

1 A comprehensive review of treatment technologies for greywater contaminants: an emphasis on
2 surfactants

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21 **Keywords**

22 Graywater; reuse, micropollutants, toxicity, removal mechanisms, case studies, linear alkyl
23 benzene sulfonate

24

25 **Abstract**

26 Surfactants are considered a key pollutant in greywater (GW). However, there is no consensus on
27 the best technologies for their removal. This review provides a comprehensive analysis of the main
28 lines of GW research. Recent literature on GW characteristics, surfactant characteristics, toxicity
29 and treatment technologies are analyzed along with case studies of GW reuse. The bibliometric
30 analysis shows that 69% of the studies on GW involve surfactants, and physicochemical
31 technologies predominate with 13.5% of the total studies. However, the toxicity of surfactants has
32 been scarcely addressed (10% of the articles). Anionic surfactants represent 60% of the world
33 production of surfactants. Concentrations in GW range from 7 to 436 mg/L and their toxicity
34 measured as lethal concentration 50 (LC₅₀) varies between 0.027-92 mg/L. Physicochemical
35 treatments show a removal efficiency between 22-99% of anionic surfactants, while biological and
36 advanced systems show between 53-99% removal efficiency. Furthermore, combined treatments
37 show removal efficiencies between 78-99%. However, high costs of advanced systems limit their
38 application on a large scale. In this sense, low-cost alternatives such as the use of reused adsorbent
39 materials, natural solutions and disinfection systems could offer up to 98% surfactant removal.
40 Regarding effluent toxicity, more research is needed, since limited studies address this gap.
41 Moreover, it is unclear whether there will be a synergistic or antagonistic effect on the toxicity
42 caused by surfactants and other pollutants on organisms and species. Along with this, the study of
43 surfactant transformation products by different technologies and their toxicity is presented as a
44 new research gap.

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49 **Introduction**

50 Water scarcity has become a global challenge that can give rise to conflicts between water users
51 in the domestic, industrial, and agricultural sectors (Gutiérrez and Glückler 2022). By 2050, it is
52 estimated that the human population facing water scarcity will increase to 1,693-2,373 million
53 people, and in the worst-case scenario, 3,061 sub-basins could be affected (He et al. 2021; Wang
54 et al. 2024). One of the most significant water stressors is agricultural irrigation. Worldwide, 307
55 million hectares of agricultural land are irrigated, mainly with surface water (Simmons et al. 2022).
56 In this context, new approaches have emerged with the aim of achieving more efficient and
57 sustainable management of water resources, such as, the conceptualization of closing the cycle for
58 the recovery of water and nutrients from wastewater is a widely explored alternative (Carrillo et
59 al. 2024; Leiva et al. 2021; Venegas et al. 2021). On the other hand, the use of alternative and
60 decentralized water sources such as rainwater or greywater is increasingly encouraged with the
61 aim of reducing imports into the urban water cycle (He et al. 2022, Vidal et al. 2024).
62 Greywater (GW) has been described as water coming from a home, excluding water from the
63 bathroom, which includes fecal matter (Shaikh and Ahammed 2020; Hamidi 2025). GW reuse has
64 emerged as a viable solution, as it could reduce domestic water consumption by approximately
65 40%. In addition, it can be considered for non-potable purposes such as crop irrigation, garden
66 irrigation, toilet flushing, and discharge into water bodies (Oteng-Pepurah et al. 2018). However,
67 the reuse of GW presents risks that must be considered due to the physical-chemical,
68 microbiological, and antimicrobial resistance characteristics of these new water sources. (Leiva et
69 al. 2025, Gutierrez et al. 2025). To aid in tracking these issues, some researchers have focused
70 their literature reviews on two key areas: characteristics and treatment systems. Meanwhile, more
71 comprehensive studies explore perceptions of reuse, as well as the risks, hazards, and barriers that

72 hinder GW reuse (Pinto et al. 2021). Thus, bibliometric analysis is a useful tool to contextualize
73 the state of the art in the research field and the guidelines of this review.

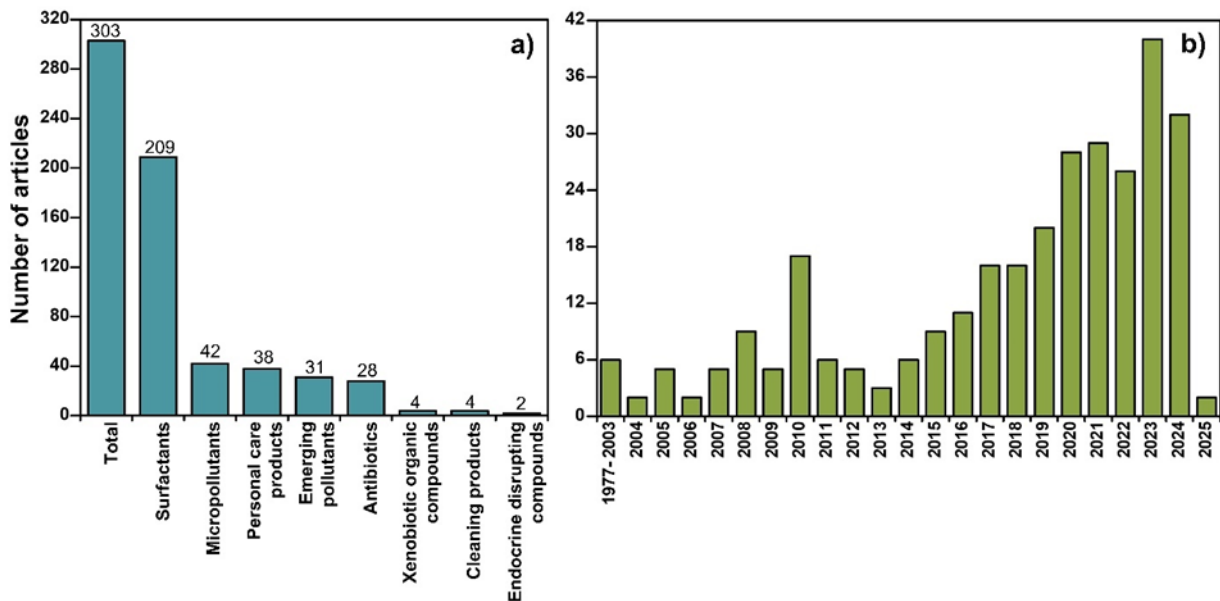
74 **1. Bibliometric analysis**

75 Bibliometrics is a quantitative approach that involves the analysis of bibliographic data drawn
76 from research studies to study research trends and future directions in a given field (Visser et al.
77 2021). The use of bibliometric analysis allows researchers to reveal the structure of their respective
78 fields and identify dominant themes (Chen et al. 2023), as well as to identify where there is a
79 knowledge gap, and thus an opportunity to address it. For this review, the Scopus database was
80 used, and the bibliometric analysis was performed using the Python library pyBibX (Pereira,
81 2022).

82 Figure 1a details the results of the search in the Scopus database, which yielded a total of 303
83 articles containing the search criteria such as: ‘greywater’, ‘treatment technologies’, and
84 ‘pollutants’ (Supplementary Material, Table S1). Among these, 69% of the articles include
85 ‘surfactants,’ which appears more frequently than others such as ‘micropollutants’ (42 articles),
86 ‘antibiotics’ (28 articles), and ‘endocrine disrupting compounds’ (2 articles). Figure 1b shows the
87 chronological distribution of articles, with papers from 1977 to 2025. Between 1977 and 2012 the
88 number of articles per year varied, with a peak in 2010, when the number of articles increased
89 considerably to 17; in previous years the average was five. From 2013 to 2024 the number of
90 articles presents an upward trend, accounting for 77.7% (203 articles) of the papers published in
91 the 1977-2025 period with an average of 21 articles per year. Such a trend indicates that treatment
92 technologies, together with the pollutants present in GW, are an area of constantly growing
93 scientific interest.

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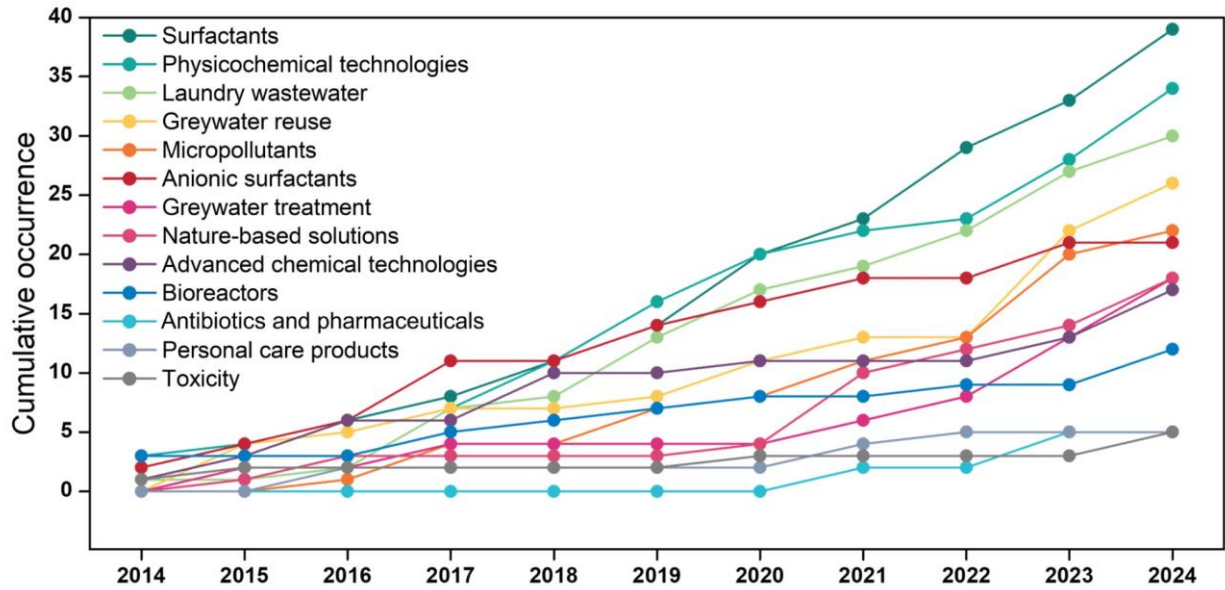


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98 **Figure 1.** Number of articles from bibliometric analysis by (a) title, abstract and keywords; and
 99 (b) publication trend by year focused on greywater. Data Source: Scopus.

100 The bibliometric analysis in Figure 2 shows the cumulative occurrence in terms of keywords (14
 101 main keywords per year) of the main topics of articles published on this topic between 2014-2024.
 102 As described above, the research tends to cover topics associated with surfactants (15.5% of the
 103 total), and in terms of treatments they are mainly focused on physicochemical technologies (13.5%
 104 of the total). However, considering the large number of pollutants that characterize GW, only one
 105 treatment, either physical or chemical, is insufficient; therefore, a combination that includes
 106 physical, chemical, and biological mechanisms in conjunction is necessary.

