Environmental Science and Ecotechnology 16 (2023) 100277

Contents lists available at ScienceDirect

Environmental Science and Ecotechnology

journal homepage: www.journals.elsevier.com/environmental-science-and-ecotechnology/

Review

Greywater reuse as a key enabler for improving urban wastewater management

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ARTICLE INFO

Article history:
Received 16 September 2022
Received in revised form
31 March 2023
Accepted 3 April 2023

Keywords:
Greywater reuse
Urban wastewater
Decentralized wastewater treatment
Sustainable wastewater management

ABSTRACT

Sustainable water management is essential to guaranteeing access to safe water and addressing the challenges posed by climate change, urbanization, and population growth. In a typical household, greywater, which includes everything but toilet waste, constitutes 50–80% of daily wastewater generation and is characterized by low organic strength and high volume. This can be an issue for large urban wastewater treatment plants designed for high-strength operations. Segregation of greywater at the source for decentralized wastewater treatment is therefore necessary for its proper management using separate treatment strategies. Greywater reuse may thus lead to increased resilience and adaptability of local water systems, reduction in transport costs, and achievement of fit-for-purpose reuse. After covering greywater characteristics, we present an overview of existing and upcoming technologies for greywater treatment. Biological treatment technologies, such as nature-based technologies, biofilm technologies, and membrane bioreactors (MBR), conjugate with physicochemical treatment methods, such as membrane filtration, sorption and ion exchange technologies, and ultraviolet (UV) disinfection, may be able to produce treated water within the allowable parameters for reuse. We also provide a novel way to tackle challenges like the demographic variance of greywater quality, lack of a legal framework for greywater management, monitoring and control systems, and the consumer perspective on greywater reuse. Finally, benefits, such as the potential water and energy savings and sustainable future of greywater reuse in an urban context, are discussed.

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1. Introduction

Sustainable water usage is becoming increasingly challenged by the effects of climate change, population increase, and urbanization. Because water management is not only strongly associated with public health but also with food security, human rights, ecosystem services, and education, increasing robustness in water management is a key development goal for many countries [1]. The solution of looking for reusable water sources locally has two main advantages over the long-distance solution: (1) it avoids moving water across long distances, potentially entailing large cost savings, and (2) it can add to the resilience and adaptability of the local water system [2,3]. Local reuse of (municipal) wastewater streams is often undervalued and only considered when existing water resources do not suffice [4].

Local reuse relies on decentralized water installations as standalone systems for the treatment of small wastewater flows. Deploying decentralized water management units, potentially complementary to a centralized grid, allows for the collection, treatment, discharge, and reuse of wastewater flows near the point of production and preferably near the point of use. Small-scale installations often suffer from challenges, such as uneven flow distribution, toxic shocks, and the need to remove nutrients as well as pathogens from a complex water stream. Source separation, which refers to splitting wastewater flows at the point of origin, can facilitate this by simplifying treatment solutions and increasing the

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https://doi.org/10.1016/j.ese.2023.100277
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potential for resource recovery, especially from less encumbered streams [5].

Household wastewater can be most easily divided into blackwater (toilet wastewater) and greywater. Greywater includes wastewater originating from all household applications other than blackwater. For example, it includes water from the washing machines, dishwashers, showers, baths, and sinks. Greywater makes up 30–50% of the organic load and 9–20% of the nutrient load of the total wastewater produced in a household [6,7]. Furthermore, an average greywater production of 60–200 L per capita is common in developed countries, for which greywater reuse could thus theoretically entail a water savings potential of 50–80% [8]. The lower degree of fecal contamination and the relatively large quantity available make greywater an attractive water resource if it can be reused effectively. Interestingly, greywater availability coincides with human activity and thus can match water supply with water demand, provided a modest buffering capacity is in place.

Much research on the reclamation and reuse of greywater streams has been undertaken using physical (e.g., membrane filtration), chemical (e.g., coagulation), and biological (e.g., suspended growth) treatment technologies [9] (see Fig. 1), with some products already on the market as consumer products for a single household and many suppliers offering building level solutions. Overall progress in the field and implementation has been slow, however, due in part to difficult uptake in building projects (separate piping issues), public risk perception and associated “yuck factor”, and due to limited innovation in the water sector, especially from technology “lock-in” effects [3,10]. The latter entails the phenomenon where a “random” early lead in innovation is sufficient for a certain technology to acquire dominance within a market, leading to a restricted advancement of other technologies [11]. Thus, investments in large-scale, centralized water systems, in particular, can cause a lock-in due to their associated high infrastructure costs.

In recent years, several comprehensive literature reviews have been published on the current status of greywater reuse in the urban context. For instance, Shaikh and Ahammed [12] provided an overview of the literature on greywater quality and quantity characteristics, and other recent reviews have delved into specific technologies for greywater reuse, such as nature-based solutions, and have often focused on constructed wetlands [6,13,14], the application of adsorbents [15,16], MBR [17], and general membrane technology applications [18]. Vuppaladadiyam et al. [19] provided a comprehensive review of past research on greywater characteristics, and treatment technologies, a discussion on reuse barriers related to quality characteristics, administrative obstacles, and public opinion, and an overview of greywater reuse experiences across the globe. Furthermore, Khalil and Liu [20] wrote a review on biological treatment technologies for greywater reuse, greywater biodegradability, and the associated issues and solutions. Despite the wide range of topics addressed by these recent review papers, a holistic and up-to-date overview of scientific progress on greywater treatment technologies has yet to be published. This review paper aims to cover this gap by providing a comprehensive overview of greywater characteristics, treatment technologies, challenges, and opportunities for decentralized wastewater management.

2. Reuse of greywater: general aspects

2.1. What is greywater?

As previously mentioned, greywater is defined as all household wastewater flows, excluding toilet wastewater (blackwater). As feces and urine are excluded, greywater is generally less subject to microbial contamination and contains lower concentrations of organics and nutrients than mixed municipal wastewater (Table 1).

2.2. Ionic composition of greywater

Greywater contains elevated concentrations of ionic species (anions and cations) due mainly to the application of counter ions (Na^+, Cl^-) or bleaching agents (B) in washing powders and detergents and additions from food processing and personal care products (PCPs) (see Table 2) [25,26], and the salinity of greywater has a large impact on its potential for reuse and infiltration [27,28].

