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Optimizing the in-line ozone injection and delivery strategy in a multistage pilot-scale greywater treatment system: System validation and cost-benefit analysis

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ABSTRACT

Greywater is a potential source of recycled water for household that has often been overlooked. Although greywater is lightly contaminated, a holistic treatment and disinfection system of greywater is still warranted to ensure public health issues associated with the cross-connection of third pipe reticulation in household are minimized. This study assessed on the treatment performance of a commercial pilot-scale greywater treatment system comprising of a multi-medium sand filter, granulated activated carbon (GAC) filter and an ozonation disinfection system. The operational volume flow rate (10–20 L/min) and ozone dosing rate (5–20 g/h) for maximum removal of contaminants in greywater were investigated. This study found that the increase in operational volume flow rate decreased the overall performance of the greywater treatment and disinfection system. The optimum operating volume flow rate was found to be 10 L/min, removing 72.6% of chemical oxygen demand (COD) and 42.9% (0.85-log removal) of *Escherichia coli* without recirculation. Recirculation of greywater was introduced to the ozonation disinfection system in order to improve the disinfection efficiency. It was found that all bacteria present in the treated greywater effluent were completely disinfected with a recirculation period of 1 h.

Introduction

Greywater is a source of wastewater generated from showers, hand wash basin, laundry or preparation of food in the kitchen [1]. It is consistently generated daily and contains low concentrations of organic compounds and pathogens when compared to domestic wastewater with sewage inputs. Therefore, greywater has a huge potential to be treated, recycled and reused, especially when the availability of freshwater is a concern in many arid countries. Treated greywater effluent can be reused for irrigation, car washing and toilet flushing to augment the availability of drinking water for other potable fit-for-purpose applications.

Though greywater is lightly contaminated, there is still a need for treatment before reuse as the microorganism content in the treated greywater effluent could potentially cause public health issues through close human contact [2]. Greywater effluent that is deemed safe for reuse can normally be obtained through several treatment barriers, which include: (i) pre-treatment for the removal of coarse materials; (ii) primary and secondary treatments to remove majority of the contaminants and (iii) tertiary disinfection treatment to ensure the effluent is microbiologically safe for handling.

To date, different processes have been used for the treatment and disinfection of greywater effluent. Some popular examples of the primary greywater treatment systems are chemical processes, biological processes and physical and physicochemical processes [3–6]. In general, these systems are operated to reduce solids,

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Table 1
Greywater characteristic for this study.

Parameters	Concentration (mg/L)[a]
pH	6.20–7.66
Turbidity	6.2–48.4
Total suspended solids (TSS)	42.6–63.3
Chemical oxygen demand (COD)	63.5–153.0
Biochemical oxygen demand (BOD_5)	45.6–58.5
Escherichia coli (*E. coli*)	0–17,900 cfu/mL
Pathogenic bacteria	0–3400 cfu/mL
Other coliforms	0–2650 cfu/mL

[a] All units are in mg/L unless specified and pH which has no units.

organic and inorganic contaminants in greywater source. On the other hand, chlorination, ultraviolet (UV), hydrogen peroxide, ozonation, advanced oxidation are the typical disinfection methods used for greywater [7,8] to ensure that the treated effluent is microbiologically safe for reuse.

Most previous studies on the treatment of greywater for reuse purpose were carried out in laboratory-scale systems, mainly for understanding the principles of the treatment systems as well as to evaluate the effectiveness of individual units of primary, secondary or tertiary disinfection treatment systems [9–13]. To date, there are limited references available in the open literatures on the treatment of greywater in pilot- or large-scale commercial systems that encompass different stages of treatment. Thus, it is necessary to evaluate the multi-stage treatment and disinfection system as a whole in a pilot- or large-scale commercial system. This is to enable the identification of treatment limitation of a complete and integrated greywater treatment system and assess the suitable operating conditions, providing insight to urban developers on the adequacy of such system for implementation in new greenfield or retrofitted brownfield developments.

