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REVIEW ARTICLE

Recent insights into greywater treatment: a comprehensive review on characteristics, treatment technologies, and pollutant removal mechanisms

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Abstract

With the rapid socio-economic and industrial development, the problem of water shortage is becoming increasingly serious. Seeking alternative water sources to reduce the need for freshwater resources is an increasing concern. Household greywater production is high and accounts for about 50–80% of domestic wastewater. In recent years, the in situ treatment and reuse of greywater have received widespread attention. Treated greywater can be used for non-potable purposes such as toilet flushing and irrigation, which can greatly reduce the pressure of freshwater resource shortage. This paper reviews the sources and characteristics of greywater and analyzes its quantity and quality. In addition, this paper outlines and summarizes various greywater treatment technologies commonly used, including physical, biological, and chemical treatment technologies, as well as combination technologies. Understanding the mechanisms of contaminant removal is essential for effective greywater treatment. While discussing different treatment technologies, we focus on the removal mechanisms of pollutants from greywater, including organics, nutrients, surfactants, and emerging contaminants. Finally, future perspectives on greywater management and reuse are presented. Through a comprehensive review, we expect that this review will help the reader to better understand the characteristics of greywater and to more rationally select the appropriate treatment technology based on the removal mechanism of pollutants.

Keywords Wastewater · Reuse · Organics removal · Nutrients removal · Surfactants, Emerging contaminants

Abbreviations

ADB	Autotrophic-denitrifying bacteria
AHTN	Tuina musk
AMO	Ammonia monooxygenase
AOB	Ammonia-oxidizing bacteria
AOC	Assimilable organic carbon
AOP	Advanced oxidation process technologies
BAC	Biological-activated carbon
BAMBi	Biologically activated membrane bioreactor
BBP	Butyl benzyl phthalate
BDD	Boron-doped diamond
BOD	Biological oxygen demand
BOD_5	5-day biochemical oxygen demand
BP	Benzophenone-3 or 2-hydroxy-4-methoxy benzophenone
C/B	COD/BOD
CFU	Colony-forming unit
CMC	Critical micelle concentration
COD/COD_{Cr}	Chemical oxygen demand
CuZ	Copper-coated zeolite
CW	Constructed wetland
DEET	Diethyltoluamide
DEHP	Phthalate di-(2-ethylhexyl) phthalate
DEP	Diethyl phthalate
DnBP	Di-n-butyl phthalate

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DO	Dissolved oxygen
DOC	Dissolved organic carbon
EC	Electrocoagulation
E. coli	*Escherichia coli*
EDCs	Endocrine-disrupting compounds
EHMC	Ethylhexyl methoxycinnamate
FC	Fecal coliforms
GAC	Granular-activated carbon
GROW	Green roof-top water recycling system
HDB	Heterotrophic-denitrifying bacteria
HHCB	Jiale musk
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
IFAS	Integrated fixed-film activated sludge
LAS	Linear alkylbenzene sulfonates
LSVF	Laterite soil vegetated filter
LSVVF	Laterite soil vegetated vermifilter
MBR	Membrane bioreactor
MSL	Multi-soil-layering
NOB	Nitrite-oxidizing bacteria
NP	Isomers of 4-nonylphenol
NP-TiO_2	Nitrogen-doped TiO_2
O_2-MBfR	Oxygen-based membrane biofilm reactor
OLR	Organic loading rate
OP	4-tertoctylphenol
PAOs	Phosphate-accumulating organisms
PCPs	Personal care products,
PG	Propylene glycol
PhACs	Pharmaceutically active compounds
PPB	Propylparaben
PPCPs	pharmaceuticals and personal care products
RO	Reverse osmosis
SDBS	Sodium dodecylbenzene sulfonate
SDS	Sodium dodecyl sulphate
SEM	Scanning electron microscope
SGF	Sand gravel filter
SMBR	Submerged membrane bioreactor
SPE	Solid polymer electrolytes
TC	Total coliforms
TDS	Total dissolved solids
TKN	Total kjeldahl nitrogen
TMA	Trimethyl amine
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
TSS	Total suspended solids
UF	Ultrafiltration
VUV/UV	Vacuum-ultraviolet
WCCW	Wall cascade CW
XOCs	Xenobiotic organic compounds

Introduction

In recent decades, water scarcity has become an increasingly serious problem. Based on this, wastewater recycling has been and continues to be implemented all over the world, including increasing water availability, fighting water shortages and droughts, and supporting environmental and public health protection. The effective and safe reuse of greywater in arid and semi-arid regions cannot only achieve water sustainability, but also better contribute to a healthy local ecosystem. It has been reported that greywater could provide Egypt with 4.15–8.30 billion cubic meters of water annually, supporting the transformation of Egypt into a country with a sustainable future (Batisha 2020). The content of pathogens and organics in greywater is low, and its proportion in domestic wastewater can reach 80% (Friedler and Hadari 2006). Due to its simple composition and a large volume of water, the local treatment and reuse of greywater is one of the most interesting issues in wastewater reuse today. The reused greywater can be used for toilet flushing, agricultural irrigation, and car washing (Etchepare and van der Hoek 2015). Therefore, if greywater can be effectively treated and reused for non-potable purposes, it is expected to significantly reduce the demand for freshwater resources and contribute to the achievement of sustainable development. It is worth noting that in recent years, many studies have found that greywater contains not only some conventional pollutants, but also a lot of emerging contaminants, such as nonylphenol, triclosan, bisphenol A, and caffeine (Khajvand et al. 2022). Besides, greywater may also contain a certain amount of dyes and heavy metals (Khajvand et al. 2022; Czech et al. 2020), and if these substances are discharged directly without any treatment, it will have a certain degree of impact on plants, animals, humans, and the ecological environment. Therefore, greywater must be treated to meet the standards before it is discharged into the environment or used for other purposes. In another aspect, although greywater has a low number of pathogenic bacteria due to the absence of fecal contamination, it still contains some amount of *E. coli* and other bacteria especially in kitchen greywater, which may be derived from washing meat products. A recent study pointed out that except the *E. coli*, untreated greywater may have a risk of *Cryptosporidium* spp. and *Campylobacter* spp. infection if used directly for toilet flushing or garden watering (Gonçalves et al. 2021).

Reuse of greywater has been achieved in several countries which have a high level of economy. Australia has established guidelines for greywater reuse and offers rebates for the installation of greywater systems. In Tokyo, Japan, greywater recycling is mandatory for buildings that are 30,000 m^2 in size or have a potential non-potable demand of more than 100 cubic meters per day. The Palo Alto and California government promote incentives to help offset the high costs associated with the installation of greywater treatment systems. In order to meet the local water standards or guidelines and to mitigate the environmental problems caused by the casual discharge of greywater, various techniques have been investigated to treat greywater, including physical, chemical, and biological methods.

Several previous reviews have discussed the sources and characteristics of greywater as well as treatment technologies (Ghunmi et al. 2011; Ghaitidak and Yadav 2013; Li et al. 2009; Benami et al. 2016). To the best of our knowledge, however, most of the reviews on this topic were published 5 years ago and none of these reviews places an emphasis on removal mechanisms of pollutants present in the greywater. Our review outlines the recent advances in the development of greywater treatment with a focus on removal mechanisms of both commonly found pollutants and emerging pollutant such as PPCPs. Understanding the removal mechanisms of organics, nutrients, surfactants as well as emerging contaminants in greywater can help guide future research directions and select the most appropriate wastewater treatment technologies, even to save costs and resources. In addition, although the previous studies have been extensive review the greywater treatment technologies, in recent years, there are some new greywater treatment technologies, such as green wall and MSL. Given the previous work, this review has further integrated the greywater treatment technologies in the past 5 years and focus on the pollutant removal mechanisms.

Based on the above reasons, this article aims to further comprehensively summarize the characteristics of greywater, analyze the quantity and quality from different sources, and compare the effect of various treatment technologies. The focus was placed on revealing the removal mechanism of organics, nutrients, surfactants, and emerging contaminants in greywater. Finally, recommendations are also provided for future research directions in greywater treatment.

Greywater characteristics

Greywater source

Generally speaking, greywater refers to household wastewater from the kitchen, bathroom, hand basin, and laundry machine, but does not include wastewater from the toilet (Eriksson et al. 2002; Saumya et al. 2015). The quality of greywater depends on geographical location, climatic feature, the lifestyle of resident, and the quality of water source. Greywater contains about 30% of the total organic load, 10% of the total nitrogen, and fewer pathogenic organisms present in domestic wastewater (Eriksson et al. 2002; Fountoulakis et al. 2016).

Greywater composition

Greywater accounts for 50–80% of domestic wastewater (Teh et al. 2015; Shaikh et al. 2019; Ghaitidak and Yadav 2013). According to previous research reports, for the greywater from washbasin, the main ingredients include soap, toothpaste, PCPs, skin cells, and moisturizing cream, soap occupied the main ingredients, dry weight accounted for about 90% (Ziemba et al. 2018). In general, handwashing greywater is biologically deficient in nitrogen, phosphorus, and other nutrients relative to carbon. Kitchen greywater contains cleaning agents, detergents, and other alkaline chemical pollutants, in addition to oil, food residues, fruit, and vegetable peel (Shaikh and Ahammed 2020). Due to the presence of a large number of biodegradable organic pollutants, kitchen greywater is more vulnerable to heat-resistant coliform contamination (Li et al. 2009). Bathroom greywater contains soap, detergent, and other surfactants, containing a large number of chemical pollutants, also contains skin, trace urine, hair, sand, body fat, and so on. Laundry greywater includes detergents, oils, and clothing fibers. These substances cause laundry greywater to contain different levels of suspended solids, salts, nutrients, organics, and pathogens. Besides, greywater also contains XOCs, which could reduce the surface tension of water and damage the living environment of aquatic organisms (Chandra Pragada and Thalla 2021).

The composition of greywater is complex, in addition to a variety of commonly reported organic compounds and nutrients, most recent studies also showed that it contains a certain amount of microcontaminants that pose a risk to the environment. The types and concentrations of emerging pollutants in greywater are summarized in Table 1. Zraunig et al. (2019) monitored the micropollutants in greywater from a large Euro-Mediterranean resort and, they found that the main types of micropollutants were PhACs and EDCs. Chandra Pragada and Thalla (2021) reported the presence of triclosan in greywater. Triclosan is a spectroscopically synthesized antimicrobial agent widely used in PPCPs, deodorants, toothpastes, body washes, and laundry detergents (Jagini et al. 2019).

The composition of greywater can also be influenced by geographic location. For example, BP, commonly used in PCPs, has been detected in greywater in many regions, with values of 7–50 ug/L in Israel and about 1 ug/L in the Netherlands, where latitude is much higher and UV intensity is more limited (Priyanka et al. 2020).

Table 1 Emerging contaminants in greywater

Emerging contaminants	Concentration (µg/L)	Geographical location	Ref.
3,4-dichloroaniline	0.05	Australia	(Turner et al. 2019)
Acesulfame	0.4		
Benzotriazole (1H-benzotriazole, 5-methyl)	16		
Butylated hydroxytoluene (BHT-2,6-di-t-butyl-p-cresol)	1.8		
Caffeine	450		
Decachlorobiphenyl	96		
DEET (N, N-diethyl-meta-toluamide)	1.5		
Dibromobiphenyl	121		
Diclofenac	0.01		
Diuron	0.05		
Galaxolide	24		
Ibuprofen	2.2		
Musk xylene (2-nitro-m-xylen)	36		
Paracetamol (acetaminophen)	0.09		
Piperonyl butoxide	1		
Propoxur	0.01		
Pyrene-d10	120		
Salicylic acid	7.1		
Tonalid	1.5		
Triclosan	21		
Triphenyl phosphate	133		
Tris(chloropropyl) phosphate isomers	1.5		
OP	0.26–0.48	France	(Deshayes et al. 2017)
NP	0.56–5.21		
DEP	2.43–42.6		
DnBP	3.22–31.0		
BBP	0.41–18.9		
DEHP	11.3–197		
PG	11.58–46.59*	India	(Ramprasad et al. 2017)
TMA	8.67–15.54*		
Acetaminophen	256.1 ± 875.3	Spain	(Zraunig et al. 2019)
Carbamazepine	1.18 ± 7.57		
Sulfamethoxazole	0.06 ± 0.39		
Atenolol	0.69 ± 2.53		
Iopromide	0.003 ± 0.006		
Hydrochlorothiazide	0.32 ±0.81		
Salbutamol	0.01 ± 0.06		
Caffeine	16.7 ± 20.8		
Estrone	0.02 ± 0.07		
Bisphenol A	0.27 ± 0.45		
Methylparaben	6.88 ± 8.91		
Triclosan	0.20 ± 0.47		
BP	7–50	Israel	(Priyanka et al. 2020)
BP	1	Netherlands	

*mg/L

Greywater quantity and quality

The quantity and quality characteristics of greywater will be affected by various factors, such as infrastructure construction, residents' lifestyle and water use habits, income, climate, religion and culture, as well as age (Chrispim and Nolasco 2017; Oteng-Peprah et al. 2018).

Greywater quantity

According to published literatures (Antonopoulou et al. 2013; Oteng-Peprah et al. 2018; Penn et al. 2012; Palmquist and Hanæus 2005; Krozer et al. 2010; Zhang et al. 2009; Mandal et al. 2011; Oh et al. 2018), there are some differences in the quantity of greywater produced by residents in economically developed countries and developing countries. Figure 1 lists the quantity of greywater in several countries. It can be seen that the proportion of greywater to total wastewater is 42.9–89.1% in all listed countries. In economically developed countries such as the USA, Israel, and Australia, the output of greywater is between 100.4 and 208 L/p·day, while in economically underdeveloped countries such as China, Ghana, and India, the yield of greywater is between 73 and 117 L/p·day, it is significantly higher in high-income countries than in low-income countries. The quantity of greywater will vary greatly due to the differences in economic conditions, geographical locations, and living habits. It is noteworthy that the total wastewater production in Australia and Malaysia is similar, with yields of 201 and 226 L/p·day, respectively, but the production of greywater in Malaysia is about half that of Australia, which may be due to the huge living habits of the inhabitants of the two regions.

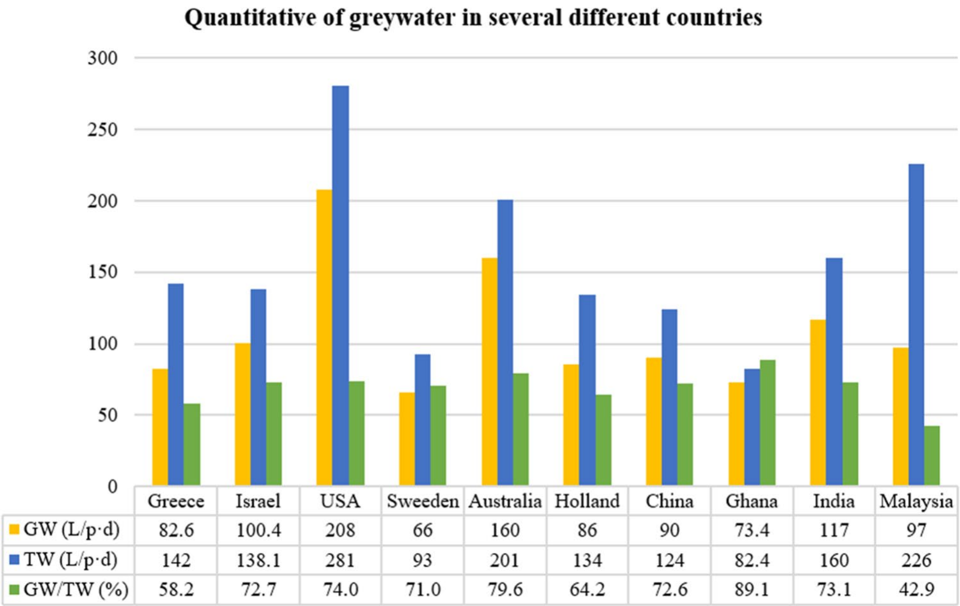
Greywater quality

According to previous research reports, different sources of household greywater (shower, washbasin, kitchen sink, washing machine) have different contributions to pollutant load (Antonopoulou et al. 2013). Table 2 shows the characteristics of different types of greywater. It can be observed that there are significant differences in the quality of greywater from different sources.

The ratio of COD to BOD determines whether wastewater is suitable for biological treatment. Li et al. (2009) reported that when C/B is less than 2.5, greywater is easy to be biodegraded. As can be seen from Table 2, the C/B of most greywater is below 3, especially the bathroom greywater, which is less than 2.5 in the literature listed in Table 2, indicating that most of the greywater has good biodegradability.

The ratio of COD:N:P is also an important parameter for the suitability of biological treatment of greywater (Li et al. 2009), and aerobic treatment is suitable when COD:N:P is 100:20:1 (Fountoulakis et al. 2009). Analyzing the literature presented in Table 2, the lack of P in laundry greywater was noted, which may be related to the worldwide ban or restriction on the use of phosphorus-containing detergents in recent years. Both bathroom and kitchen greywater exhibited a distinctive feature-deficient in N. It is probably due to the absence of urine and feces in greywater that causes this feature to appear in greywater.

The pH of the greywater from different sources was significantly different, with laundry greywater almost always having a pH greater than 9, much higher than that of other sources. This may be due to the alkalinity of the detergent or soap used for laundry. In addition, kitchen greywater has the lowest pH, which is because greywater generated in kitchens



	Greece	Israel	USA	Sweeden	Australia	Holland	China	Ghana	India	Malaysia
🟨 GW (L/p·d)	82.6	100.4	208	66	160	86	90	73.4	117	97
🟦 TW (L/p·d)	142	138.1	281	93	201	134	124	82.4	160	226
🟩 GW/TW (%)	58.2	72.7	74.0	71.0	79.6	64.2	72.6	89.1	73.1	42.9

Fig. 1 Quantitative of greywater in several different countries (GW, greywater; TW, total wastewater) (Antonopoulou et al. 2013; Penn et al. 2012; Palmquist and Hanæus 2005; Krozer et al. 2010; Zhang et al. 2009; Oteng-Peprah et al. 2018; Mandal et al. 2011; Oh et al. 2018)

Table 2 Characteristics of different types of greywater

Greywater Type	pH	TSS (mg/l)	TDS (mg/l)	Turbidity (NTU)	Surfactant (mg/l)	COD (mg/l)	BOD (mg/l)	TN (mg/l)	NH_4-N (mg/l)	NO_3−N (mg/l)	TP (mg/l)	*E.coli* (CFU/100ml)	Total Coliforms (CFU/100ml)	Ref
Laundry	9.95	-	-	70	-	1353	-	-	<0.28	<0.36	-	-	-	(Hardie et al. 2021)
Laundry	-	-	749	106	-	-	290	-	-	-	-	-	-	(Saumya et al. 2015)
Laundry	9.66	-	-	45	40.82	-	-	-	-	-	-	-	-	(Corona et al. 2021)
Laundry	9.2±0.5	60±20	-	71±3	-	628 ± 20	-	-	-	-	-	-	-	(Khosravanipour Mostafazadeh et al. 2019)
Laundry	7.1	95	-	162	37	466	-	33	-	-	1.3	3.6×10^5	4.8×10^5	(Alsulaili and Hamoda 2015)
Bathroom	6.13	81	-	-	-	445	349	-	-	-	-	4.5×10^5	1.10×10^8	(Noutsopoulos et al. 2018)
Bathroom	7.7	57.5	-	68	7.1	302	138	23	-	-	3	3.3×10^4	-	(Santasmasas et al. 2013)
Bathroom	6.0	88	192	-	-	345	180	5.3	0.24	0.01	14	-	-	(Yashni et al. 2020)
Bathroom	6.45	78	74.24	-	-	324	130	10	0.022	0.01	18	-	-	(Yashni et al. 2020)
Bathroom	6.3-6.73	-	-	70.7-160.3	-	251–507.5	81–270.8	-	-	-	-	2.5×10^4–6.1×10^5	-	(Oh et al. 2016)
Kitchen	6.25	3589	-	252	-	2074.5	604.5	-	-	-	-	-	-	(Bakare et al. 2017)
Kitchen	8.74	-	-	139	12.6	855	200	28.05	6.89	0.01	15.7	-	-	(Dal Ferro et al. 2021)
Kitchen	6.20	733	-	104.3	-	2016	564	-	-	-	-	-	-	(Arifin et al. 2020)
Kitchen	5.94	533	-	54.4	-	384	537	-	-	-	-	-	-	(Arifin et al. 2020)
Kitchen	6.2	308	245	-	-	602	293	-	4.7	11.4	5.3	-	-	(Vakil et al. 2014)
Mixed	6.5–7.3	16–59	280–350	37–173	29.8–75.5	92–668	-	-	0.60–4.75	0.50–2.5	0.89-2.07	1.0×10^5–6.0×10^5	2.2×10^5–1.0×10^6	(Chrispim and Nolasco 2017)

Table 2 (continued)

Greywater Type	pH	TSS (mg/l)	TDS (mg/l)	Turbidity (NTU)	Surfactant (mg/l)	COD (mg/l)	BOD (mg/l)	TN (mg/l)	NH_4-N (mg/l)	NO_3–N (mg/l)	TP (mg/l)	*E.coli* (CFU/100ml)	Total Coli-forms (CFU/100ml)	Ref
Mixed	7.1	51	-	-	-	310	117	-	1.9	-	9.4	-	-	(Shaikh and Ahammed 2020)
Mixed	7.08±0.31	63±114	-	68.4±39.8	-	158±112	116±67	10.4±9.3	4.88±2.92	0.02±0.04	-	-	-	(Zraunig et al. 2019)
Mixed	-	55.3–122.9	-	-	-	88.7–204.1	-	-	29.7–41.2	<0.1	2.8–4.9	-	-	(Deng et al. 2020)
Mixed	8.63±0.7	-	-	4±0.5	5.29±0.8	74±6	-	-	-	9.5±1.02	26.7±2.5	-	-	(Priyanka et al. 2020)
Synthetic	6.62	90.7	-	54.9	-	322	140	-	-	-	-	2.91×10^4	6.13×10^4	(Bakheet et al. 2020)
Synthetic	7.06±0.08	-	-	-	198±11	214±12	-	-	4.8±0.2	2.68±0.28	-	-	-	(Patil and Munavalli 2016)
Synthetic		87.3		40.23	18.65	246.63	44.37				6.59			(Abdel-Shafy et al. 2014)
Synthetic	7.6	79	291	133	6.45	463	-	-	11.3	0.93	0.53	2.6×10^5	4.3×10^5	(Mohamed et al. 2018)
Synthetic	7.11±0.03	2.46±0.15	-	-	128±4	413±3	-	11.8±0.3	3.41±0.13	-	-	-	-	(Ren et al. 2022)

is mainly contaminated with food particles as well as oil is degraded more rapidly under anoxic conditions compared to the greywater generated from other sources (Bakare et al. 2017). Kitchen greywater has a higher TSS and turbidity than other sources, which may be due to the huge amount of food residues in kitchen greywater. Surfactants are present in graeywater from different sources, and their concentration ranges vary widely.

Potential sources of pathogens found in greywater may be fecal pollution, peripheral pathogens, and food treatment (Chrispim and Nolasco 2017). It is found that bathing and washing are the main sources of *E. coli* in greywater, and the concentration of *E. coli* is highly variable. The TC can reach up to 1.10×10^8 CFU/100ml in bathroom greywater. The concentration of *E. coli* is also highly variable, ranging from 2.6 to 6.0×10^5 CFU/100ml.

Greywater treatment technologies and pollutant removal mechanisms

Physical technologies

Filtration

In recent years, there has been increasing interest in using waste as a filtration medium to treat greywater. Dalahmeh et al. (2014) found that bark filter has better effect than sand filter in treating greywater with high organic load and low hydraulic load. As an organic matter, bark has a richer microbial community than sand filter, and has better degradation of COD (Miranda et al. 2012). In addition, Trois et al. (2010) believe that the organics produced by bark degradation provides electron donors for denitrification, which is beneficial to the removal of TN in the system. Mohamed et al. (2018) developed a filtration system consisting of ceramic wastes as the treatment technology for bathroom greywater. When the HRT was 3 h, the removal efficiency of COD, TSS, TN, and turbidity were 38.8%, 58.47%, 66.66%, and 88.31%, respectively. The ceramic filter media contains 43.6% Al_2O_3, and the main functional groups on the media are C=C, C=O, and C-O=H. These functional groups have the ability to expose to the interface of the filter media, and the organic pollutant molecules in the greywater combine with the negatively charged binding sites, resulting in the organic pollutants in the greywater being attracted to the surface of the filter media and achieving the removal of pollutants.

Membrane filtration is a typical filtration method. In recent years, its application in greywater treatment has attracted more and more attention. Reang and Nath (2021) combined UF and RO to treat greywater, it was found that the removal rate of BOD in the system can reach 98%. The removal mechanism is since the pore size of UF membrane is smaller than the size of surfactants molecules, UF membrane plays the role of retaining the turbidity of a dirty mixture solution in greywater, while RO mainly removes surfactants to further reduce turbidity and TSS. Kim and Park (2021) used ceramic UF membranes to treat laundry greywater containing anionic surfactants and successfully achieved the retention of SDBS (a typical anionic surfactant) by controlling the operating parameters. At low concentrations, SDBS mostly existed as free monomers and was poorly removed. While, at concentrations just below its CMC, monomeric SDBS transformed into pre-micelles. As the concentration of pre-micelles increases, the clogging of the mesopores reduces the porosity of the membrane and improves the retention of SDBS in the early stages of the UF filtration process. When the concentration is higher than CMC, the pre-micelles are converted to micelles, which can retain the free monomer in the concentrated differential polarization layer. Due to the long-term deposition of micelles, this micellar-induced concentrated polarization layer leads to the formation of a pre-sieving layer that can promote SDBS retention. In addition, the removal of SDBS is affected by the pH of the system, when the pH of the solution is high (>4), most of the charges on the membrane surface are negative, and these negative charges interact with SDBS by charge repulsion, resulting in increased retention of SDBS.

Adsorption

Activated carbon is an ideal adsorbent due to its high specific surface area and porosity (Zipf et al. 2016). Patel et al. (2020) conducted batch and continuous adsorption studies on greywater using activated carbon prepared from sawdust, sugarcane bagasse, and pine needles. All the three adsorbents showed removal efficiencies of more than 90% for COD and BOD. Amiri et al. (2019) used a combined adsorbent of activated carbon, natural zeolite, and nano zero-valent iron to treat greywater, achieving removal rates of 85.75%, 91.81%, and 98.1% for COD, TDS, and turbidity, respectively. The isothermal adsorption study showed that the Langmuir isotherm could better explain the experimental data of adsorption equilibrium, indicating that the adsorption process was monomolecular layer adsorption, and the kinetic study showed that the R^2 of the pseudo-second-order model was closer to the experimental data.

Hess and Morgenroth (2021) used BAC filters to remove residual TOC from MBR-treated greywater, with the primary removal mechanisms for TOC being GAC adsorption and biodegradation. Monitoring over a period of more than 900 days showed that adsorption and biodegradation were equally important throughout the operating cycle and across the filter bed. Biodegradation removing 50% of the TOC, but a higher percentage of 89% at the upper part of the filter.

Of the biodegraded carbon, only 1% was assimilated into biomass and 99% left the system as CO_2. Similarly, Sharaf and Liu (2021) used GAC to treat greywater generated from households and office buildings and evaluated the individual effect of adsorption and biodegradation mechanisms on the overall treatment process, they found that adsorption mechanism was responsible for more than 74% of the overall treatment process while biodegradation process contributed to the remaining less than 26%. Therefore, the adsorption process dominated the overall treatment process and pore diffusion within the particles was determined to the rate-limiting step for the adsorption process. The adsorption method has the advantages of low cost and great effect. In the future, it is advisable to focus on the development of low-cost adsorbents to further reduce the cost of greywater treatment.

Biological technologies

CW

CW has a wide application in the field of greywater treatment with both wastewater treatment and landscaping. The two main factors of CW in wastewater treatment are plants and media (Dordio et al. 2007; Dordio and Carvalho 2013; Wu et al. 2015). At present, typical CW fillers include zeolite, vermiculite, gravel, limestone, fly ash, slag, gravel and soil, clay minerals, and some industrial byproducts (Lu et al. 2016). The operation results of Lu et al. (2016) showed that maifanite and steel slag had higher removal rate of pollutants because of their larger specific surface area. Wurochekke et al. (2014) chose *Lepironia articulata* as wetland plant, and combined with pretreatment system to treat the greywater of a rural residence. The removal efficiency of organic matter by this system was more than 80%.

In recent years, the effectiveness of CW in removing emerging contaminants from greywater was investigated. Ramprasad et al. (2017) used a novel CW (GROW) to remove chemical and microbial contaminants from greywater, GROW has not only great removal effect on conventional pollutants, but also achieves 91.4%, 85.7%, 93.4%, and 88.9% for FC, SDS, PG, and TMA respectively. Ren et al. (2021) investigated the effect and mechanism of CW on the removal of conventional pollutants and PCPs from greywater. The target PCPs consist of DEET, DEP, HHCB, AHTN, and EHMC. The results showed that the effluent water meets the reuse standard of reclaimed water, and the main pathway of PCPs removed by CW was a combination of plant uptake, microbial degradation, and substrate adsorption, and the specific removal mechanism depended on the type of PCPs. Such as the EHMC, which is highly biooxidizable, was mainly removed by biodegradation, while HHCB and AHTN were mainly removed by adsorption.

The use of CW is highly influenced by ambient temperature and has limited efficiency in winter. Deng et al. (2020) incorporated oxic/anoxic process and Fe/C micro-electrolysis into a vertical CW to develop ME-(O/A)CW for low carbon greywater treatment. ME-(O/A)CW achieved 94.3%, 86.2%, 98.0%,, and 92.7% removal of NH_4^+-N, TN, TP, and COD, respectively, at HLR of 0.9 $m^3/(m^2 \cdot day)$ and ambient temperature of −11.5 to 8°C. The removal mechanism of pollutants is show in Fig. 2. In the vegetation layer, through the assimilation process of the plants, N and P can be partly removed by the absorption of plant roots. During this period, N is transformed into amino acid for protein synthesis, P is utilized to synthesize adenosine triphosphate, nucleic acid, phospholipid, etc. (Wu et al. 2014). Effective nitrification, phosphorus-accumulating and organic-degradation were proceeded in the aerobic layers: organics is gradually degraded and eventually converted to CO_2 and H_2O. NH_4^+ is converted to NO_2^- and NO_3^- by AOB and NOB in turn, and P is converted to poly-P by PAOs. Through in situ H_2-/Fe^{2+}-supply by Fe/C micro-electrolysis, efficient H_2-/Fe^{2+}-mediated autotrophic denitrification and Fe^{3+}-based phosphorus immobilization were developed in the anaerobic layers: On the one hand, [H]/H_2 and Fe^{2+} produced by Fe/C-ME continuously support the ADB for denitrification process in the anaerobic layer and effectively remove N from the system. On the other hand, HDB utilized residual organics as electron donor for heterotrophic denitrification. Meanwhile, phosphorus is partly released by PAOs, which could react with Fe^{3+} in the system to produce $FePO_4 \cdot 2H_2O$, thus achieves phosphorus immobilization.

MBR

Because of the small footprint, high biochemical efficiency, and good effluent quality, MBR has been widely used in the field of wastewater treatment (Bani-Melhem et al. 2015). Fountoulakis et al. (2016) used the SMBR system to treat the real greywater of a single house in Greece, and conducted a 9-month monitoring. The operation results show that the average COD concentration of the effluent is about 60 mg/L. Najmi et al. (2020) used SMBR to remove PCPs from greywater. When the HRT was 16 h, color and turbidity removal efficiencies were as high as 97.65% and 97.92%, respectively. COD and BOD were completely removed. Triclosan, methylparaben, and propylparaben, as the most concentrated pollutants in the prepared PCP-rich greywater, were removed by up to 98.20%, 99.96%, and 99.97%, respectively.