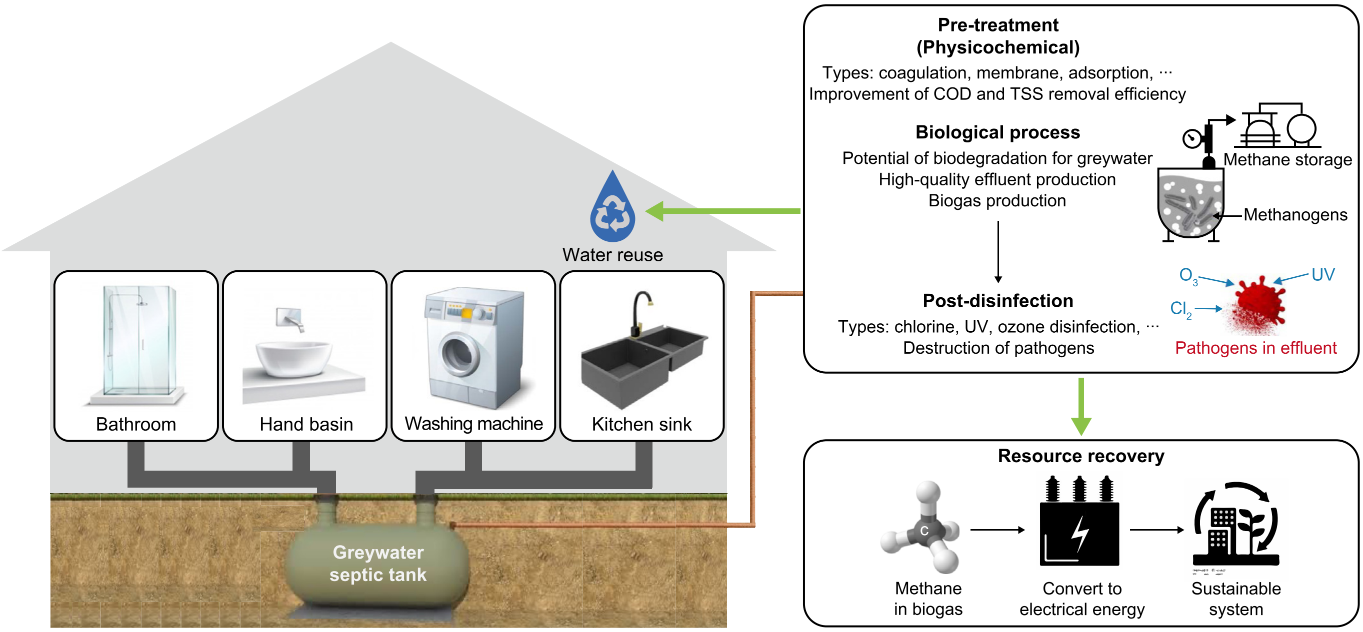

Fig. 1. Sources to collect greywater and integrated process for greywater treatment and resource recovery in household application.

Table 1
Characteristics of mixed greywater. Data adapted from Refs. [5,21–24]. BOD = Biochemical Oxygen Demand, COD = Chemical Oxygen Demand, TDS = Total Dissolved Solid, TSS = Total Suspended Solid, VSS = Volatile Suspended Solid, TN = Total Nitrogen, TP = Total Phosphorous, CFU = Colony-Forming Unit, FC = Fecal Coliforms, TC = Total Coliforms.

Parameter	Unit	Mean	Range
pH	-	7.1	6.1–8.4
BOD_5	mg L^{-1}	195	90–375
COD	mg L^{-1}	394	92–682
TDS	mg L^{-1}	377	280–597
TSS	mg L^{-1}	66	16–202
VSS	mg L^{-1}	39	-
Turbidity	NTU	80	37–173
TN	mg L^{-1}	9.7	8–11
NH_3–N	mg L^{-1}	4.1	0.6–9.2
NO_3–N	mg L^{-1}	0.8	0.4–2.5
TP	mg L^{-1}	5.5	0.9–11
FC	log10 CFU per100 mL	4.5	3.6–5.8
TC	log10 CFU per 100 mL	4.9	4.1–6

Much research has been performed on the longer-term effects of irrigation with (treated) greywater on soil characteristics and potential phytotoxicity due to elevated salt concentrations, leading to conflicting insights both in favor and against the practice [29–33]. Trace metals are present in relatively low concentrations, with the recent increase in plastic-based plumbing leading to even fewer instances of high zinc and copper concentrations [8,34]. However, longer-term irrigation with greywater may still lead to the accumulation of trace metals in soils exceeding regulations [35].

2.3. Microbial composition of greywater

Concerning microbial contamination, pathogen levels in greywater are generally reported to be considerably lower than in combined municipal wastewater and are typically similar to those present in secondary treated municipal wastewater (see Table 3) [40,41]. However, even this level of microbial contamination still entails significant public health risks while reusing untreated greywater [42]. Even after treatment, pathogens might pose a significant health risk during reuse practices, such as food-crop irrigation [43]. Important sources of pathogens in greywater include fecal contamination from washing practices (e.g., from bathing, showering, and the washing machine) and (incorrect) handling of contaminated foods (e.g., through the kitchen sink) [39,44]. Previous investigations on the presence of pathogens in raw greywater have indicated relatively high concentrations of *Salmonella* spp., *Pseudomonas aeruginosa*, *Staphylococcus aureus* (all ranging up to 10^4 CFU per 100 mL), *Legionella pneumophila* (ranging up to 10^5 CFU per 100 mL), and fecal coliforms (10^3–10^9 CFU per 100 mL), such as *Escherichia coli* (present up to 10^6 CFU per 100 mL) [26,36–39]. Furthermore, the presence of protozoa, helminthes, and other significant sources of microbial contamination has also been observed [39].

Table 2
Prevalent elements in mixed greywater. Data adapted from Refs. [5,21,24].

Parameter	Unit	Mean	Range
Na	mg L^{-1}	182.2	7.4–480
Cl	mg L^{-1}	181	9–227
Ca	mg L^{-1}	162.08	31.6–437.61
S	mg L^{-1}	137.5	0.5–257
Mg	mg L^{-1}	55.69	5.30–140.01
K	mg L^{-1}	9.05	0.2–24
Al	mg L^{-1}	2.44	1.48–3.39
B	μg L^{-1}	600	-
Fe	μg L^{-1}	360	180–570
Zn	μg L^{-1}	64.4	55.3–77.8
Cu	μg L^{-1}	61.8	47.0–70.2
Ba	μg L^{-1}	18.2	15.5–21.8

Table 3
The microbial composition of mixed greywater. Data adapted from Refs. [26,36–39].

Parameter	Unit	Mean	Range
Fecal coliforms	log10 CFU per 100 mL	4.15	3.6–5.8
Total coliforms	log10 CFU per 100 mL	5.8	3–6.7
Fecal enterococci	log10 CFU per 100 mL	4.7	1.4–9
Escherichia coli	log10 CFU per 100 mL	4.1	3.6–6.3
Staphylococcus aureus	log10 CFU per 100 mL	0.3	-
Salmonella spp.	log10 CFU per 100 mL	3.5	0–3.9
Pseudomonas aeruginosa	log10 CFU per 100 mL	3.7	-

2.4. Xenobiotics

Xenobiotic organic compounds (XOCs) are artificially synthesized chemicals found in the environment, and municipal wastewaters mostly originate from household products, such as PCPs, preservatives, and detergents [45]. Greywater contains significant concentrations of XOCs, the majority of which reach concentrations up to 10 μg L^{-1} [46]. In the case of surfactants (often expressed as methylene blue active substances (MBASs)), the concentrations are often higher (>10 mg L^{-1}) [5].

