Institution Of Civil Engineers. Proceedings. Engineering Sustainability, vol. 160, page 119-131

Greywater recycling: A review of treatment options and applications

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Key words: greywater, recycling, technologies.

Abstract

Wastewater is an immense resource which could have significant applications in regions of water scarcity. Greywater has particular advantages in that it is a large source with a low organic content. Through critical analysis of data from existing greywater recycling applications this paper presents a review of existing technologies and applications; collating a disparate information base and comparing / contrasting the strengths and weaknesses of different approaches. Findings suggest that simple technologies and sand filters have been shown to achieve only a limited treatment of the greywater whereas membranes were reported to provide good removal of the solids but could not efficiently tackle the organic fraction. Alternatively, biological and extensive schemes achieved good general treatment of greywater with a particularly good removal of the organics. The best overall performances were observed within the schemes combining different types of treatment to ensure effective treatment of all the fractions.

Introduction

Wastewater recycling has been and continues to be practiced all over the world for a variety of reasons including; to increase water availability, combat water shortages and drought, and support environmental and public health protection.[1] The increase in water demand is due mainly to the steady rise in the world's population which also generates an increase in wastewater production. Consequently wastewater, if recycled, becomes a significant source of water that could potentially cover for the lack of fresh water observed elsewhere. Worldwide, the most common application for wastewater recycling is agricultural irrigation.[2] However, other options such as industrial, recreational, environmental and urban reuse have been practised.[3] The potential sources identified for urban reuse are sewage[4], greywater[5] and rain water[6], where greywater is defined as domestic wastewater excluding toilet flush. In some cases, mixed rain and grey waters[7] have been used as well as a 'light greywater' including only the sources from the bathroom.[8]

The advantage of recycling greywater is that it is a large source with a low organic content. To illustrate, greywater represents up to 70% of total consumed water but contains only 30% of the organic fraction and from 9 to 20% of the nutrients.[9] Moreover, in an individual household, it has been established that greywater could support the amount of water needed for toilet flushing and outdoor uses such as car washing and garden watering.[10] For example in the UK, on average, toilet flushing and outdoor use represent 41% of total domestic water usage whereas greywater from shower, bath, hand basin, laundry and dishwasher correspond to 44% (Table 1). However, at larger scale, other applications such as irrigation of parks, school yards,

cemeteries and golf courses, fire protection and air conditioning have been considered.[12]

That greywater recycling is both feasible and can contribute to sustainable water management is now widely accepted. However, greywater only schemes are currently the poor relations of water recycling activities on the global stage. This paper provides a long overdue review of existing technologies and applications; collating a disparate information base and comparing / contrasting the strengths and weaknesses of different treatment options. Our ambition in presenting the data in this way is to provide a critical and context sensitive analysis of the performance attributes of technologies used for greywater treatment. The focus on treatment performance means that a formal comparison of just how sustainable each technology option is cannot be explicitly addressed. However, the ability to meet published quality criteria for sub-potable water uses is a pre-condition for considering these technologies for application and it is in this context that the information presented is of value. Of relevance to both practitioners and researchers, the material also comprises a contemporary account of greywater reuse applications.

Treatment technologies for greywater recycling

Investigations into the treatment and recycling of greywater have been reported since the 1970's.[13-16] The first technologies studied were mainly physical treatment options such as coarse filtration or membranes often coupled with disinfection.[14, 15] Later in the 1980's and 1990's, biological based technologies such as rotating biological contactor[17], biological aerated filters[2, 18] and aerated bio-reactors[19-21] were investigated. During the same period, simple physical separators coupled with

disinfection processes were being developed and installed in single houses.[19, 22, 23] In the late 1990's reports also emerged on the use of advanced technologies such as MBRs[24-27] and alternatively cheaper extensive technologies such as reed beds [28-31] and ponds.[32, 33] Interestingly, only three chemical treatments, photocatalysis[35], electro-coagulation[34] and conventional coagulation[36], were reported in the literature.

Schemes for greywater recycling have been found in most parts of the world. No specific trend could be identified between the types of treatment used and the locations; although it is thought that poorer countries will favour the use of low cost and low maintenance technologies for economic reasons. For instance, Dallas and Ho[37] investigated the use of fragments of PET plastic from water bottles as a cheaper media in constructed wetlands in Costa Rica. Similarly, in Jordan, Bino[38] used a simple, low cost and easy to build treatment system made of plastic barrels. Further, in Oman, Prathapar *et al.*[39] designed and tested a low cost, low maintenance system based and activated carbon, sand filtration and disinfection for the treatment of ablution water in a mosque.

No international regulations have been published to control the quality of treated effluent for reuse. However, many countries have individually produced their own guidelines depending on their needs. Because the main issue when using recycled water is the potential risk to human health, the standards are usually based on microbial content. However, as has often been shown, the aesthetics of the water to be reused is probably as important because of the perception of the public. [40, 41] Therefore, the standards include parameters for the treatment of the organics and solids fractions such as biochemical oxygen demand (BOD), suspended solids (SS)

and turbidity. Examples of standards of countries from around the world are reported in Table 2. The differences seen in the regulations for water reuse in different countries result in a range of values for the chosen water quality parameters. For instance, standards for BOD, turbidity, faecal coliforms and total coliforms range from 5-40 $mg.L^{-1}$, 2-20 NTU, 0-10^3 $cfu.100mL^{-1}$ and 0-10^4 $cfu.100mL^{-1}$ respectively. Consideration of all of the standards from around the world suggests that specific targets of BOD <10 $mg.L^{-1}$, turbidity <2 NTU and a non detectable level of faecal $coliforms.100mL^{-1}$ is a sensible conservative level and will be used as the main performance criteria throughout this paper.

Twenty six of the sixty four schemes reviewed were pilot or bench scale systems for research purpose. The other 38 systems were full scale as they were fitted in buildings and the treated greywaters were reused for specific applications. The different applications reported were toilet flushing, irrigation or garden watering, outdoor use and cleaning, laundry and infiltration (Table 3). Toilet flushing and irrigation were the most commonly used applications with 54% and 36% of the schemes respectively. Most of the full scale schemes were installed in individual houses; only twelve of them were at a bigger scale such as stadiums, hotels, group of houses or residences. The different schemes reported varied a lot in size and the treated effluent flow rates were found to vary between 0.01 and 622 $m^3.day^{-1}$. However, 70% of the schemes (of which the flow rate was known) had a flow rate below 3.4 $m^3.day^{-1}$ (Figure 1).

Another way to evaluate these schemes is to classify them by type of treatment. It was then possible to group them into five categories as follow: simple (coarse filtration and disinfection), physical (sand filter, adsorption and membrane), biological

(biological aerated filter, rotating biological contactor and membrane bioreactor), extensive (constructed wetlands) and chemical (photocatalysis, electro-coagulation and coagulation).

Most of these technologies are operated with a screening or sedimentation stage before and/or a disinfection stage (UV, chlorine) after. For instance, Nolde[17] reported the treatment of greywater with a rotating biological contactor preceded by a sedimentation tank and followed by UV disinfection. Similarly, Friedler[25] reported the use of a 1 mm screen and disinfection with hypochlorite respectively before and after a membrane bioreactor. The most commonly used technologies are the biological systems followed by physical and extensive treatments (Table 4).

Simple treatment systems

Simple technologies (Table 5) used for greywater recycling are usually two-stage systems based on a coarse filtration or sedimentation stage to remove the larger solids followed by disinfection (Figure 2).[5, 19, 23] Mars[45] reported the use of even simpler systems with only a coarse filter or a sedimentation tank in Western Australia where the regulation allows the reuse of greywater after such simple treatment for subsurface irrigation.

Simple technologies provide only a limited treatment of the greywater in terms of organics and solids. To illustrate, average removals of 70, 56 and 49% for COD, suspended solids and turbidity have been reported in the literature (Table 5). However, good removal of micro-organisms due to the disinfection stage have been observed with total coliforms residuals below 50 cfu.100mL^{-1} in the treated

effluents.[19, 23] Consequently, these systems are preferably used at small scale such as single household. Moreover, they are usually used to treat low strength greywater from bath, shower and hand basin due to the limited treatment they can achieve and subsequent applications are toilet flushing and garden watering. Little information is available in the literature on the hydraulic performance of these systems; however, the hydraulic retention time (HRT) should be short as a result of their simplicity. March *et al.*[5] reported an HRT of 38 hours for a large scale system installed in an 81-room hotel in Spain.

Simple systems are marketed and promoted as being simple to use and with low operational costs.[46] However, two systems installed in individual households in the United Kingdom with similar capital and operational and maintenance (O & M) costs of £1195 and £50/year and £1,625 and £49/year respectively were found to be economically unsustainable as the water savings were not sufficient to cover the O & M costs.[19, 23] Only the scheme located in the hotel in Spain was reported to be economically viable. Indeed, the system including two 300 µm nylon filters, a sedimentation tank and disinfection with sodium hypochlorite had a capital cost of 17,000 € (~£11,500) and the O & M cost were calculated at 0.75 € (~£0.50) per cubic meter. A saving of 1.09 € (~£0.74) per cubic meter was then attained and a pay back period of 14 years was obtained with the system operative only 7 months per year.

Chemical treatment systems

Only three schemes using a chemical technology for greywater recycling were reported in the literature (Table 6; Figure 3). The treatment technology of two of the schemes was based on coagulation with aluminium. The first one was a combination

of coagulation, sand filter and granular activated carbon (GAC) for the treatment of laundry greywater.[36] The second combined electro-coagulation with disinfection for the treatment of a low strength greywater.[34] The final example provided a good treatment of the greywater with BOD and suspended solids residuals of 9 $mg.L^{-1}$, a turbidity residual of 4 NTU and undetectable levels of *E. Coli*. However, it should be noted that the source had a really low organic strength with a BOD concentration of 23 $mg.L^{-1}$ in the raw greywater. The first system also achieved good treatment with residuals of 10 $mg.L^{-1}$ for BOD and below 5 $mg.L^{-1}$ for the suspended solids, with the coagulation stage itself achieving 51% of the BOD removal and 100% of the suspended solids removal. The two technologies achieved these treatments with rather short contact times. Indeed, the hydraulic retention times in the two schemes were around 20 and 40 minutes. Similarly, the third scheme based on photocatalytic oxidation with titanium dioxide and UV achieved good treatment within a relatively short time. Indeed, with an HRT of less than 30 minutes, it was reported to achieve a 90% removal of the organics and 6 log removal of the total coliforms.[35]

Capital costs of US$0.08/$m^3$ (~£0.04/m^3) and 0.11 €/m^3 (~£0.07/m^3) and O & M costs including energy, consumables, sludge treatment and labour of US$0.19/$m^3$ (~£0.10/m^3) and 0.40 €/m^3 (~£0.27/m^3) were reported for the electro-coagulation system[34] and the coagulation, sand filter and GAC system[36] respectively. No information on water savings were available, it was therefore not possible to assess the viability of these schemes.

Physical treatment systems

Physical systems (Table 7 & Figure 4) can be divided into two sub-categories; sand filters and membranes. Sand filters have been found to be used alone[47] or in combination with disinfection[15] or with activated carbon and disinfection.[15, 22, 39] Used as a sole treatment stage, sand filters provide a coarse filtration of the greywater. Similarly to the simple technologies previously reviewed, sand filters achieved limited treatment of the different fractions present in the greywater. To illustrate, Itayama *et al.*[47] described the treatment of high strength kitchen sink water by a soil filter and reported removal of 67% for the BOD and 78% for suspended solids with respective residual concentrations of 166 and 23 $mg.L^{-1}$, well short of any published standards for reuse. When coupled with a disinfection stage, only the removal of micro-organisms is obviously improved. Indeed, Hypes *et al.*[15] in their investigation of the treatment of bath and laundry greywater by an earth filter combined with chlorine based disinfection observed poor removal of the turbidity and suspended solids with removals of 47 and 16% respectively. However, the system achieved a 4.8-log removal of the total coliforms and a residual concentration of 34 $cfu.100mL^{-1}$ was measured in the effluent. Finally, sand filters in association with activated carbons and disinfection does not result in a significant improvement in the removal of the solids. Indeed, average removals of 61 and 48% were reported for turbidity and suspended solids respectively. Nevertheless, good micro-organism removal rates were again reported. Prathapar *et al.*[39] and Hypes *et al.*[15] described total coliform concentrations in the treated effluents of 0 and 4 $cfu.100mL^{-1}$. Similarly, CMHC[22] reported a faecal coliform residual of 8 $cfu.100mL^{-1}$ after treatment by sedimentation and a multi media filter.

Hypes *et al.*[15] and Itayama *et al.*[47] reported hydraulic loading rates of 0.32, 0.24 and 0.086 $m^3.m^{-2}.d^{-1}$ for three systems based on filtration through soil. These were extremely low hydraulic loading rates in comparison to typical values reported for similar systems for the treatment of other waters and wastewaters. Indeed, Metcalf and Eddy[48] reported hydraulic loading rates ranging from 115 to 576 $m^3.m^{-2}.d^{-1}$ for simple, dual and multi-media filters with sand and/or anthracite for the treatment of wastewater. Similarly, Vigneswaran and Visvanathan[49] reported hydraulic loading rates of 2-5 and 120-360 $m^3.m^{-2}.d^{-1}$ for slow and rapid sand filter respectively.

Alternatively, treatment by membranes provided a limited removal of the organics but an excellent removal of the dissolved and suspended solids. To illustrate, removal of up to 100% of the turbidity and suspended solids have been recorded[14, 50, 51], and otherwise residual concentrations below 2 NTU for the turbidity and below 10 $mg.L^{-1}$ for the suspended solids, sufficient to meet the strictest standards for reuse, were generally observed. In contrast, Birks[47] and Sostar-Turk *et al.*[36] reported BOD residuals of 86 and 53 $mg.L^{-1}$ respectively, above the criteria for reuse, after treatment with ultra-filtration (UF) membranes.

However, the pore size of the membrane used will have an important impact on the treatment achieved. For example, Ramon *et al.*[51] compared the performance of a nano-filtration (NF) membrane with a molecular weight cut off (MWCO) of 0.2 kDa and three UF membranes with MWCO of 30, 200 and 400 kDa for the treatment of shower water. The performance was shown to be better with lower pore sizes especially in terms of organics removal. Indeed, COD removal of 45, 49, 70 and 93% were reported for the membranes with MWCO of 400, 200, 30 and 0.2 kDa respectively. Differences in turbidity removal performance were less obvious with

similar orders of removal of 92, 94, 97 and 98%. Similarly, Sostar-Turk *et al.*[36] investigated the use of a UF membrane (0.05 µm pore size) followed by a reverse osmosis (RO) membrane for the treatment of laundry wastewater. The UF membrane decreased the BOD from 195 to 86 $mg.L^{-1}$ corresponding to a removal of 56%. The RO membrane then decreased the BOD from 86 to 2 $mg.L^{-1}$ corresponding to a removal of 98%. A similar trend was observed for the removal of suspended solids with values of 49 and 56% for the UF and RO membranes respectively. Very little information was available on the removal of micro-organisms by membranes; however, Jefferson *et al.*[53] reported an average total coliforms removal of 3 log after filtration of greywater through a micro-filtration membrane revealing limited action of the membrane for mico-organisms removal. Similarly, Judd and Till[54] reported a general breakthrough of *E. Coli* when treating sewage with a micro-filtration membrane. They also found that this phenomenon was enhanced in the presence of proteins suggesting that proteins, when adsorbed on the surface of the membrane, facilitated the transport of the bacteria through the pores.

The main issue when operating membranes is fouling. This will have an influence on the operation of the systems and the costs as membrane cleaning will be needed. Interestingly, Sostar-Turk et al.[36] observed no fouling when treating laundry wastewater with a UF membrane for 150 minutes at a flux of about 130 $L.m^{-2}.h^{-1}$ and with a RO membrane for 120 minutes at a flux of about 37 $L.m^{-2}.h^{-1}$. Similarly, Ahn et al.[50] reported no fouling during 12 hours for the treatment of greywater through two UF membranes and one MF membrane at flux around 200 $L.m^{-2}.h^{-1}$. These results suggested that no fouling under those conditions occurred in the short term. However, Nghiem *et al.*[55] investigated the fouling of UF membranes during synthetic greywater

treatment. They observed that the fouling increased linearly with the organic matter (humic acid) concentration. To limit membrane fouling the membrane stage can be preceded by a pre-treatment such as screening or sand filter for example. To illustrate, Ward[56] studied a process combining both physical processes, sand filter and membrane, and disinfection for the treatment of a low strength greywater. With a residual of 8 $mg.L^{-1}$ for the BOD and undetectable levels of turbidity and *E. Coli*, the system was good enough to meet the strictest standards for reuse. This high level of treatment was possible because of the sequence of processes. Indeed, the sand filter provided a pre-treatment by removing the bigger particles. Reductions of the BOD from 23 to 17 $mg.L^{-1}$ and turbidity from 18 to 17 NTU were observed. The rest of the treatment was then achieved by the membrane and disinfection stages.

Biological treatment systems

A wide range of biological processes have been used for greywater recycling (Table 8 & Figure 5). Processes such as fixed film reactors[17, 19-20, 56-57], rotating biological contactor[17, 58], anaerobic filters[38, 59], sequencing batch reactor[21], membrane bioreactors[2, 24-27, 60] and biological aerated filters (BAF)[2, 18, 52, 61-62] were reported in the literature. Biological systems were rarely used individually and when it was the case it was for investigation of the processes at pilot scale.[2, 52] In most cases, the biological processes were preceded by a physical pre-treatment such as sedimentation[17, 38, 59] or screening[18, 57-58] and/or followed by disinfection.[17, 19, 63] They were also combined with membranes in processes such as MBRs[24-26], sand filter[63], activated carbon[18, 19] and constructed wetland.[61]

Biological schemes when installed at full scale were the type of treatment most commonly seen in bigger buildings. Indeed, systems could be found in student

residences [18-19, 58], multi-storey buildings [17, 20] and stadiums.[62, 64] Hydraulic retention times (HRTs) ranging from 0.8 hours up to 2.8 days were reported for the biological systems. Higher HRTs were observed for systems treating very high strength greywaters such as laundry water[24] and mixed greywater[38] with BOD concentrations of 645 and 300-1200 $mg.L^{-1}$ respectively. However, HRTs in biological systems were reported to be on average 19 hours. Very little information was available on solids retention time (SRT) in the biological systems. Organic loading rates were found to vary between 0.10 and 7.49 $kg.m^{-3}.day^{-1}$ for COD and between 0.08 and 2.38 $kg.m^{-3}.day^{-1}$ for BOD. In detail, the average organic loading rate in MBRs was 0.88 $kg_{COD}.m^{-3}.day^{-1}$ which is lower than the typical values of 1.2-3.2 $kg_{COD}.m^{-3}.day^{-1}$ reported by Stephenson *et al.*[65] for wastewater treatment. In contrast, the average organic loading rate found for the other systems such as BAF, RBC and bio-films was 1.32 $kg_{BOD}.m^{-3}.day^{-1}$ which is in the range of 0.3-1.4 $kg_{BOD}.m^{-3}.d^{-1}$ reported for these systems.[48]

Independent of the number and type of processes included, all schemes with a biological stage achieved excellent organic and solids removal. Indeed, all the biological systems reviewed but two were reported to meet the most stringent BOD standard for reuse with residual concentrations below 10 $mg.L^{-1}$. Similarly, the turbidity concentrations in the effluents were below 8 NTU for all the systems reviewed. And finally, all schemes but one had suspended solids residual below 15 $mg.L^{-1}$. In terms of micro-organisms, once again, those schemes including a disinfection stage achieved excellent removals with an average 5.2 log removal for faecal coliforms and 4.8 log for total coliforms. Residual concentrations for both faecal and total coliforms were always below 20 $cfu.100mL^{-1}$. Interestingly, MBRs

were the only systems to achieve good micro-organism removal without the need for a disinfection stage. To illustrate, average removal of both faecal and total coliforms were reported at 5 log and the corresponding residual concentrations were below 30 cfu.100mL^{-1}. Additionally, MBRs achieved excellent removal of the organic and solid fractions with average residuals of 3 mg.L^{-1} for BOD, 3 NTU for turbidity and 6 mg.L^{-1} for suspended solids.[2, 24-25, 27, 60] However, Jefferson *et al.*[53] reported that at small scale, the variation in strength and flow of the greywater and potential shock loading affect the performance of biological based technologies.

To illustrate, Laine[2] investigated the effect of domestic product spiking on biomass from an MBR and reported that products such as bleach, caustic soda, perfume, vegetable oil and washing powder were relatively toxic with EC_{50} of 2.5, 7, 20, 23 and 29 mL.L^{-1} respectively. Moreover, Jefferson *et al.*[66] studied the reliability of a BAF and an MBR under intermittent operation of air, feed and both. The performance of the MBR was not affected by interruption of the feed, air or both as the time taken by the process to return to its original performance level was always very short (in fact no interruption in performance level was observed). A similar result was found when the feed was stopped for 25 days. However, in comparison, the BAF did not exhibit the same robustness. Although short term interruptions (30 minutes) did not have an effect on the BAF performance, longer cessation of the feed and/or air, generated an increase in the effluent concentrations and the recovery times for all the parameters. Indeed, after an interruption of the feed of 8 hours, the recovery times were 4, 4, 40 and 48 hours for turbidity, suspended solids, faecal coliforms and total coliforms respectively. Similarly, after the same interruption of the air, the recovery times were 4, 4, 24, 28 and 24 hours for BOD, turbidity, solids, faecal coliforms and total

coliforms respectively. The longest recovery times were observed after the interruption of both air and feed simultaneously with 40, 40, 4, 24, 48 hours for BOD, turbidity, solids, faecal coliforms and total coliforms respectively. Finally, none of the parameters had recovered to their pre-interruption levels within 48 hours of the interruption of the feed for 25 days.

Again, limited information is available about the costs of the systems. Surendran and Wheatley[18] reported a capital cost of £3,345 for the construction and installation of a retro-fit system in a 40-student residence composed of a buffering tank with screening, an aerated biofilter, a deep bed filter and GAC. The O & M costs were £128/year including the energy, labour and consumables. With water savings of £516/year, the pay back period is 8-9 years. They estimated that if the system was fitted in a new building the capital cost could be reduced to £1,720 and then the adjusted pay back period would be 4-5 years. The system reported by McQuire[57] comprising a screening filter, a treatment tank with bio-film grown on aggregate balls, a particle filter and UV disinfection unit installed in an individual house was estimated to cost between Aus$6,200 and Aus$8,200 (£2,514-£3,325). Alternatively, Bino[38] reported a low cost, easy to built system composed of four plastic barrels installed in a 6- person house with a capital cost of US$370 (~£197). No information on the operational costs and water savings were reported for these two schemes. Finally, Gardner and Millar [63] reported a capital cost of Aus$5,500 (£2,230) and O & M costs of Aus$215/year (£87/year) for a system based on a septic tank, a sand filter and UV disinfection. However, the water savings of Aus$83/year (£34/year) were not enough to cover the costs. Similarly, Brewer *et al.*[19] estimated the costs of an aerated bioreactor combined with a sand filter, GAC and disinfection with bromine installed

in a student residence at £30,000 for the capital cost. But once again, the O & M costs of £611/year exceeded the water savings of £166.

Extensive treatment technologies

Extensive technologies for greywater treatment usually comprise constructed wetlands such as reed beds and ponds (Table 9 & Figure 6). These are often preceded by a sedimentation stage to remove the bigger particles contained in the greywater and a sand filter to remove any particles or media carried by the treated water. The most common type of plants used in reed beds is *Phragmites australis*.[28, 31, 67-68] However, they are considered noxious weed species in Costa Rica so Dallas *et al.*[32] and Dallas and Ho[37] investigated an alternative macrophyte, *Coix lacryma-jobi*. Alternatively, two studies have investigated the use of a range of plants. Frazer-Williams *et al.*[68] reported the use of *Iris pseudocorus, Veronica beccabunga, Glyceria variegates, Juncus effuses, Iris versicolor, Caltha palustris, Lobelia cardinalis* and *Mentha aquatica* in their GROW system. Similarly, Borin *et al.*[67] reported a system planted with ten different species (*alisma*, *iris*, *typha*, *metha*, *canna*, *thalia*, *lysimachia*, *lytrum*, *ponyederia* and *preselia*).

The constructed wetlands reported in the literature showed good ability to treat greywater. Indeed, an average BOD residual of 17 $mg.L^{-1}$ was observed and more than half of the extensive treatment schemes reviewed reported a residual BOD concentration below 10 $mg.L^{-1}$. Similarly, average residual concentrations of 8 NTU for turbidity and 13 $mg.L^{-1}$ for suspended solids were reported. In contrast, poor removal of micro-organisms was described. Average removal of 3.6 and 3.2 log were reported for faecal and total coliforms respectively, with residual concentrations

generally above 10^2 cfu.100mL^{-1} for both indicators. In terms of hydraulics, for the extensive systems reported, HRT was found to vary from a couple of hours up to a year for on particular scheme composed of three ponds.[33] However, after removing the extremes, the HRT for extensive technologies was on average 4.5 days. Borin *et al.*[67] compared the performance of two constructed wetlands, one planted with the common reed *Phragmites australis* and the second with a range of ten species. However, no significant differences in treatment effectiveness were observed between the two systems. To illustrate, concentrations in the effluent of 25.8 and 26.6 mg.L^{-1} for the BOD, 20 and 30 mg.L^{-1} for the total suspended solids and 51.2 and 50.5 mg.L^{-1} for the COD were reported for the systems with the ten species and *Phragmites australis* respectively.

Besides being seen as environmentally friendly technologies, constructed wetlands have been considered as cheap options. Indeed, Dallas *et al.*[32] and Shrestha *et al.*[31] described reed beds with capital costs of US$1,000 (£531) and US$430 (£229) respectively and very low operating costs.

Discussion and conclusions

A review of the standards for greywater recycling and the characteristics of greywaters showed that a technology used for the treatment of greywater for reuse should be able to achieve excellent treatment of the organic, solids and microbial fractions (Table 2). On the other hand, the review of the greywater recycling schemes reported to date proved that different types of technologies achieved very different performance. Simple technologies and sand filters have been shown to achieve only a limited treatment of the greywater whereas, membranes were reported to provide a good removal of the solids but could not efficiently tackle the organic fraction.

Alternatively, biological and extensive schemes achieved good general treatment of greywater with a particularly good removal of the organics. Although less information was available about chemical systems, they showed promising abilities to treat greywater with short retention times. Micro-organism removal was sufficient to meet the standards only in schemes including a disinfection stage; however, MBRs were the only systems able to achieve good microbial removal without the need for disinfection.

In conclusion, the best performances were observed within those schemes combining different types of treatment to ensure effective treatment of all the fractions. For instance, Ward[56] reported the treatment of a low strength greywater with an aerated biological reactor followed by a sand filter, GAC and disinfection with residual concentrations of 2 $mg.L^{-1}$ for BOD, 1 NTU for turbidity and <1 $cfu.100mL^{-1}$ for total coliforms. Similarly, Friedler *et al.*[58] investigated the treatment of bathroom greywater by a rotating biological contactor combined with a sedimentation tank, a sand filter and disinfection with hypochlorite and reported residuals of 0.6 NTU, 5 $mg.L^{-1}$, 2 $mg.L^{-1}$ and 1 $cfu.100mL^{-1}$ for turbidity, suspended solids, BOD and faecal coliforms respectively. In contrast, MBRs were the only individual technology (although they comprise a combination of activated sludge and membrane) to be credited with similar performance.To illustrate, Laine[2] reported residuals of 1 $mg.L^{-1}$ for BOD, 1 NTU for turbidity, 4 $mg.L^{-1}$ for suspended solids and 1 $cfu.100mL^{-1}$ for total coliforms in a greywater treated by a side-stream membrane bioreactor. In the same way, Liu *et al.*[27] reported effluent concentrations of <5 $mg.L^{-1}$ for BOD, <1 NTU for turbidity, and undetectable levels of suspended solids and coliforms following treatment by a submerged membrane bioreactor. All these systems met the most

stringent standards for reuse; however, the level of treatment required is often dependent on the reuse applications (Table 2). Consequently, technologies generating a lesser quality effluent may still be of interest for applications where the standards are less strict.

A review of the HRT applied to each type of system demonstrated that the two reviewed chemical systems worked with very low HRT, below an hour. With an average HRT of 19 hours, the biological systems proved to be efficient over rather short periods of time. Finally, the extensive technologies were the systems working at the highest HRT with an average value of 4.5 days. The shorter HRTs observed with biological technologies than with extensive systems for similar performance give an advantage to the biological treatments.

Another feature of greywater recycling systems which influences their application is the footprint as space is often limited in urban environments. Systems using biological, chemical or physical technologies have been found to generally have a smaller footprint than extensive technologies. For example, Fittschen and Niemczynowicz[28] reported a footprint of about 1000 m^2 for a scheme including a sedimentation tank, a reed bed, a sand filter and a pond treating the greywater of a 100-inhabitant village, corresponding to 10 m^2 per inhabitant connected. Similarly, Dallas *et al.*[32] reported the treatment of the greywater of 7 persons from 3 houses by a sedimentation tank, two reed beds and a pond with a total footprint of about 40 m^2, corresponding to 5.7 m^2 per person. In contrast, Nolde[17] reported a system composed of a sedimentation tank, a rotating biological contactor and disinfection installed in

the 15 m^2 basement of 70-person multi-storey building, corresponding to 0.2 m^2 per person connected.

Finally, we would note that the value of the contribution which the reviewed technologies can make to sustainable water management will vary as a function of local circumstances and regional preferences. Ensuring that greywater recycling systems are complementary with Integrated Water Resources Management in catchments or urban contexts will drive a variety of solutions and a variety of measures of sustainability. Information on Life Cycle Cost and total energy requirements for greywater treatment options is sparse. The trade-offs between scale of application, embedded energy in capital equipment, operating energy requirements, pollutant emissions, reject stream disposal, social costs, etc. etc. are the subject for a subsequent paper. However, the power of circumstance to modify preference can be demonstrated by the fact that a concern with carbon footprint might preclude the use of high energy requirement technologies such as the MBR but at larger scales of application and where higher variation in greywater quality is found, the energy consumption of an MBR compared with other options would be much more favourable. The review presented above provides a comprehensive data set for developing more detailed and evidenced sustainability assessments.

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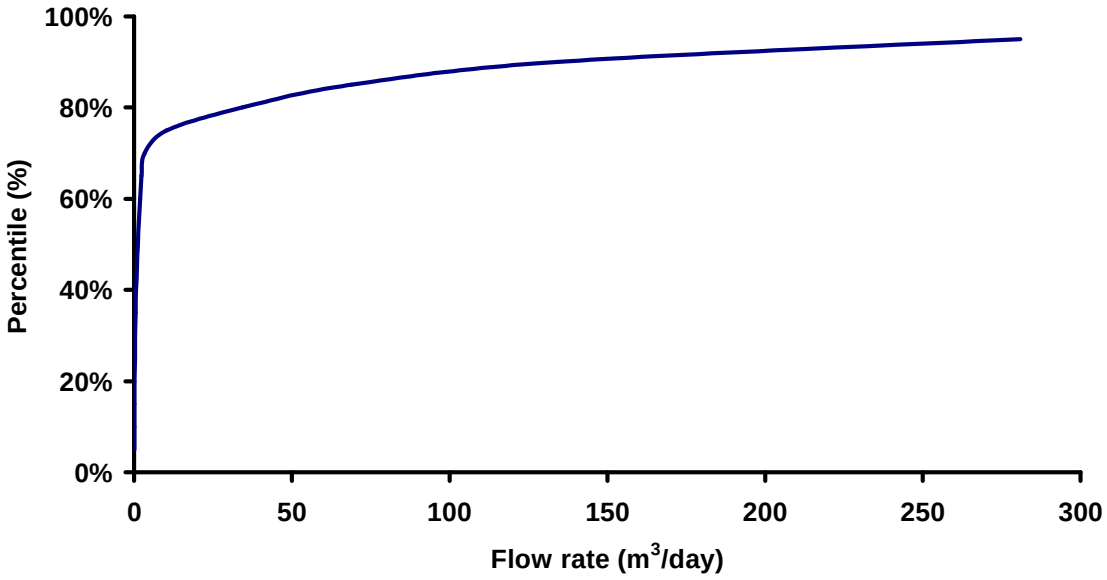


Fig. 1: Distribution of the flow rates of the reported technologies.

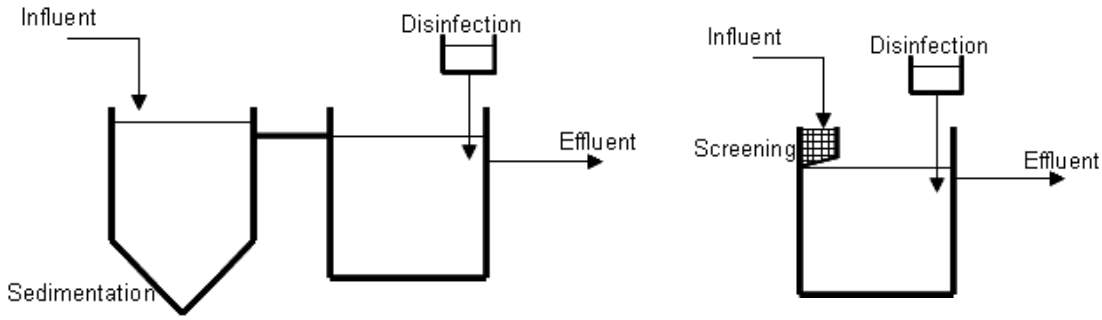


Fig. 2: Typical flow diagram of simple systems with either screening or sedimentation and disinfection.

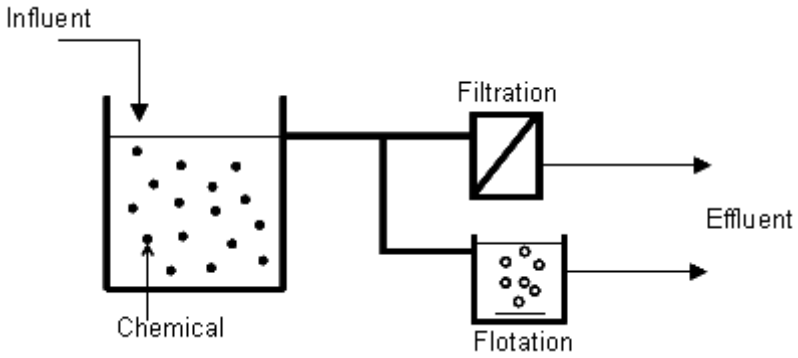


Fig. 3: Typical flow diagram of chemical technologies with separation by filtration or flotation.

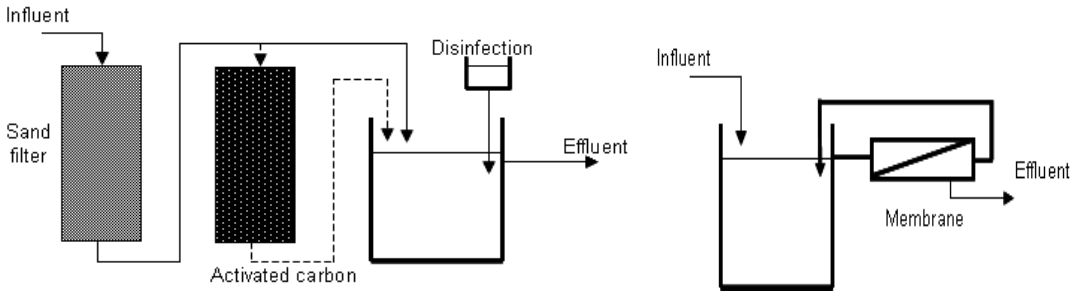


Fig. 4: Typical flow diagram for physical technologies.

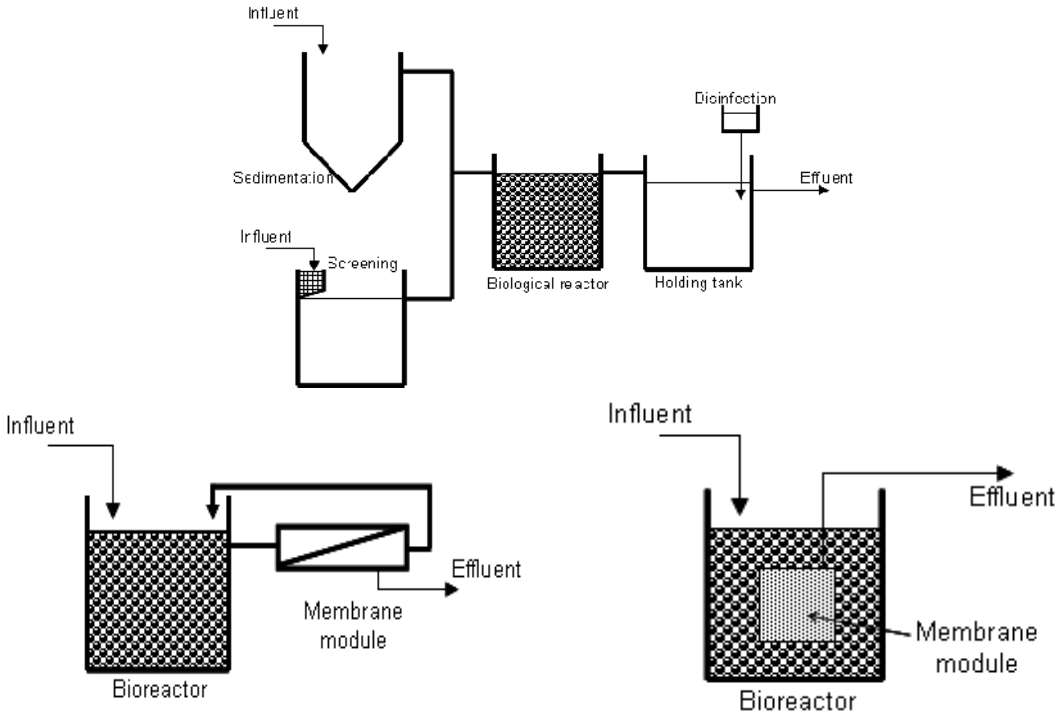


Fig. 5: Typical flow diagram of biological technologies and side-stream and submerged MBRs.

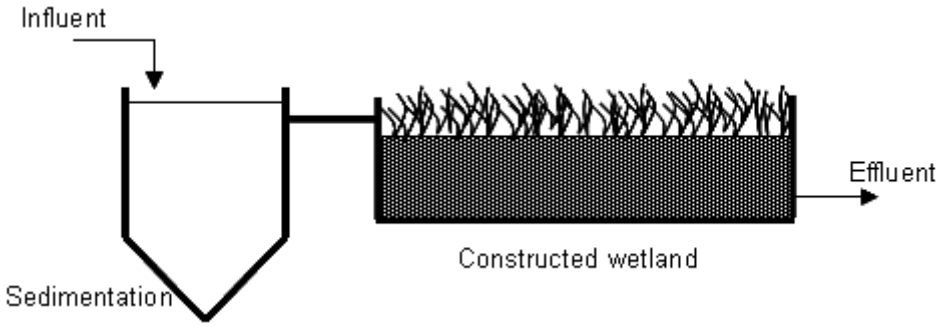


Fig. 6: Typical flow diagram of extensive technologies.

Table 1: Distribution of domestic water usage.[11]

Toilet flushing	35%
Wash basin	8%
Shower	5%
Bath	15%
Laundry	12%
Dishwasher	4%
Outside use	6%
Kitchen sink	15%

Table 2: Standards for wastewater reuse.

	Application	Parameters				
		BOD_5 ($mg.L^{-1}$)	TSS ($mg.L^{-1}$)	Turbidity (NTU)	Faecal Coliforms ($cfu.100mL^{-1}$)	Total Coliforms ($cfu.100mL^{-1}$)
Japan [42]	Toilet flushing	-	-	<2	-	ND
	Landscape	-	-	<2	-	<1000
	Recreational	-	-	<2	-	ND
Israel [29]	Wastewater reuse	10	10	-	<1	-
Spain, Canary Islands[1]	Wastewater reuse	10	3	2	-	2.2
USA, California[1]	Unrestricted water reuse	-	-	2 avg 5 max	-	2.2 avg 23 max in 30 days
USA, Florida[1]	Unrestricted water reuse	20	5	-	25% of sample ND and 25 max	-
Australia, Queensland [43]	Greywater reuse for garden watering in unsewered area	20	30	-	-	100
Canada, British Columbia [44]	Unrestricted urban reuse	10	5	2	2.2	-

Table 3: Distribution of applications for greywater reuse.

Applications	
Toilet flushing	54 %
Irrigation and Garden watering	36 %
Outdoor use and cleaning	5 %
Laundry	2.5 %
Infiltration	2.5 %

Table 4: Distribution of the schemes by type of treatment.

Technology	Number	%
Simple	8	12.5
Physical	13	20.3
Biological	25	39.1
Extensive	15	23.4
Chemical	3	4.7
Total	64	100

Table 5: Performance data of simple technologies.

Location	Building type / Application	Scheme	HRT (flow rate, loading rate)	Performance									
				COD ($mg.L^{-1}$)		BOD ($mg.L^{-1}$)		Turbidity (NTU)		SS ($mg.L^{-1}$)		Total coliforms (cfu/100mL)	
				In	Out	In	Out	In	Out	In	Out	In	Out
Spain[5]	Hotel / Toilet flushing	Screening + Sedimentation + Disinfection	38 hours	171	78	-	-	20	17	44	19	-	-
UK[19]	House / Toilet flushing	Filtration + Disinfection	-	74	11	-	-	2	1	-	-	TNTC	46
UK[19]	House / Toilet flushing	Filtration + Disinfection	-	157	47	-	-	21	7	-	-	2.10^5	13
UK[23]	Houses / Toilet flushing	Coarse filtration +Disinfection	-	-	166	-	40	-	40	-	35	-	ND[+]
USA[69]	House / Toilet flushing and irrigation	Cartridge filter	-	-	-	-	-	21	7	19	8	2.10^8	2.10^6
Australia[45]	House / Garden watering	Sedimentation + Trench	-	-	-	-	-	-	-	405	100	-	-
Australia[45]	House / Garden watering	Sedimentation	-	-	-	-	-	-	-	310	195	-	-
Australia[45]	House / Garden watering	Screening + Trench	-	-	-	-	-	-	-	155	76	-	-

TNTC: too numerous to count.

Table 6: Performance data of chemical technologies.

	Building type / Application	Scheme	HRT (flow rate, loading rate)	Performance									
				COD ($mg.L^{-1}$)		BOD ($mg.L^{-1}$)		Turbidity (NTU)		SS ($mg.L^{-1}$)		Total coliforms (cfu/100mL)	
				In	Out	In	Out	In	Out	In	Out	In	Out
UK[35]	Bench scale	Photocatalytic oxidation (TiO2/UV)	<30 minutes	139-660º	26-139º	-	-	-	-	-	-	10^6	0
Slovenia[36]	Pilot scale	Coagulation + Sand filter + GAC	~ 40 minutes	280	20	195	10	-	-	35	<5	-	-
Taiwan[34]	Pilot scale	Electro-coagulation + Disinfection	~ 20 minutes (28 m^3/day)	55	22	23	9	43	4	29	9	5100*	ND*

* as *E. Coli*; º as TOC.

Table 7: Performance data of physical technologies.

Location	Building type / Application	Scheme	HRT (flow rate, loading rate)	Performance									
				COD ($mg.L^{-1}$)		BOD ($mg.L^{-1}$)		Turbidity (NTU)		SS ($mg.L^{-1}$)		Total coliforms (cfu/100mL)	
				In	Out	In	Out	In	Out	In	Out	In	Out
Japan[47]	House / Garden watering	Soil filter	(0.086 $m^3/m^2/day$)	271	42	477	166	-	-	105	23	-	-
USA[15]	Pilot scale	Earth filter + Disinfection	2 hours (0.32 $m^3/m^2/day$)	-	-	-	-	17	9	549 ~	460~	2.10^6	34
USA[15]	Pilot scale	Earth filter + Activated carbon + Disinfection	(0.24 $m^3/m^2/day$)	-	-	-	-	23	9	500 ~	394~	1.10^5	4
Oman[39]	Mosque / Irrigation	Filtration + Activated carbon + Sand filter + Disinfection	(1.3 m^3/day)	51	35	-	-	13	6	9	4	>200	0
Canada[22]	Apartment building / Toilet flushing	Screening + Sedimentation + Multi-media filter + Ozonation	(1 m^3/day)	-	-	130	-	82	26	67	21	8870*	8*
UK[56]	Pilot scale	Sand filter + Membrane + Disinfection	(4.37 m^3/day)	65	18	23	8	18	0	-	-	5.10^3 *	0*
Israel[51]	Bench scale	UF membranes (400kDa)	-	146	80	-	-	18	1.4	-	-	-	-
		UF membranes (200kDa)	-	146	74	-	-	17	1	-	-	-	-
		UF membranes (30kDa)	-	165	51	-	-	24	0.8	-	-	-	-
		NF membranes	-	226	15	-	-	30	1	28	0	-	-
Slovenia[36]	Pilot scale	RO membrane	-	130	3	86	2	-	-	18	8	-	-
		UF membrane	-	280	130	195	86	-	-	35	18	-	-
Korea[50]	Hotel / Toilet flushing	Membranes	-	64	10	-	-	10	0	-	-	-	-
USA[14]	Pilot scale	Coarse filtration + RO + Disinfection	-	-	-	-	-	30	0	102	<10 0	5.10^7	0
UK[52]	Pilot scale	UF membrane	-	451	117	274	53	-	-	-	-	-	-

* as *E. Coli*; ~ as Total solids.

Table 8: Performance data of biological technologies.

Location	Building type / Application	Scheme	HRT (flow rate, loading rate)	Performance									
				COD ($mg.L^{-1}$)		BOD ($mg.L^{-1}$)		Turbidity (NTU)		SS ($mg.L^{-1}$)		Total coliforms (cfu/100mL)	
				In	Out	In	Out	In	Out	In	Out	In	Out
Japan[64]	Stadium / Toilet flushing	Screening + Sedimentation + Flotation + Rotating filters + Sand filter + Disinfection	(622 m^3/day)	243	6	336	20	-	-	207	10	-	10
Japan[59]	House	Anaerobic filter + Submerged biofilter + Sedimentation + Disinfection	(1.735 m^3/day)	-	11	-	8	-	-	-	6	-	-
Korea[21]	Pilot scale	Sequencing batch reactor + MF hollow fibre membranes	13 hours (1.2 m^3/day)	79	30	5	5	-	-	185	-	-	-
China[27]	Pilot scale	Screening + Membrane bioreactor	3.6 hours	130-322	<40	99-212	<5	146-185	<1	15-50	0	-	ND
Israel[58]	Student flats / Toilet flushing	Screening + Rotating biological reactor + Sedimentation + Sand filter + Disinfection	~18 hours	158	40	59	2	33	1	43	8	6.10^5_+	1^+
Israel[58]	Student flats / Toilet flushing	Screening + Membrane bioreactor + Disinfection	~18 hours	206	47	95	1	80	0	103	13	3.10^5_+	27^+
Jordan[38]	House / Irrigation	Sedimentation + Anaerobic filter	1-2 days	-	-	300-1200	375	-	-	-	107	-	-
Denmark[24]	Industrial laundry	Membrane bioreactor	2-2.5 days (60 m^3/day)	1700	50	645	2	-	-	-	-	-	-
Germany[17]	Apartment building / Toilet flushing	Sedimentation + Rotating biological contactor + UV Disinfection	(2.1 m^3/day)	100-200	-	43-85	<4	-	-	-	-	10^4-10^5	$<10^4$
Germany[17]	House / Toilet flushing	Fluidized bed reactor + UV Disinfection	(0.04 m^3/day)	113-633	-	60-256	<4	-	-	-	-	10^3-10^5	$<10^4$
Finland[20]	Apartment building / Toilet flushing	Aerated biofilter + UV Disinfection	-	8000	75	-	-	-	-	-	-	1.10^6_+	20^+
Australia[57]	House / Toilet flushing, laundry and garden watering	Screening + Biofilm + UV Disinfection	-	-	-	-	9	-	6	-	9	-	0*