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109 **Figure 2.** Graph of topic occurrence over the last 10 years.

110 Studies on bioreactor-based biological technologies and nature-based solutions (NsB) account for
 111 only 4.8% and 7.1% of the total, respectively. Moreover, few studies – only 5 as of 2024 – are
 112 focused on the toxicity that GW may present. Future research should also integrate this topic,
 113 especially as it is also evident from the analysis that GW reuse has been increasing (10.3% of all
 114 articles) and that the possible risks of both reuse due to the presence of certain pollutants such as
 115 surfactants and the use of treatment technologies that alone are inadequate are not being
 116 considered.

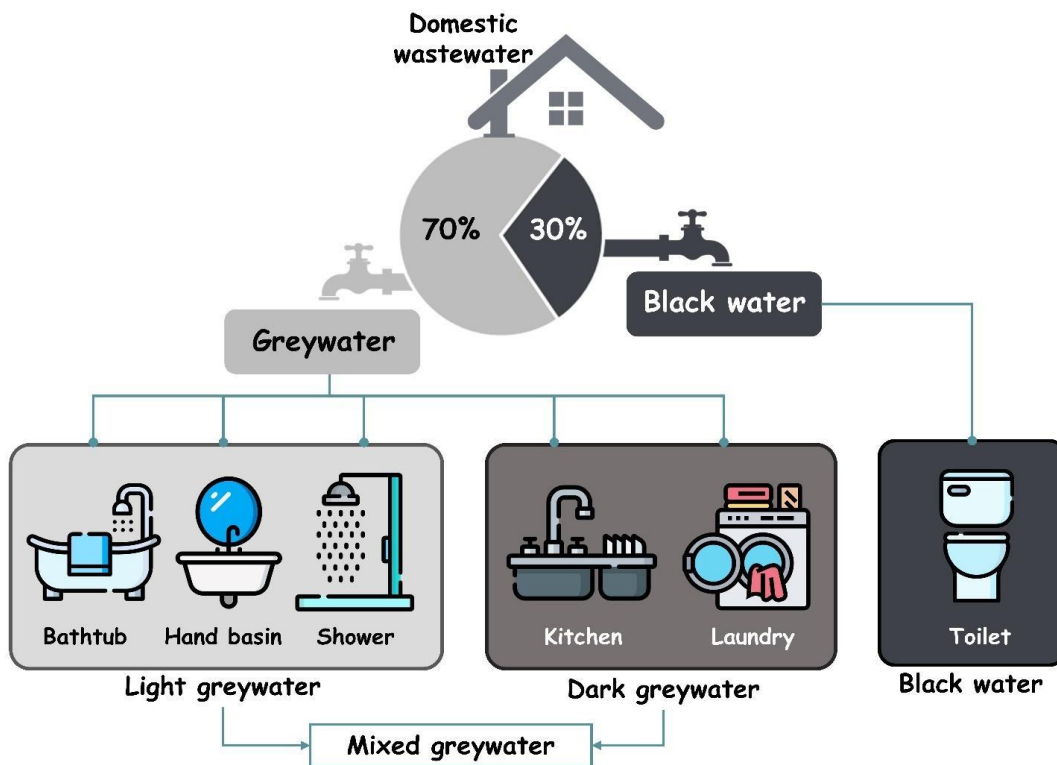
117 The bibliometric analysis identified key trends, knowledge gaps and areas for future research.
 118 Therefore, the aim of this review is to provide a comprehensive analysis of the current state of
 119 research on GW reuse, focusing on the available treatment technologies with an emphasis on
 120 surfactants, with the purpose of promoting sustainable water resource management and improving
 121 safety in GW reuse.

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124 **2. Greywater: origin and composition**

125 GW is domestic sewage from showers, hand sinks, washing machines, dishwashers, and kitchen
126 sinks. As shown in Figure 3, a distinction can be made between light GW from showers and hand
127 sinks and dark GW from kitchens and washing machines (Rodríguez et al. 2021). GW accounts
128 for between 50% and 80% of the sewage generated in households and residential buildings. It also
129 accounts for 60% to 75% of the total water volume of domestic sewage and 9–14%, 20–32%, 18–
130 22%, and 29–62% of the nitrogen (N), phosphorus (P), potassium, and organic matter, respectively
131 (Gross et al. 2005, Leiva et al. 2025).



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133 **Figure 3.** Types of greywater by source.

134 Table 1 shows concentrations of contaminants present in GW. The temperature of GW is typically
135 around 37°C, a factor that could promote microbial growth and induce precipitation in
136 supersaturated water, of calcite, for example. The dispersion in GW concentrations is due to their
137 dependence on their source (Supplementary Material, Table S2). Turbidity and total suspended

138 solids (TSS) values range between 14-406 NTU (Nephelometric Turbidity Units) and 38-1852
139 mg/L, respectively. These parameters could result in clogged GW treatment facilities (Eriksson et
140 al. 2002). Electrical conductivity (EC) values range from 318 to 126,000 $\mu\text{S}/\text{cm}$. These values are
141 directly related to dissolved solids, which have been found at concentrations between 78–920 mg/L
142 (Mahmoudi et al. 2021). pH of GW tends to be alkaline, in a range of 7 to 8, due to the use of
143 sodium hydroxide-based soaps (Bakare et al. 2017).

144 **Table 1.** Physicochemical characteristics of greywater.

Parameter	Unit	Average \pm SD	Range	References
Turbidity	NTU	184.1 \pm 125.6	14.0 - 406.0	[1-6]
TSS	mg/L	410.7 \pm 549.3	37.6 - 1852.0	[1-3,7-10]
EC	μ S/cm	14680.8 \pm 41746.7	318.0 - 126000.0	[3,7-10]
pH	-	7.6 \pm 1.2	6.2 - 10.0	[1-5,7-10]
COD	mg/L	831.3 \pm 991.5	193.0 - 3491.0	[1-4,6,7,9-10]
BOD ₅	mg/L	407.9 \pm 425.4	43.0 - 1363.0	[1-4,9,10]
TN	mg/L	6.7 \pm 5.3	2.5 - 15.5	[8,9]
TP	mg/L	1.4 \pm 1.0	0.1 - 2.7	[9,10]
Chlorine	mg/L	68.0 \pm 143.0	0.5 - 390.5	[1,4,5,10]
Surfactants	mg/L	140.8 \pm 165.9	42.0 - 436.0	[9]
Total coliforms	MPN/100 mL	1.0 \times 10 ⁵ \pm 2.4 \times 10 ⁵	3.7 - 6.0 \times 10 ⁵	[1]
<i>E. coli</i>	CFU/100 mL	3.1 \times 10 ⁵ \pm 2.6 \times 10 ⁵	2.5 \times 10 ⁴ - 6.1 \times 10 ⁵	[11]

145 TSS: Total Suspended Solids; EC: Electrical Conductivity; COD: Chemical Oxygen Demand; BOD₅: Biological Oxygen Demand; TN: Total Nitrogen; TP: Total
 146 Phosphorus. NTU: Nephelometric Turbidity Units; MPN: Most Probable Number; SD: Standard Deviation.

147 Number References: [1]: Vakil et al. (2014); [2]: Manouchehri and Kargari (2017); [3]: Patel et al. (2022); [4]: Patil et al. (2022); [5]: Rodrigues et al. (2022); [6]:
 148 Sotiropoulou et al. (2023); [7]: Antonopoulou et al. (2013); [8]: Alfiya et al. (2018); [9]: Noutsopoulos et al. (2018); [10]: Oteng-Peprah et al. (2018); [11]: He et al.
 149 (2022).

150 Chemical oxygen demand (COD) values vary between 193 and 3491 mg/L. The total COD in GW
151 is distributed among the following fractions: 34% dissolved, 36% suspended, and 27% colloidal
152 (Sotiropoulou et al. 2023). The average concentration of COD in dark GW is up to five times
153 higher than that in light GW (Shaikh and Ahammed 2020). Through the COD/BOD₅ ratio
154 (biodegradability index), it is possible to determine the suitability of a biological GW treatment
155 (Khanam and Patidar 2022; Khalil and Liu, 2021). Li et al. (2009) reported that GW exhibits easy
156 biodegradability, with a biodegradability index of less than 2.5.

157 In GW, N comes from the kitchen, specifically cleaning products rich in ammonia and protein-
158 rich foods. It is possible to obtain values of 2.5-16 mg/L for total nitrogen (TN). Meanwhile, P
159 comes from laundry detergents with concentrations between 0.1-2.7 mg/L for total phosphorus
160 (TP) (Khanam and Patidar 2022). In the case of sewage, values increase to 20-80 mg/L and 4-14
161 mg/L, respectively (Oteng-Peprah et al. 2018; Alfiya et al. 2018).

162 Fecal coliform (FC) concentrations in GW ranging from 0 to 10⁶-10⁷ colony forming units per 100
163 mL (CFU/100 mL) have been found (Friedler et al. 2006; Mahmoudi et al. 2021, Leiva et al. 2025).
164 Since GW contains easily degradable organic compounds from the kitchen, a resurgence of enteric
165 bacteria such as fecal indicators could occur, potentially leading to an overestimation of fecal
166 loads. Total coliform (TC) values between 3.4-5.5 log₁₀/100 mL have been found for laundry GW,
167 while for GW from showers and hand sinks, the values increase to 2.7-7.4 log₁₀/100 mL and can
168 vary according to household patterns (Vakil et al. 2014; He et al. 2022).

169 Xenobiotic organic compounds (XOCs) are complex aromatic compounds that include surfactants,
170 synthetic fragrances, preservatives, plasticizers, and antibiotics, many of which are persistent and
171 have the potential to affect water quality and aquatic ecosystems (Glover et al. 2021).

172 Some XOCs have been associated with antibiotic-resistant bacteria (ARB), while others, such as
173 bisphenol A (BPA), exhibit endocrine-disrupting properties (Werkneh et al. 2022). XOCs such as

174 triclosan and tonalite have been found in GW at concentrations of 15.6 µg/L (Leal et al. 2010a)
175 and 2.2 µg/L (Hernández Leal et al. 2011), respectively. These concentrations are higher than those
176 found in sewage (0.05-5.20 µg/L for triclosan). Despite these findings, Glover (2022) identified
177 98 compounds classified as high risk in untreated GW and 14 compounds as GW surrogates for
178 aquatic toxicity. However, given the limited data available, further research is necessary to better
179 understand the potential risks associated with XOCs in GW.

180 **3. Occurrence of surfactants in greywater**

181 Some of the contaminants present in GW are surfactants, originating from detergents or cleaning
182 products. They have antimicrobial properties, which can stimulate the evolution and growth of
183 resistant bacteria. It has also been found that they inhibit microorganisms from absorbing minerals
184 present in the soil and can strongly adsorb to sludge, soil and sediment. They are typically
185 composed of a polar head group and a non-polar hydrocarbon tail (Ying 2006).