Linear alkylbenzene sulfonates (LASs) are among the most prevalent domestically used surfactants and can be found in about 80% of household detergents. These chemicals comprise a hydrophobic alkyl chain and a hydrophilic head with a benzene ring and a sulfonate group that reduces the dissolved oxygen concentration by reducing the water's surface tension [47]. As such, these molecules contribute significantly to the total presence of detergents in greywater (in shower and washing machine wastewater in particular), with concentrations of up to 1 g L^{-1} in washing machine wastewater [48–50] and concentrations of 1–10 mg L^{-1} in domestic sewage [51]. Moreover, the presence of LASs in wastewater can cause problems such as a reduction in bacterial respiration rates and biodegradation [52]. In addition, A COD/BOD_5 ratio of up to 4 has been found for light greywater streams, which can be attributed to a large presence of nonbiodegradable chemicals [5,44,53]. Elevated concentrations of pharmaceuticals and biocides have also been reported in greywater [46,54,55]. The presence of many XOCs thus poses significant human health risks related to the potable reuse of greywater and consumption of plants irrigated with reclaimed greywater [56,57]. Furthermore, the environmental persistence of some XOCs poses a potential threat towards terrestrial and aquatic ecosystems as well [45].

2.5. How the variability of greywater influences treatment efficiency

In terms of quantity, as previously mentioned, greywater accounts for a large fraction (75–90%) of the total domestic wastewater flow, with a per capita production of 60–200 L day^{-1} in developed countries. Greywater production also temporally matches domestic water consumption, following a diurnal pattern [8,58,59]. The temperature of greywater can fluctuate substantially, ranging from common tap water temperatures (range 10–20 °C) to shower and bath (20–40 °C) temperatures and occasionally to high-temperature peaks (>60 °C) coming from the dishwasher and washing machine. These temperature fluctuations may affect treatment efficiencies and may also call for additional precautions against scaling [5,60].

Greywater characteristics are thus highly variable and mainly depend on the collected greywater flows, climatic and sociocultural influences, and the original water source [9]. This underscores the necessity of tailoring greywater treatment solutions to local circumstances. In order to select certain greywater characteristics, for instance, to improve reclaimed greywater quality, individual greywater flows can be excluded from reuse. A study by Friedler [25] showed that pollutants in combined greywater were unevenly spread among different household applications. The high concentrations of contaminants were found in kitchen sinks (42% of COD, 58% of VSS), and washing machine effluent (22% of COD, 37% of PO_4^{3-}, 40% of Na) only constituted 13–26% fractions of the total daily discharge of greywater.

3. Technologies for greywater treatment

3.1. Biological treatment technologies

3.1.1. Biofilm technologies

Fixed-bed biofilm technologies, such as the Rotating Biological Contactor (RBC), which consists of stacks of rotating discs (Fig. 2a), have been widely used to treat household greywater as they allow for high flexibility and system reliability [61]. Pathan et al. [62] obtained 50% organics (BOD_5) removal with a 40% immersion in greywater, and the organic removal efficiency improved to >90% with an organic loading rate at 5.0 g BOD_5 m^{-2} day^{-1} when using multi-stage RBC [63].

Moving-bed biofilm reactors (MBBRs) use free-moving biocarriers (with large surface areas of 500–3000 m^2 m^{-3}) for organics and nitrogen removal (Fig. 2b) and are also widely applied in municipal wastewater treatment [64]. MBBRs have also been tested for the treatment of greywater. For instance, Al-Wasify et al. [65] used an aerated MBBR to treat greywater in Egypt and achieved an effluent quality fit for irrigation purposes. In Brazil, a pilot-scale MBBR was installed to treat greywater (influent 247 mg per L COD) and maintained 70% COD removal [66]. Another study conducted in Germany by Saidi et al. used a multistage MBBR system to treat greywater (8–11 m^3 d^{-1}) with an HRT of 1.2–1.6 days. The system consisted of ten tanks, each with a capacity of 1.3 m^3. The first eight tanks and the 10th were MBBRs, while the 9th was a sedimentation tank, achieving 94% COD removal overall and yielding 22 mg L^{-1} of COD in the MBBR effluent [67]. MBBR technology, in combination with other approaches, has also been commercialized for household greywater reuse.

The membrane biofilm reactor (MBfR) method combines biofilm technology with a membrane unit (see section 3.1.2) and allows biofilm formation by supplying a gaseous substrate through a porous membrane. This technology is also called a membrane-aerated biofilm reactor (MABR). An MBfR has been shown in the literature to be able to remove organic and inorganic contaminants, such as surfactants and nitrogen, in greywater [50,68,69]. Zhou et al. [50] reported an MBfR successfully achieved 93.8% of surfactant removal and 80% of TN removal at an organic loading rate of 4.26 g COD m^{-2} day^{-1}.

3.1.2. MBR technologies

The MBRs can produce excellent effluent qualities by controlling hydraulic retention time (HRT) and solid retention time (SRT) independently and enabling the filtering of suspended solids [70,71]. In most cases, these systems are aerated; thus, the removal process is aerobic. A pilot-scale MBR has been operated at 2 h HRT to treat the greywater generated from households with more than 80% of COD removal efficiency irrespective of the sludge age [72]. When porous membranes are used, undetectable coliform levels cannot be guaranteed in the permeate produced by the MBR [17,71], however. This and other particles coming through cause severe biofouling on reverse osmosis (RO) systems downstream. To combat this, biocarriers can be combined with MBR to yield more than 95% surfactant removal [73–75]. Anaerobic membrane bioreactors (AnMBRs) have also been tested, and these combine an anaerobic bioreactor with membrane filtration, as shown in Fig. 2c. AnMBRs reduce operational energy demands significantly because aeration is not required while producing renewable energy in the form of methane. Since employing AnMBR to treat greywater is nascent compared to aerobic MBR, there is limited evidence to judge its performance in a decentralized set up, however.

