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Management of greywater: environmental impact, treatment, resource recovery, water recycling, and decentralization

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ABSTRACT

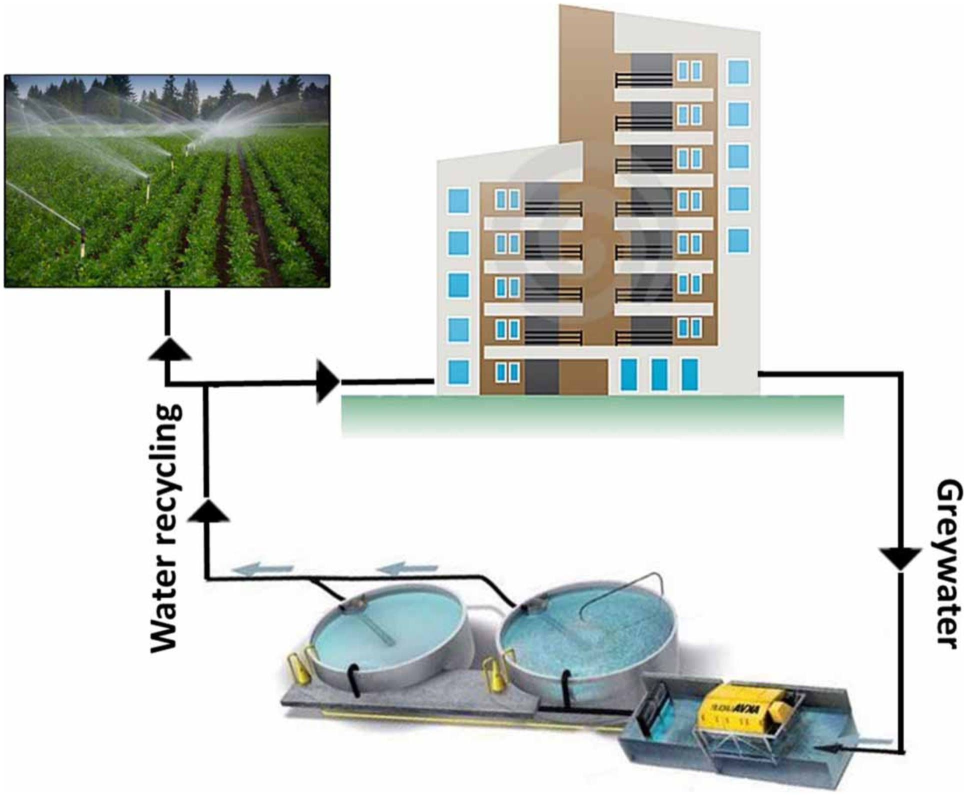
Wastewater generated from households can be classified into greywater and blackwater. Greywater makes up a substantial portion of household wastewater. Such water consists of wastewater released from kitchen sinks, showers, laundries, and hand basins. Since the greywater is not mixed with human excreta and due to the low levels of pathogenic contamination and nitrogen, it has received more attention for recycling and reusing in recent decades. Implementing decentralized greywater treatment systems can be an effective solution to overcome water scarcity by supplying a part of water requirement, at least non-potable demand, and decreasing pollutant emissions by eliminating long-distance water transportation in remote regions, like rural and isolated areas. This review focuses on greywater management in terms of reducing environmental risks as well as the possibility of treatment. Effective management of water reclamation systems is essential for a decentralized approach and to ensure the protection of public health. In this regard, the environmental impacts of disposal or reusing the untreated greywater are discussed. Furthermore, the most appropriate technologies that can be employed for the decentralized treatment of greywaters like constructed wetlands, waste stabilization ponds, membrane systems, and electrochemical technologies are described. