greywater to meet the EU Standard for Bathing Water (76/160/EEC), which allows < 10,000/100 mL total coliforms, <1000/100 mL *E. coli* and <100/100 mL Pseudomonas aeruginosa. The treated greywater effluent from the recycling system is used for toilet flushing. In addition, a large scale RBC was reported to recycle 20 m^3/d (i.e. 7300 m^3/year) from a hotel in Germany (Nolde, 2005). By considering the freshwater costs and operation and maintenance costs of the RBC system, the payback period was found to be 6.5 years, and an additional 3 years were required to make a profit (Nolde, 2005). This case study shows that implementing greywater recycling systems can be profitable, especially in commercial buildings where there is high water use (e.g. hotels, restaurants, shopping malls, stadiums and office buildings), and thus high freshwater saving potential for greywater recycling.

Lu and Leung (2003) performed a study on the feasibility of greywater recycling in Hong Kong. The study proposed three major considerations to be involved in the planning of wastewater reuse: conceptual planning, feasibility investigation, and planning of facilities. According to Lu and Leung (2003), elucidating the concept of wastewater reuse to the general public is mandatory prior to system implementation. Then, the infrastructure of the wastewater recycling system and cost estimation must be carefully developed to support the future development of the country. The later steps of planning will involve an investigation of how achievable the project is based on market assessment, an analysis of the current greywater recycling system and its alternatives, and an evaluation of the technological, financial, and financial impacts of connecting pipelines to a decentralized greywater recycling system as opposed to a centralized wastewater treatment plant. Last but not least, the planning requires investigation of the social acceptance and financial analysis of renovating existing buildings to install greywater recycling facilities. The study by Lu and Leung (2003) may provide guidance for future development of greywater recycling systems in other countries.

6.2. Developing countries

The direct reuse of greywater without treatment is commonly found in developing nations, where greywater is commonly used for irrigation. Jordan is a densely populated developing country, and 15% of its total population lives below the national poverty line. The high population density has resulted in food and water security issues over the past 20 years (Faruqui and Al-Jayyousi, 2002). For instance, in Ain El Beida in Jordan, kitchen greywater and ablution wastewater from the bathroom (i.e. excluding the water used to wash diapers) were reused directly for food crop irrigation. The greywater was generated by 15 participating families, where kitchen greywater was collected from a discharge pipeline located at either the kitchen sink or from a pipeline modified to divert the water to the plantations. Through this pilot-scale project, families who reused greywater for irrigation reduced their food expenses and water consumption, and some families were able to sell their surplus of food crops. This indirectly helps to reduce food and water stress levels within the nation. In addition, Faruqui and Al-Jayyousi (2002) suggested that the adverse effects of using untreated greywater for irrigation was insignificant when small quantities of greywater were reused. However, the negative impacts on the ground salinity would be substantial if large volumes of greywater were reused for irrigation, or if greywater was reused for irrigation for a long period of time (Faruqui and Al-Jayyousi, 2002). Hence, proper treatment is crucial prior to reuse to avoid adversely affecting the environment and to prevent pathogens from spreading into groundwater supplies.

Similarly, in India, a pilot-scale greywater recycling unit was installed to treat greywater from five households (Mandal et al., 2011). In that project, the authors investigated the amount of water that could be conserved through greywater recycling. The treatment of greywater was done through a series of process of screening, filtering, equalizing and aeration. The report showed that out of 0.08 m^3/p/d of greywater produced from showers, laundry and basins, 0.025 m^3/p/d is required for toilet flushing and the remaining 0.055 m^3/p/d could be used for crops irrigation. As documented in the study, the recycling of greywater in toilet flushing and crops irrigation could result in 48% reduction in the freshwater (Mandal et al., 2011). In fact, based on the extrapolation data from this study in Madhya Pradesh, India, a total of 64 m^3 of freshwater could be saved daily. This inferred that practising big scale greywater recycling could benefits the environmental via reduction of water resources depletion.

Obtaining freshwater and discharging wastewater are equally critical in Palestine's rural areas. Palestine installed 161 greywater recycling systems to provide services for 225 families and 27 schools, and designated one of the systems for irrigation purposes (Allen et al., 2010). Despite the reduction of freshwater consumption due to the introduction of the greywater recycling systems, greywater recycling has received limited attention in Palestine due to the lack of public awareness and lack of social acceptance on reusing greywater for irrigation.

7. Greywater treatment in Malaysia

As compared to other countries, Malaysia is in its infancy for greywater recycling. Greywater is not commonly reused in Malaysia due to the limited resources and knowledge on the implementation and management of greywater recycling, and is conventionally treated together with blackwater (i.e. wastewater from toilets) in a centralized treatment facility (Mah et al., 2009).

7.1. *State-of-the-art of greywater recycling*

The centralized wastewater treatment system in Malaysia involves four major stages (Indah Water Konsortium, 2012). The sewage influent will first undergo pre-treatment to remove coarse particles. The effluent from primary treatment unit will then be sent to a secondary treatment unit, such as activated sludge systems, SBRs, contact stabilization and RBCs for further treatment before discharging. The effluent from secondary treatment unit can usually be safely discharged into environmental water courses (Indah Water Konsortium, 2012). However, these treatment processes were found to be relatively complex, expensive and very sensitive to the changes in the environment (Alkhatib et al., 2006; Casey et al., 2003). Additionally, the lack of nutrients in greywater would limit the treatment efficiency of a biological treatment system (Li et al., 2009). Disinfection is required as the last treatment step to remove both pathogenic bacteria and odours from greywater, thus ensuring that treated greywater has good hygiene and aesthetics.

Out of the few available studies on greywater recycling in Malaysia, Mah et al. (2009) published a paper on the conceptual modelling of greywater recycling. This pilot project, Ecological Sanitation (Ecosan) was introduced and mathematical modelling was established via simulation in Kuching, Sarawak in 2003. The hypothetical treatment process was used to treat greywater generated from the kitchen, showers, and washing machine. The major treatment unit of Ecosan project was wetlands with integrated aerobic filter (Mah et al., 2009). The purpose of this project was to reduce pollution caused by discharge of greywater into stormwater drains by treating aforementioned low strength greywater. Mah et al. (2009) found that the implementation of this pilot project not only helped to reduce the pollutants in the stormwater drain, but also showed that treated greywater is suitable for non-potable reuse and a predicted average reduction of 40% of potable water consumption could be achieved. Despite the difficulties faced by local ministry in decision making and managing such treatment due to the lack of experience, the Ecosan project in Sarawak opened up an opportunity and possibility of implementing greywater recycling in Malaysia.

Apart from the Ecosan project, a few pilot-scale greywater recycling systems have been studied in Malaysia in recent years. For instance, a greywater recycling system with maximum capacity of 14.4 m^3/d capacity is located at Monash University Malaysia (Oh et al., 2015). The recycling system consists of a sand filter, an activated carbon filter and an ozone disinfection unit. The ozone dosage of this recycling system was optimized to improve the disinfection efficiency and the pilot-scale system can produce treated greywater that meets the non-potable reuse standards (i.e. < 20 mg/L BOD_5, <2 NTU, pH 6–9). The study also indicated that the amount of freshwater or potable water saved via this greywater recycling system can supply the water demand for 140 persons, which is equivalent to 28 families with an average of 5 members. On the other hand, an ablution greywater recycling system was constructed in two mosques located at Batu Pahat, Johor (Mohamed et al., 2016). Ablution greywater has low pollutant strength, and was treated with a simple sand-gravel filter. The treated greywater could be utilized for toilet flushing or garden watering to cope with the high freshwater demands of these daily activities.

Due to the limited case studies conducted in Malaysia, it can be deduced that Malaysia lacks a proper evaluation of greywater recycling system performance, cost benefit analysis, and a health risk assessment. Thus, the following section reviews the challenges faced by Malaysia in implementing greywater recycling systems and possible approaches that could be adopted to overcome the obstacles.

7.2. *Challenges of greywater treatment in Malaysia*

The challenges of greywater recycling are not merely limited to minimizing water usage and maximizing water recycling: there is also a need to balance between environmental sustainability while simultaneously addressing issues of user safety, economic viability, utilities and politics (Alkhatib et al., 2006; Chen et al., 2012; Harding, 2006). The latter stage involves justifying the practicality of the greywater recycling systems through the implementation of engineering tools, such as life cycle assessment (LCA), material flow analysis (MFA) and environmental risk assessment (ERA) (Chen et al., 2012). MFA analyzes the volume of water intake, recycling and discharge. An LCA can be conducted to evaluate the emissions from the process and indirectly state its sustainability, while an ERA serves to identify potential risks to the environment when implementing a greywater recycling system. A detailed evaluation based on different perspectives is required to overcome the obstacles in greywater recycling.