There has been considerable attention to surfactants that might limit microbial activity in anaerobic circumstances [76]; concentrations of only 18.9 and 6.3 mg L^{-1} of LAS have been found to inhibit acidogenic and methanogenic activities, respectively, and micro-aeration in AnMBR allows disintegration of aggregated biomass, thereby enhancing the biodegradation of anionic surfactants [77]. A linear relationship between fouling rate and LAS concentration has also been observed in the AnMBR treatment of sewage [78], highlighting the fouling risk these compounds represent. Other approaches to reduce membrane fouling in AnMBR include dislodging the cake layer under high cross-flow velocity on the membrane surface or via biogas sparging along the membrane surface, which can be applied to mitigate the fouling rate [79]. This sparging is decreased in anaerobic fluidized bed membrane bioreactors (AFMBRs), limiting energy demand to 0.05 kWh m^{-3}, accomplished using biocarriers, such as granular

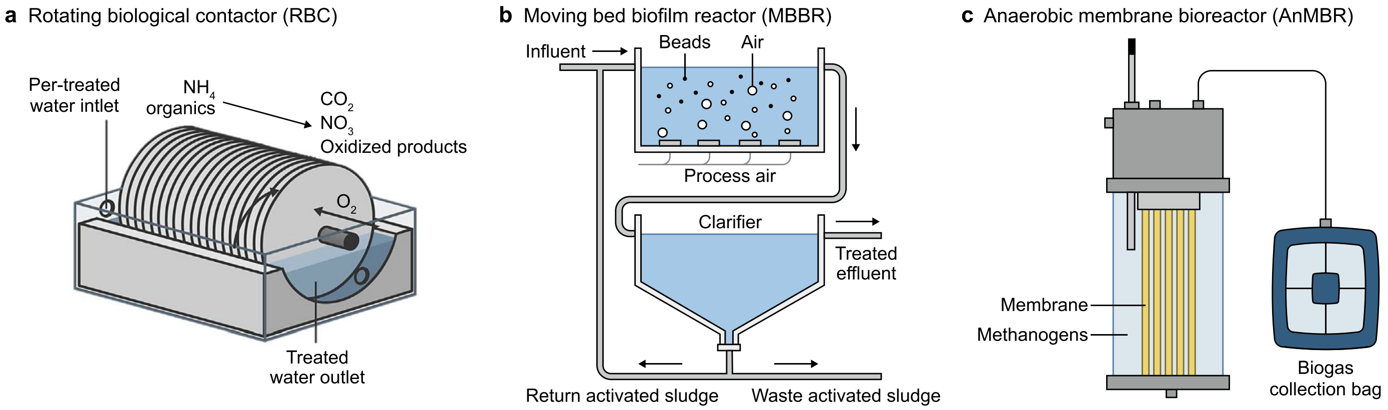

Fig. 2. Schematic representation of rotary biological contactor (**a**), moving-bed biofilm reactor (**b**), and anaerobic membrane bioreactor (**c**) for biological greywater treatment technologies.

activated carbon (GAC), fluidized by recirculating a bulk suspension in the absence of biogas sparging [80].

Membrane-less anaerobic systems such as anaerobic filters or even up-flow anaerobic sludge blanket reactors (UASB) have also shown up to 60–70% BOD_5 removal efficiency [81,82]. This is lower than with membrane filtration alone but more straightforward from an operational perspective. Anaerobic filters have been deployed for greywater treatment in public areas such as airports and have also been integrated with ultraviolet (UV) disinfection as a post-treatment to meet international reuse recommendations [81].

3.1.3. Comparative analysis of treatment technologies

A key issue for greywater reuse is the variation in greywater characteristics depending on the demography, seasonal variations, and living standards. Thus, there is no single universal treatment strategy. Thus, modular architecture for greywater treatment allows for a wide range of options that can be applied as fit-for-purpose deployments and adapted, for instance, to changes in demography [83]. The overall biodegradability of greywater can be characterized by its COD/BOD_5 ratio, and conventional wastewater measurements on untreated greywater generally demonstrate favorable COD/BOD_5 ratios for biodegradation [84].

A detailed comparative analysis of the various treatment strategies employed in different case studies is presented in Table 4. Laundry greywater contains high concentrations of chemical compounds (such as soaps and oils) as well as a significant amount of non-biodegradable fibers. This leads to a considerable increase in the COD/BOD_5 ratio, thereby discouraging the use of traditional biological methods. The preferred treatment method in most cases circles around physio-chemical techniques such as coagulation and ultrafiltration (UF) methods, and these methods yielded a comparatively higher quality treated effluent (laundry wastewater) with the removal of BOD_5 of up to 94.33%. Bathroom greywater can contain organics like hair, and fecal matter along with surfactants and XOCs found in personal care products. Treatment here thus depends on the end use of the treated water and may require post-processing. An extensive review of the efficacies of various treatment strategies for greywater and the impact of different operating parameters has been performed by Khalil and Liu [20], in which the authors concluded that an improved characterization of greywater could help determine the appropriate treatment strategy (although this may be difficult to implement in practice).

As seen in Table 4, two-stage water treatment systems were shown to have a better performance than other singular treatment strategies. However, with current advances in membrane and electrochemical technologies, the use of single-staged MBR systems could suffice to reach required effluent standards. The technical feasibility of greywater treatment with modular construction offers great flexibility in adapting to a catchment area's dynamic development.

3.2. Physico-chemical methods

3.2.1. Membrane filtration

Membrane reactors appear to be ideal for decentralized greywater treatment due to their small footprint and the fact that it is not sensitive to toxic pulses or highly uneven flows. Microfiltration (MF), UF, nanofiltration (NF), and RO membranes can be tailored for greywater treatment depending upon the target contaminants to be removed. However, the biggest disadvantage is that a concentrate is made, and nothing is actually removed by using the membranes themselves. With an MF membrane, particle materials are rejected by membrane filtration almost completely, generating suitable permeate qualities for immediate water reuse purposes. Increasing the transmembrane pressure (TMP) or feed flow rates tend to increase membrane rejection because the cake layer formed on membrane can play a role as a secondary membrane [88]. Indeed, porous membranes, such as MFs, provide relatively small rejection efficiency associated with organic impurities compared to NF and RO membranes, thus requiring suitable post-treatment [89]. This issue is not present with MBR, however, as smaller organic compounds are typically almost completely removed in this case.

Membrane fouling is unavoidable and also adds a barrier to greywater conveyance [84,89,90] as well as a requirement for cleaning strategies, including chemical additions. With greywater, a membrane fouling rate is typically proportional to organic foulant

Table 4
Performance evaluation of various strategies for greywater treatment.