186 Surfactants are primarily classified into three categories: anionic, non-ionic, and cationic. Anionic
187 surfactants include alkylbenzene sulfonates, which are the most used in household detergent
188 formulations and for industrial purposes. They are used in commercially available formulas and
189 are a highly complex mixture of linear molecules (linear alkylbenzene sulfonates, LAS) and
190 branched molecules (branched alkylbenzene sulfonates, BAS). LAS are generally classified as
191 biodegradable; however, their widespread use has led to accumulation in the environment. LAS
192 concentrations in GW range from 7 to 436 mg/L (Kurniawan et al. 2023). The persistence of LAS
193 or BAS in the absence of oxygen is a significant environmental concern, as they can accumulate
194 in anaerobic sediment and sludge obtained from activated sludge treatment plants. LAS may even
195 inhibit anaerobic biodegradation. The lack of oxygen negatively affects the natural degradation of
196 these compounds, inhibiting mineralization and leading to the generation of sulfophenylcarboxylic
197 acids (Verge et al. 2001; Zígolo et al. 2020).

198 Strong associations among ARB, antibiotics such as ciprofloxacin and ceftriaxone, and cationic
199 and non-ionic surfactants have been found in laundry GW (Monsalves et al. 2023). These findings
200 suggest that the presence of surfactants may play a key role in promoting the selection of ARBs.
201 This underscores the importance of incorporating disinfection systems into GW treatment
202 processes to mitigate the environmental and health impacts of treated laundry effluents.

203 **3.1 Toxicity**

204 The toxicity of surfactants could be influenced by water properties such as pH, dissolved oxygen
205 and suspended solids, the type and concentration of surfactants, as well as their absorption, and
206 biotic factors related to the species tested (Badmus et al. 2021). To understand the fate of
207 surfactants, it is essential to analyze their physicochemical properties. Compounds with a high
208 molecular weight and an octanol-water partition coefficient (K_{ow}) greater than five tend to adsorb
209 readily onto sediments or suspended solids, aiding their removal by processes such as coagulation
210 and sedimentation (Jardak et al. 2015).

211 Table 2 shows chemical properties and toxicity of surfactants found in GW. The 50% lethal
212 concentration (LC_{50}) of non-ionic, cationic, and anionic surfactants for a variety of organisms
213 ranges between 210-500,000 $\mu\text{g/L}$, 80-2,800,000 $\mu\text{g/L}$ and 110-92,000 $\mu\text{g/L}$, respectively (Khalil
214 and Liu 2021). The environmental effects of these surfactants can be quite severe, as they can
215 interfere with the growth of algae, bacteria, and fish, even at low concentrations of up to 0.2 mg/L
216 in water (Kurniawan et al. 2023).

217 Perfluorinated surfactants represent the largest subgroup of anionic surfactants and are classified
218 among the most widespread persistent organic pollutants. Particular attention has been paid to
219 polyfluorinated and perfluorinated alkyl substances (PFASs), which are considered to be among
220 the most widespread organic pollutants for biota and humans (Ghisi et al. 2019). Among them,
221 two representative compounds stand out: perfluorooctanoic acid (PFOA) and perfluorooctane

222 sulfonic acid (PFOS), mainly due to the exceptional stability of their carbon-fluorine bonds, which
223 greatly limits their environmental degradation (Jardak et al. 2015; Hamid et al. 2023). These
224 substances also exhibit hydrophobicity, lipophilicity, and high thermal stability, further
225 contributing to their persistence in environmental systems (Supplementary Material, Table S3)
226 (Hamid et al. 2023).

227 The toxicity of PFASs, particularly PFOA and PFOS, has been extensively documented in animal
228 studies, showing effects such as developmental toxicity, neurotoxicity, tumor induction, and
229 endocrine disruption. Although human evidence remains limited, their persistence and
230 bioaccumulation, particularly in the liver, with half-lives of 3.8 years for PFOA and 5.4 years for
231 PFOS, have prompted precautionary regulations (Ghisi et al. 2019). Reflecting these concerns, the
232 U.S. Environmental Protection Agency (EPA) established in 2016 a lifetime health advisory level
233 of 70 ng/L for PFOA and PFOS, individually or combined, in drinking water (Sunderland et al.
234 2019). Major exposure pathways include contaminated drinking water and effluents from sewage
235 treatment plants (Llorca et al. 2012; Xiao et al. 2012; Ghisi et al. 2019). Acute toxicity data also
236 reveal their hazardous nature, with LC₅₀ values of 34.7 mg/L for PFOA in *Daphnia magna* and
237 0.91 mg/L for PFOS in *Pimephales promelas* (Hamid et al. 2023).

238 **Table 2.** Types of surfactants and associated toxicity.

Type	Surfactans	Toxicity value	Toxicity level	Persistence level	Observations	References
Anionic	Poly and perfluoroalkyl substances (PFASs); Perfluorooctanoic acid (PFOA), perfluorooctane sulfonate (PFOS)	LC ₅₀ = 34.7 mg/L (<i>Daphnia magna</i>), 0.91 mg/L (<i>Pimephales promelas</i>)	High toxicity	Highly persistent	Bioaccumulative, Endocrine disrupting chemical, carcinogenic, regulated globally	[1-4]
	Linear alkylbenzene sulphonate (LAS)	EC ₅₀ = 9.2 mg/L (<i>Daphnia magna</i>)	Low toxicity	Low persistence	Biodegradable, widely used	[1-3,8]
	Branched alkylbenzene sulfonates (BAS), Branched Alkyl Benzenes Sulfonates (BABS); α -Olefin sulfonates (AOS)	LC ₅₀ = 0.280 mg/L (Fish: <i>O. mossambicus</i>)	Moderate toxicity	Moderate persistence	Slow degradation due to branching, lower biodegradability	[1-3,9]
	Sodium lauryl ether sulfate (SLES), sodium dodecyl sulfate (SDS) o sodium lauryl sulfate (SLS)	LD ₅₀ = 1260-1288 mg/kg (rats, oral); EC ₅₀ = 0.35 mg/L (Marine diatoms); EC ₅₀ = 6 mg/L (<i>Daphnia magna</i>)	Low toxicity	Low persistence	Biodegradable and low environmental risk	[1-2,5,10]
	Alkyl carboxylate, Alkyl Sulfates	EC ₅₀ = 0.8-16.0 mg/L (<i>Daphnia magna</i>)	Very low toxicity	Very low persistence	Less harmful and are biodegradable	[1-2,5-6]

Non-ionic	4-Nonylphenol, Nonylphenol ethoxylates (NPEs)	LC ₅₀ = 0.027 mg/L (<i>Artemia sinica</i>), LC ₅₀ = 0.175 mg/L (<i>Pseudochromis fridamani</i>), EC ₂₀ = 0.829 mg/L (<i>Selenastrum capricornutum</i>); PNEC = 0.33 µg/L	High toxicity	Moderate persistence	Endocrine disrupting chemical, carcinogenic, regulated in the EU	[1-2,5-7]
	Alkyl polyglycoside (APG), D-Glucopyranose, oligomeric, C10-16-alkyl glycosides, Lauryl glucoside	PNEC = 176 µg/L; EC ₅₀ = 40 mg/L (<i>Daphnia magna</i>)	Very low toxicity	Very low persistence	Highly biodegradable, renewable by-products	[5,8-10]
Cationic	Benzyl dimethyl dodecyl ammonium chloride (BAC-12)	PNEC = 0.42 µg/L	High toxicity	Moderate persistence	Toxic to microbiota and aquatic fauna, antibiotic resistance	[1,7]
	Cetyl Trimethyl Ammonium Bromide, Hexadecyltrimethylammonium bromide (HDTMA)	EC ₅₀ = 0.12 mg/L (<i>Actinobacter junii</i>); EC ₅₀ = 15.7 mg/L (<i>Saccharomyces cerevisiae</i>); EC ₅₀ = 0.037 mg/L (<i>Daphnia magna</i>)	High toxicity	Moderate persistence	Toxic to aquatic environments and bioaccumulative in sediments	[5,10]

239 EC: effective concentration; LC: Lethal concentration; LD: Lethal doses; PNEC: Predicted no-effect concentration.

240 References: [1]: Jardak et al. (2015); [2]: Collivignarelli et al. (2019); [3]: Hamid et al. (2023); [4]: Venditti et al. (2022); [5]: Jena et al. (2023); [6]: Penserini et al.

241 (2023) [7]: Glover et al. (2021); [8]: Han and Jung (2021); [9]: Ghosh et al. (2022); [10]: Crini et al. (2024).

242 Anionic surfactants, which account for approximately 60% of global surfactant production and are
243 widely used in detergents, are characterized by a negatively charged polar head and a hydrophobic
244 tail. These properties contribute to their accumulation in treatment sludge due to their tendency to
245 adsorb on organic matter. Their relatively low molecular weight also facilitates their solubility in
246 water (Jardak et al. 2015). Although in most cases they are considered biodegradable, their
247 persistence and the by-products generated during their degradation depend on structural
248 characteristics and environmental conditions, which could lead to toxic effects on the environment
249 and human health (Penserini et al. 2023).

250 Among anionic surfactants, LAS are widely used and have demonstrated a moderate level of
251 toxicity, with an EC₅₀ of 9.2 mg/L for *Daphnia magna* and an LC₅₀ of 0.28 mg/L for the fish
252 species *Oreochromis mossambicus* for Alkyl benzene sulfonate (BAS) (Ghosh et al. 2022).
253 Sodium dodecyl sulfate (SDS), another common anionic surfactant, presents a broader toxicity
254 range, with LC₅₀ values between 1 and 13.9 mg/L for various aquatic organisms (Zicarelli et al.
255 2024). In general, anionic surfactants tend to be more toxic to fish than non-ionic ones (Mustapha
256 & Bawa-Allah 2020). Supporting this, a study evaluating the toxicity of dark GW on zebrafish
257 larvae (*Danio rerio*) reported that the non-ionic surfactant decyl glucoside (APG) exhibited the
258 lowest toxicity, while α -olefin sulfonate (AOS) and LAS showed moderate effects. These findings
259 highlight the relevance of surfactant type and structure in determining their ecotoxicological
260 impact (Han and Jung 2021).

261 Non-ionic surfactants such as nonylphenol ethoxylates (NPEs) generate estrogenic effects in
262 amphibians, mammals, and fish (Badmus et al. 2021). Studies indicate that surfactants can also be
263 toxic to a variety of pests such as aphids, spider mites, thrips, and caterpillars (Gangwar et al. 2016;
264 Li et al. 2019; Price and McGraw 2025). NPEs represent a class of nonionic surfactants of high
265 environmental concern with moderate risk to both water and soil. Although once widely used, they

266 are now being replaced by more biodegradable and less toxic compounds (Glover et al. 2021). In
267 terms of joint action toxicity results of surfactants, their effect is not clear. On the one hand, a
268 process of antagonism has been generated, attributable to competition for binding sites in exposed
269 fish. However, authors such as Osuala et al. (2017) report synergistic interactions, which may
270 increase the toxicity of surfactants.

