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Greywater recycling: treatment options and applications

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Wastewater is an immense resource that could find 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 by collating a disparate information base and comparing/contrasting the strengths and weaknesses of different approaches. Simple technologies and sand filters have been shown to have a limited effect on greywater; membranes are reported to provide good solids removal but cannot efficiently tackle the organic fraction. Alternatively, biological and extensive schemes achieve a good general treatment of greywater with particularly effective removal of organics. The best overall performances were observed within schemes that combine different types of methods to ensure effective treatment of all the fractions.

1. INTRODUCTION

Wastewater recycling has been, and continues to be, practised all over the world for a variety of reasons including increasing water availability, alleviating water shortages and drought, and supporting environmental and public health protection.[1] Increases in water demand, due mainly to the steady rise in the world's population, also generates increased wastewater production. Consequently wastewater, if recycled, is a significant source that could potentially aid problems caused by lack of fresh water. 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] Potential sources identified for urban reuse are sewage,[4] greywater[5] and rainwater,[6] where greywater is defined as domestic wastewater excluding toilet flush. In some cases, mixed rain and greywaters[7] have been used as well as 'light greywater', including only sources from bathrooms.[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 9–20% of the nutrients.[9] Moreover, in individual households, 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 water use represent 41% of total domestic water usage; greywater from showers, baths, hand basins, laundry and dishwashers correspond to 44% (Table 1).[11] On a larger scale, other greywater applications have been considered, for example irrigation of parks, school yards, cemeteries and golf courses, fire protection and air conditioning.[12]

It is now widely accepted that greywater recycling is feasible and can contribute to sustainable water management. 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. The aim of 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, this paper also comprises a contemporary account of greywater reuse applications.

2. TREATMENT TECHNOLOGIES FOR GREYWATER RECYCLING

Investigations into the treatment and recycling of greywater have been reported since the 1970s.[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 1980s and 1990s, biological-based technologies such as rotating biological contactors,[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 individual houses.[19,22,23] In the late 1990s, reports also emerged on the use of advanced technologies such as membrane bio-reactors (MBRs)[24–27] and cheaper extensive technologies such as reed beds[28–31] and ponds.[32,33] Interestingly, only three chemical treatments—electro-coagulation,[34] photocatalysis[35]

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Use	Fraction of total water demand: %
Toilet flushing	35
Wash basin	8
Shower	5
Bath	15
Laundry	12
Dishwasher	4
Outside use	6
Kitchen sink	15

Table 1. Domestic water usage[11]

and conventional coagulation[36]—have been reported in the literature.

Schemes for greywater recycling are found in most parts of the world. No specific trend could be identified between location and types of treatment used, 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 an inexpensive filter 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. In Oman, Prathapar *et al.*[39] designed and tested a low-cost, low-maintenance system based on 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 just as important to the public.[40,41] The produced standards thus include parameters for treatment of the organics and solids fractions, such as biochemical oxygen demand (BOD), suspended solids (SS) and turbidity. Examples of standards for wastewater reuse in different countries are reported in Table 2.[1,29,42–44] The differences in regulations 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, 2–20 NTU, 0–10^3 cfu/100 ml and 0–10^4 cfu/100 ml, respectively. Consideration of all of the standards from around the world suggests that specific targets of BOD <10 mg/l, turbidity <2 NTU and a non-detectable level of faecal coliforms per 100 ml is a sensible conservative level and will be used as the main performance criteria throughout this paper.

A total of 64 schemes were reviewed in this work—26 were pilot or bench-scale systems for research purpose; the other 38 were full-scale systems fitted in buildings and the treated greywaters were reused for specific applications (toilet flushing, irrigation or garden watering, outdoor use and cleaning, laundry and infiltration (Table 3)). Toilet flushing and irrigation were the most commonly used greywater applications (54 and 36% of the schemes, respectively). Most of the full-scale schemes were installed in individual houses; 12 were on a bigger scale, e.g. stadiums, hotels, group of houses or residences. The different schemes reported varied in size with treated effluent flow rates found to vary between 0·01 and 622 m^3/d. However, 70% of the schemes (for which flow rates were known) had a flow rate below 3·4 m^3/d (Fig. 1).

The schemes were also evaluated according to treatment type. The following five categories were identified

(*a*) simple (coarse filtration and disinfection)
(*b*) chemical (photocatalysis, electro-coagulation and coagulation).
(*c*) physical (sand filter, adsorption and membrane)
(*d*) biological (biological aerated filter, rotating biological contactor and membrane bioreactor)
(*e*) extensive (constructed wetlands)

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

	Application	BOD_5: mg/l	TSS: mg/l	Turbidity: NTU	Faecal coliforms: cfu/100 ml	Total coliforms: cfu/100 ml
Japan[42]	Toilet flush	—	—	<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 av. 5 max.	—	2·2 av. 23 max. in 30 d
USA, Florida[1]	Unrestricted water reuse	20	5	—	25% of sample ND, 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	—

*not detectable

Table 2. Standards for wastewater reuse

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Application	%
Toilet flushing	54
Irrigation and garden watering	36
Outdoor use and cleaning	5
Laundry	2·5
Infiltration	2·5

Table 3. Distribution of applications for greywater reuse in reviewed systems

2.1. Simple treatment systems

Simple technologies (see Table 5[5,19,23,45,46]) used for greywater recycling are usually two-stage systems based on coarse filtration or sedimentation to remove larger solids followed by disinfection (Fig. 2). Mars[45] reported the use of even simpler systems comprising only a coarse filter or sedimentation tank in Western Australia where regulations allow the reuse of such simply treated greywater for subsurface irrigation.