Treatment technologies	Parameters/Permissible limits[a]	Typical values	Effluent concentration	Removal %	References
Coagulation and sand filtration (Laundry wastewater)	BOD_5 (mg L^{-1})/<10	**Refer Table 1**	17.00 ± 8.00	94.30	[85]
RBC	TSS (mg L^{-1})/10		2.00 ± 0.50	95.80 ± 1.00	[86]
	BOD_5 (mg L^{-1})/<10		4.50 ± 0.30	95.00 ± 0.30	
	COD (mg L^{-1})/100		13.00 ± 1.20	95.70 ± 0.40	
	Total N (mg L^{-1})/10		0.55 ± 0.10	93.90 ± 1.60	
Submerged MBR	pH/6–9		6.90	-	[23]
	COD (mg L^{-1})/100		45.00	88.00 ± 9.50	
	Total N (mg L^{-1})/10		3.57	88.00 ± 7.30	
	Total P (mg L^{-1})/0.1		0.74	56.00 ± 18.00	
	Anionic surfactant (mg L^{-1})		4.58	90.00	
MBR	BOD_5 (mg L^{-1})/<10		4.00 ± 2.00	97.00	[75]
	COD (mg L^{-1})/100		16.00 ± 4.00	91.00	
	Total N (mg L^{-1})/10		2.18 ± 0.30	58.00	
	Total P (mg L^{-1})/0.1		0.05	88.00	
UASB	BOD_5 (mg L^{-1})/<10		96.95	67.50	[87]
	COD (mg L^{-1})/100		165.42	57.80	
	TKN (mg L^{-1})/2		28.00	14.10	
	Total P (mg L^{-1})/0.1		10.45	78.40	
UASB + MBR (Two stages)	BOD_5 (mg L^{-1})/<10		6.10	97.40	[87]
	COD (mg L^{-1})/100		8.50	97.80	
	TKN (mg L^{-1})/2		0.95	94.40	
	Total P (mg L^{-1})/0.1		0.05	89.70	

[a] WHO Guidelines for Drinking water quality (WHO, 2006).

content, as discussed above [90]. In general, membrane fouling caused by organic compounds is not removed easily by permeate backwashing because of membrane pore blocking. To reduce the fouling, a ceramic diffuser can be installed underneath the hollow-fiber MF membrane (0.1 μm) to treat greywater [91], where the aeration provided by the ceramic diffuser causes a scouring action to clean the membrane. The use of a ceramic membrane thus has great potential for greywater treatment over polymeric membranes due to its excellent chemical resistance and membrane hydrophilicity.

In addition, membrane functionality can be improved by integrating with various unit technologies, such as chemical oxidation. For instance, a photocatalytic membrane reactor with TiO_2 particles under UV illumination has already been applied to treat greywater [92]. However, a reconcentration step must be considered here in a subsequent process to recover the catalysts such as TiO_2 particles. Otherwise, they may escape from this hybrid membrane reactor [93].

3.2.2. *Sorption and ion exchange*

Elucidating the mechanisms of the adsorptive behavior of organic pollutants present in greywater is an area of intense research. The charge of adsorbents, such as activated carbon, may play an important role in the adsorption capacity of surfactants from greywater. For example, LASs can be adsorbed into positively charged adsorbents to yield more than 90% removal efficiency, which is more than negatively charged or nonionic resins allow (0.6–1.7 vs. 0.02–0.6 g LAS g^{-1}) [16,94], and here the solution pH above or below the point of zero-charge of the adsorbent is a critical parameter. With greywater, adsorption equilibria can be described by Langmuir isotherms [95]. Thus, the adsorption capacity with respect to the organics present in greywater may be limited by the monomolecular layer formed on the adsorbent without interactions between adsorbate molecules [94], as illustrated in Fig. 3a.

Adsorbents can also be used as biofilter media to induce biodegradation and physicochemical adsorption [95,96]. After the adsorption sites of GAC are saturated by organics, bacteria subsequently accumulate to form biological activated carbon (BAC). In an integrated MBR-BAC process, biodegradation has already been found to be the most dominant organic removal mechanism, particularly in the upper region of the filter bed [96]. Nevertheless, an overall removal efficiency of less than 26% based upon greywater TOC was observed [95]. A similar level of TOC removal efficiency (25–42%) has been observed by operating a pilot-scaled BAC filter in greywater treatment showing that these systems perform less than their fully biological analogs described earlier [95,97].

Natural zeolites are also considered to be adsorbents in greywater treatment due to their excellent ion-exchange ability and adsorption capacities, as illustrated in Fig. 3b. The aluminum (Al^{3+}) atom substitution for silicon (Si^{4+}) in the zeolite framework generates a negative charge for high cation-exchange capacity [97]. About 97% of NH_4^+-N can be removed from greywater through natural zeolites, and adjusting the solution pH from 4 to 6 determines the amount of removal of NH_4^+-N more than other parameters [98]. Magnetic ion exchange resin with strong-base functional groups has also been designed to remove dissolved organic carbon in greywater [99], but here combining coagulation is necessary to prevent the agglomeration of resin [99,100].

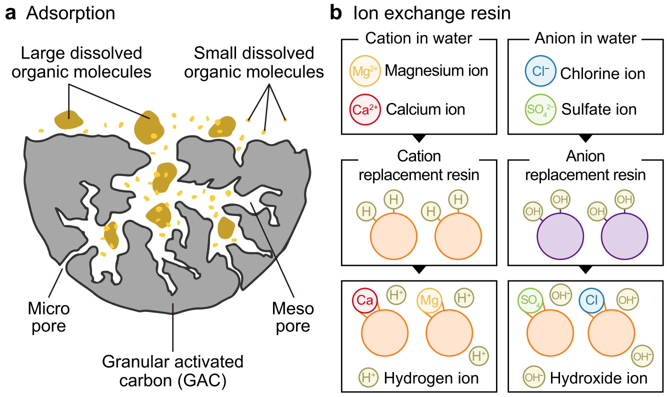

Fig. 3. Removal mechanisms of organic molecules and ionic species of greywater with GAC adsorption (**a**) and ion exchange resin (**b**).

3.3. *Nature-based solutions*

Nature-based solutions (NBSs) have also been investigated for greywater treatment due to their inherent advantages of low-energy demand and organic removal efficiency [101]. Constructed wetlands (CWs) may be considered the cornerstone NBS for greywater treatment, whereas other available NBS, like green roofs and walls, can also mimic the technique of conventional CW treatment processes [6]. Both biodegradation and physicochemical functionality, such as precipitation, filtration, and adsorption through CWs, improve organic removal efficiency [14,102]. For example, Collivignarelli et al. [103] observed 89% COD removal through CW treatment of greywater. Planted wetlands lead to better COD removal efficiencies than unplanted set ups through oxygenation of the beds, causing aerobic degradation in the root zones [104] and in nutrient uptake. Thus, CWs may be suitable as a post-treatment for biological greywater treatment [105].