271 **3.2 Associated risk**

272 The environmental implications of surfactants in GW are significant, as they affect water quality,
273 soil, plants and various living organisms, including animals and humans. Their toxicity can alter
274 the respiration and reproduction of aquatic organisms, and their accumulation can lead to foaming,
275 which reduces water oxygenation and promotes eutrophication processes. Some surfactants, such
276 as nonylphenol, tend to settle and can be persistent and bioaccumulative, leading to long-term toxic
277 effects (Badmus et al. 2021; Glover et al. 2021; Jena et al. 2023).

278 Irrigation with untreated GW can alter soil structure and affect nutrient uptake by plants. The
279 surfactants present in GW reduce the capillary rise of water in the soil, which increases its
280 hydrophobicity, as well as its pH, salinity, and boron levels, further affecting its physicochemical
281 properties (Li et al. 2009). Other effects are increases in alkalinity and bulk density and decreases
282 in hydraulic conductivity, aggregate stability, and soil porosity (Pinto and Maheshwari 2010;
283 Nyagatare et al. 2021). Most plants are very sensitive to surfactants and have a significant influence
284 on plant vitality. For example, Gräf et al. (2022) evaluated the effects of GW irrigation on trees
285 such as *Tilia cordata* and *Acer pseudoplatanus*, reporting that anionic surfactants caused leaf
286 necrosis. Ghisi et al. (2019) found low accumulations of PFOA and PFOS in peeled potatoes and
287 cereal seeds, while short-chain compounds can accumulate at elevated levels in leafy vegetables
288 and fruits.

289 Some surfactants have serious health implications for humans through direct contact, ingestion, or
290 consumption of contaminated food. Compounds such as sodium lauryl ether sulfate (SLES), LAS,
291 and benzyl dimethyl dodecyl ammonium chloride (BAC-12) can cause skin, eye, and respiratory
292 tract irritation, leading to dermatitis and other complaints (Jardak et al. 2015; Glover et al. 2021;
293 Hamid et al. 2023). In addition, substances such as nonylphenol, BAC-12, and hexadecyltrimethyl
294 ammonium bromide (HDTMA) are associated with severe eye damage and exhibit systemic
295 toxicity when ingested, highlighting the need for appropriate management to reduce the risks of
296 exposure (Glover et al. 2021; Penserini et al. 2023; Crini et al. 2024). These risks therefore
297 highlight the need for proper management of surfactants in GW to reduce their environmental
298 impact.

299 **4. Greywater treatment**

300 Surfactants pose a significant challenge for GW reuse due to their potential environmental and
301 health impacts. Effective treatment technologies are therefore essential to remove surfactants from
302 GW. Table 3 provides a summary of the various technologies applied to GW treatment,
303 highlighting their efficacy by surfactant type and associated toxicity. However, relatively few
304 studies focus specifically on surfactant type removal as the primary treatment objective. Additional
305 removal efficiencies for parameters such as organic matter, nutrients and microbiological
306 indicators are presented in Supplementary Table S4. Even more limited are studies assessing
307 toxicological risks, as few incorporate effluent toxicity testing as an integral part of GW treatment
308 assessment. The most common methods include physicochemical and biological treatments,
309 usually complemented by disinfection processes or advanced treatments. This review focuses on
310 the degradation and removal mechanisms of surfactants, which vary depending on their structure
311 and type. Additionally, combined technologies are discussed as integrated approaches to enhance
312 treatment efficiency.

Table 3. Overview of greywater treatment technologies: surfactant removal efficiency by GW type and toxicity assessment.

Technology	Type of greywater	Efficiency by surfactant (%)	Toxicity	References
Physicochemical				
Biofilter (gravel, tezontle and fibre)	Mixed GW	LAS: 22-78	Reduced phytotoxicity in lettuce to 21%	[1]
Sand filter, and granular active carbon filter (GAC)	Mixed GW	LAS: 95-98 NP: 84-98		[2-3]
Coagulation, sedimentation, sand filter, and granular active carbon filter	Mixed GW	LAS: 80-99 AS: 99	Seed germination test with treated GW was 93.33%; SAR = 2.84	[2,4-5]
Polyelectrolyte multilayer (PEM) membranes	Mixed GW	LAS: 97-99 SLS: 68-99 AOS: 49-99		[6]
Multi-layer slow sand filter (MSSF)+ micro filter (MF) + ultrafilter (UF)	Mixed GW	LAS: 86-99		[7-9]
Ultra-filtration (UF), Forward osmosis (FO) and reverse-osmosis (RO) membranes	Laundry GW	AS: 92-99 SDBS: 90		

Biological

Green wall	Synthetic mixed GW	AS: 63 NP:40-90		[10-12]
Green wall	Kitchen GW	AS: 78-83		[13-14]
Constructed wetland	Mixed GW	LAS: 90 AS: 99 CS: 45 NiS:85		[15-17]
Constructed wetland	Light GW	SDS:85-96	Phytotoxicity: visible plant deterioration	[18-19]
Wetlands constructed with GROW system (Green Roof Water Recycling System).	Mixed GW	SDS:85-96		[13,20]
Microalgal-bacterial biofilm	Synthetic mixed GW	LAS: 95-99		[21-22]
Submerged membrane bioreactor (SMBR)	Mixed GW	AS: 60-95		[23-25]
Membrane biofilm MBR	Synthetic mixed GW	LAS:71-99	<i>A. pseudoplatanus</i> had foliar necrosis with treated GW (15.5%)	[26-28]
Sequencing batch reactor (SBR)	Mixed GW	AS: 80-92	13.6% inhibition of <i>A. fischeri</i> luminescence test	[29-30]

Moving Bed Bio Reactor (MBBR)	Laundry GW	AS: 57-99 NiS:88-99	[31-32]
Integrated Fixed-film Activated Sludge	Synthetic mixed GW	LAS: 88-94	[33]
Advanced chemical			
Electrocoagulation/ Electroflotation	Laundry GW	AS: 80-98 CS: 93 NiS: 80	[34-37]
Photocatalysis (UV, O ₃ , TiO ₂)	Mixed GW	SDBS: 53-74 AS:53	Toxicity analysis of degradation products, rat oral LD ₅₀ : 3057,19 mg/kg; Bioluminescence inhibition toxicity tests (<i>V. fischeri</i>) of less than 20% are considered non-toxic. [38-39]
Conventional ozonation, electro-oxidation (EOX)	Laundry GW	AS:59-86 PFOA: 64-99	Bioluminescence inhibition toxicity tests (<i>V. fischeri</i>) were reduced to 22.4% [40-41]
Electro-Hybrid Ozone-Coagulation Process (E-HOC)	Laundry GW	LAS: 90-99	[42]
Fenton/Solar photo-Fenton	Laundry GW	LAS: 82 BiAS: 98 SDS: 89-96	LCA; human toxicity, non-cancer (HNC): 3.40x10 ⁻⁶ CTUh; Ecotoxicity, freshwater (EF): 23.1 CTUe [43-44]

Combined

Membrane bioreactor+Chlorination	Light GW	SLS:98-99	[45]
Electro-coagulation (EC) unit and submerged membrane bioreactor (SMBR) technology	Mixed GW	AS:96	[23]
SMBR and disinfection with UV lamp	Mixed GW	AS:80	[46]
Bio-enhanced granular-activated carbon dynamic biofilm reactor	Synthetic mixed GW	LAS: 90-98	[47]
Anaerobic/aerobic/anoxic sequencing batch reactor (SBR) and a solar photocatalytic reactor (SPCR)	Synthetic mixed GW	AS: 88-95	[29]
Ceramic filter with membrane bioreactor (MBR)	Synthetic mixed GW	LAS (C10–C13): 90-99	[48]
Biological treatment combined with UV/O ₃	Dark GW	AS:99	[49]
Adsorption + Phytoremediation	Dark GW	AS: 99	[50]
Biofilter + granular active carbon filter (GAC)	Dark GW	LAS: 98	[44]
Thermophilic aerobic membrane reactor (TAMR)+nanofiltration (NF) + activated carbon (AC)	Dark GW	AS:78 NiS: 95	LCA; human toxicity, non-cancer (HNC): 5.41x10 ⁻⁶ CTUh; Ecotoxicity, freshwater (EF): 10.6 CTUe [51]

315 GW: Greywater; LCA: Life cycle analysis; LAS: linear alkylbenzene sulfonates; AOS: Sulfonatos oxofenil; NP: nonylphenol; SDS: sodium dodecyl sulphate; SLS:
316 sodium lauryl sulphate; DBAS: dodecylbencenosulfonato; SDBS: sodium dodecylbenzene sulfonate; AS: anionic surfactants; SLS: lauryl sulfate; CS: cationic
317 surfactants; NiS: non-ionic surfactants; BiAS: Bismuth active substance; C: carbon chain.

318 References: [1]: Pérez-López et al. (2018); [2]: Noutsopoulos et al. (2018); [3]: Faccenda et al. (2022); [4]: Cardoso and Bodnar (2022); [5]: Melián et al. (2023);
319 [6]: Athullya et al. (2022); [7]: Babaei et al. (2019); [8]: Morris et al (2022); [9]: Kim and Park (2021); [10]: Boano et al. (2020); [11]: Costamagna et al. (2023);
320 [12]: Abd-ur-Rehman et al. (2023); [13]: Jena et al. (2023); [14]: Dal Ferro et al. (2021); [15]: Ravichandran et al. (2021); [16]: Ren et al. (2021); [17]: Monsalves
321 et al. (2023); [18]: Ramprasad and Philip (2016); [19]: Ramprasad and Philip (2018); [20]: Ramprasad et al. (2017); [21]: Li et al. (2024); [22]: Zhou et al (2023);
322 [23]: Bani-Melhem and Smith (2012); [24]: Bani-Melhem et al. (2015); [25]: Liberman et al. (2016); [26]: Zhou et al. (2020); [27]: Ren et al. (2022); [28]: Gräf et
323 al. 2022; [29]: Priyanka et al. (2022); [30]: Priyanka et al. (2020a); [31]: Bering et al. (2018); [32]: David et al. (2013); [33]: Eslami et al. (2017); [34]: Barişçi and
324 Turkay (2016); [35]: Dimoglo et al. (2019); [36]: Dimoglo et al. (2023); [37]: Akarsu and Deniz (2020); [38]: Dai et al. (2024); [39]: Priyanka et al. (2020b); [40]:
325 Turkay et al. (2017); [41]: Alnaimat et al. (2024); [42]: Luo et al. (2022); [43]: Esteban García et al. (2021); [44]: Melián et al. (2023); [45]: Santasmasas et al.
326 (2013); [46]: Fountoulakis et al. (2016); [47]: Wang et al. (2022); [48]: Hasan et al. (2015); [49]: Benis et al (2021); [50]: Siswoyo et al. (2019); [51]: Collivignarelli
327 et al. (2019).

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329

330

4.1 Physicochemical treatments

331
332 Physicochemical treatments for surfactant removal include processes such as adsorption,
333 coagulation, sedimentation, filtration (sand, activated carbon), ion exchange, electrocoagulation,
334 and membrane separation (Badmus et al. 2021; Borah et al., 2023; Jena et al. 2023). Their
335 effectiveness varies depending on the type of surfactant and the technology applied. For instance,
336 biofilters achieve 27-78% removal depending on the filter media (Pérez-López et al. 2018), while
337 sand and activated carbon filters reach efficiencies of 95-99%. Membrane-based technologies,
338 including ultrafiltration (UF), forward osmosis (FO), and reverse osmosis (RO), generally offer
339 higher performance, with reported removal rates of 86-99% (Babaei et al. 2019; Morris et al.
340 2022). These systems operate primarily via size exclusion and electrostatic repulsion mechanisms,
341 influenced by operational factors such as pore size, pressure, pH, and temperature (Jena et al. 2023;
342 Kim and Park 2021).

343 Adsorption is among the most widely used and studied techniques due to its simplicity and high
344 removal efficiency (up to 99%) (Noutsopoulos et al. 2018; Cardoso and Bodnar 2022). The process
345 relies on physical retention mechanisms, particularly electrostatic interactions in the case of ionic
346 surfactants, and is enhanced by micelle formation and colloidal associations that favor entrapment
347 within porous media (Badmus et al. 2021). Common adsorbents include activated carbon, sand,
348 clays, zeolites, and resins, while alternative materials such as coconut fiber (Prodanovic et al.
349 2020), biochar (Kozyatnyk et al. 2023), and nanomaterials like graphene (Khalil et al. 2021) are
350 being explored for their sustainability and performance (Verma et al. 2021). However, adsorption
351 is limited by saturation of the adsorbent and the need for regeneration.

352 Coagulation, on the other hand, is effective for anionic or structurally complex surfactants,
353 promoting their agglomeration and removal through sludge sedimentation (Badmus et al. 2021).
354 Currently, natural organic coagulants are favored over inorganic or synthetic alternatives due to

355 their lower toxicity and environmental compatibility. In fact, low molecular weight organic
356 coagulants have shown superior performance in treating laundry GW compared to inorganic
357 coagulants (Melián et al. 2023). Nevertheless, the resulting sludge may still contain detergent
358 residues classified as hazardous under Regulation (EC) No. 1272/2008.

359 Surfactant removal efficiency varies depending on both the surfactant type and the treatment
360 method. For instance, LAS have shown removal rates of approximately 78% with biofilters, 80–
361 99% with coagulation processes, and up to 99% with membrane-based treatments. NP, a non-ionic
362 and persistent surfactant, has demonstrated removal efficiencies of 84–98% using sand filters
363 combined with activated carbon, highlighting its strong affinity for adsorptive surfaces. In the case
364 of SLS/SDS, a widely used anionic surfactant in household products, removal efficiencies in
365 membrane systems range from 68% to 99%, depending on system configuration and operational
366 conditions. Athullya et al. (2022) demonstrated that multilayer membranes applied to GW
367 treatment effectively removed 13 different surfactants, including sulfonates and phenyl-containing
368 compounds, with efficiencies ranging from 49% to 99%, the lowest corresponding to structurally
369 complex surfactants such as those with phenyl or ester groups.

370 Regarding the toxicity of LAS surfactants, Pérez-López et al. (2018) evaluated their effects on
371 seed germination and root growth of *Lactuca sativa*. The biofilter treatment using gravel and the
372 species *Schoenoplectus americanus* showed low toxicity, with only 11% inhibition, indicating its
373 suitability for reuse. Similarly, Cardoso and Bodnar (2022) evaluated GW treated by a coagulation-
374 flocculation system, obtaining a high quality effluent in which more than 93% of the seeds
375 germinated successfully.

376 **4.2 Biological treatments**

377 Biological degradation of surfactants involves the enzymatic transformation by microorganisms
378 of high molecular weight compounds into low molecular weight compounds under both aerobic

379 and anaerobic conditions. Key mechanisms include enzymatic oxidation, bond rupture, and the
380 breakdown of aromatic rings. Linear and naturally derived surfactants are readily biodegradable,
381 whereas branched, aromatic, or fluorinated surfactants exhibit greater resistance to degradation
382 (Jardak et al. 2016; Borah et al. 2023; Li et al. 2024).

383 Biological treatments can be categorized according to their operating conditions— aerobic,
384 anaerobic, or combined systems. Aerobic technologies, such as fixed-film integrated activated
385 sludge, submerged membrane bioreactors (SMBR), sequencing batch reactors (SBR), membrane
386 biofilm reactors (MBR), green walls, microalgal–bacterial biofilms, and moving bed bioreactors
387 (MBBR), have demonstrated surfactant removal efficiencies ranging from 62% to 99%.
388 Anaerobic–aerobic hybrid systems, including hybrid MBRs, constructed wetlands, and green roof
389 water recycling wetlands (GROW), integrate both redox environments to enhance performance.
390 However, treatment performance is strongly influenced by system design, configuration,
391 operational conditions, as well as the specific characteristics of the GW and the type of surfactants
392 present.

393 Among biological treatments, aerobic ones have emerged as the most recommended for treating
394 GW (Bani-Melhem et al. 2015; Liberman et al. 2016; Kurniawan et al. 2023). The GW is
395 considered easily biodegradable, with a biodegradability index below 2.5 (Li et al. 2009), which
396 makes it suitable for aerobic treatment processes. These systems can achieve removal efficiencies
397 of more than 80% biodegradable organic substances, especially when complete mineralization is
398 achieved (Zhou et al. 2020; Priyanka et al. 2022). This not only ensures effective reduction of
399 contaminants but also minimizes the risk of odor generation and the growth of toxic intermediary
400 metabolites (Van de Walle et al. 2023; Li et al. 2024).

401 In contrast, anaerobic treatments are deficient at removing organic compounds such as surfactants.
402 For example, LAS may inhibit anaerobic biodegradation due to the lack of specific metabolic

403 pathways in anaerobic bacteria, resulting in lower removal efficiencies of anionic surfactants.
404 Furthermore, concentrations as low as 6.3 mg/L have been shown to inhibit the activity of
405 methanogenic microorganisms (Khuntia et al. 2019). Leal et al. (2010b) compared an upflow
406 anaerobic sludge blanket reactor (UASB) to an SBR. The systems consisted of 5.0 and 3.6 L
407 reactors and operated with hydraulic retention times (HRT) of 12 and 6 hours, respectively. It was
408 found that the UASB system removed only 24% of anionic surfactants, while the SBR removed
409 97%. This difference is mainly due to the limited biodegradability of surfactants like LAS and
410 cationic compounds under anaerobic conditions (Jardak et al. 2016). The removal achieved by the
411 UASB system is probably due to adsorption onto sludge particles, particularly facilitated by the
412 presence of extracellular polymeric substances (EPS) in the anaerobic biofilm matrix. These EPS
413 contain functional groups capable of interacting with surfactant molecules, enhancing their
414 retention within the sludge rather than promoting their biodegradation (Zhou et al. 2023).

415 Biofilm technologies have demonstrated high efficiencies in removing surfactants, particularly
416 anionic compounds such as LAS. For instance, microalgal-bacterial biofilms achieved removal
417 rates of 95-99% for LAS (Li et al. 2024; Zhou et al. 2023), while integrated fixed-film activated
418 sludge systems reported efficiencies between 88-94% (Eslami et al. 2017). Membrane-based
419 systems such as MBRs and SMBR showed LAS removal efficiencies of 71-99% and 60-95% for
420 general anionic surfactants, respectively (Bani-Melhem et al. 2015; Liberman et al. 2016; Zhou et
421 al. 2020; Ren et al. 2022). The SBR removed 80-92% of anionic surfactants, and MBBR exhibited
422 broader variability, with 57-99% for anionic and 88-99% for nonionic surfactants (David et al.
423 2013; Bering et al. 2018; Priyanka et al. 2020a).

424 The MBRs are widely used for GW treatment due to their high efficiency, but their performance
425 is often hindered by high energy consumption, membrane fouling, and alterations in the
426 rheological properties of the mixed liquor (Awasthi et al. 2024). Elevated concentrations of

427 surfactants can exacerbate these issues by inhibiting microbial activity, particularly under
428 anaerobic conditions, and by promoting the accumulation of soluble microbial products and EPS.
429 These compounds form a gel-like fouling layer on the membrane surface, reducing permeability
430 and increasing transmembrane pressure, which necessitates more frequent cleaning and elevates
431 operational costs (Bani-Melhem and Smith 2012; Verma et al. 2021; Borah et al. 2023). Despite
432 these challenges, Ittisupornrat and Theeparaksapan (2023) found that key microbial taxa, such as
433 *Proteobacteria* and *Planctomycetes*, remained dominant in the MBR biofilm, demonstrating
434 resilience to surfactant toxicity and contributing to system stability and fouling mitigation.

435 Other biological technologies classified as NbS have been widely studied for GW treatment. These
436 include biofilters (Pérez-López et al. 2018), green walls (Dal Ferro et al. 2021) and constructed
437 wetlands (CWs) (Ramprasad and Philip 2016, Gutierrez et al. 2025). CWs involve mechanisms
438 such as adsorption, biodegradation, and phytodegradation for surfactant removal (Ravichandran et
439 al. 2021; Ren et al. 2021). Ramprasad and Philip (2018) examined SDS removal pathways in a
440 planted CW, reporting that after 35 days, 5.2% was taken up by plants, 13.1% was metabolized,
441 and 58.2% remained as recalcitrant SDS adsorbed in the soil matrix. Similarly, Monsalves et al.
442 (2023) used a vertical subsurface flow constructed wetland (VFCW) to treat GW from laundries.
443 They reported removal efficiencies of 99% for anionic surfactants, 45% for cationic surfactants,
444 and 85% for non-ionic surfactants. They also found a positive correlation between the
445 biodegradation index and the presence of cationic and non-ionic surfactants, and a negative
446 correlation for anionic surfactants.

447 Regarding toxicity, Priyanka et al. (2022) evaluated treated GW by bioluminescence inhibition
448 tests with *Aliivibrio fischeri* after treatment with an SBR system, reporting only 13.6% inhibition,
449 indicating non-toxic conditions. On the other hand, Ramprasad and Philip (2018) evaluated the

450 impact of SDS on plant growth, observing that SDS accumulated mainly in the roots, leading to
451 visible signs of root deterioration.

452 **4.3 Advanced chemical treatments**

453 Chemical and advanced treatments are highly effective for removing recalcitrant surfactants,
454 particularly when complete oxidation or mineralization is required. These processes involve the
455 breakdown of complex chemical structures into simpler compounds and, ideally, into harmless
456 end-products such as carbon dioxide, water, and mineral salts. Such technologies are especially
457 suitable for treating GW with high concentrations of surfactants, or those with branched chains,
458 aromatic rings, or fluorinated groups that exhibit greater persistence and resistance to degradation.
459 However, key challenges include high operational costs, particularly for energy and chemical
460 inputs, as well as the potential formation of toxic or recalcitrant byproducts (Badmus et al. 2021;
461 Melián et al. 2023). Some of the most widely used technologies are
462 electrocoagulation/electroflotation (Akarsu and Deniz 2021), photocatalysis (Dai et al. 2024),
463 electro-oxidation (Turkay et al. 2017) and photo-Fenton (Esteban García et al. 2021; Melián et al.
464 2023) .

465 Electrocoagulation (ECO) and electroflotation (EF) are two similar electrochemical techniques
466 that use electrical energy to remove impurities and contaminants. These processes dissolve
467 metallic electrodes via an electric current, generating coagulant ions in situ that effectively
468 eliminate surfactants (Jena et al. 2023). Authors have reported high surfactant removal efficiencies
469 using ECO and EF treatments, achieving 80-98% removal of anionic surfactants, 93% for cationic
470 surfactants, and 80% for non-ionic surfactants (Barişçi and Turkay 2016; Akarsu and Deniz 2021;
471 Dimoglo et al. 2023). Tabash et al. (2024) demonstrated the potential for process optimization in
472 the treatment of laundry GW with high concentrations of surfactants, detergents, and suspended

473 solids. Optimal operational parameters were identified, including an A/V ratio of 30 m²/m³, a
474 current density of 10 mA/cm², 50 minutes of electrolysis, and a settling period of 12 h.

475 Advanced oxidation processes (AOPs) include ozonation (O₃), Fenton and photo-Fenton reactions,
476 and UV irradiation combined with hydrogen peroxide (H₂O₂). These methods employ strong
477 oxidants or generate highly reactive species, such as hydroxyl radicals (•OH), which can oxidize
478 and mineralize virtually any organic compound producing CO₂ and inorganic ions under
479 appropriate conditions (Badmus et al. 2021; Borah et al. 2023). These technologies have been
480 applied mainly to dark GW, such as laundry effluents, and have achieved removal efficiencies of
481 surfactants such as LAS, SDS BIAS ranging from 82-99% (Esteban García et al. 2021; Melián et
482 al. 2023).

483 However, while AOPs can achieve high removal efficiencies and even complete mineralization,
484 incomplete degradation may lead to the formation of intermediate transformation products. Some
485 of these subproducts can be more toxic, persistent, or mobile than the parent compounds. Table 4
486 summarizes examples of degradation mechanisms and intermediate subproducts formed during
487 various AOPs. Melián et al. (2023) investigated the metabolic pathway of LAS degradation via
488 the photo-Fenton process, identifying benzene sulfonic, acetic, and formic acids as intermediates.
489 Their results showed that 28.6% of the COD in the effluent corresponded to acetic acid, 15.2% to
490 benzene sulfonic acid, and 0.4% to formic acid. Similarly, Dos Santos et al. (2024) reported
491 complete mineralization of SDS into short-chain carboxylic acids using ECO, attributing this to
492 the action of free radicals and reactive chlorine species.

493 Photocatalysis is an advanced oxidation process that employs solar or UV light to activate
494 catalysts, such as TiO₂, in the presence of oxidants like ozone (O₃), leading to the degradation of
495 surfactants. While reported efficiencies of photocatalysis can reach 89-96%, actual removal
496 depends on the surfactant type. For example, some systems achieved 53-74% removal for SDBS

497 and 36-53% for general anionic surfactants. Dai et al. (2024) applied a solar photocatalytic
 498 treatment for GW using modified TiO₂ (G-NP-TiO₂) and found that SDBS removal occurred
 499 through adsorption and hydroxyl radical oxidation, primarily targeting the methyl groups of its
 500 hydrocarbon chain. Similarly, Priyanka et al. (2020) treated residential GW using VUV/TiO₂,
 501 where UV-activated TiO₂ generated reactive oxygen species capable of breaking down surfactants
 502 into simpler subproducts. The degradation of SDBS followed two main pathways: oxidation at α -
 503 , β -, or branched-chain carbons, and cleavage near adjacent carbon atoms, leading to lower-toxicity
 504 intermediates or structurally altered products. These findings highlight the effectiveness of TiO₂-
 505 based photocatalysis in degrading anionic surfactants like SDBS, with the added benefit of reduced
 506 toxicity in the transformation products.

507 **Table 4.** Examples of degradation mechanisms and intermediate subproducts formed during
 508 various advanced oxidation processes.

Surfactants	Degradability	Intermediate sub-products	Technology	Associated risk	References
Linear alkylbenzenesulfonates (LAS)	Moderate-high	Carboxylic acids; benzenesulfonic, acetic and formic acids	Photo-Fenton	Low, acceptable for irrigation reuse	[1]
Linear alcohol ethoxylates (LAE)	Moderate	n-alkanes, polyethylene glycol, some carboxylic acids and ethanol	Photo-Fenton	Low, acceptable for irrigation reuse	[1]
Dodecil sulfato de sodio (SDS)	High	1-dodecanol and sulfate ion; C-11 and C-10 dicarboxylic acids, undecanedioic acid and sebacic acid, finally shorter length dicarboxylic acids	Electrochemical oxidation	Low, generally complete degradation is generated.	[2]
Sodium dodecylbenzen	Moderate	α -carbon, β -carbon or branched carbon in the	Photocatalysis	Low, decreases	[3]

esulfonate
(SDBS)

alkane chain;alkane chain,
ultimately forming phenolic
hydroxyl groups

VUV/TiO₂

toxicity
throughout
degradation

509 [1]: Melián et al. (2023); [2]: Dos Santos et al. (2024); [3]:Dai et al. (2024)

510 The toxicity of degradation intermediates is a major concern, as these compounds can be as
511 harmful, or even more harmful, than the parent surfactants, yet they remain poorly studied and
512 documented. Dai et al. (2024) estimated the oral LD₅₀ (rat) of several by-products formed during
513 the photocatalytic degradation of SDBS and found that only one of the thirteen identified
514 subproduct was classified as “harmful”. This highlights the importance of allowing sufficient
515 reaction time to ensure complete mineralization and safe water quality. Similarly, Turkay et al.
516 (2017) evaluated the toxicity of treated effluents using the E-peroxone process and ozonation,
517 reporting reduced bioluminescence inhibition in *Vibrio fischeri* to 22% and 25%, respectively.
518 However, they also noted that elevated chlorine concentrations (230 mg/L) could be highly toxic
519 to aquatic organisms.

520 **4.4 Combined treatments**

521 Some studies have recommended exploring the use of combined technologies, as they often yield
522 superior results in terms of efficiency and effectiveness (He et al. 2022; Kurniawan et al. 2023).
523 The implementation of a single treatment technology is often insufficient to address the wide
524 variety of surfactants and contaminants present in GW. Therefore, it is often necessary to
525 implement a treatment train that integrates different mechanisms, including biological,
526 physicochemical and advanced disinfection processes, tailored to the desired water quality and
527 reuse limits.

528 Systems integrating biological, chemical, and physical processes, such as MBRs with chlorination,
529 electrocoagulation with sulfates, and adsorption coupled with phytoremediation, achieved removal
530 efficiencies ranging from 88% to 99% for various surfactants (Bani-Melhem and Smith 2012;

531 Santasmasas et al. 2013). Notably, biological treatments combined with UV disinfection or
532 adsorption techniques reached up to 99% removal for anionic surfactants (Fountoulakis et al.
533 2016). Additionally, ceramic filters paired with membrane bioreactors were highly effective in
534 removing LAS homologues (C10–C13), achieving up to 99% efficiency (Hasan et al. 2015). These
535 results highlight the importance of integrated treatment approaches, particularly when addressing
536 the persistence of surfactants like SLS, LAS, and non-ionic surfactants in different types of GW.
537 Toxicity in combined systems depends on treatment type and the balance between removal
538 efficiency and by-product formation. Melián et al. (2023) found that both photo-Fenton and
539 biofilter + GAC treatments produced reusable GW, but the photo-Fenton process showed higher
540 environmental impacts, except for non-carcinogenic toxicity and eutrophication, due to its higher
541 energy and chemical use. Similarly, Mosquera-Romero et al. (2023) reported increased toxicity
542 when EC was applied before a CW, attributed to the formation of chlorinated by-products (ClO_3^- ,
543 ClO_4^-), these compounds can inhibit microbial activity within the CW and increase the
544 phytotoxicity of the treated water.

545 Beyond their effectiveness in contaminant removal, combined technologies excel in optimizing
546 system operation. Integrated solutions such as SMBRs or MBRs coupled to disinfection units
547 allow multiple stages to be consolidated in compact configurations, improving process efficiency
548 and reducing space usage (Santasmasas et al. 2013; Fountoulakis et al. 2016). Also, the
549 combination of electrocoagulation with SMBR has been shown to decrease membrane fouling by
550 13%, reduce operating costs and minimize sludge generation (Bani-Melhem and Smith 2012).

551 Several studies have assessed the economic feasibility of GW treatment technologies, revealing
552 wide cost variability depending on the process complexity and integration level. The NbS, such as
553 CW, offer the lowest treatment costs, with reported values of 0.33 €/m³ (Hamidi et al. 2025).
554 Similarly, hybrid systems like CW + GAC showed competitive operational costs (0.71 €/m³)

555 compared to more energy-intensive technologies (Melián et al. 2023). For instance, combined
556 biological and AOPs reported moderate costs (0.65 €/m³) (Benis et al. 2021), while high-
557 performance systems like thermophilic aerobic membrane reactors coupled with nanofiltration
558 (TAMR + NF) achieved high surfactant removal (85-95%) but incurred higher operational costs
559 (2.24 and 5 €/m³, respectively). The photo-Fenton process reached 6.71 €/m³, highlighting the
560 trade-off between removal efficiency and cost (Melián et al. 2023). Moreover, electrochemical
561 systems integrated with CW show promising removal efficiencies but face limitations due to high
562 capital costs, especially in low-income regions, prompting current research into low-cost electrode
563 materials (Mosquera-Romero et al. 2023).

564 Another advantage is the adaptability of combined technologies to different types of GW with
565 different contamination levels, including laundry GW (rich in surfactants) or mixed domestic GW.
566 The combined technologies demonstrated improved surfactant removal performance in different
567 types of GW. Efficiencies ranged from 88-99% for mixed water, 78-99% for dark GW, and up to
568 98-99% for light GW. In comparison, physical technologies performed worse, with efficiencies
569 between 22-99% overall for mixed GW. Biological technologies achieved an efficiency range of
570 40-99% for all water types, while advanced chemical technologies achieved efficiencies of 53-
571 99% in dark and mixed GW. In summary, combined technologies enhance the efficiency and
572 adaptability of GW treatment, making them ideal for applications demanding high quality
573 standards and sustainable practices such as GW reuse.