	Building type / Application	Scheme	HRT (flow rate, loading rate)	Performance									
				COD ($mg.L^{-1}$)		BOD ($mg.L^{-1}$)		Turbidity (NTU)		SS ($mg.L^{-1}$)		Total coliforms (cfu/100mL)	
				In	Out	In	Out	In	Out	In	Out	In	Out
Australia[63]	House / Toilet flushing and outdoor use	Septic tank + Sand filter + UV Disinfection	-	-	-	97	6	-	1	48	3	2.10^5	9
Norway[61]	Houses / Irrigation	Septic tank + Aerated biofilter + Constructed wetland	-	-	62	-	<10[#]	-	-	-	-	-	<100
Germany[60]	Pilot scale	Membrane bioreactor	10 hours	493	24	-	-	-	-	7	4	-	-
UK[18]	Student residence / Toilet flushing	Screening + Aerated biofilter + Deep-bed filter + Activated carbon	-	-	-	-	9	-	1	-	6	-	995
UK[52]	Pilot scale	Biological aerated filter	4 hours (0.4 $m^3/m^2/h$)	363	80	131	5	-	-	109	8	-	-
UK[19]	Student residence / Toilet flushing	Biological reactor + Sand filter + GAC + Disinfection	(263 m^3/year)	201	62	-	-	212	5	-	-	7.10^5	3
UK[2]	Pilot scale	Biological aerated filter	3.7 hours (0.328 m^3/day)	128	13	41	4	-	3	52	6	2.10^6	2.10^4
UK[2]	Pilot scale	Submerged membrane bioreactor	13.6 hours (0.071 m^3/day)	128	7	41	1	-	4	52	4	2.10^6	2
UK[2]	Pilot scale	Membrane aeration bioreactor	0.8 hours (0.225 m^3/day)	128	17	41	9	-	7	52	13	2.10^6	2.10^4
UK[2]	Pilot scale	Side-stream Membrane bioreactor	2.8 days (0.137 m^3/day)	273	2	181	1	-	1	58	4	3.10^4	1
UK[62]	Pilot scale	Biological aerated filter + UF membrane	1.2 hours	80	6	-	-	25	0	52	1	6.10^5	<1
UK[56]	Pilot scale	Biological reactor + Sand filter + GAC	(2.88 m^3/day)	34	12	21	2	20	1	-	-	2.10^2	<1
UK[62]	Arena / Toilet flushing	Biological aerated filter	1.25-5 hours (120 m^3/day)	84	14	-	-	-	-	31	3	3.10^5	3.10^3

[+] as Faecal Coliforms; [#] as BOD_7.

Table 9: Performance data of extensive technologies.

Location	Building type / Application	Scheme	HRT (flow rate, loading rate)	Performance									
				COD ($mg.L^{-1}$)		BOD ($mg.L^{-1}$)		Turbidity (NTU)		SS ($mg.L^{-1}$)		Total coliforms (cfu/100mL)	
				In	Out	In	Out	In	Out	In	Out	In	Out
UK[68]	Pilot scale	Horizontal flow reed bed	2.1 days	452	111	151	51	63	12	87	31	6.10^7	10^4
		Vertical flow reed bed	2 hours batch	452	27	151	5	63	2	87	9	6.10^7	2.10^4
		Constructed wetland	2.1 days	452	139	151	71	63	26	87	19	6.10^7	2.10^6
Israel[29]	House / Irrigation	Sedimentation + Vertical flow constructed wetland	8 -24 hours	839	157	466	0.7	-	-	158	3	5.10^{7+}	2.10^{5+}
USA[69]	House / Toilet flushing and irrigation	Aquacell + Sand filter	-	-	-	120	4	64	4	40	17	4.10^7	5.10^4
USA[69]	House / Toilet flushing and irrigation	Aquacell + Sand filter + Copper dosing + Disinfection	-	-	-	-	-	79	4	36	5	2.10^7	6.10^5
USA[69]	House / Toilet flushing and irrigation	Aquacell + Sand filter + Copper and silver dosing +Disinfection	-	-	-	-	-	15	3	19	7	6.10^8	3.10^4
Costa Rica[32]	3 Houses / Irrigation	2 Reed beds + Pond	> 10 days (0.755 m^3/day)	-	-	167	3	96	5	-	-	2.10^{8+}	198^+
Costa Rica[37]	Pilot scale	Trench and plants	4-5 days (0.01 m^3/day)	-	-	254	13	103	-	-	-	8.10^{7+}	2050^+
Nepal[31]	House / Toilet flushing, cleaning and garden watering	Sedimentation + Reed bed	(0.5 m^3/day)	411	29	200	5	-	-	98	3	-	-
Germany[30]	Houses	Sedimentation + Constructed wetlands	(70 L/p/day)	258-354	-	-	-	-	-	-	-	3.10^5 *	10^4 *
Switzerland[70]	Research centre / Infiltration	Sedimentation + Sand filter + Constructed wetland	-	311	27	130	5	-	-	-	-	-	-
Italy[67]	University	Reed beds	7 days (0.09 m^3/day)	151	51	42	26	-	-	25	20	-	-
Sweden[28]	Village / Irrigation	Sedimentation + Reed bed + Sand filter	4 days	361	56	$165^{\#}$	$<5^{\#}$	-	-	-	-	3.10^6	<20
Sweden[33]	Student residence / Toilet flushing	Lime gravel filter + 3 Ponds + Sand filter	~ 1 year	-	-	$47^{\#}$	$0^{\#}$	-	-	-	-	9.10^4	172

* as *E. Coli*; $^+$ as Faecal Coliforms; $^{\#}$ as BOD_7.



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Greywater recycling: A review of treatment options and applications

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2007-01-01T00:00:00Z
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http://dx.doi.org/10.1680/ensu2007.160.3.11
Pidou, M. & Memon, F.A. & Stephenson, T. & Jefferson, B. & Jeffrey, P. Greywater recycling: treatment options and applications, Institution Of Civil Engineers. Proceedings. Engineering Sustainability, Vol. 160, 2007, page 119-131

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