CWs can also efficiently remove nutrients present in greywater [106]. Wetland plants can assist with the removal of nitrogen and phosphorus because these can be adsorbed into their roots [102]. Fecal coliforms can also be removed by CWs (94–98%) [107]. Nevertheless, the effluent in CWs typically needs further disinfection to meet reuse standards [103,107]. CWs have also been successfully utilized to remove propylene glycol (PG), and trimethyl amine (TMA) from different sources of greywater [102,107,108], and one study showed that sodium dodecyl sulfate (SDS), a representative anionic surfactant, frequently found in greywater, was removed at 94% by CWs alone [108], which is a better rate of removal than MBRs [102]. Finally, the substrate, as well as plant litter, can decompose inside the wetlands [109], and effluent quality can be maintained by controlling its hydraulic retention time [109,110].

4. Challenges to greywater reuse

4.1. *Tailoring treatment processes for greywater reuse and quality control*

The superior quality of greywater relative to mixed domestic wastewater is the basis for an important argument in favor of increased greywater recycling and reuse. However, as discussed in the introduction, elevated levels of contaminants, such as organic micropollutants, salts, and pathogens, require the need for greywater treatment, even for low-quality applications, such as irrigation. When a high degree of circularity is pursued in a (small-scale) water system, excessive accumulation of these contaminants must also be considered [111]. Furthermore, variability in greywater quality necessitates a certain level of robustness in the treatment process. As was illustrated in previous sections, sufficient attention must be paid to disinfection practices in order to tackle (in-line) microbial regrowth, for instance, by applying in-line (e.g., in contact chambers or through residual disinfectants) or post-line disinfection (e.g., UV disinfection) [5]. Particular attention is required when direct human exposure to the reused water is conceivable through accidental ingestion of treated greywater or inhalation of aerosols. However, if greywater treatment follows existing guidelines, epidemiological research suggests no significant health impact [112,113].

Greywater covers a wide range of contaminants, including particulates, colloidal materials, microbiological contents, dissolved organics, and inorganics. The compounds present in the water vary from source to source and depend on lifestyle, customs, installation types, for example, kitchen, bathroom or laundry, and use of chemical household products [55]. The complexity of contaminants introduced by various human activities brings an additional challenge to producing high-quality reclaimed water from greywater beyond conventional processes. So far, a large range of technologies has been developed for greywater reuse, from simple staged processes consisting of prefiltration followed by disinfection to advanced physicochemical and biological processes [99], as discussed above. Nevertheless, technologies for greywater treatment suffer from the variability of feed and shock loading such that these processes need to be optimized and intensified for greywater reuse purposes. For water reuse and energy production, system flows throughout the greywater treatment process should also be designed holistically. For example, organics present in greywater can be maintained at a high level in the concentrated flow due to membrane filtration, which can be treated anaerobically for bioenergy recovery.

4.2. *Legal framework*

In many countries, a lack of a legal framework for greywater management obstructs the development and implementation of wastewater reuse systems. This is especially the case for urban reuse purposes or when considering specific household applications, as a direct personal judgment of target water qualities is often required. On greywater reuse specifically, guidelines are often based on recommendations by inter-governmental organizations, such as the World Health Organization, covering greywater reuse for agricultural irrigation [114], and the National Sanitation Foundation (NSF/ANSI standard 350), which provides water quality guidelines for nonpotable urban applications (toilets and irrigation) [115]. Water quality guidelines often focus on a small range of aesthetic (e.g., turbidity and BOD) and hygienic (e.g., total coliforms) parameters as well, and no international reuse guidelines for the direct potable reuse of greywater have been introduced as of yet.

For existing reuse guidelines, the water quality parameters considered and the categorization of reuse options are not generally in sync between nations and organizations, which hampers effective comparison between the policies of the two [116,117]. In Europe, a new regulation has recently been approved on the minimum requirements for agricultural reuse of wastewater streams that will come into force in June 2023 [118]. In addition, plumbing codes in California, USA [119], Chile [120], and Queensland, Australia [121] already provide regulations and guidance on the installation and operation of (closed-loop) greywater reuse systems.

4.3. *Monitoring and controlling greywater systems*

As greywater reuse is most often considered on a decentralized and small scale, a faster response to treatment process malfunctions is required than for centralized and larger scale systems. This requires rapid, preferably online, monitoring practices. No single parameter sensor can indicate the water quality as a whole, and as such a multi-parameter approach becomes necessary [122]. In reuse systems that apply membrane technology, membrane integrity could, for instance, be monitored by continuously tracking turbidity, TOC, conductivity, and/or sulfate levels as key parameters [123]. Moreover, fluorescence spectroscopy can effectively detect the presence of low concentrations of organic compounds in effluent [124]. Today, the possibility for online detection of microbial contamination in decentralized water systems is limited, but microbial fingerprinting techniques are promising [125]. However, these technologies are not yet cost-efficient in smaller-scale installations.

Another obstacle to adopting reuse systems is the lack of effective and standardized testing procedures to evaluate health and environmental risks associated with specific treatment systems for specific (micro-)pollutants [126]. Legislation surrounding greywater reuse is often implemented in a one-size-fits-all manner, pinning down high-quality standards for reuse and thus simplifying compliance and control and minimizing perceived risks by the public. However, this ignores the benefits of a fit-for-purpose approach to decentralized water recycling and discourages certain reuse applications, and leads to potentially unnecessary treatment costs [114,127].

4.4. *The consumer perspective*

The consumer perspective is another crucial factor before implementing greywater reuse systems. This perspective sits on a more local and household-level scale. Decentralization (at least partly) shifts responsibility from larger institutions, such as public water providers, to the individual level, in certain cases demanding behavioral changes from users that range from choices of detergents to the use of water itself.

In many cases, building developers are the primary client for greywater systems. However, they are often influenced by their own end customer and their requirements in a more direct manner. Consumers themselves have been shown to have varying degrees of acceptance of greywater reuse systems, depending on a wide range of factors. One major factor in public acceptance of greywater reuse is the degree of human contact with the reclaimed water, with the consumer being most reluctant to accept potable reuse [128]. In light of this, the “yuck-factor” is often mentioned, a term describing the instinctive reaction of disgust associated with reclaimed water, independent of the actual water quality [129].

However, more reasoned arguments also determine consumer acceptance of greywater reuse. For example, economic incentives, such as cost savings on water expenditures, lead to a higher degree of acceptance towards water reuse practices, and this sits alongside evidence that reducing personal environmental impact can be a strong driver of acceptance [130–132]. Trust in authorities also determines the acceptance of water reuse [128].

Some authors also consider “social justice” in terms of water equity, another important aspect that governs the social acceptance of decentralized technologies [2]. Additionally, research by Garcia-Cuerva et al. [130] indicates that regions that have recently experienced a drought have a higher percentage of reclaimed water supporters. Another important factor is the quality of the operational regime that can be put in place, which entails maintenance aspects and frequency of system malfunctions (e.g., unpleasant odors), which has been shown to influence acceptance to a large extent [133]. When it comes to the communication necessary to increase public acceptance of greywater reuse, a mix of addressing all of these concerns is recommended as acceptance is to a large extent influenced by both [134], and addressing an individual's normative beliefs, both social and personal, has been shown to influence behavior and acceptance [132,135].