There are several obstacles that limit the implementation of greywater recycling and reuse systems in Malaysia. Legal constraints have always been a challenge when upscaling greywater reuse systems (Reschke, 2013). As discussed earlier by Mah et al. (2009), although the state government was interested in recycling greywater, the ministry could not approve the greywater recycling system because of the lack of experience in both managing and maintaining greywater recycling systems. According to Lim (2011), the current focus of wastewater treatment is still on the development of centralized systems handled by Malaysian government.

The lack of public awareness on the water crisis in Malaysia has contributed to the slow development of greywater recycling systems. For Malaysia to become a developed nation, Malaysia is encouraged to put more effort into utilizing relatively new and sustainable solutions to resolve water shortages. In addition to that, another major factor that influences the success of greywater recycling in Malaysia would be the public acceptance of greywater reuse (Boyjoo et al., 2013). Hence, the local society and government agencies should build up public awareness on the urgent issue of saving water and promote the benefits of reusing greywater to the Malaysian public (Harding, 2006).

The other public concern on reusing greywater would be the financial considerations (Prathapar et al., 2005). The current piping system in a typical Malaysian household does not separate the collection of greywater from blackwater or sewage. Prior to installing a greywater recycling system, a dual piping system has to be installed or modified from the existing pipelines to divert greywater to a separate collection tank (Khatun and Amin, 2011; Prathapar et al., 2005). There will be additional costs involved with this modification, including changing of the pipelines for circulation and installation of the greywater treatment system. Moreover, the operational and maintenance costs present a significant financial barrier to greywater recycling, and hence only stakeholders with a high awareness of the benefits of recycling greywater and strong concerns on environmental issues will be sufficiently attracted to install a greywater recycling system (Prathapar et al., 2005).

To encourage the implementation of greywater recycling, subsidies or rebates could be provided by the government and public sector to stakeholders who install greywater recycling systems (Boyjoo et al., 2013; Hophmayer-Tokich, 2006). Unlike Australia, Malaysia currently has no subsidy from the government that provides 370 USD (Currency exchange rate retrieved on 8 May 2015: 1 AUS to 0.74 USD) to households that purchase a greywater recycling unit after the year 2009 (Allen et al., 2010). The price of various greywater treatment and reuse systems in Australia ranges from $ 20 –$ 15,000. Low budget greywater recycling systems usually consist of a simple diversion system without further treatment. A higher investment cost is required for systems such as Aqua Reviva from New Water which functions as an automatic reuse system (PlanetArk, 2007). The large gap in prices for various techniques would confuse users, who may not have the necessary knowledge to balance between the investment costs and an appropriate treatment system.

The current lack of comprehensive studies on the characterization of greywater is another obstacle against implementation of greywater recycling in Malaysia. The design of a greywater recycling system requires detailed analysis of the physico-chemical properties of greywater, not only to identify the potential health risks of raw greywater from potential pathogens, but also to ensure appropriate treatment method selection and design. Water pinch analysis was done in a mosque in University Teknologi Malaysia (UTM) and a maximum freshwater use reduction of 85.5% could be achieved by greywater reuse (Manan et al., 2006). A review by Morel and Diener (2006) elaborated on the characteristics of mixed greywater generated from 9 households, but this does not sufficiently represent the properties of the greywater generated within different states in Malaysia. There is a need for researchers in Malaysia to conduct a comprehensive greywater characterization since the characteristics vary through different states or locations, time periods, and cultures.

Last but not least, selection of a proper treatment technology for greywater recycling systems is a significant but worthwhile challenge as an appropriate selection of treatment technology will lead to high energy efficiency, lower capital and operational costs, higher treated greywater quality, and hence, better public acceptance to greywater recycling.