Simple technologies provide only limited treatment of greywater in terms of organics and solids. To illustrate, average removals of 70, 56 and 49% for chemical oxygen demand (COD), SS and turbidity respectively have been reported in the literature (Table 5). However, effective removal of micro-organisms in the disinfection stage has been reported, with total coliform residuals below 50 cfu/100 ml in the treated effluents.[19,23] These systems are preferably used on a small scale, such as single households. Moreover, they are usually used to treat low-strength greywater from baths, showers and hand basins 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 a HRT of 38 h for a large-scale system installed in an 81-room hotel in Spain.

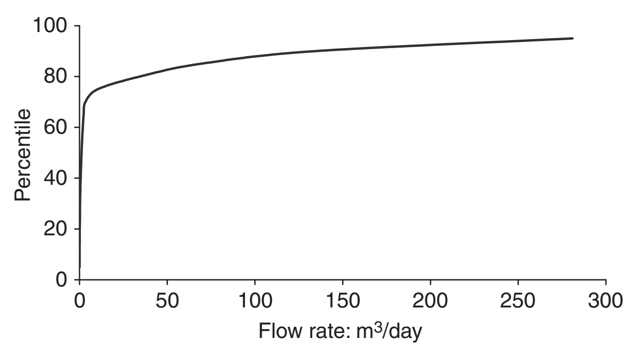

Fig. 1. Distribution of the flow rates of reported technologies

Technology	Number of schemes reviewed	Fraction of total: %
Simple	8	12·5
Chemical	3	4·7
Physical	13	20·3
Biological	25	39·1
Extensive	15	23·4
Total	64	100

Table 4. Distribution of reviewed schemes by type of treatment

Location	Building/ application	Scheme	HRT: h	COD: mg/l		BOD: mg/l		Turbidity: NTU		SS: mg/l		Total coliforms: cfu/100 ml	
				In	Out	In	Out	In	Out	In	Out	In	Out
Spain[5]	Hotel/toilet flushing	Screening + sedimentation + disinfection	38	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[46]	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	—	—

*too numerous to count
†not detectable

Table 5. Performance data of simple technologies

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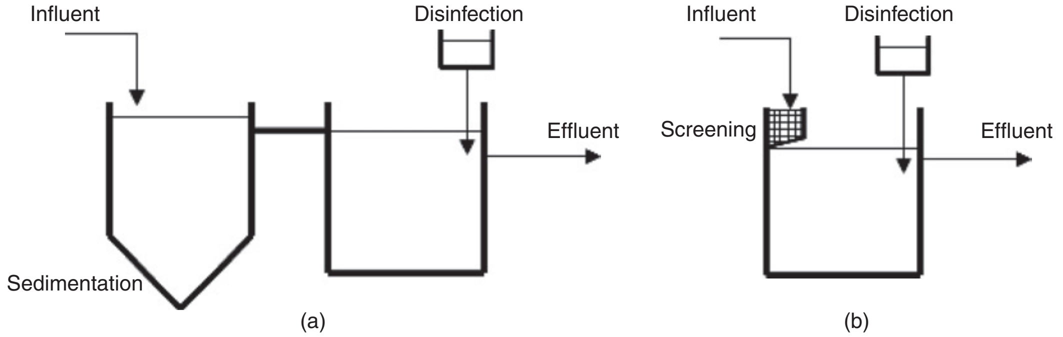

Fig. 2. Typical simple systems with disinfection and (a) sedimentation or (b) screening

These systems are marketed and promoted as being simple to use and with low operational costs.[47] However, two systems installed in individual households in the UK with similar capital and operational and maintenance (O & M) costs (£1195 and £50/year and £1625 and £49/year respectively) were found to be economically unsustainable as the water savings were not sufficient to cover O & M costs.[19,23] Only the scheme located in the hotel in Spain was reported to be economically viable. Indeed, this system (including two 300 μm nylon filters, a sedimentation tank and disinfection using sodium hypochlorite) had a capital cost of 17 000€ (~£11 500) and O & M cost was calculated at 0·75€ (~£0·50)/m^3. A saving of 1·09€ (~£0·74)/m^3 was calculated and a pay back period of 14 years was obtained with the system operative for only 7 months a year.