The mechanism of organics removal from greywater by MBR is mainly through the degradation of microorganisms. Ziemba et al. (2018) used handwashing greywater to cultivate cells in order to investigate the mechanism of organic carbon removal. When nutrients in greywater only ensure cellular maintenance with little growth, the reduction of

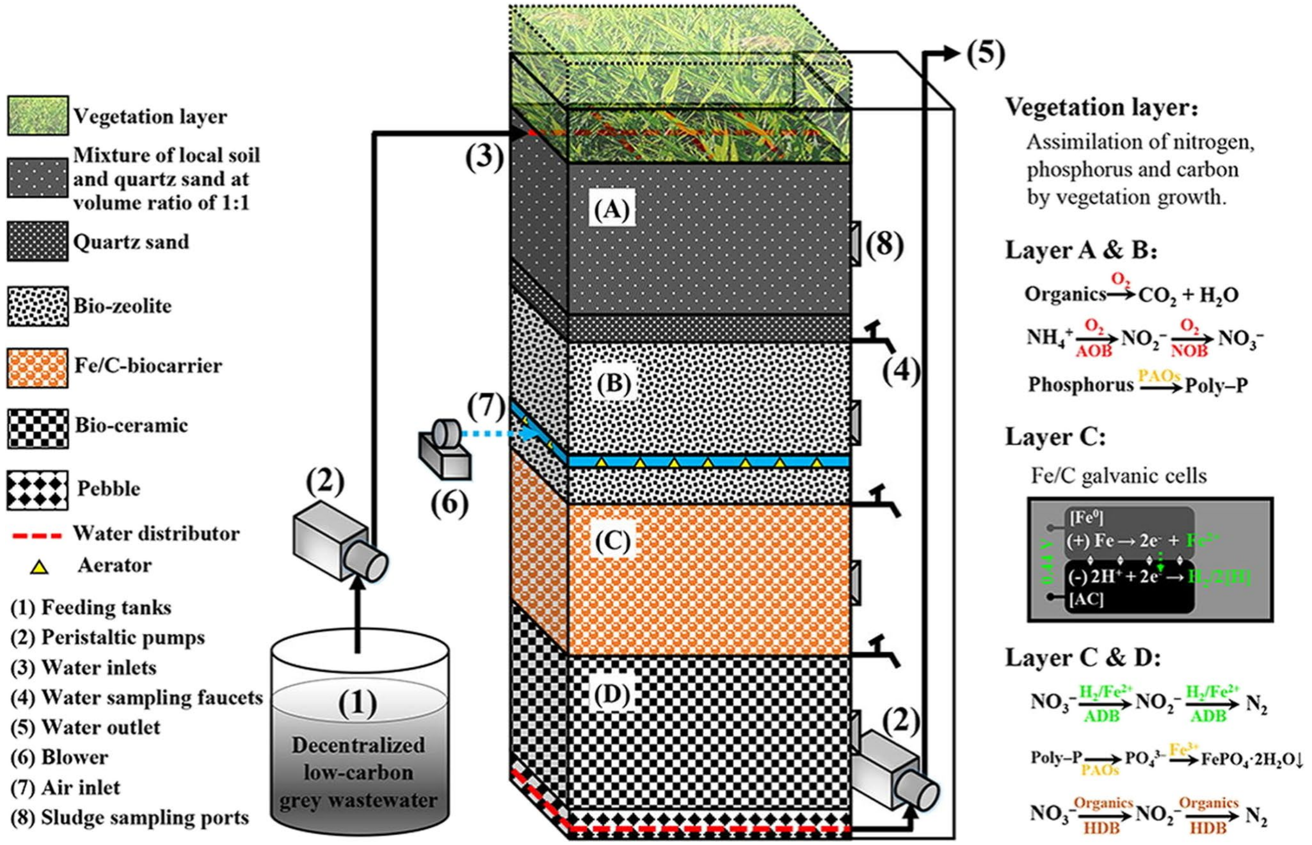


Fig. 2 Schematic diagram of the reaction systems and the reaction mechanisms of ME-(O/A)CW (reprinted with permission from Deng et al. (2020). Copyright 2020 Elsevier)

AOC is mainly attributed to maintenance functions and the removal of organic carbon will be maintained for about 6 days, which is time consuming. While when nutrients are balanced, the removal of organic carbon takes only minutes or hours. Removal of carbon by dosing nutrient-balanced greywater in the BAMBi system achieved 95%, involving a removal mechanism that includes microbial growth requirements and microbial maintenance of cellular functions. The removal of N consists of (a) integration into the biomass by growth and (b) removal by denitrification. Zhou et al. (2020) treated greywater using O_2-MBfR. They found that the DO concentration in the reactor gradually decreased from 1.67 to 0.37 mg/L as the feed load increased, forming a composite biofilm consisting of distinct aerobic, aerobic-anoxic, and aerobic-anoxic-anaerobic layers, which achieved the simultaneous removal of both organics and N (Fig. 3). When the feed loading is low, O_2 enters directly to the biofilm attached to the membrane surface; at this time, the biofilm has a high DO concentration. With the increase of feed loading, the thickness of the biofilm increases and the DO concentration gradually decreases. In other words, in the system, the liquid phase surface of the biofilm has a high DO concentration, which gradually decreases and forms an anoxic layer inside the biofilm. The extremely low internal O_2 concentration at this time makes the removal of organics accompanied by denitrification, i.e., the aerobic-anoxic-anaerobic biofilm includes nitrification, partial nitrification, aerobic and anaerobic denitrification processes at the same time to achieve the simultaneous removal of organics, and nitrogen. In addition, the ratio of COD/TN in greywater significantly affects the removal efficiency of COD. Ren et al. (2022) found in the treatment of greywater using O_2-MBfR that the COD removal rate decreases when COD/TN is reduced to 10:1. The reason is that higher NH_4^+-N concentration leads to lower DO concentration in the system and insufficient electron acceptors, which affects the biodegradation of organics. Zhou et al. (2021) reduced the COD/TN ratio from 40 to 20 g COD/g N of greywater in a O_2-MBfR system, which increased the relative abundance of nitrification and denitrification-related genera and also led to an increase in AMO activity, allowing ammonia oxidation and LAS mineralization to be co-metabolized, resulting in effective removal of organic matter and nitrogen under low DO conditions. In addition, the proper biofilm thickness is critical for biological denitrification. The influent flow rate of the system affects the biofilm thickness, when the flow rate is too fast,

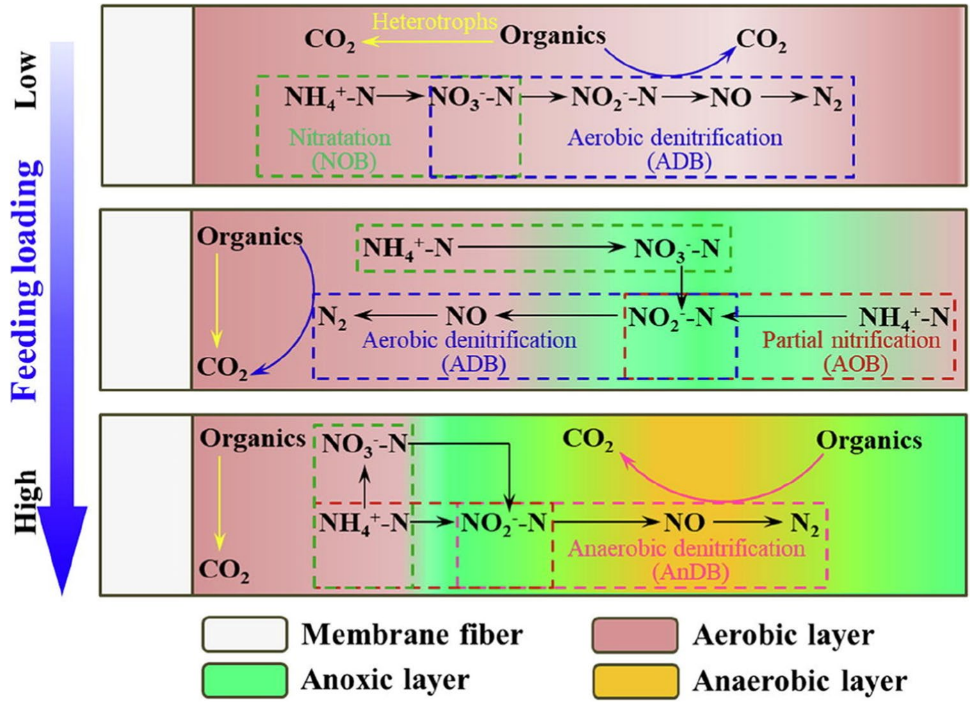


Fig. 3 The proposed nitrogen and organics removal pathways in the two-dimensional biofilm of the MBfR systems (reprinted with permission from Zhou et al. (2020). Copyright 2020 Elsevier)

the biofilm is only a thin layer, which cannot provide anoxic environment for denitrification process and can lead to high nitrate content in the effluent (Pradhan et al. 2020).

Biofilter

Biofilter has becoming an attractive method due to the advantages of low energy consumption and construction costs as well as easy maintenance (Jung et al. 2019).

Zhang et al. (2021) used a dual-mode biofilter to treat rainwater and greywater, and proved that the dual-mode biofilter can effectively remove most of the pollutants. Barron et al. (2020) reported that the selection of plant species is critical to the removal of nitrogen and phosphorus, and that species such as *Carex appressa* and *Canna x generalis* can maintain a low effluent concentration in the two switched water sources. Jung et al. (2019) added a CuZ medium layer on top of the sand filter medium layer of the biofilter. They found that CuZ exerted effective antibacterial properties, improved biological filter greatly enhanced the removal rates of *E. coli*. Patil et al. (2021) developed a laboratory scale vegetated vermifilter system consisting of SGF, and LSVVF/LSVF for the greywater treatment. In LSVF, the removal efficiency of BOD_5, TKN, and P was 50–60%, 30–50%, and 30–50% respectively. The corresponding values in LSVVF were 60–80%, 40–64%, and 35–68%. This indicated that earthworms played a crucial role in the removal of organics. All in all, the choice of fillers and plants in a biofilter is important for the treatment efficiency. Song et al. (2017) investigated the ability of biomass, collected from biofilters treating real greywater, to remove PPB from synthetic greywater and the interactions between adsorption and biodegradation during PPB removal by aerobically attached growing biomass. The sorption behavior of PPB on biomass is consistent with the Langmuir isotherm. The removal mechanism as follows: PPB is first adsorbed on biomass and then removed by biodegradation. It was also found that biodegradation resulted in complete mineralization of PPB, making the adsorption sites on biomass available for subsequent sustained adsorption.

Green wall

Green (vegetated) infrastructure that passively treats various polluted water sources is considered one of the most environmentally friendly and low-maintenance water recycling solutions available (Boyjoo et al. 2013). In recent years, green wall treatment technology has been applied to the treatment of greywater. Dal Ferro et al. (2021) constructed an innovative WCCW system for the treatment of kitchen greywater by combining the multifunctional advantages of green walls (e.g., esthetics, low surface area requirements) and CW systems (e.g., high pollutant removal efficiency, water recycling). Removal efficiencies of 90%, 50%, 30%, 70%, and 80% were achieved for TSS, TN, TP, COD, and *E. coli*, respectively.

Pradhan et al. (2019) uses an integrated green wall system to treat greywater (Fig. 4). Six different plants were selected, including *Alternanthera dentata*, *Ruellia brittoniana*, *Koeleria glauca*, *Typha domingensis*, *Acalypha wilkesiana*, and

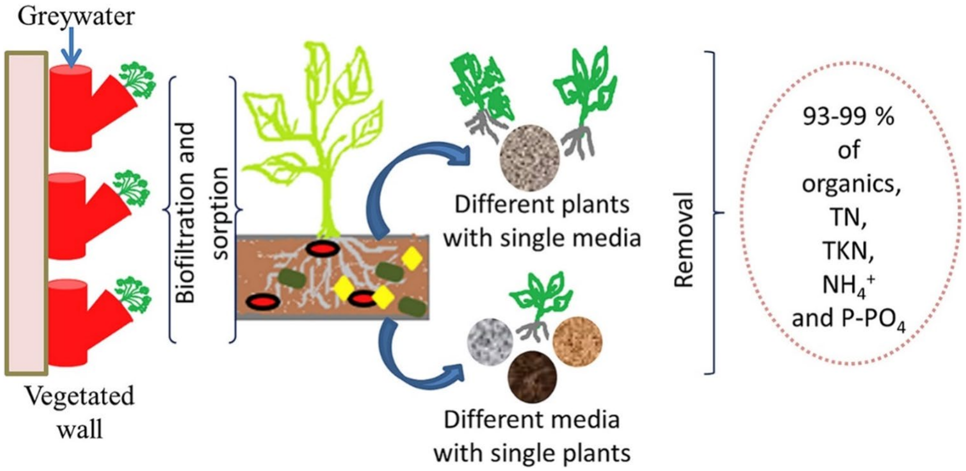


Fig. 4 An integrated green wall system for greywater treatment (reprinted with permission from Pradhan et al. (2019). Copyright 2019 Elsevier)

Portulaca grandiflora. Plants belonging to these families can effectively remove organic matter, ammonium nitrogen, and phosphate from polluted water through rhizofiltration, rhizodegradation, and phytoextraction processes (Hussain et al. 2018). The selected media included perlite, coco coir, light-weight expanded clay, sand, spent coffee grounds, and date stones. Two different designs of test columns were used, depending on whether only the medium or the medium and the plant were tested. Media selection was found to have a much greater effect on treatment performance than plant selection, with percent removal of all monitored contaminants (organics, solids, nitrogen, and phosphorus) greater than 90% when using with high surface area and small diameter media such as coco coir, spent coffee grounds, and sand. The mechanism of organic pollutant degradation is mainly through the interaction of bacteria with the medium. In addition, plants also contribute to enhance nitrogen and phosphorus removal. Prodanovic et al. (2017) explored the role of media in green wall systems for the removal of contaminants from greywater. Experiments were conducted with (1) hydraulically slow coir, rock wool, and fyto-foam; (2) hydraulically fast perlite, vermiculite, expanded clay, growstone, and river sand as media, respectively. Slow media demonstrated higher and more consistent contaminant removal performance. The average removal efficiencies of TSS, TN, TP, COD, and *E.coli* were about 90%, 50%, 30%, 70%, and 80%, respectively. However, slow media were easily clogged and therefore are not suitable as the sole media for green walls. Fast media corresponded to average removal efficiencies of about 80%, 30%, 15%, 30%, and 20%, respectively, without blockage problems. Perlite and coir are the most effective fast and slow media for removing contaminants, respectively. In coconut fiber, the main mechanism for removal of organics and nitrogen is biodegradation, and denitrification has enough time to take place. For perlite with short retention times, physicochemical processes are predominant, indicating the importance of media properties. In both tests, TP removal was dominated by biological processes. Therefore, in the actual selection of filter media for green walls, a combination of fast and slow media can be considered to achieve the best removal effect.

Others

In recent years, some researchers have used MSL to achieve degradation of pollutants. Song et al. (2018) reported that the mechanism of TP removal in MSL is that free phosphate or adsorbed phosphate is chemically combined with iron ions or iron hydroxide and removed by filtration or adsorption. The removal effect is influenced by the production of iron ions in the system and the diffusion of water flow. Adequate aeration allows the conversion of Fe^{2+} to Fe^{3+} in the aerobic layer, thus improving the adsorption of phosphate by the soil.

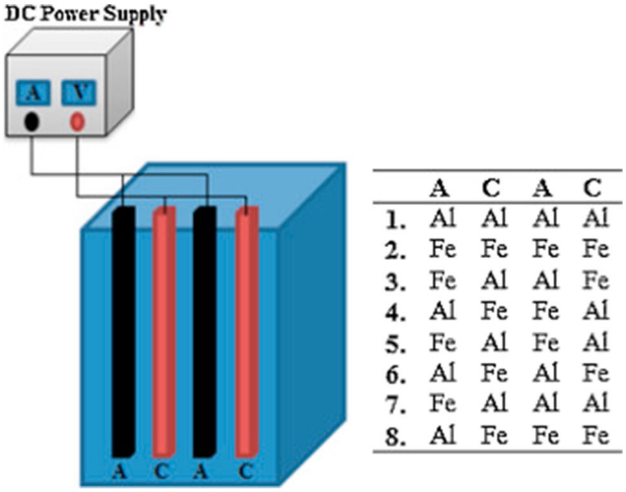
A *Chlorella variabilis* system for greywater from washbasins and bathrooms was developed by Oktor and Çelik (2019). Captured CO_2, sunlight, and a nutrient-rich aquatic greywater medium are the only requirements for the growth of microalgae cultures (Chiu et al. 2015). In this study, *Chlorella* used the organics and nutrients in graeywater to grow successfully in the light greywater of washbasins and bathrooms. The remediation rates of COD, BOD_5, TN, and TP were up to 92.3%, 91.9%, 85.6%, and 97%, respectively. Besides, the microbiological analysis showed that the effluent could be reused for toilet flushing.

Eslami et al. (2017) investigated the effect of organic loading rate on the biodegradation of LAS, oils and fats in graeywater by IFAS. The optimum removal efficiencies of COD, LAS, and oil and grease were 92.52%, 94.24%, and 90.07%, respectively, at an OLR of 0.44 gCOD/L·day. Evaluation of the loading rates showed that the removal of COD, oil, and grease increased as the OLR increased to 0.44 gCOD/L·day and decreased as the OLR continued to increase. SEM images indicated that the biofilm formed on the media inside the IFAS reactor played an important role in the adsorption and biodegradation of LAS and oil and grease from graeywater. The linear relationship between the influent COD values and the LAS removed showed that the ratio of influent COD (mg/L) to LAS removed (mg/L) was 0.4. Jabornig and Favero (2013) have pointed out that OLR can significantly affect the degradation of COD due to the fact that high OLR implies an increase in the amount of xenobiotic compounds in greywater, causing a negative impact on the microbial population, which affected the removal of organic pollutants from the system. In addition, since LAS could contribute more than 70% of COD in greywater (Cui et al. 2022), an increase of OLR led to an increase of LAS, and the high surface loading of LAS reduced the activity of aerobic bacteria and could even lead to cell lysis, which continuously inhibited the biodegradation of organic matters (Zhou et al. 2020). In other words, during the treatment of greywater using biological methods, the appropriate OLR needs to be controlled to ensure the activity of microorganisms in the system.

Chemical technologies

The chemical processes used in greywater treatment include coagulation, photocatalytic oxidation, and ion exchange. Pidou et al. (2008) used coagulation process and magnetic ion exchange resin process for shower greywater treatment. Under optimal conditions, aluminum and iron salt coagulation had similar removal effects. In addition, the coagulation process could achieve better treatment results than the magnetic ion exchange resin process, but for turbidity and PO_4^{3-} reduction, the magnetic ion exchange resin was superior, and both processes did not have significant TN reduction. Barişçi and Turkay (2016) treated greywater using EC with hybrid electrode combinations. Eight different electrode combinations were evaluated (Fig. 5). The highest COD removal efficiency were obtained for the Al-Fe-Fe-Al hybrid combination. Iron or aluminum ions generated by electrochemical oxidation of Al and Fe electrodes may form monomeric species and polymeric hydroxyl metal complexes, thus providing effective ion and particle coagulation (Kobya et al. 2014). Therefore, the main mechanism of pollutants removal by EC involves electrooxidation together with EC.

Ghaderpoori and Dehghani (2015) reported that the combination of UV/H_2O_2 can reduce LAS levels by up to 96.5% within 30 min. These results proved that the H_2O_2 material combined with UV light can effectively remove LAS detergent in wastewater. Priyanka et al. (2020) performed solar photocatalytic treatment of greywater collected from residential apartments using NP-TiO_2 coated on gravels. Solar photocatalytic degradation significantly removed organic matter (TOC removal of 93.7%). The removal efficiency of TKN, nitrate, phosphate, and surfactants were 50%, 43%, 55%, and 75%, respectively. In addition, NP-TiO_2 also showed excellent removal effect of BP. The main removal mechanisms involve non-specific hydroxyl radical attack, demethylation, and bond breaking between carbonyl groups and benzene rings carrying hydroxyl and methoxy groups. Through a number of reactions, BP was degraded to aliphatic compounds, and finally, the aliphatic byproducts are oxidized to CO_2 and H_2O. Chandra Pragada and Thalla (2021) developed a ternary composite catalyst for the removal of triclosan from greywater. The pseudo-first-order kinetic model for photodegradation of triclosan under solar radiation fitted better than the pseudo-second-order kinetic model. The removal rate of triclosan from greywater was 83.27%. Triclosan was found to undergo three different reaction mechanisms, including generating different intermediates through hydroxylation, OH radical attack on aromatic rings, as well as dechlorination reactions. These intermediates were subsequently degraded to other smaller organic intermediates and further mineralized to CO_2 and H_2O. The effectiveness of different treatment technologies for the removal of pollutants from greywater is summarised in Table 3.



	A	C	A	C
1.	Al	Al	Al	Al
2.	Fe	Fe	Fe	Fe
3.	Fe	Al	Al	Fe
4.	Al	Fe	Fe	Al
5.	Fe	Al	Fe	Al
6.	Al	Fe	Al	Fe
7.	Fe	Al	Al	Al
8.	Al	Fe	Fe	Fe

Fig. 5 Experimental set-up for EC process (reprinted with permission from Barişçi and Turkay (2016). Copyright 2019 Elsevier)

Combined technologies

Due to the fact that greywater contains a variety of different pollutants, a single treatment technology may not achieve satisfactory treatment results at most cases. Therefore, there is a necessity to integrate different treatment methods into a system to remove as more pollutants as possible so that the discharge could meet the requirement of standard limits set by different countries. In view of this, the combination process of different treatment technologies is increasing attracting attention. Bani-Melhem and Smith (2012) used a combined process of electroflocculation and

Table 3 Removal efficiencies of different greywater treatment technologies

Technology	Process	Greywater source	Target	Removal efficiency	Ref
Filtration	Ceramic waste filter	Bathroom	COD, TSS, TN, turbidity	Removal COD 38.8%, TSS 58.47%, TN 66.66%, turbidity 88.31%.	(Mohamed et al. 2018)
	a. Bark filters	Synthetic	COD, TP	a: COD 40–74%, TP 73–83%	(Dalahmeh et al. 2014)
	b. Charcoal filters			b: COD 76–90%	
	c. Sand filters			c: COD 65–93%	
	UF + RO	Laundry	TDS, turbidity, BOD	Removal TDS 96.70%, turbidity 99.60%, BOD 93.10%.	(Reang and Nath 2021)
Adsorption	Activated carbon	Mixed	TDS, COD, BOD, PO_4^{3+}, NO_3^-, turbidity	Removal TDS 91.4%, COD 95.6%, BOD 93.3%, PO_4^{3+} 93.7%, NO_3^- 89.2%, turbidity 94%.	(Patel et al. 2020)
	Combined adsorbent	Mixed	COD, TDS, turbidity	Removal COD 85.75%, TDS 91.81%, turbidity 98.1%.	(Amiri et al. 2019)
CW	GROW	Mixed	BOD, COD, TSS, NO_3^-, TP, TN, FC, SDS, PG, TMA	Removal BOD 90.8%, COD 92.5%, TSS 91.6%, NO_3^- 83.6%, TP 87.9%, TN 91.7%, FC 91.4%, SDS 85.5%, PG 93.4%, TMA 88.9%.	(Ramprasad et al. 2017)
	ME-(O/A)CW	Mixed	NH_4^+, TN, TP, COD	Removal NH_4^+ 94.3%, TN 86.2%, TP 98.0%, COD 92.7%.	(Deng et al. 2020)
	Filter-mini CW	Mixed	COD, BOD, SS, NH_3^-, turbidity	Removal COD 84.57%, BOD 81.42%, SS 54.7%, NH_3^- 39.83%, turbidity 45.01%.	(Wurochekke et al. 2014)
MBR	SMBR and UV disinfection	Mixed	COD, TN, TP, TSS, turbidity, anionic surfactant	Remove COD 87%, TN 40%, TP 69%, TSS 92%, turbidity97%, anionic surfactant 80%.	(Fountoulakis et al. 2016)
	O_2-MBfR	Synthetic	TCOD, PCOD, LAS, InON, and TN	Removal TCOD 95%, PCOD 97%, LAS 98%, InON 99%, TN 82%.	(Zhou et al. 2020)
	SMBR	Synthetic	Color, turbidity, COD, BOD, triclosan, methylparaben, propylparaben	Removal color 97.65%, turbidity 97.92%, COD 100%, BOD 100%, triclosan 98.20%, methylparaben 99.96%, propylparaben 99.97%.	(Najmi et al. 2020)
Biofilter	Dual-mode biofilters	Mixed	TSS, TOC, TP, TN, BOD_5	Removal TSS 94%, TOC 88–91%, TP 58–81%, TN 79–91%, BOD_5 98%.	(Barron et al. 2020)
	Dual-mode biofilters	Mixed	TSS, TN, NO_3^-, TP, TOC, COD, BOD_5	Removal TSS 96%, TN 74%, NO_3^- 63%, TP 93%, TOC 81%, COD 80%, BOD_5 89%.	(Zhang et al. 2021)
	Vegetated vermifilter system	Diluted greywater	BOD_5, TKN, P	Removal BOD_5 60–80%, TKN 40–64%, P 35–68%.	(Patil et al. 2021)