7.3. Opportunities for greywater recycling in Malaysia

Based on all the successful examples and constructive experiences from other countries, greywater recycling is indeed an attractive approach to achieve water sustainability in Malaysia. Nevertheless, the high capital costs of the greywater treatment system combined with the high installation costs of modifying current pipelines to separate greywater from blackwater are the main factors deterring the public from implementing the greywater recycling system (Pinto and Maheshwari, 2007). However, the greywater recycling systems in Batu Pahat, Johor showed that the freshwater consumption was reduced up to 41.73%–50.83% (Mohamed et al., 2016). Corresponding to the volume of freshwater saved, a total of 490.15 USD (exchange rate of 1 USD to 4.40 MYR, retrieved on 17 April 2017) could be saved per annum (Mohamed et al., 2016). On the other hand, the pilot-scale greywater recycling system studied by Oh et al. (2015) reduced the freshwater bills of up to 0.23 USD/m^3 of greywater treated. The study also inferred that increasing greywater recycling capacity could significantly reduce the volume of freshwater consumption and utility bills based on the Malaysian water tariffs. Similarly, Memon et al. (2005) performed an economic evaluation on a small-scale greywater recycling system (i.e. a house with 3 adults, 2 children and a dog) and a large-scale greywater recycling system (i.e. student hostel with 40 residences). In this assessment, the total initial capital costs for the small-scale and large-scale systems were reported to be 2528.66 USD and 5205.15 USD (exchange rate 1 British Pound to 1.56 USD, retrieved on: 20 July 2015), respectively. A total of 31 m^3/year of water and 53.62 USD/year could be saved in the small scale system while 420 m^3/year and 804.34 USD/year could be saved in the large-scale system (Memon et al., 2005). In addition to that, a long-term simulation across 15 years on the large-scale greywater recycling system with a freshwater price of 1.26 USD/m^3, discount rate of 4%, and complete reuse of greywater for toilet flushing, suggested that greywater recycling systems could, in fact, offer profits.

On the other hand, the high initial capital cost of a greywater recycling system could be reduced to encourage widespread adoption of greywater recycling systems. The initial capital cost of a greywater recycling system consists of the following costs: site preparation for the recycling system; pipework; treatment unit; and installation and commissioning. These capital costs can be reduced based on the project location. For instance, the local environment authority, the Department of Environment (DOE) should encourage housing developers in the country to incorporate the dual piping system in new properties, which helps the general

Malaysian public save the cost of renovating existing buildings to accommodate future greywater recycling systems. Moreover, subsidies from the local government will help reduce the financial burden of purchasing a greywater recycling system, and help indirectly prompt a higher public acceptance of greywater recycling.

The implementation of decentralized treatment or onsite treatment can be a solution to the high cost of centralized recycling systems (Naylor et al., 2012). The decentralized wastewater treatment system uses natural or mechanical parts to collect, treat, discharge or reclaim wastewater without passing through centralized treatment facilities (Casey et al., 2000). Similarly, the cluster treatment facility provides decentralized wastewater treatment for two or more dwellings, but not the entire community (Casey et al., 2000; Massoud et al., 2009). This concept can be implemented in densely populated residential areas (e.g. high-rise buildings) or sparsely populated residential areas to recycle greywater directly within houses. As a result, a decentralized or cluster treatment system can vastly reduce the amount of energy required to transfer greywater and treated greywater to and from the centralized treatment system.

Fig. 4 illustrates the difference between centralized and decentralized systems. This clearly shows that long pipelines are required to connect each dwelling in different households to transfer the wastewater to a centralized treatment system, while a relatively short pipeline is required to manage a decentralized treatment system. Therefore, the simplicity and cost effectiveness of a decentralized greywater treatment system makes it an attractive option for remote areas, such as rural villages, that have no access to pipelines connected to centralized treatment facilities (Geisinger and Chartier, 2005; Hophmayer-Tokich, 2006). This is because construction of the long piping system used for transferring wastewater to a centralized system can be costly (Otis et al., 1996).

Moreover, other than providing the community with the benefits such as ease of management and remote quality control of the decentralized greywater treatment system, a decentralized greywater system allows users to monitor the system's performance and maintain it when necessary (Al-Jayyousi, 2003; Norton, 2009). Furthermore, other than remote areas, condominiums, apartments, or office buildings with high population densities and high freshwater consumption rates can benefit from can adoption of decentralized greywater treatment systems. For instance, a new multistorey building in Metropolitan area of Barcelona has implemented the decentralized greywater recycling system to reduce the impact of water scarcity (Domènech and Saurí, 2010).

The centralized treatment system is usually inaccessible to the public, and this indirectly results in reduced understanding, awareness and public involvement in the wastewater treatment process (Massoud et al., 2009). The centralized treatment system requires numerous pumps and installation of a piping system, which increases energy consumption and system costs (Massoud et al., 2009). Geisinger and Chartier (2005) reported that 60%–70% of the total project cost of centralized wastewater treatment is contributed by the collection system. Hence, a decentralized system was suggested as an alternative to centralized treatment to reduce the cost of the collection system by increasing the flexibility of pipeline arrangement and collection system (Geisinger and Chartier, 2005).