2.2. Chemical treatment systems

Only three schemes using chemical technology for greywater recycling are reported in the literature (see Table 6[34–36] and Fig. 3). Two of the three schemes were based on coagulation with aluminium. The first used 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 low-strength greywater.[34] This system provided good treatment of greywater with BOD and SS residuals of 9 mg/l, a turbidity residual of 4 NTU and undetectable levels of *E. coli*. However, it should be noted that the source had a very low organic strength with a BOD concentration of 23 mg/l in the raw greywater. The first system[36] was also effective, with residuals of 10 mg/l for BOD and below 5 mg/l for SS and the coagulation stage itself achieving 51% of BOD removal and 100% SS removal. These two technologies achieved these results in relatively short contact times. Indeed, the HRTs were around 20 and 40 min.

The third reported chemical scheme, based on photocatalytic oxidation with titanium dioxide and UV, also achieved good results within a relatively short time. With an HRT of less than 30 min, this method was reported to achieve 90% removal of the organics and removal of total coliforms of 10^6 cfu/100 ml.[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/GAC system[36] respectively. With no information on water savings available, it was not possible to assess the viability of these schemes.

2.3. Physical treatment systems

Physical systems (Table 7[14,15,22,36,39,48–52] and Fig. 4) can be divided into two sub-categories—sand filters and membranes. Sand filters are used alone[48] or in combination with disinfection[15] or with activated carbon and disinfection.[15,22,39] Used as a sole treatment stage, sand filters provide coarse filtration of greywater. Similarly to the simple technologies, sand filters achieve only limited treatment of the different fractions present in greywater.

Itayama *et al.*[48] described the treatment of high-strength kitchen sink water by a soil filter. They reported removal of 67% BOD and 78% SS, with respective residual concentrations of 166 and 23 mg/l—well short of any published standards for reuse.

When coupled with a disinfection stage, only removal of micro-organisms was obviously improved. Hypes *et al.*[15] investigated the treatment of bath and laundry greywater by an earth filter combined with chlorine-based disinfection; they observed poor treatment of turbidity and SS, with removals of 47 and 16% respectively. However, the system achieved good removal of total coliforms and a residual concentration of 34 cfu/100 ml was measured in the effluent.

The use of sand filters in association with activated carbon and disinfection does not result in a significant improvement in solids removal. Indeed, average removals of 61 and 48% were reported for turbidity and SS respectively. Nevertheless, good micro-organism removal rates were again reported. Prathapar *et al.*[39] and Hypes *et al.*[15] reported total coliform concentrations of 0 and 4 cfu/100 ml in treated effluents. Similarly, Canada Mortgage and Housing Corporation (CMHC)[22] reported a faecal coliform residual of 8 cfu/100 ml after treatment by sedimentation and a multi-media filter.

Hypes *et al.*[15] and Itayama *et al.*[48] reported hydraulic loading rates of 0·32, 0·24 and 0·086 m^3/m^2 per day for three systems based on filtration through soil. These were extremely low rates in comparison with typical values reported for similar systems for the treatment of other waters and wastewaters. Indeed, Tchobanoglous *et al.*[53] reported hydraulic loading rates ranging from 115 to 576 m^3/m^2 per day for simple, dual and multi-media filters with sand and/or anthracite for the treatment of wastewater. Similarly, Vigneswaran and Visvanathan[54] reported hydraulic loading rates of 2–5 and 120–360 m^3/m^2/d for slow and rapid sand filters respectively.

Treatment by membranes provides limited removal of organics but an excellent removal of dissolved and suspended solids.

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Location	Building/application	Scheme	HRT (flow rate, loading rate): min	COD: mg/l		BOD: mg/l		Turbidity: NTU		SS: mg/l		Total coliforms: cfu/100 ml	
				In	Out	In	Out	In	Out	In	Out	In	Out
UK[35]	Bench scale	Photocatalytic oxidation (TiO_2/UV)	<30	139–660†	26–139†	—	—	—	—	—	—	10^6	0
Slovenia[36]	Pilot scale	Coagulation + sand filter + GAC	~40	280	20	195	10	—	—	35	<5	—	—
Taiwan[34]	Pilot scale	Electro-coagulation + disinfection	~20 (28 m^3/d)	55	22	23	9	43	4	29	9	5100*	ND*

*not detectable; as *E. coli*
†as TOC

Table 6. Performance data of chemical technologies

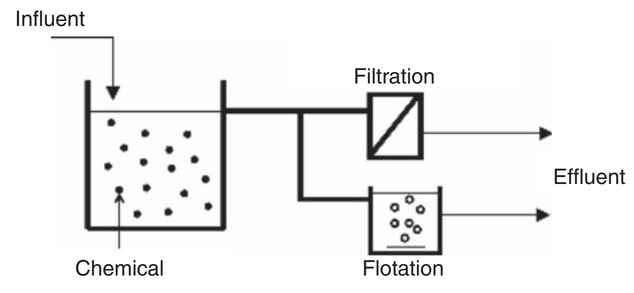

Fig. 3. Typical chemical technology with separation by filtration or flotation

Removals of up to 100% turbidity and SS have been recorded[14,49,50] and residual concentrations below 2 NTU for turbidity and below 10 mg/l for SS (sufficient to meet the strictest standards for reuse) are generally observed. In contrast, Birks[51] and Sostar-Turk *et al.*[36] reported BOD residuals of 86 and 53 mg/l respectively—above the criteria for reuse—after treatment with ultra-filtration (UF) membranes.