However, consumer perception of centralized water supply systems might be the most important factor that influences the perception of decentralized systems. Since the dawn of centralized water supplies, incidents with contaminants and deteriorated water quality have occurred regularly [136], negatively influencing public trust in tap water [137].

5. Opportunities for greywater reuse

5.1. The potential for high water savings: the first and foremost driver of greywater treatment

Water savings and the resulting alleviation of stress on water bodies, together with the associated cost reductions, are key arguments in favor of greywater reuse, and this can be attributed to the large availability of greywater, up to 90% of all domestic wastewater produced [59]. Key water savings come from avoiding water transport via piped networks, which is of special interest, particularly in large, growing cities. Greywater reuse for toilet flushing alone could allow for water savings of up to 30% for households and up to 60% for office buildings [138]. Additionally, considering reuse for garden irrigation can increase savings by 40% for households [139]. Considering average wastewater quantities in developed countries and assuming complete reuse of all greywater streams, total water savings of up to 80% could theoretically be achieved [8].

Alongside the available quantities of greywater, recycling is also preferable because greywater production temporally matches water consumption, in contrast to variable rainwater harvesting. The greywater flows are available for reuse depending on the number of occupants and their associated water use, with a higher number of users leading to more stable greywater production and use, although flow equalization remains crucial. For this, storage of treated greywater is an important point of attention as varying use (e.g., through toilet flushing) can certainly temporarily exceed the water flow throughout the treatment system. Consequently, water savings depend greatly on the considered storage options, with larger storage basins leading to less overflow and larger buildings benefiting from more equalization. Furthermore, as mentioned earlier, storage systems also have to be supplied with a means of disinfection.

With increasing reuse, another important concern is the increased likelihood of odor, piping blockage, corrosion, and sedimentation in the sewer network due to more concentrated wastewater streams, as the less concentrated streams are the most suited to be reused (e.g., for toilet flushing). Research by Penn et al. [140,141] shows that in terms of the effect of greywater reuse on the water grid, there is little evidence to suggest that there is an increased risk of piping blockage, except in more upstream pipes where the lower flow rates decrease the ability to carry solids along. Greywater reuse has also been shown to flatten diurnal trends in water flows across the grid. Associated lower wastewater flow rates through the sewer system in dense urban areas would also prevent the necessity of increasing sewer pipeline sizes, thus avoiding the large associated costs.

5.2. Energy savings and sustainability

The water sector is known to have a considerable energy consumption and greenhouse gas (GHG) footprint and is also extremely vulnerable to the effects of climate change [142]. The energy cost to transport water in centralized water management systems in the United States is estimated to be, on average, four times the energy required for the actual water treatment and is as high as 20 times in California, with treatment and transport making up 4% of the nation's total electricity consumption [143,144]. An additional energy cost of 2.5 kWh m^{-3} has been estimated for the transport of water over a distance of 100 km with a 250 m height increase [145]. When energy requirements for pumping in centralized water supply systems are high, small-scale greywater reuse especially has the potential to reduce energy consumption for water provision significantly [146], provided the greywater system's pumping costs do not exceed the energy savings.

Due to coming climate change mitigation measures in the water sector, water supply costs are expected to increase globally [147]. This indicates the importance of including a sustainability assessment before the introduction of new approaches in water management. For greywater reuse systems, the question of (long-term) sustainability in terms of energy and material use and GHG emissions is subject to a rapidly growing body of research. Here, life cycle assessments (LCAs) have been frequently used to assess the environmental impact throughout the entire life cycle of the technology and can be used ex-ante to steer system design and policy choices [148,149]. In terms of energy consumption, the principal advantages of decentralized water management are (1) a reduction in energy requirements for the conveyance of water, (2) the possibility of thermal energy recovery as human activities increase the water temperature, and (3) allowing source separation between energy-poor and energy-concentrated water streams.

5.3. Saving energy within buildings

Since tackling the energy use of single buildings forms an important objective in decreasing total energy use, looking into energy recovery solutions at this scale is worthwhile [150]. Of the total household energy consumption in the European Union, 14.8% is used to heat water [151]. Moreover, more effective insulation of buildings could lead to a being used to heat water. In this case, thermal energy recovery of greywater may allow for household energy savings of up to 40% [152]. As a whole, however, when decentralized greywater treatment units are installed, the total household energy consumption is expected to increase [153].

In Table 5, the energy demand, advantages, challenges, and costs of several greywater reuse systems from the literature are presented. For reference, centralized water management, including potable water production and distribution and wastewater collection and treatment, generally has an energy consumption of 0.58–2.11 kWh m^{-3} [154]. For energy savings or production in decentralized greywater treatment, system design must be holistically considered. For instance, for MBRs, many opportunities exist to meet multiple water-quality criteria in greywater treatment, but more than 50% of the energy requirements are for aeration for microbial growth and membrane fouling reduction. Low energy fouling control and its optimization in MBR systems require more study [155].

In terms of energy recovery, organics present in greywater can be maintained at high levels in the concentrated flow when membrane filtration is used, after which it could be treated anaerobically to recover bioenergy in the form of methane. Toward this end, the AFMBR discussed above is a promising technology [80], provided there is a need for methane on-site or at least a means to avoid its emission or to capture it. Here again, though, membrane fouling needs to be controlled effectively and economically. Although the energy produced by the AFMBR may be satisfied by using only a small portion of the gaseous methane energy produced [80], further research is needed to address methane yield per the unit of biodegradable organics in greywater treated by AFMBRs.

Table 5
Energy demand and operational characteristics of greywater treatment systems.