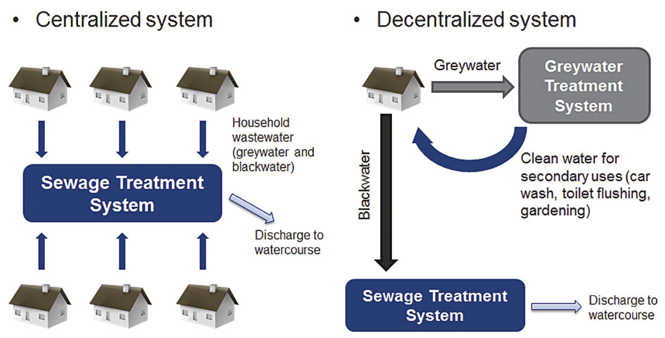

Fig. 4. Conceptual illustration of centralized and decentralized water treatment system.

The selection of appropriate greywater treatment technologies, and most importantly, disinfection technologies, becomes crucial as the hygiene of treated greywater plays a vital role in improving public acceptance. The fewer pathogens present in treated disinfected greywater, the lower the health risk posed by reusing greywater, and hence the higher the likelihood that greywater recycling is widely accepted by the Malaysian public. Therefore, an appropriate sequence of treatment is crucial to ensure the cleanliness of the treated greywater. For instance, the proposed sequence of treatment units for greywater recycling systems for light greywater is screening, chemical treatment, and membrane filtration as the polishing step to eradicate pathogenic bacteria; in contrast, the proposed sequence of treatment units for mixed or high strength greywater is screening, biological treatment, and membrane filtration, as biological treatment presents decent treatment efficiencies under the presence of macronutrients and trace-nutrients in greywater (Leong et al., 2017).

Malaysian researchers should also focus on optimizing the greywater treatment process to achieve higher treatment efficiencies. The treatment system in the greywater recycling system is the main contributor to high installation and maintenance costs. Studies have suggested that simple, single treatment steps are favourable, as these singular treatment units are easy to maintain and effectively removes the pollutants (Brame et al., 2011). For instance, membrane filtration can effectively reduce the dissolved and suspended solids concentration as well as pathogenic bacteria (Pidou et al., 2007). Incorporation of anti-microbial nanomaterials (e.g. heavy metal biocides such as silver and copper) on the membrane could enhance the membrane filtration by adding an extra layer of disinfection on top of regular filtration (Brame et al., 2011).

Based on the reviewed practices, Malaysia can kick-start greywater recycling projects by recycling only light greywater (e.g. ablution water, sink water and bathroom greywater) for toilet flushing and garden watering in houses. In the process, Malaysians gain needed technical experience on managing decentralized greywater recycling systems. Due to the low pollutant concentration in light greywater, only simple physical treatment units, such as sand filters or activated carbon filters, are required. Furthermore, the simple setup ensures that users can monitor the greywater recycling system easily. At the same time, the local government authorities could encourage housing developers to construct dual-pipelines in newly developed properties, hence easing the financial burden of installing decentralized greywater recycling systems within households. Subsequently, to adapt to the increasing greywater recycling capacity (e.g. recycling of high strength or mixed greywater) in the future, greywater recycling systems may be developed further, and the technical, economical, environmental, and social viability of employing greater treatment capacities and more complex recycling systems in households can be investigated.

8. Conclusions

Exponential population growth has caused the fresh water consumption in Malaysia to rise drastically. Hence, there is an urgent need for water conservation by considering greywater recycling for non-potable daily activities which do not require high quality water. Case studies in this paper can serve as a decision-making tool for countries to kick start greywater recycling projects. Past greywater recycling projects and experiences from other countries have been evaluated to identify obstacles/challenges faced in initiating greywater recycling. Based on the findings, a comprehensive study of the greywater characteristics is urgently needed in Malaysia to design and implement a practical greywater recycling system based on the quantity and quality of greywater. Malaysia can initiate greywater recycling efforts by recycling light greywater from ablution activities and bathrooms. A physical filtration system coupled with disinfection unit can be employed for the recycling of light greywater. To ensure the safety of reuse in toilet flushing and irrigation, the treated greywater has to be monitored periodically to ensure that the quality of treated greywater meets pH 6–9, TSS <20 mg/L, < 5 NTU, BOD_5 < 20 mg/L and <10 CFU/100 mL of *E. coli*. Last but not least, the local government plays an important role in promoting water sustainability by offering financial support via subsidies and rebates when installing greywater recycling systems and by providing public education to continuously create awareness of the advantages of greywater recycling.

Conflict of interest

No conflict of interest.

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