Thus, the main aim of this study was to assess the treatment performance of a commercial pilot-scale greywater treatment system comprising of a multi-medium (sand) filter, activated carbon filter and an ozone disinfection system. Conventionally, ozone disinfection is conducted for treated effluent retained in a tank, where ozone is in contact with the effluent for a fixed period of time. This study examined the use of an in-line ozone disinfection system to eliminate the requirement of an additional disinfection tank, thus reducing the physical footprint and overall cost of the pilot-scale system. This study also evaluated the cost-benefit analysis of having an installed greywater treatment system for recycling purpose against the typical Malaysian households with only the conventional dual-reticulation water system.

Materials and methods

Greywater

Bathwater from a group of workers in a factory located in the coordinate (3.0692105, 101.5965965) was collected in a polyvinyl chloride (PVC) tank and transported to Monash University Malaysia for treatment on a weekly basis. The characteristics of the collected greywater are as listed in Table 1.

Pilot-scale greywater treatment system

Fig. 1 shows the schematic of the pilot-scale greywater treatment system that was used in this study. The pilot-scale system has a 1.3 m^3 PVC feed water tank, which is connected to a multi-medium filter with a stainless steel housing and dimension of 19.05 × 145 cm (D × H) (ER-19M, BACFREE), followed by a granular activated carbon (GAC) filter (BACFREE), which has similar capacity as the ER-19M and an ozone generator (CTO-20, Corona Discharge Ozone Generator). The treated greywater effluent after disinfection was stored in another 1.3 m^3 PVC water holding tank (clean water tank).

This pilot-scale greywater treatment system was also fitted with two centrifugal pumps to facilitate the transfer of greywater source to the treatment system, as well as for the recirculation of treated greywater effluent to the ozone injector. The system was also fitted with several sampling valves along the treatment process to allow sampling of treated greywater effluent at different stages of the greywater treatment system.

Evaluating the performance of pilot greywater treatment system

The pilot-scale greywater treatment system was operated in two different conditions in order to evaluate the performance of the system and to determine the optimum operating condition: (i) without recirculation of treated greywater; (ii) with recirculation of treated greywater. In the first condition, disinfected greywater effluent was directly stored in the clean water holding tank

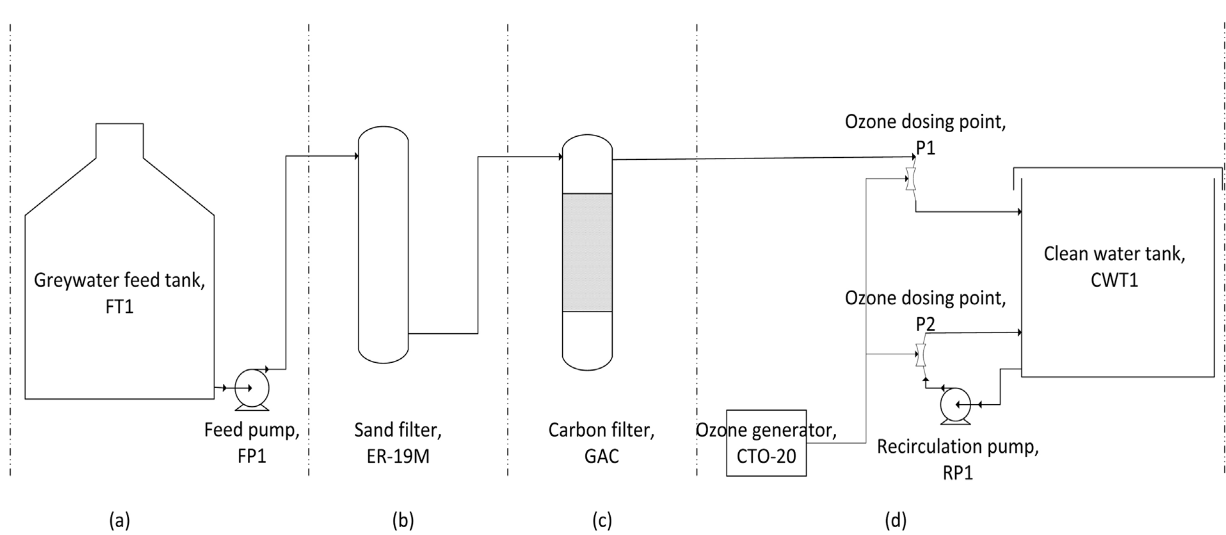

Fig. 1. Schematic diagram of the pilot-scale greywater treatment system; (a) greywater feed tank; (b) multi-medium sand filtration unit; (c) GAC column; (d) ozonation disinfection; (e) recirculation loop with ozonation.

Table 2
HRT (minutes) in treatment columns with respect to different process flowrate.

	Sand filter (ER-19M)	Carbon filter (GAC column)
10 L/min	3.50	3.50
15 L/min	2.33	2.33
20 L/min	1.75	1.75

without further recirculation. The operating volume flow rate of the greywater fed into the pilot-scale system was varied from 10–20 L/min to obtain a feed flow rate that produces the optimum treated greywater effluent quality from the treatment process. Hydraulic retention time (HRT) of each treatment unit is listed in Table 2.

In the second condition, the treated greywater effluent stored in the clean water holding tank was continuously recirculated through the ozone injector for a fixed period of time (1–2 h). An oxidation–reduction potential (ORP) sensor was installed to monitor the treated greywater effluent quality in the clean water holding tank. When the greywater treatment system was operated under low dosage of ozone, bacteria present in the treated greywater effluent cannot be completely disinfected. Furthermore, the contact time between the treated greywater effluent and ozone was very short. Under such condition, recirculation of the treated greywater effluent for additional contact with ozone could improve the disinfection efficiency. Due to the fact that ozone is a highly oxidative gas that has harmful effects to public health when exposed to the environment, the ozone disinfection system should be operated under the lowest possible dosage (<20 g/h) [14,15]. Therefore, recirculation of treated greywater effluent is a technically feasible option that is being investigated in this study.

The experimental runs conducted in this study are listed in Table 3. The raw greywater and treated greywater effluent samples were tested for pH, COD, BOD_5, TSS and turbidity in accordance to the American Public Health Association (APHA) Standard Methods (Eaton et al., 2005). Each greywater quality parameter was analysed in triplicates. Plate count method was used to determine the concentration of *Escherichia coli*, coliforms and other pathogenic bacteria present in the collected greywater samples.

Results and discussion

Greywater treatment without recirculation

Based on Table 4, the lowest operating volume flow rate of 10 L/min produced the optimum treated greywater effluent quality from the pilot-scale treatment system with an overall turbidity, TSS, COD removal of 80.38%, 60.18% and 72.59%, respectively. The treatment performance of the pilot-scale system declines with the increasing greywater feed flow rate. This declination in treatment performance is mainly attributed to the short contact time of greywater with the filtration media and ozone injector, which reduces the attachment of contaminants onto the media.

This outcome was further supported by the negative ORP values and bacteria content of the treated greywater effluent in the clean water holding tank that increase with the feed flowrate. Negative ORP values indicate that the amount of ozone in the system is insufficient to effectively disinfect the microorganisms present in greywater [16]. Therefore, the pilot-scale greywater treatment system should be operated at the lowest flowrate of 10 L/min and the ozone concentration injected into the system should be optimized in order to obtain the most suitable and cost-effective ozone dosage that can effectively disinfect the microorganisms present in the system.

From the individual performance of the respective treatment units in the pilot-scale greywater treatment system, the most apparent reduction of organic and inorganic contaminants occurred in the GAC filter where the reduction of COD can reach as high as 69% (refer to Table 4). Most of the suspended solids were also removed by the GAC filter. In addition, higher removal efficiencies in terms of COD, BOD_5 and TSS were also achieved from the use of GAC filter due to the adsorption of contaminants on the granulated activated carbon media [17]. The adhesion of bacteria colonies on GAC contributed to the formation of biofilm [18]. The formation of biofilm can also be attributed to the accumulation of nutrients on the GAC which indirectly promotes the grow of bacteria [18], especially when the system is idle. However, Yin et al. [18] suggested that the increase in the removal efficiency of contaminants could also be attributed to the biofilm formation on the GAC filter, which altered the surface charge density of GAC filter. Modification of the surface charge density of the GAC filter, to a certain extent, enhanced the adsorption of contaminants especially the positively charged matters [18].

In terms of bacteria removal, the pilot-scale greywater treatment system was unable to completely disinfect all the bacteria present in the treated greywater effluent for all the investigated flowrates at the constant ozone dosing rate of 10 g/h. Furthermore, the amount of bacteria remained in the treated greywater effluent also increased with the operating volume flowrate. Based on Table 4, negative disinfection efficiency was observed especially at high flowrates (e.g., 20 L/min). When the system operates at high flowrate, there is possibility that bacteria could not adhere on the treatment unit (e.g., SF and GAC) and flushed out of the system. This has led to the increase in bacteria concentration at the outlet of each treatment units. As the concentration of bacteria accumulates at the ozone disinfection system, the short contact time of ozone with the greywater does not allow effective disinfection. Hence, leading to the negative

Table 3
Experimental runs conducted on the pilot greywater treatment system.

Run	Fixed parameter	Manipulated parameter
1	O_3 dosing rate: 10 g/h (single pass process)	Q: 10 L/min
2		Q: 15 L/min
3		Q: 20 L/min
4	Q: 10 L/min (without recirculation)	O_3 dosing rate: 5 g/h
5		O_3 dosing rate: 10 g/h
6		O_3 dosing rate: 15 g/h
7		O_3 dosing rate: 20 g/h
8	Q: 10 L/min (recirculation loop flow rate: 20 L/min; O_3 dosing rate: 10 g/h)	Duration: 1 h
9		Duration: 2 h
10	Q: 10 L/min (recirculation loop flow rate: 20 L/min; O_3 dosing rate: 15 g/h)	Duration: 1 h
11		Duration: 2 h

Table 4
Overall and individual unit's greywater treatment efficiency at different flowrates.

		Flowrates (L/min)		
Unit operation	Parameter	10	15	20
Sand filter, ER-19M	Turbidity (%)	47.90 ± 0.49	25.00 ± 1.43	13.60 ± 1.13
	TSS (%)	41.60 ± 0.90	21.20 ± 2.39	15.12 ± 1.31
	COD (%)	16.30 ± 1.58	20.00 ± 0.42	22.20 ± 3.49
	E. coli (%)/LRV[a]	−61.90 ± 35.36/−0.21-log ± 0.08-log	28.60 ± 10.61/0.15-log ± 0.07-log	−57.10 ± 15.91/−0.20-log ± 0.05-log
	Total coliform (%)/LRV[a]	−8.00 ± 8.34/−0.03-log ± 0.03-log	−27.60 ± 24.08/−0.1-log ± 0.08-log	−12.90 ± 29.51/−0.05-log ± 0.11-log
Carbon filter, GAC	Turbidity (%)	62.00 ± 0.39	51.00 ± 0.92	45.00 ± 0.15
	TSS (%)	31.80 ± 0.00	32.60 ± 1.33	26.00 ± 1.80
	COD (%)	69.00 ± 1.64	60.20 ± 0.27	49.50 ± 2.03
	E. coli (%)/LRV[a]	11.80 ± 41.84/0.05-log ± 0.18-log	33.30 ± 58.93/0.18-log ± 0.55-log	87.90 ± 1.94/0.92-log ± 0.07-log
	Total coliform (%)/LRV[a]	52.10 ± 13.06/0.28-log ± 0.11-log	29.70 ± 11.19/0.15-log ± 0.07-log	15.50 ± 4.00/0.07-log ± 0.02-log
Ozonation, CTO-20	Turbidity (%)	0.90 ± 0.00	1.29 ± 1.47	8.76 ± 0.4
	TSS (%)	0.00 ± 0.00	0.00 ± 0.00	2.82 ± 2.4
	COD (%)	−5.71 ± 5.88	−34.88 ± 2.14	−9.43 ± 7.75
	E. coli (%)/LRV[a]	60.00 ± 40.31/0.4-log ± 0.65-log	0.00 ± 29.46/0.00-log ± 0.14-log	−25.00 ± 23.6/−0.1-log ± 0.09-log
	Total coliform (%)/LRV[a]	13.06 ± 28.81/0.06-log ± 0.15-log	50.51 ± 2.03/0.31-log ± 0.02-log	−29.15 ± 23.8/−0.11-log ± 0.08-log
Overall	Turbidity (%)	80.38 ± 0.02	63.67 ± 0.28	56.66 ± 2.76
	TSS (%)	60.18 ± 0.62	46.90 ± 0.82	38.94 ± 0.94
	COD (%)	72.59 ± 0.19	57.04 ± 0.74	57.04 ± 2.84
	E. coli (%)/LRV[a]	42.86 ± 34.47/0.85-log ± 0.38-log	52.38 ± 11.49/0.32-log ± 0.10-log	76.19 ± 3.54/0.62-log ± 0.07-log
	Total coliform (%)/LRV[a]	54.99 ± 23.72/0.35-log ± 0.23-log	55.61 ± 0.62/0.35-log ± 0.00-log	−23.20 ± 3.27/−0.09-log ± 0.01-log

n.a: not available.
[a] LRV = log removal value.

disinfection efficiencies. Besides the short contact time, the presence of bacteria in the clean water holding tank also imply that there is a need to systematically investigate on the ozone dosing rate in order to obtain an optimized dosing rate which is suitable for effective disinfection of greywater. Therefore, subsequently the feed flowrate to the system was fixed at 10 L/min while the ozone dosing rate was varied from 5 to 20 g/h.

Based on the results from Table 5, disinfection using ozone was ineffective at lower dosing rates (5 and 10 g/h). When the ozone dosing rate was increased, however, the disinfection efficiency of bacteria was also significantly increased. It was found that the ozone dosing rates of 15 and 20 g/h could effectively disinfect all the microbes that present in the treated greywater effluent. Otherwise, the removal efficiency of contaminants in the system remains similar to those in Table 4.

Greywater treatment with recirculation

The treated greywater effluent was recirculated for duration of 1–2 h at low ozone dosage rates (5 and 10 g/h) and samples of treated greywater effluent after recirculation were taken for analysis. The treated greywater effluent quality after recirculation is presented in Table 6. Upon recirculation, the ORP values of the treated greywater effluent increased from a negative value to ORP values ranging from 50 to 100 mV (as shown in Table 6), indicating that there is adequate amount of ozone in the system for disinfection.

At the ozone dosing rate of 5 g/h, *E. coli* and other coliforms were completely disinfected from the treated greywater effluent within 1 h of recirculation. Meanwhile, the pathogenic bacteria colonies decreased from 500 to 150 cfu/mL when the recirculation period was prolonged from 1 to 2 h at the same ozone dosing rate. This shows that recirculation of the treated greywater effluent could elevate the effectiveness of ozone disinfection. However, prolonged recirculation time will be required to completely disinfect the pathogenic bacteria prior to reuse at the ozone dosing rate of 5 g/h. When the ozone dosing rate was increased to 10 g/h, all bacteria present in the treated greywater effluent can be completely disinfected with a recirculation period of 1 h.

Despite the increase in effectiveness of ozone disinfection system, the turbidity and TSS values of the treated greywater effluent were found to increase after recirculation period of 1 h. The increase in turbidity and TSS values of the treated greywater effluent after recirculation was unforeseeable because the multi-medium and GAC filtration unit works to reduce turbidity and suspended solids. The higher turbidity and TSS concentration in the treated greywater effluent after recirculation was found to be mainly contributed by the pitting of PVC tank.

Pitting of the PVC tank did not occur when the pilot-scale greywater treatment system was operated without the recirculation line. This is due to the fact that ozone quickly disintegrates upon generation and since disinfection only occurs during the in-line injection pipeline, the residual ozone in the PVC tank was minimal. This is also the predominant reason why the ORP values in the single pass study were of negative values. When the pilot-scale greywater treatment system was operated under the recirculation mode, the treated greywater effluent was continuously recirculated through the in-line injection pipeline, carrying more residual ozone to the PVC tank. This is evident based on the positive ORP values 1–2 h after recirculation of the treated greywater effluent. After the experimental runs on recirculation were completed, holes on the cover and the side PVC tank were spotted. The reactive radicals generated through the degradation of

Table 5
Effluent quality under various ozone dosing rate (feed flowrate: 10 L/min).

	Ozone dosing (g/h)			
Parameter	5	10	15	20
pH	7.0	7.0	6.9	6.9
Turbidity (NTU)	17.4	20.0	23.8	21.7
TSS (mg/L)	21.0	15.8	43.0	40.3
COD (mg/L)	18.5	22.5	37.0	35.5
E. coli (cfu/mL)	500.0	2000.0	0.0	0.0
Total coliform (cfu/mL)	2900.0	1400.0	0.0	0.0
Pathogenic bacteria (cfu/mL)	3400.0	1850.0	0.0	0.0

Table 6
Effluent quality under various ozone dosing rate and recirculation duration.

Parameter	Ozone dosing (g/h) (recirculation duration)/ORP (mV)			
	5 (1 h)/50	5 (2 h)/92	10 (1 h)/64	10 (2 h)/100
pH	7.11	7.19	6.96	6.93
Turbidity (NTU)	10.10	9.38	16.90	16.80
TSS (mg/L)	15.00	15.00	27.30	26.30
COD (mg/L)	20.00	20.30	26.00	50.00
BOD_5 (mg/L)	3.00	0.75	4.50	0.00
E. coli (cfu/mL)	0.00	0.00	0.00	0.00
Total coliform (cfu/mL)	0.00	0.00	10100.00	450.00
Pathogenic bacteria (cfu/mL)	500.00	150.00	0.00	0.00

ozone would attack the PVC material, causing it to pit, thus contributing to higher turbidity and TSS values.

However, the increase of BOD_5 values was expected as ozone is able to oxidize recalcitrant compounds, contributing to the increase biodegradability of the treated greywater effluent [19]. Since pitting of the PVC tank was observed after recirculation, this would have most likely contributed to the increase in COD values after treatment.

Cost-benefit analysis of the pilot-scale greywater treatment system

In overview, it was documented that Malaysians consume freshwater of approximately 226 L/capita/day where at least 41% of it ends up as greywater [20]. When this pilot-scale greywater treatment system is operated at a flowrate of 10 L/min continuously, it is capable of treating 14.4 m^3 of greywater daily. This implies that the pilot-scale system has the potential to conserve drinking water for at least 140 person (28 households with 5 person in a family) for other potable activities, from using the treated and disinfected greywater effluent. The amount of drinking water that can be conserved using this greywater treatment system will be significant if this pilot-scale system is further being scaled-up.

However, it is also of great importance to evaluate the treatment cost to ensure the competitiveness and long-term sustainability of the greywater treatment system. Table 7 shows the costs that are involved in the adoption and operation of the greywater treatment system evaluated in this study. There are two schemes which are being considered in the cost evaluation: (i) single pass treatment and disinfection at a flowrate of 10 L/h and ozone dosage of 15 g/h and (ii) greywater treatment with 1 h recirculation at a feed flowrate of 10 L/h, recirculation flowrate of 20 L/h and ozone dosing rate of 10 g/h. Since the greywater treatment system is targeted for installation in future green buildings, the water tariff taken as a benchmark for comparison of treatment cost and electricity tariff for evaluation of operational cost are based on the domestic building tariff in Malaysia.

The operational cost of the pilot-scale greywater treatment system takes into account of the cost to operate the feed pump, recirculation pump as well as ozone generation. The operational cost was evaluated based on an average operational time of 324 days with 1 month of downtime for maintenance and cleaning annually. Since this is a semi-continuous system due to intermittent supply of greywater, the total operational hours is 10 h/day for a single pass system and 16 h/day for a recirculation system to process 6.0 m^3 of greywater daily (i.e., 10 h of treatment and 6 h of recirculation).

Based on Table 7, the operation of this pilot-scale greywater treatment system using Scheme i could potentially save up to USD464.64/year. The savings of utility bills would be greater with the increase in treatment capacity. It was found that operating the pilot-scale greywater treatment system would enable consumers to have greater savings if the system was operated under Scheme (i). This is due to the fact that the period of operation is shorter (i.e., faster turnover) for such system without recirculation. However, operation under Scheme (ii) can be advantageous to cope with sudden spike in the amount of bacteria into the system. The recirculation of treated greywater effluent can ensure that bacteria are completely disinfected prior to reuse.

In addition, the specific energy of this system is 1.09 and 1.68 kWh/m^3 for Schemes (i) and (ii), respectively. It is interesting to note that the specific energy of these two schemes were comparable to those of a centralized wastewater treatment plant (Pimpama-Coomera, Gold Coast), with a specific energy of 1.80 kWh/m^3 [21]. This shows that there is definitely a prospect to implement such system in high-density residential units at better energetic cost. The implementation of decentralized greywater treatment system could also help to reduce the increasing burden of centralized sewage treatment plants due to influx of population in urban areas.

Table 7
Operational and treatment cost of pilot greywater treatment system.

Parameters	
Maximum system capacity (continuous system)	14.4 m^3/day
Treatment capacity of Schemes (i) and (ii)	6.0 m^3/day
Water tariff (domestic–condominium/Apartments)	USD 0.28[a]/m^3 (SYABAS, 2014)
Average electricity tariff (Domestic)	USD 0.09[a]/kWh (Tenaga Nasional, 2014)
Electricity consumption (Scheme (i))	6.55 kWh/day
Electricity consumption (Scheme (ii))	10.09 kWh/day
Operational cost (electricity to operate pumps and ozone generator)	Scheme (i): USD 0.58[a]/day Scheme (ii): USD 0.90[a]/day
Maintenance and cleaning	Scheme (i) and (ii): USD 112.30[a]/year
Total treatment cost (operational + maintenance and cleaning cost)	Scheme (i): USD 0.15[a]/m^3 Scheme (ii): USD 0.21[a]/m^3
Savings (water tariff – total treatment cost)	Scheme (i): USD 0.23[a]/m^3 Scheme (ii): USD 0.18[a]/m^3

[a] Exchange rate of RM 1 to USD 0.28 applied (retrieved on: 11 am, 12 January 2015).

The outcome of this cost-benefit analysis showed that the implementation of greywater treatment system in high-density residential units can be beneficial due to the higher water tariffs imposed compared to domestic water usage in detached houses and more efficient energy consumption. A simple greywater treatment system proposed in this study could produce treated greywater effluent that meets the standard for non-potable usage, reduce freshwater consumption as well as reduce utility cost within the building premise.

Conclusion

In conclusion, the implementation of this greywater reclamation system can mitigate water shortage and relief water stress. Reclaimed greywater can reduce large amount of freshwater used in non-potable activities such as toilet flushing, garden watering and outdoor washing. Subsequently, the treatment performance of this pilot-scale greywater treatment system was successfully assessed. It was found that at least 15 g/h of ozone dosage was required to completely disinfect the bacteria present in the greywater without recirculation. Meanwhile, the ozone dosing rate can be further reduced to 10 g/h for complete disinfection by recirculating treated greywater for 1 h. Calculations have shown that installation of greywater treatment system could potentially reduce the utility costs borne by the consumers staying in domestic high-rise buildings.

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References

[1] G. Oron, M. Adel, V. Agmon, E. Friedler, R. Halperin, E. Leshem, D. Weinberg, Greywater use in Israel and worldwide: standards and prospects, Water Res. 58 (2014) 92–101, doi:http://dx.doi.org/10.1016/j.watres.2014.03.032. 24747140.
[2] A. Maimon, E. Friedler, A. Gross, Parameters affecting greywater quality and its safety for reuse, Sci. Total Environ. 487 (2014) 20–25, doi:http://dx.doi.org/10.1016/j.scitotenv.2014.03.133. 24751591.
[3] M. Pidou, F.A. Memon, T. Stephenson, B. Jefferson, P. Jeffrey, Greywater recycling: treatment options and applications, Proc. ICE-Eng. Sustain. 160 (2007) 119–131.
[4] S. Paris, C. Schlapp, Greywater recycling in Vietnam — application of the HUBER MBR process, Desalination 250 (3) (2010) 1027–1030, doi:http://dx.doi.org/10.1016/j.desal.2009.09.099.
[5] L.D. Nghiem, N. Oschmann, A.I. Schäfer, Fouling in greywater recycling by direct ultrafiltration, Desalination 187 (1–3) (2006) 283–290, doi:http://dx.doi.org/10.1016/j.desal.2005.04.087.
[6] S. Jabornig, E. Favero, Single household greywater treatment with a moving bed biofilm membrane reactor (MBBMR), J. Membr. Sci. 446 (2013) 277–285, doi:http://dx.doi.org/10.1016/j.memsci.2013.06.049.
[7] G.P. Winward, L.M. Avery, T. Stephenson, B. Jefferson, Chlorine disinfection of grey water for reuse: effect of organics and particles, Water Res. 42 (1–2) (2008) 483–491, doi:http://dx.doi.org/10.1016/j.watres.2007.07.042. 17904612.
[8] Z. Ronen, A. Guerrero, A. Gross, Greywater disinfection with the environmentally friendly hydrogen peroxide plus (HPP), Chemosphere 78 (1) (2010) 61–65, doi:http://dx.doi.org/10.1016/j.chemosphere.2009.09.067. 19853883.
[9] M.J. Sharrer, Y. Tal, D. Ferrier, J.A. Hankins, S.T. Summerfelt, Membrane biological reactor treatment of a saline backwash flow from a recirculating aquaculture system, Aquacult. Eng. 36 (2) (2007) 159–176, doi:http://dx.doi.org/10.1016/j.aquaeng.2006.10.003.
[10] P.M. Alvárez, F.J. Beltrán, F.J. Masa, J.P. Pocostales, A comparison between catalytic ozonation and activated carbon adsorption/ozone-regeneration processes for wastewater treatment, Appl. Catal. B: Environ. 92 (3–4) (2009) 393–400, doi:http://dx.doi.org/10.1016/j.apcatb.2009.08.019.
[11] E.C. Wert, S. Gonzales, M.M. Dong, F.L. Rosario-Ortiz, Evaluation of enhanced coagulation pretreatment to improve ozone oxidation efficiency in wastewater, Water Res. 45 (16) (2011) 5191–5199, doi:http://dx.doi.org/10.1016/j.watres.2011.07.021. 21855954.
[12] R. Gehr, M. Wagner, P. Veerasubramanian, P. Payment, Disinfection efficiency of peracetic acid, UV and ozone after enhanced primary treatment of municipal wastewater, Water Res. 37 (19) (2003) 4573–4586, doi:http://dx.doi.org/10.1016/S0043-1354(03)00394-4. 14568042.
[13] S.H. Lin, C.H. Wang, Industrial wastewater treatment in a new gas-induced ozone reactor, J. Hazard. Mater 98 (1–3) (2003) 295–309, doi:http://dx.doi.org/10.1016/S0304-3894(03)00003-7. 12628794.
[14] H.H. Chang, H. Hao, S.E. Sarnat, A statistical modeling framework for projecting future ambient ozone and its health impact due to climate change, Atmos. Environ. 89 (2014) 290–297, doi:http://dx.doi.org/10.1016/j.atmosenv.2014.02.037. 24764746.
[15] E. Samoli, R.D. Peng, T. Ramsay, G. Touloumi, F. Dominici, R.W. Atkinson, A. Zanobetti, A. Le Tertre, H.R. Anderson, J. Schwartz, A. Cohen, D. Krewski, J.M. Samet, K. Katsouyanni, What is the impact of systematically missing exposure data on air pollution health effect estimates? Air Qual. Atmos. Health 7 (2014) 415–420, doi:http://dx.doi.org/10.1007/s11869-014-0250-2.
[16] J. Charpentier, M. Florentz, G. David, Oxidation–reduction potential (ORP) regulation: a way to optimize pollution removal and energy savings in the low load activated sludge process, Water Sci. Technol. 19 (1987) 645–655.
[17] A. Matilainen, N. Vieno, T. Tuhkanen, Efficiency of the activated carbon filtration in the natural organic matter removal, Environ. Int. 32 (3) (2006) 324–331, doi:http://dx.doi.org/10.1016/j.envint.2005.06.003. 16091290.
[18] C. Yin, M. Aroua, W. Daud, Review of modifications of activated carbon for enhancing contaminant uptakes from aqueous solutions, Sep. Purif. Technol. 52 (3) (2007) 403–415, doi:http://dx.doi.org/10.1016/j.seppur.2006.06.009.
[19] P. Xu, M.-L. Janex, P. Savoye, A. Cockx, V. Lazarova, Wastewater disinfection by ozone: main parameters for process design, Water Res. 36 (4) (2002) 1043–1055, doi:http://dx.doi.org/10.1016/S0043-1354(01)00298-6. 11848343.
[20] FOMCA, Malaysians waste a lot of water—Wa-ter waste, New Straits Times, 2011.
[21] M.N. Chong, A. Ho, T. Gardner, A. Sharma, B. Hood, Assessing decentralised wastewater treatment technologies: correlating technology selection to system robustness, energy consumption and fugitive GHG emission, Int. Conf. Integr. Water Manag. (2013) 2–5.