Table 3 (continued)

Technology	Process	Greywater source	Target	Removal efficiency	Ref
Green wall	WCCW	Kitchen	COD, BOD_5, anionic surfactants, TKN, NH_4^+	Removal COD 86%, BOD5 83%, anionic surfactants 82%, TKN 57%, NH_4^+ 43%.	(Dal Ferro et al. 2021)
	Green wall with hydraulically slow media	Synthetic	TSS, TN, TP, COD, *E. coli*	Removal TSS 90%, TN 50%, TP 30%, COD 70%, *E. coli* 80%.	(Prodanovic et al. 2017)
	Green wall with hydraulically fast media	Synthetic	TSS, TN, TP, COD, *E. coli*	Removal TSS 80%, TN 30%, TP 15%, COD 30%, *E. coli* 20%.	(Prodanovic et al. 2017)
Other biology methods	IFAS	Synthetic	COD, LAS, oil and grease	Removal COD 92.52%, LAS 94.24%, oil and grease 90.07%.	(Eslami et al. 2017)
	Chlorella variabilis system	Mixed	COD, BOD_5, TN, and TP	Removal COD 92.3%, BOD_5 91.9%, TN 85.6%, TP 97%.	(Oktor and Çelik 2019)
Chemical	EC	Mixed	Anionic surfactants, TP, TN, PO_4^{3-}, NO_3^-, NO_2^-, TSS, turbidity	Removal anionic surfactants 98.92%, TP 91.78%, TN 83.15%, PO_4^{3-} 16.08%, NO_3^- 83.47%, NO_2^- 97.76%, TSS 100%, turbidity 99.16%.	(Barişçi and Turkay 2016)
	NP-TiO_2	Mixed	TOC, TKN, NO_3^-, PO_4^{3-}, surfactants	Removal TOC 93.7%, TKN 50%, NO_3^- 43%, PO_4^{3-} 55%, surfactants 75%.	(Priyanka et al. 2020)
	UV/H_2O_2	Synthetic	LAS	Removal LAS 96.5% within 30 min.	(Ghaderpoori and Dehghani 2015)

SMBR for the treatment of greywater, and they found that the aluminum hydroxide produced in solution facilitated the rapid adsorption of soluble phosphorus in the bioreactor due to its large specific surface area, and in addition, the excess aluminum ions (Al^{3+}) reacted with phosphate ions to form $AlPO_4$ in the reactor which precipitated down. The removal mechanism of P by chemical method is shown in Fig. 6. Bakheet et al. (2020) used a sequential combination of green wall biofiltration and electrochemical disinfection to treat greywater. Passive green wall biofiltration system was used firstly to remove organic contaminants, followed by disinfected using BDD electrode with a SPE to further reduce microbial levels. The synergistic effects between reactive oxygen species and electrochemically generated free chlorine contributed to the inactivation processes and cell membrane degradation of selected fecal indicator organisms. Electrochemical systems may also reduce the color of greywater effluent by degrading organic contaminants. Li et al. (2022) developed a new process (VUV/UV/O_3) combining O_3 and VUV/UV and elucidated the fate of organic fractions by VUV/UV/O_3 enhanced coagulation. The greywater contained tryptophan-like and tyrosine-like proteins, as well as humic-like material from land. In the VUV/UV/O_3 enhanced coagulation, the highest removal rates of UV_{254}, LAS, DOC, and COD_{Cr} in greywater could reach up to 47.54%, 58.92%, 17.96%, and 15.76%, respectively. VUV/UV/O_3 enhanced coagulation was effective for the removal of biopolymers, humic substances, and low molecular weight acids $\leq$30 kDa, while it was not effective for that of 0.22 μm to 100 kDa. The particle size of flocs in the filtrate obtained by increasing the membrane pore size increased significantly, indicating that macromolecular organic matter was more likely to form flocs. VUV/UV/O_3 improved coagulation for the removal of various organic pollutants and improved settling by changing flaky flocs into dense flocs. These results suggest that VUV/UV/O3 is effective for pre-oxidation of pollutants for improved coagulation on greywater treatment.

Future outlook in greywater reuse

With the decreasing of the freshwater resources on the earth, reuse of wastewater is of great importance to alleviate water stress. Some international agencies and countries are proposing to pay attention to the reuse and management of wastewater. For example, the United Nations Development Program launched the "Water Action Decade" to mobilize people to take action for more rational management of freshwater resources (UNDP 2017). The USA issued Guidelines for Water Reuse (USEPA 2012), which provides recommendations on water management, types of reuse, regulation, and treatment technologies. Greywater, which as a major part of domestic wastewater in households, can be used for a variety of purposes other than drinking after treatment, and can make an important contribution to reducing freshwater demand. Countries such as Australia, Japan, and the USA have issued their own guidelines for greywater reuse. Some of these countries offer incentives to encourage their citizens to install greywater treatment systems in their houses, while others have made it a mandatory campaign. Australia, for example, encourages the installation of systems that reuse greywater through a program that provides $500 AUD. Federal policy regulations in the USA even provide financial incentives for the installation of greywater reuse systems in new homes (Yu et al. 2013). In addition, China recently released the "Five-Year Action Plan to Improve Rural Habitat Environment (2021–2025)" (China 2021), emphasizing the connection between the rural toilet revolution and domestic wastewater treatment, promoting the different treatment methods according to local conditions, encouraging association of households, villages, and towns as one to treatment. It can be seen that the reuse of greywater has attracted widespread attention worldwide, and governments have formulated corresponding policies to facilitate the treatment and reuse of greywater. In the future, more countries around the world should be encouraged to actively promote greywater reuse initiatives. Based on households, villages, or communities, oriented to the destination of greywater, different discharge standards for greywater treatment should be developed. For example, greywater used for irrigation in farm or garden needs to limit the concentration of surfactants, while the N and P elements needed for plant growth may not be strictly required. In addition, the government can provide economic and technical support to areas with less developed economy and lower level of wastewater treatment and strengthen the propaganda to make the concept of greywater recycling deeply rooted in people's minds.

Conclusion

This work provides a review on greywater in terms of its sources, characteristics, and pollutant removal mechanisms of different treatment technologies. The quality of greywater from different sources shows different characteristics, but

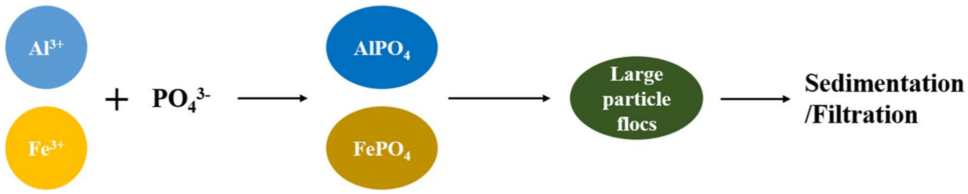


Fig. 6 The removal mechanism of P by chemical method

most of them have good biodegradability. Greywater also contains a large number of emerging contaminants, mainly from various PPCPs. Physical methods have excellent removal efficiency for turbidity and TSS. Biological methods can effectively remove organic pollutants from greywater, but it is not always effective for N and P removal. The suggestions for the choice of treatment technologies and the further exploration of pollutions removal mechanism are as follows: (1) Physical technologies could be used as the pretreatment for biological treatment to reduce the load on the biodegradation stage, and the chemical methods could also be used in combination with biological methods in order to assist phosphorus removal. (2) Adsorption has the satisfactory removal efficiency not only on conventional pollutants, but also on emerging contaminants in greywater. In the future, the research and development of low-cost adsorbents can be further intensified, and adsorbents containing different functional groups should be prepared according to the specific characteristics of pollutants in greywater. (3) The research on the emerging contaminants in greywater becomes urgent, including investigation of the adverse effects of different types of emerging pollutants on the environment, and development of more stringent and reasonable greywater management standards.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Zhiqin He, Yun Li, and Benkun Qi. The first draft of the manuscript was written by Zhiqin He and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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