The pore size of the membrane used will have an important impact on the treatment achieved. Ramon *et al.*[50] 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 MWCOs of 30, 200 and 400 kDa for the treatment of shower water. The performance was shown to be better with membranes of lower pore size, especially in terms of organics removal. Indeed, COD removals of 45, 49, 70 and 93% were reported for membranes with MWCOs of 400, 200, 30 and 0·2 kDa respectively. Differences in turbidity removal were less obvious, with similar orders of removal of 92, 94, 97 and 98% for the four MWCOs. 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 BOD from 195 to 86 mg/l, corresponding to a removal of 56%. The RO membrane then decreased the BOD from 86 to 2 mg/l, corresponding to a removal of 98%. A similar trend was observed for the removal of SS with values of 49 and 56% reported for the UF and RO membranes respectively. Very little information is available on the removal of micro-organisms by membranes. However, Jefferson *et al.*[55] 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[56] 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, facilitate the transport of bacteria through pores.

The main issue when using membranes is fouling; this has an effect on system operation and 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 min at a flux of about 130 l/m^2 per h and with a RO membrane for 120 minutes at a flux of about 37 l/m/h. Similarly, Ahn *et al.*[49] reported no fouling over 12 h of greywater treatment through two UF membranes and one micro filtration (MF) membrane at a flux around 200 l/m^2 per h. These results suggest

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Location	Building/application	Scheme	HRT (flow rate, loading rate)	COD: mg/l		BOD: mg/l		Turbidity: NTU		SS: mg/l		Total coliforms: cfu/100 ml	
				In	Out	In	Out	In	Out	In	Out	In	Out
Japan[48]	House/garden watering	Soil filter	(0·086 $m^3/m^2/d$)	271	42	477	166	—	—	105	23	—	—
USA[15]	Pilot scale	Earth filter + disinfection	2 h (0·32 $m^3/m^2/d$)	—	—	—	—	17	9	549†	460†	2×10^6	34
USA[15]	Pilot scale	Earth filter + activated carbon + disinfection	(0·24 $m^3/m^2/d$)	—	—	—	—	23	9	500†	394†	1×10^5	4
Oman[39]	Mosque/irrigation	Filtration + activated carbon + sand filter + disinfection	(1·3 m^3/d)	51	35	—	—	13	6	9	4	>200	0
Canada[22]	Apartment building/ toilet flushing	Screening + sedimentation + multi-media filter + ozonation	(1 m^3/d)	—	—	130	—	82	26	67	21	8870*	8*
UK[52]	Pilot scale	Sand filter + membrane + disinfection	(4·37 m^3/d)	65	18	23	8	18	0	—	—	5×10^3*	0*
Israel[50]	Bench scale	UF membrane (400 kDa)	—	146	80	—	—	18	1·4	—	—	—	—
Israel[50]	Bench scale	UF membrane (200 kDa)	—	146	74	—	—	17	1	—	—	—	—
Israel[50]	Bench scale	UF membrane (30 kDa)	—	165	51	—	—	24	0·8	—	—	—	—
Israel[50]	Bench scale	NF membrane	—	226	15	—	—	30	1	28	0	—	—
Slovenia[36]	Pilot scale	RO membrane	—	130	3	86	2	—	—	18	8	—	—
Slovenia[36]	Pilot scale	UF membrane	—	280	130	195	86	—	—	35	18	—	—
Korea[49]	Hotel/toilet flushing	Membranes	—	64	10	—	—	10	0	—	—	—	—
USA[14]	Pilot scale	Coarse filtration + RO + disinfection	—	—	—	—	—	30	0	102	<100	5×10^7	0
UK[51]	Pilot scale	UF membrane	—	451	117	274	53	—	—	—	—	—	—

*as *E. coli*
†as total solids

Table 7. Performance data of physical technologies

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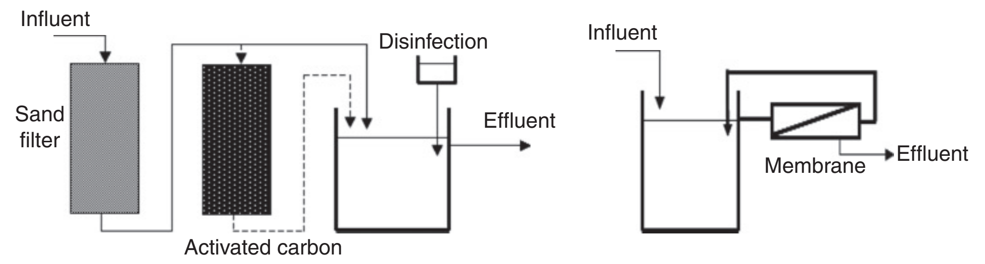

Fig. 4. Typical physical technologies

that no fouling under those conditions occurred in the short term. However, Nghiem *et al.*[57] investigated fouling of UF membranes in synthetic greywater treatment. They observed that the fouling increased linearly with the organic matter (humic acid) concentration. To limit fouling, the membrane stage can be preceded by a pre-treatment such as screening or sand filter. Ward[52] studied a process combining both physical processes, sand filter and membrane, and disinfection for the treatment of low-strength greywater. With a residual of 8 mg/l for BOD and undetectable levels of turbidity and *E. coli*, the system was sufficient 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 larger particles. Reductions of BOD from 23 to 17 mg/l and turbidity from 18 to 17 NTU were observed. Further treatment was then achieved in the membrane and disinfection stages.