574 **5. Greywater reuse case studies**

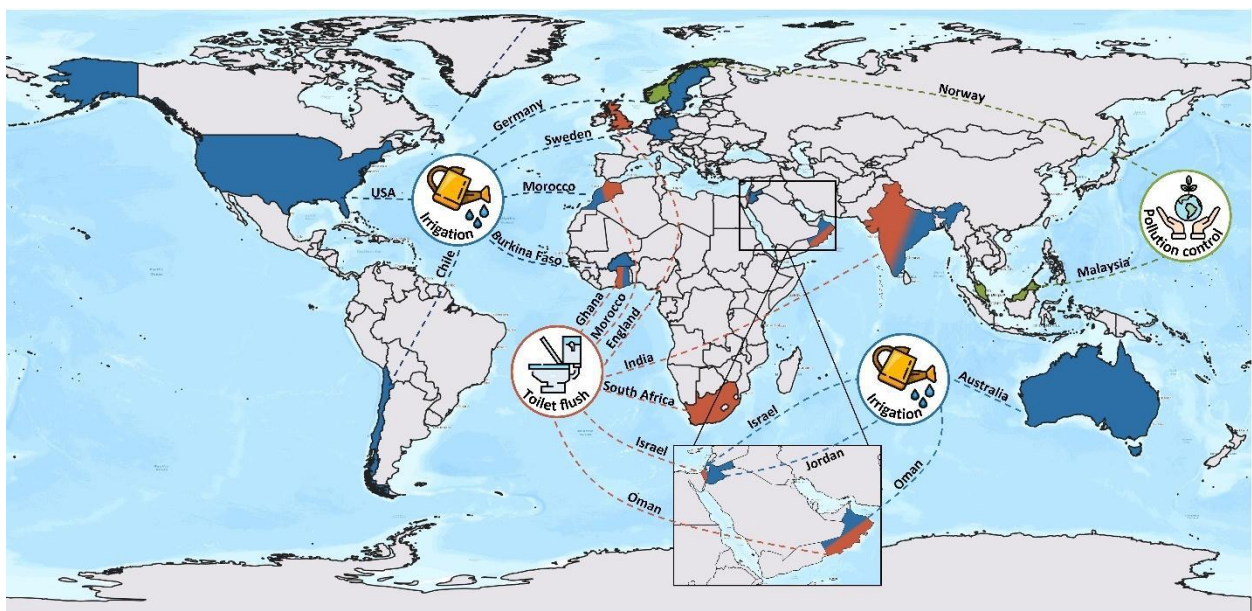
575 It has been estimated that in developed countries, the volume of GW generated can range from 90
576 to 120 L/person/day. Meanwhile, in low-income countries, it could be around 20-30 L/person/day.
577 However, these values may vary depending on lifestyle, habits, geographic location, and water
578 availability (Oteng-Peprah et al. 2018). GW reuse can promote greater adaptability and resilience

579 in local water systems and reduce the costs of transportation for treatment (Van de Walle et al.
580 2023). It has been estimated that reuse could achieve a reduction in domestic water consumption
581 of approximately 40%. It has also been found that on-site or decentralized reuse systems improve
582 supply reliability compared to centralized systems. However, the additional costs of on-site
583 treatment outweigh the monetary benefits related to water and sewage utility bills by more than
584 140% (Momeni et al. 2022).

585 GW reuse is an increasingly common practice that involves the treatment and reuse of sewage.
586 GW reuse has increased worldwide, with notable developments in countries such as Australia,
587 England, Jordan, the United States, Morocco, Japan, Indonesia, Malaysia, and Israel (De Gisi et
588 al. 2016; Oh et al. 2018; Awasthi et al. 2024). Australia is a leader in the development of guidelines
589 for GW reuse, including state-specific regulations. In New South Wales, untreated GW is allowed
590 for underground irrigation, and Sydney has implemented the GW Reservoir Policy, successfully
591 reusing 25 million m³ of water per year. Reuse criteria across the country vary depending on GW
592 characteristics, treatment levels, and intended applications (Oh et al. 2018; Awasthi et al. 2024).
593 California has advanced in promoting GW use through potential incentives, focusing on various
594 non-potable applications for homes and apartments. In 2009, GW was incorporated into building
595 standards under Chapter 15 of the California Plumbing Code (Khosrowshahi Asl et al. 2023). In
596 other cities such as Tokyo, Japan, recycling is mandatory for buildings with an area greater than
597 30,000 m², and there may also be subsidies for some of the costs associated with implementing
598 treatment systems (Ogoshi et al. 2001). The global regulatory framework for GW reuse varies
599 reflecting differences in regulatory frameworks, technological capabilities, and local water scarcity
600 challenges. Specific GW reuse standards have been established in nations such as the USA,
601 Australia, Japan, Canada, China, Israel, and Taiwan (Noutsopoulos et al. 2018). For each activity
602 to be carried out, the regulations become more or less strict in terms of the concentration of certain

603 parameters (Oron et al. 2014; Rodriguez et al. 2022). The main regulated parameters relate to pH,
604 solids, organic matter (mainly BOD₅) and nutrients. In terms of microbiological contamination,
605 fecal coliforms are mainly regulated. However, specific compounds such as surfactants are poorly
606 regulated indicating they are not a regulatory priority. Countries with guidelines or regulations on
607 surfactants include Spain, Germany, Italy, Greece, Indonesia, India, China, and Japan, with
608 permissible concentrations ranging broadly, from 0.5 to 30 mg/L (De Gisi et al. 2016; Boano et al.
609 2020; Crini et al. 2024) (Supplementary Material, Table S5).

610 Once treated, GW can be used for a variety of purposes, including flushing toilets, watering green
611 areas, pollution and environmental control, and domestic activities (gardening, lawn watering, car
612 washing, etc.). Figure 4 shows a map of GW reuse in different countries around the world, with
613 the main applications: irrigation, pollution control, and toilet flushing. The most common use for
614 GW reuse in urban areas is toilet flushing, which can reduce household water demand by up to
615 30% (Mahmoudi et al. 2021).



616

617 **Figure 4.** Geographic locations of selected case studies and their greywater reuse applications.

618 Some developed countries such as Australia, Singapore, Malaysia, and various European countries
619 have promoted the reuse of GW for agricultural irrigation, pollution control, and environmental
620 purposes (Oh et al. 2018; He et al. 2022). Meanwhile, less developed countries such as African
621 countries, reuse GW for flushing toilets (Awasthi et al. 2024). For example, in Norway,
622 Klosterenga, an apartment building, combines energy and water savings by reusing GW for garden
623 irrigation (Gisi et al. 2016). In contrast, Ghana faces challenges due to limited data on GW
624 generation, characteristics, and reuse practices, which hampers sustainable management efforts
625 (Dwumfour-Asare et al. 2017).

626 Gyapong-Korsah et al. (2023) conducted a study on the direct (untreated) use of laundry water
627 from households in Kumasi, Ghana, which was used to clean floors, wash cars, and refill toilets.

628 Ilemobade et al. (2013) presented a case study on the reuse of GW from sinks and showers in a
629 university building in Johannesburg, South Africa. Another type of GW reuse is the irrigation of
630 gardens or trees. In Ein Al-Baida Tafila, Jordan, hand washing water from a rural household was
631 used for this purpose (Al Arni et al. 2022). In addition, in Western Sydney, Australia, laundry
632 water from single-family homes treated by a domestic GW recycling unit is used for landscape
633 irrigation (Pinto and Maheshwari 2010).

634 Public acceptability is the main barrier to reuse systems succeeding and being reliable and long-
635 lasting. Therefore, Amaris et al. (2021) studied preferences regarding treated GW reuse. They
636 found that uses requiring more direct contact are the least preferred, and that willingness to reuse
637 GW decreases as qualitative appearances worsen. Reuse for drinking water was the least accepted.

638 In the best-case scenario they examined (transparent and odorless effluent), acceptability of
639 indirect uses increased by 16.3% and 18.7% and direct uses by 13.8% to 18.9%. Meanwhile,
640 Oteng-Peprah et al. (2018) state that technology, quality assurance, financial incentives, and
641 human resources have a major influence on people's intentions to adopt a treatment and reuse

642 system. Even when these factors are in place, it is vital for households to have the financial
643 resources to implement the system, understand the technology, and be assured of the quality of the
644 treated water.

645 Table 5 provides detailed information on case studies of GW reuse in different countries. Few
646 studies have incorporated surfactants as a key variable in the assessment of the characteristics of
647 GW intended for reuse. Regarding the reuse of GW for landscape irrigation, studies have indicated
648 that surfactant concentrations above 10 mg/L can have negative effects on the physical properties
649 of the soil and plants (Gräf et al. 2022; Borah et al. 2023). Although there are no international
650 guidelines or standards developed by bodies such as the USEPA (USEPA 2012) or the European
651 Union (EC 2020), it is advisable to keep surfactant levels below detectable limits, or at least
652 between 1-2 mg/L, to minimize adverse effects. Some case studies have reported anionic surfactant
653 concentrations in treated GW of 0.02 (Rahman et al. 2023), 0.4 (Al-Ismaili et al. 2017), and 0.6
654 mg/L (Compaoré et al. 2023), demonstrating a quality suitable for irrigation. Meanwhile, for less
655 demanding uses such as toilet flushing, surfactant concentrations may be higher, ranging from
656 approximately 2 to 24 mg/L (Dwumfour-Asare et al. 2017; Craddock et al. 2020).

657 In some case studies, preliminary treatment is used, consisting mainly of primary treatment with
658 screens/sieves (Mandal et al. 2011; Laaffat et al. 2019), settling tanks (Dalahmeh et al. 2016; De
659 Gisi et al. 2016; Al-Ismaili et al. 2017), and degreaser (Mah et al. 2008). One of the simplest and
660 most widely used treatments is the layered filter or filter media, but it is not sufficient (Al-Ismaili
661 et al. 2017; Abushammala et al. 2021; Sami et al. 2024). Secondary biological treatments such as
662 planted filters (Compaoré et al. 2023), CW, (Mah et al. 2008; Laaffat et al. 2019; Masi et al. 2010),
663 green roofs (De Gisi et al. 2016; Rahman et al. 2023), or even combined biological treatment
664 (Friedler et al. 2005) have been found to be optimal for GW reuse. As for disinfection, only a few

665 case studies considered this step necessary, using chlorine (Friedler et al. 2005; Mandal et al. 2011;
666 Al-Ismaili et al. 2017) or ultraviolet light treatments (Laaffat et al. 2019; Masi et al. 2010).

667 It is important to note that few studies have explored treatment trains for GW reuse that fully
668 comply with existing regulations (Friedler et al. 2005; Masi et al. 2010). Sami et al. (2024)
669 evaluated four GW treatment configurations, achieving average surfactant removal efficiencies
670 above 91% across all units. The study also incorporated a Water Quality Index (WQI) assessment
671 to determine the treated water's suitability for various reuse applications. However, while some of
672 these systems are simple and cost-effective, real-world deployment of advanced or hybrid
673 treatment technologies, such as AOPs, remains limited. The main obstacles are high capital and
674 operating costs, complex maintenance requirements, and poor adaptability to decentralized or rural
675 contexts. In addition, issues such as sludge management and energy demand may compromise
676 their long-term viability in the absence of adequate infrastructure and technical support
677 (Mosquera-Romero et al. 2023; Hamidi et al. 2025).