Technology	Scale (m^3 day^{-1})	Energy demand (kWh m^{-3})	Efficiency	Cost (€ m^{-3})	Advantage	Challenges	References
Membrane bio-reactor	3-30	5.6-6.1[a]	BOD$_5$ = 96-98%, COD = 90-92%, TN = 49-63%, TP = 88-90% [75],[b]	-	Low footprint, good biomass retention for increased organic removal	Energy-intensive. High operating and maintenance costs are required. Frequent fouling problems and chemical cleaning are needed.	[156]
Membrane bio-reactor + Chlorination	1.5	2.9	COD = 90%, BOD$_5$ = 95%, SS = 98%, Surfactant = 98%, *E.coli* = log4.	5-6	Low footprint, good biomass retention for increased organic removal, extra disinfection to avoid health risks, compliance with water standards	An additional cost of chlorination apart from the challenges mentioned for membrane bioreactors	[155]
Integrated fixed-film activated sludge	0.03	-	COD = 92.52%, LAS = 94.24%, Oil and grease = 90.07%	-	Higher resistance to organic and hydraulic loading than conventional activated sludge	High construction and maintenance cost, expert knowledge required, high energy consumption due to aeration	[157]
Aerobic fluidized bed reactor	0.14	-	COD = 73%, Anionic surfactant = 57%, TN = 42%, TSS = 66%, DOC = 52%	-	Excellent mixing and high mass transfer for good biodegradation, fluidized materials accommodate microbial growth	Expert knowledge is required for maintenance and operation.	[158]
Moving bed biofilm reactor + UV disinfection	1	2.4	COD = 93%, BOD$_5$ = 97%,	-	Higher biomass concentration, higher organic removal, lower hydraulic residence times, sound mixing and mass transfer, and disinfection ensure microorganisms removal	Manual monitoring is required. Insects are attracted to biofilm reactors. Biocarriers can wash out of the reactor over time.	[159]
Rotating biological contactor	0.0043-0.3000	1.2	COD = 84-89%, BOD$_5$ = 94%, TSS = 90%, TKN = 75%	0.1	Low operational cost, low technical personnel requirements, good organic removal	Limited removal of pathogens and extra filtration is often needed to filter biofilm particles.	[160]
Gravity-driven membrane bioreactor	0.0014-0.0029	0.02-0.04	TOC = 80-95%	-	No backwashing or chemical and physical cleaning are required, and low energy requirement	Low permeate flux, membrane fouling	[161]
Nano-filtration membrane treatment	52	10	COD = 98.0-99.7%, TOC = 97.7-99.6%, Salinity = 70%, SS = 100%, *E. coli* = 100%	5-6	Higher rejection efficiency, potent for the separation of small organic molecules, used in the desalination process	Prone to membrane fouling, high operating cost involves membrane cleaning, an energy-intensive process	[162]
Moving bed biofilm membrane reactor	0.2	1.26-4.42	COD = 64%, BOD$_5$ = 95%, TSS = 98%, TN = 79%, PO$_4$-P = 91%, NH$_4$-N = 78%	-	Higher biomass concentration, higher organic removal, lower hydraulic residence times, sound mixing and mass transfer, lower membrane fouling	Manual monitoring is required. The choice of bio-carriers is important for fouling reduction and microorganism growth.	[163]
Electrocoagulation	-	6.89-15.5	COD = 31-98%, TP = 80-94%, TN = 47-83%, TSS = 99%	-	No chemicals are needed, and efficient removal of suspended solids	High energy requirement, high operational cost	[164]
Horizontal flow constructed wetland	0.023-0.07	-	COD >89%, BOD$_5$ > 88%, TSS >85%, TP = 50.7-54.6%, TN = 42.5-77.6%	-	Good organics removal, low energy requirement, low operating cost, serve aesthetic purposes.	High HRT, limited removal of pathogens, and a high amount of space is required	[103]

[a] Highest energy consumption is associated with the smallest scale (increasing economies of scale).
[b] Data are derived from a separate study but for a similar type of treatment setup.

5.4. General sustainability assessment

In terms of direct and long-term environmental impacts, greywater reuse systems are a double-edged sword. Masmoudi Jabri et al. [159] compared the direct reuse of greywater to discharge into the environment followed by the same treatment on the scale of a residential building through LCA and found that reuse significantly decreased toxicity effects in the environment (by 1.6–16.2%) and eutrophication potential (by 17%). However, GHG emissions (by 2%) and human toxicity effects (by 51.8%) increased with greywater reuse. The latter was mainly due to the footprint of polyvinyl chloride piping, which was necessary to transport the treated greywater throughout the building. In another study, Kobayashi et al. [165] found that local greywater reuse could reduce GHG emissions, eutrophication potential, and human health risks for community water provision compared to a centralized water supply, with positive effects increasing with scale (5–3500 people served). They also emphasized that the construction phase was found to be the major contributor (40–90%) to all assessed impact categories.

In terms of environmental impacts, nature-based solutions in greywater reuse have generally been deemed to be the least impactful [6], but they evidently require the largest land footprint. Furthermore, when considering decentralized reuse options, the local energy source used is a major contributor to the total environmental impact of the system [148,166], highlighting the importance of connecting clean energy sources to decentralized water management. Finally, future research may address the impact and resource requirements of greywater reuse systems and compare them to centralized alternatives, as the sustainability of such decentralized systems has been shown to be heavily context-specific.

6. Conclusions

In light of global challenges, such as climate change and rapid urbanization, improving the robustness and sustainability of water management is of critical importance. For this reason, the available knowledge on greywater, its reuse potential, and state-of-the-art of greywater reuse technologies was collected and discussed in this review. The main arguments in favor of considering local greywater reuse can be categorized as follows: (1) high availability of greywater quantities, e.g., matching the presence of users in buildings; (2) a generally lower degree of pollution, entailing lower treatment needs than general domestic wastewaters; and (3) advantages related to high energy content and sustainability.

The key obstacles to reuse were found to be (1) the presence of challenging greywater quality characteristics, which may entail human and environmental health risks; (2) a lack of a legal framework for greywater management; (3) the assurance of good monitoring practices to guarantee consumer safety; and (4) negative consumer perspectives on such reuse practices. A particular focus was provided on the energy consumption of greywater treatment systems and the potential for energy savings, showing a high potential for energy efficiency, even at small scales. Furthermore, we showed that a shift of responsibility from centralized (e.g., government) to decentralized (e.g., individual households) control could lead to increased monitoring and control of the necessary treatment and a greater focus on the importance of consumer perspectives. Overall, we have a positive outlook on integrating extensive greywater reuse in water management. A holistic view of local management needs and context-specific implementations of reuse solutions may allow for a more robust water system as a whole.

CRediT authorship contribution statement

Arjen Van de Walle: Investigation, Writing-original draft. **Minseok Kim:** Investigation, Writing-original draft. **Md Kawser Alam:** Investigation, Writing-original draft. **Xiaofei Wang:** Investigation, Writing-Review & Editing. **Di Wu:** Investigation, Writing-Review & Editing. **Smruti Ranjan Dash:** Investigation, Writing-Review & Editing. **Korneel Rabaey:** Conceptualization, Investigation, Writing-Review & Editing. **Jeonghwan Kim:** Conceptualization, Investigation, Writing-Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

KR and AVDW are supported by De Watergroep. This work was conducted within the framework of the CAPTURE (Centre for Advanced Process Technology for Urban Resource recovery) initiative. XW is supported by the Special Research Fund from Ghent University, BOF.PDO.2021.0036.01. This work was also supported under the framework of the international cooperation program managed by the National Research Foundation of Korea (2020K2A9A1A06103416) and by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (2022R1A4A3029607). We would like to thank Tim Lacoere for his contributions to the figures.

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