2.4. Biological treatment systems

A wide range of biological processes have been used for greywater recycling (Table 8[2,17–21,24,27,38,51,52,58–65] and Fig. 5). Processes such as fixed film reactors,[17,19,20,52,58] rotating biological contactors,[17,59] anaerobic filters,[38,60] sequencing batch reactors,[21] membrane bioreactors[2,24–27,61] and biological aerated filters (BAFs)[2,18,51,62,63] have been reported. Biological systems are rarely used individually; reported cases are pilot-scale investigations.[2,51] In most cases in the literature, biological processes are preceded by physical pre-treatment such as sedimentation[17,38,60] or screening[18,58,59] and/or followed by disinfection.[17,19,64] They are also combined with sand filters,[64] activated carbon,[18,19] constructed wetlands[62] or membranes in processes such as MBRs.[24–26]

Biological schemes, when installed at full scale, are the type of treatment most commonly seen in bigger buildings. Indeed, systems can be found in student residences,[18,19,59] multi-storey buildings[17,20] and stadiums.[63,65] HRTs ranging from 0·8 h to 2·8 days have been reported for 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 respectively. However, HRTs in biological systems are reported to be on average 19 h. Very little information is available on solids retention time (SRT) in these biological systems. Organic loading rates were found to vary between 0·10 and 7·49 kg/m^3/d for COD and between 0·08 and 2·38 kg/m^3/d for BOD. In detail, the average organic loading rate in MBRs was reported to be 0·88 kg$_{COD}$/m^3/d, which is lower than the typical values of 1·2–3·2 kg$_{COD}$/m^3/d reported by Stephenson *et al.*[66] for wastewater treatment. In contrast, the average organic loading rate found for the other systems such as BAF, rotating biological contactor (RBC) and bio-films was 1·32 kg$_{BOD}$/m^3/d, which is in the range of 0·3–1·4 kg$_{BOD}$/m^3/d reported for these systems.[53]

Regardless of the number and type of processes included, all schemes with a biological stage achieved excellent organic and solids removal. Indeed, all but two of the biological systems reviewed met the most stringent BOD standard for reuse with residual concentrations below 10 mg/l. Turbidity concentrations in the effluents were below 8 NTU for all the systems reviewed. All schemes but one achieved SS residual below 15 mg/l. In terms of micro-organisms, once again, the 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/100 ml. Interestingly, MBRs were the only systems found to achieve good micro-organism removal without the need for a disinfection stage. To illustrate, average removals of both faecal and total coliforms were reported at 5-log and the corresponding residual concentrations were below 30 cfu/100 ml. Additionally, MBRs achieved excellent removal of the organic and solid fractions, with average residuals of 3 mg/l for BOD, 3 NTU for turbidity and 6 mg/l for SS.[2,24,25,27,61]

Jefferson *et al.*[55] reported that, at small scale, variations in the strength and flow of greywater and potential shock loading affect the performance of biological-based technologies. 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 median effective concentration (EC_{50}) values of 2·5, 7, 20, 23 and 29 ml/l respectively. Moreover, Jefferson *et al.*[67] 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, the BAF studied did not exhibit the same robustness. Although short-term interruptions (30 min) did not affect BAF performance, longer cessations of the feed and/or air generated an increase in effluent concentrations and recovery times for all the parameters. Indeed, after an eight-hour feed interruption, recovery times were reported to be 4, 4, 40 and 48 h for turbidity, SS, faecal coliforms and total coliforms respectively. Similarly, after the same duration of air interruption, the recovery times were 4, 4, 24, 28 and 24 h respectively. The longest recovery times were observed after interruption of both air and feed simultaneously (40, 40, 4, 24, 48 h respectively). None of the parameters recovered to pre-interruption levels within 48 h of a 25-day feed interruption.

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Location	Building/application	Scheme	HRT (flow rate, loading rate)	COD: mg/l		BOD: mg/l		Turbidity: NTU		SS: mg/l		Total coliforms: cfu/100 ml	
				In	Out	In	Out	In	Out	In	Out	In	Out
Japan[65]	Stadium/toilet flushing	Screening + sedimentation + flotation + rotating filters + sand filter + disinfection	(622 m^3/d)	243	6	336	20	—	—	207	10	—	10
Japan[60]	House	Anaerobic filter + submerged biofilter + sedimentation + disinfection	(1·735 m^3/d)	—	11	—	8	—	—	—	6	—	—
Korea[21]	Pilot scale	Sequencing batch reactor + MF hollow fibre membranes	13 h (1·2 m^3/d)	79	30	5	5	—	—	185	—	—	—
China[27]	Pilot scale	Screening + membrane bioreactor	3·6 h	130–322	<40	99–212	<5	146–185	<1	15–50	0	—	ND
Israel[59]	Student flats/toilet flushing	Screening + rotating biological reactor + sedimentation + sand filter + disinfection	~18 h	158	40	59	2	33	1	43	8	6×10^5*	1*
Israel[59]	Student flats/toilet flushing	Screening + membrane bioreactor + disinfection	~18 h	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/d)	1700	50	645	2	—	—	—	—	—	—
Germany[17]	Apartment building/ toilet flushing	Sedimentation + rotating biological contactor + UV disinfection	(2·1 m^3/d)	100–200	—	43–85	<4	—	—	—	—	10^4–10^5	<10^4
Germany[17]	House/toilet flushing	Fluidised bed reactor + UV disinfection	(0·04 m^3/d)	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[58]	House/toilet flushing, laundry and garden watering	Screening + biofilm + UV disinfection	—	—	—	—	9	—	6	—	9	—	0*
Australia[64]	House/toilet flushing and outdoor use	Septic tank + sand filter + UV Disinfection	—	—	—	97	6	—	1	48	3	2×10^5	9
Norway[62]	Houses/irrigation	Septic tank + aerated biofilter + constructed wetland	—	—	62	—	<10†	—	—	—	—	—	<100
Germany[61]	Pilot scale	Membrane bioreactor	10 h	493	24	—	—	—	—	7	4	—	—
UK[18]	Student halls/toilet flushing	Screening + aerated biofilter + Deep-bed filter + activated carbon	—	—	—	—	9	—	1	—	6	—	995
UK[51]	Pilot scale	Biological aerated filter	4 h (0·4 m^3/m^2/h)	363	80	131	5	—	—	109	8	—	—
UK[19]	Student halls/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 h (0·328 m^3/d)	128	13	41	4	—	3	52	6	2×10^6	2×10^4
UK[2]	Pilot scale	Submerged membrane bioreactor	13·6 h (0·071 m^3/d)	128	7	41	1	—	4	52	4	2×10^6	2
UK[2]	Pilot scale	Membrane aeration bioreactor	0·8 h (0·225 m^3/d)	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/d)	273	2	181	1	—	1	58	4	3×10^4	1
UK[63]	Pilot scale	Biological aerated filter + UF membrane	1·2 h	80	6	—	—	25	0	52	1	6×10^5	<1
UK[52]	Pilot scale	Biological reactor + sand filter + GAC	(2·88 m^3/d)	34	12	21	2	20	1	—	—	2×10^2	<1
UK[63]	Arena/toilet flushing	Biological aerated filter	1·25–5 h (120 m^3/d)	84	14	—	—	—	—	31	3	3×10^5	3×10^3

*as faecal coliforms
†as BOD_7

Table 8. Performance data of biological technologies (BOD_7, measurement after 7 days)

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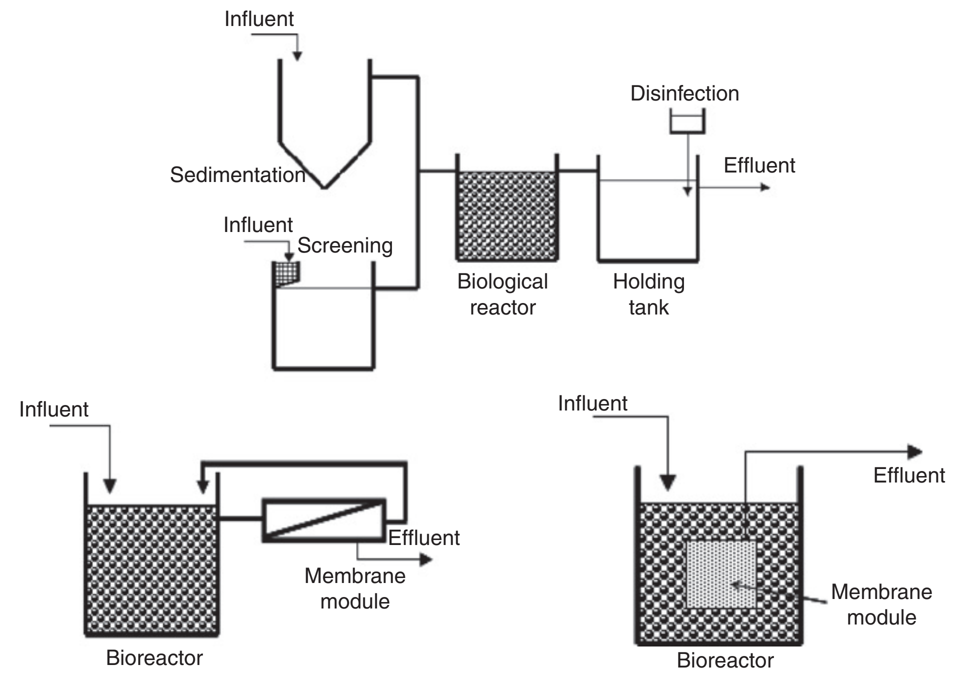

Fig. 5. Typical biological technologies and sidestream and submerged MBRs

Again, limited information is available regarding system costs. Surendran and Wheatley[18] reported a capital cost of £3345 for the construction and installation of a retrofit system (comprising a buffering tank with screening, aerated biofilter, deep bed filter and GAC) in a residence hall for 40 students. O & M costs were reported to be £128/year, including energy, labour and consumables. Water savings of £516/year result in a pay back period of 8–9 years. Surendran and Wheatley estimated that if the system was fitted in a new building, capital cost could be reduced to £1720 and the adjusted pay back period would be 4–5 years. A system reported by McQuire[58] comprising a screening filter, treatment tank with bio-film grown on aggregate balls, particle filter and UV disinfection unit installed in an individual house was estimated to cost between Aus$6200 and Aus$8200 (£2514–£3325). Bino[38] reported a low-cost, easy to build system composed of four plastic barrels installed in a six-person house with a capital cost of US$370 (~£197). Unfortunately, no information on O & M costs or water savings was reported for these two schemes. Gardner and Millar[64] reported a capital cost of Aus$5500 (£2230) and O & M costs of Aus$215/year (£87/year) for a system based on a septic tank, sand filter and UV disinfection. However, the achieved water savings of Aus$83/year (£34/year) were not sufficient to cover these costs. Brewer *et al.*[19] studied an aerated bioreactor combined with a sand filter, GAC and disinfection with bromine installed in a student residence. The capital cost was reported to be £30,000 and, again, O & M costs of £611/year exceeded water savings of £166/year.

2.5. Extensive treatment technologies

Extensive technologies for greywater treatment usually comprise constructed wetlands such as reed beds and ponds (Table 9[28–33, 37,46,68–70] and Fig. 6). These are often preceded by sedimentation to remove larger particles in the greywater and followed by sand filtering to remove any particles or media carried by the treated water. The most common plant used in reed beds is *Phragmites australis*.[28,31,68,69] However, as this is considered a noxious weed species in Costa Rica, Dallas *et al.*[32] and Dallas and Ho[37] investigated an alternative macrophyte, *Coix lacryma-jobi*. Two studies investigated the use of a range of plants. Frazer-Williams *et al.*[69] 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.*[68] 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 show good ability to treat greywater. An average BOD residual of 17 mg/l was observed; more than half of the extensive treatment schemes reviewed reported a residual BOD concentration below 10 mg/l. Similarly, average residual concentrations of 8 NTU for turbidity and 13 mg/l for SS have been reported. However, poor removal of micro-organisms was described. Average removals of 3·6-log and 3·2-log were reported for faecal and total coliforms respectively, with residual concentrations generally above 10^2 cfu/100 ml for both indicators. In terms of hydraulics, for the extensive systems reported, the HRT was found to vary from a couple of hours to a year for one particular scheme comprising three ponds.[33] However, after removing extreme data, the average HRT for extensive technologies is 4·5 days. Borin *et al.*[68] compared the performance of two constructed wetlands, one planted with the common reed *Phragmites australis* and the second with a range of ten species. No significant differences in treatment effectiveness were observed for the two systems. To illustrate, effluent concentrations of 25·8 and 26·6 mg/l for BOD, 20 and 30 mg/l for total SS and 51·2 and 50·5 mg/l for COD were reported for the ten-species system and *Phragmites australis* respectively.

Apart from being regarded as environmentally friendly technologies, constructed wetlands are also considered to be inexpensive. Indeed, Dallas *et al.*[32] and Shrestha *et al.*[31] described reed beds with capital costs of just US$1000 (£531) and US$430 (£229) respectively and very low operating costs.

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Location	Building/application	Scheme	HRT (flow rate, loading rate)	COD: mg/l		BOD: mg/l		Turbidity: NTU		SS: mg/l		Total coliforms: cfu/100 ml	
				In	Out	In	Out	In	Out	In	Out	In	Out
UK[69]	Pilot scale	Horizontal flow reed bed	2·1 d	452	111	151	51	63	12	87	31	6×10^7	10^4
UK[69]	Pilot scale	Vertical flow reed bed	2 h batch	452	27	151	5	63	2	87	9	6×10^7	2×10^4
UK[69]	Pilot scale	Constructed wetland	2·1 d	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 h	839	157	466	0·7	—	—	158	3	$5 \times 10^{7\dagger}$	$2 \times 10^{5\dagger}$
USA[46]	House/toilet flushing and irrigation	Aquacell + sand filter	—	—	—	120	4	64	4	40	17	4×10^7	5×10^4
USA[46]	House/toilet flushing and irrigation	Aquacell + sand filter + copper dosing + disinfection	—	—	—	—	—	79	4	36	5	2×10^7	6×10^5
USA[46]	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]	Three houses/irrigation	2 reed beds + pond	>10 days (0·755 m^3/d)	—	—	167	3	96	5	—	—	$2 \times 10^{8\dagger}$	$198^\dagger$
Costa Rica[37]	Pilot scale	Trench and plants	4–5 days (0·01 m^3/d)	—	—	254	13	103	—	—	—	$8 \times 10^{7\dagger}$	$2050^\dagger$
Nepal[31]	House/toilet flushing, cleaning and garden watering	Sedimentation + reed bed	(0·5 m^3/d)	411	29	200	5	—	—	98	3	—	—
Germany[30]	Houses	Sedimentation + constructed wetlands	(70 l per person/d)	258–354	—	—	—	—	—	—	—	3×10^{5}*	10^{4}*
Switzerland[70]	Research centre/infiltration	Sedimentation + sand filter + constructed wetland	—	311	27	130	5	—	—	—	—	—	—
Italy[68]	University	Reed beds	7 days (0·09 m^3/d)	151	51	42	26	—	—	25	20	—	—
Sweden[28]	Village/irrigation	Sedimentation + reed bed + sand filter	4 days	361	56	$165^\ddagger$	$<5^\ddagger$	—	—	—	—	3×10^6	<20
Sweden[33]	Student residence/toilet flushing	Lime gravel filter + 3 ponds + sand filter	~1 year	—	—	$47^\ddagger$	$0^\ddagger$	—	—	—	—	9×10^4	172

*as *E. coli*
†as faecal coliforms
‡as BOD_7

Table 9. Performance data of extensive technologies

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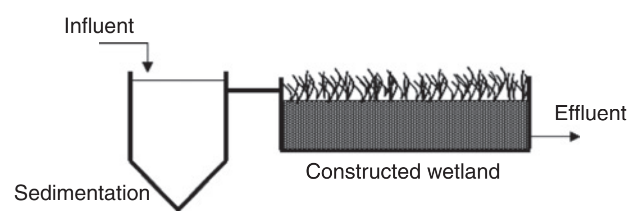

Fig. 6. Typical extensive technology

3. DISCUSSION AND CONCLUSIONS

This review of standards for greywater recycling and the characteristics of greywaters shows that technologies used to treat greywater for reuse are effective on organic, solids and microbial fractions (Table 2). However, the different greywater recycling schemes reported to date achieve very different performance levels. Simple technologies and sand filters have been shown to have only a limited effect on greywater, whereas membranes have been reported to provide good solids removal but cannot efficiently tackle the organic fraction. Alternatively, biological and extensive schemes achieve good general treatment of greywater with particularly good removal of organics. Although less information is available in the literature on chemical systems, those that are reported show promising abilities to treat greywater with short retention times. Micro-organism removal was found to be sufficient to meet the standards only in schemes including a disinfection stage; MBRs were the only systems reported to achieve good microbial removal without the need for disinfection.

In conclusion, the best performance levels were observed in schemes that combine different types of treatment to ensure effective treatment of all the fractions. For instance, Ward[52] 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 for BOD, 1 NTU for turbidity and <1 cfu/100 ml for total coliforms. Similarly, Friedler *et al.*[59] 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, 2 mg/l and 1 cfu/100 ml for turbidity, SS, 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 for BOD, 1 NTU for turbidity, 4 mg/l for SS and 1 cfu/100 ml for total coliforms in greywater treated by a sidestream membrane bioreactor. Liu *et al.*[27] reported effluent concentrations of <5 mg/l for BOD, <1 NTU for turbidity and undetectable levels of SS and coliforms following treatment by a submerged membrane bioreactor. All these systems met the most stringent standards for greywater reuse; however, the level of treatment required is often dependent on the reuse applications (Table 2). Technologies that generate a lesser quality effluent may thus still be of interest in applications with less stringent standards.

Investigation of the HRTs of each type of system revealed that two of the reported chemical systems worked with very low HRTs of under an hour. With an average HRT of 19 h, biological systems proved to be efficient over relatively short periods of time. Extensive technologies operate with the highest HRTs (average 4·5 d). With similar levels of performance for biological and extensive systems, the shorter HRTs of the former are an obvious advantage.

Another feature of greywater recycling systems that influences their application is footprint as space is often limited in urban environments. Systems using biological, chemical or physical technologies are generally smaller than extensive technologies. For example, Fittschen and Niemczynowicz[28] reported a footprint of about 1000 m^2 for a system including a sedimentation tank, reed bed, sand filter and pond for greywater treatment of a 100-inhabitant village, i.e. corresponding to 10 m^2 per inhabitant connected. Dallas *et al.*[32] reported on the treatment of greywater produced by seven people from three houses by a sedimentation tank, two reed beds and a pond. This system had a total footprint of about 40 m^2, corresponding to 5·7 m^2 per person. Nolde[17] studied a system composed of a sedimentation tank, rotating biological contactor and disinfection stage installed in the 15 m^2 basement of a 70-person multi-storey building, that is 0·2 m^2 per person connected.

It should be noted that the level of contribution that the reviewed technologies 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 forward 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, and so on are the subject of future work. However, the power of circumstance to modify preference can be demonstrated by the fact that concerns with 'carbon footprints' 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.

It is hoped that this review provides a comprehensive dataset for the stimulus and development of more detailed sustainability assessments in this area.

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