678 **Table 5.** Summary of the main conclusions found from the greywater reuse case studies.

Type	Origin	City	Country	Treatment	Reused for	Water quality for reuse	References
Dark GW	Home	Uagadugú	Burkina Faso	Biological treatment	Irrigation	pH: 7.6; EC: 0.2 $\mu\text{s/cm}$; $\text{PO}_4^{3-}\text{-P}$: 0.9 mg/L; $\text{NO}_3^{-}\text{-N}$: 10.1 mg/L; COD: 134.6 mg/L; BOD: 28.7 mg/L; CF: 1.9×10^7 CFU/100 mL; <i>E. coli</i> : 9.1×10^4 CFU/100mL	[1]
Mixed GW	Home people)	(4 Leipzig	Germany	Physical pretreatment, biological treatment	Irrigation	pH: 7.7; TSS: 6.0 mg/L; BOD: 9 mg/L; COD: 42 mg/L; TN: 11 mg/L TP: 0.2 mg/L; AS: 0.4 mg/L; <i>E. coli</i> : 4.4×10^4 MPN/100mL	[2]
Mixed GW	Community of 20 households	Ayigya and Bomso, Kumasi	Ghana	Untreated	Toilet flushing and irrigation	pH: 6.8-9.7; TSS: 372-4720 mg/L; COD: 400-2000 mg/L; TKN: 7-29 mg/L TP: 10-23 mg/L; BAK:1.2-6.3 mg/L; <i>E. coli</i> : 5-7 CFU/100mL	[3]
Bathroom, laundry	Urban home	Nagpur	India	Physicochemical with disinfection	Toilet flushing and irrigation	pH: 8.4; EC: 435.0 $\mu\text{s/cm}$; $\text{PO}_4^{3-}\text{-P}$: 2.1 mg/L; TN: 52.4 mg/L; COD: 56.0 mg/L; CF: $2.0 \cdot 10^2$ CFU/100mL; <i>E. coli</i> : $463.0 \cdot 10^2$ CFU/100mL	[4]
Mixed farm GW	Family house (6 people)	Negev desert	Israel	Biological treatment	Irrigation	pH: 7.5; EC: 1.3 ds/m; TSS: 3 mg/L; COD: 157 mg/L; TN: 10 mg/L TP: 6.6 mg/L; AS: 0.6 mg/L; CF: 2×10^5 CFU/100mL	[5]
Light GW	Seven apartments in a building	Haifa, Technion Institute of Technology campus	Israel	Physical pretreatment, biological treatment with disinfection	Toilet flushing	Turbidity: 0.6 NTU; TSS: 7.9 mg/L; COD: 40.0 mg/L; BOD: 2.3 mg/L; CF: 0.1 CFU/100mL	[6]
Not specified	Household with seven members	Mukaiftah	Jordan	Pretreatment with physicochemical treatment	Irrigation	pH: 7.8; TSS: 17.0 mg/L; TP: 3.7 mg/L; BOD: 28.0 mg/L; <i>E. coli</i> : 4.4 MPN/100mL	[7]
Mixed GW	Nine single-family dwellings (5 people)	Kuching	Malaysia	Physical pretreatment with biological treatment	Pollution control and outside use	TSS: 2.7 mg/L; TP: 0.3 mg/L; TN: 9.2 mg/L; $\text{NO}_3^{-}\text{-N}$: 5.3 mg/L; COD: 10.6 mg/L; BOD: <2.0 mg/L; CF: 646 MPN/100mL; <i>E. coli</i> : 389 MPN/100mL	[8]
Mixed GW	Agronomy and Veterinary Science Institute of Rabat (IAV)	Rabat	Morocco	Physical pretreatment, biological treatment with disinfection	Toilet flushing	pH: 6.9; Turbidity: 2 NTU; BOD: 10 mg/L; COD: 25 mg/L; TKN: 9 mg/L TP: 0.7 mg/L; AS: 24 mg/L; CF: 1×10^4 CFU/100mL	[9]

Light GW	Primary school	Marrakech	Morocco	Physical pretreatment, biological treatment with disinfection	Irrigation	pH: 7.8; EC: 540.0 $\mu\text{s}/\text{cm}$; Turbidity: 8.0 NTU; PT: 0.4 mg/L; TN: 4.1 mg/L; COD: 8.5 mg/L; BOD: 5.7 mg/L; CT: 1.0×10^1 CFU/100mL; <i>E. coli</i> : 7.0 MPN/100mL	[10]
Mixed GW	35-unit residential apartment buildings	Oslo	Norway	Physical pretreatment with biological treatment	Pollution control and outside use	TP: 0.03 mg/L; TN: 2.5 mg/L; COD: 19.0 mg/L; CF: 0 CFU/100mL	[11]
Bathroom, kitchen	Individual household	Muscat	Oman	Physicochemical with disinfection	Irrigation	pH: 8.2; EC: 522.0 $\mu\text{s}/\text{cm}$; CT: 129.8/0 MPN/100mL; <i>E. coli</i> : 50/0 MPN/100mL	[12]
GW for ablution	Middle East College (MEC) Mosque	Dhofar	Oman	Physicochemical	Irrigation	pH: 9.1; Turbidity: 1.5 NTU; NO_3^- -N: 2.8 mg/L; BOD ₅ : 0.7 mg/L	[13]
Dark GW	Urban home	Santa Clara, California	United states	Untreated	Irrigation	pH: 9.4; EC: 7.8 $\mu\text{s}/\text{cm}$; TDS: 50.7-697.4 mg/L; PO_4^{3-} -P: 5.8 mg/L; SAR: 0.8; BOD: 975.0 mg/L; CF: $2-1.0 \times 10^4$ MPN/100mL	[14]
Mixed GW	Eight single-family houses	Södertälje	Sweden	Pretreatment with physicochemical treatment	Irrigation	pH: 8.4; EC: 918 $\mu\text{s}/\text{cm}$; TSS: 1.4 mg/L; BOD: 2 mg/L; COD: 15 mg/L; TN: 7.5 mg/L TP: 0.6 mg/L; AS: 0.02 mg/L; Na: 116 mg/L	[15]

679 AS: Anionic surfactant

680 References: [1]: Compaoré et al. (2023); [2]: Dwumfour-Asare et al. (2017); [3]: Rahman et al. (2023); [4]: Mandal et al. (2011); [5]: Gross et al. (2007); [6];
681 Friedler et al. (2005); [7]: Dalahmeh et al. (2016); [8]: Mah et al. (2008); [9]: Masi et al. (2010); [10]: Laaffat et al. (2019); [11]; De Gisi et al. (2016); [12]: Al-
682 Ismaili et al. (2017); [13]: Abushammala et al. (2021); [14]: Sami et al. (2024); [15]: Khosrowshahi Asl et al. (2023).

683 Although GW reuse offers many benefits, there are significant constraints that need to be considered
684 when implementing it. The choice of technology depends on factors such as scale, end use, socio-
685 economic aspects related to the cost of water, and regional customs and practices. At present, barriers
686 such as community skepticism about its use in horticulture and irrigation remain, particularly in
687 developing countries (De Gisi et al. 2016; Al-Ismaili et al. 2017; Gyapong-Korsah et al. 2023). This is
688 because adoption rates appear to be low due to limited awareness programs, particularly in developing
689 countries (Borah et al. 2023). However, a study in India has shown that the environmental and health
690 benefits of GW reuse outweigh the costs associated with the system (Godfrey et al. 2009).

691 **6. Conclusions and future challenges**

692 Since 2013, the study of GW has been steadily increasing, with most attention on its characteristics
693 and treatment, in particular relative to the presence of surfactants. The main difference between GW
694 and sewage lies in the concentrations of surfactants found. Despite their importance, studies on
695 treatment technologies have mainly focused on physicochemical methods such as filtration, which do
696 not completely remove the surfactants present in GW. These compounds tend to adhere to solid
697 matrices, requiring proper disposal to avoid their mobilization between the liquid and solid phases and
698 prevent an environmental impact. Surfactants, mainly anionic surfactants, are highly toxic, with
699 potential effects such as endocrine disruption, eye corrosion, dermal irritation, and damage to the
700 respiratory tract. Furthermore, they may bioaccumulate in the fatty tissues of living organisms. It is
701 essential to study the effect of the interaction of surfactants with other XOCs present in GW. These
702 compounds could generate a synergistic response, increasing the damage to living organisms and the
703 ecosystem. One of the main current limitations in the environmental risk assessment of surfactants in
704 GW is the limited application of ecotoxicological models capable of predicting effects under real
705 exposure conditions. There is a need to move towards the development and validation of models that
706 integrate the toxicity of transformation products. Models based on Quantitative Structure Activity

707 Relationships (QSAR) allow prediction of effects of individual compounds or mixtures. While new
708 epigenetic approaches emerge as a promising tool to understand how environmental conditions
709 generate heritable phenotypic responses. Integrating these tools would allow progress towards a
710 comprehensive assessment of surfactant-associated risk.

711 In this context, a treatment train is an ideal solution to address the variety of pollutants present in GW.
712 Combined technologies consisting of pre-treatment together with aerobic biological treatment have
713 proven effective in the removal of surfactants. In addition, advanced oxidation technologies can
714 remove up to 99% of surfactants; however, their high operational cost limits large-scale application,
715 and the formation of potentially toxic byproducts requires further investigation. This is in accordance
716 with actual case studies in certain countries, e.g., in developed countries where it is possible to
717 implement such technologies. However, in developing countries, where water scarcity is a reality, only
718 physico-chemical technologies can be used due to their ease of implementation and low cost.
719 Therefore, developing cost-reducing strategies such as the use of renewable energy or the reuse of
720 adsorption materials could lead to the economic and energy optimization of these technologies. In the
721 future, nature-based treatments could offer sustainable and low-cost solutions. Their use as
722 decentralized systems would promote the safe reuse of GW. The adaptability of advanced technologies
723 and combination with these systems could consolidate integrated and sustainable GW management.

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1193 **CRedit authorship contribution statement**

1194 **Yenifer González:** Conceptualization, Writing – review and editing, Writing – original draft,
1195 Visualization, Investigation, Formal analysis. **Valentina Carrillo:** Data curation, Software,
1196 Visualization, Writing – review and editing. **Gloria Gómez:** Data curation, Software, Visualization,
1197 Writing – review and editing. **Marta Carballa:** Writing – review and editing, Supervision. **Gladys**
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1199 **Declaration of competing interest**

1200 The authors declare that they have no known competing financial interests or personal relationships
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1203 Data will be made available on request.

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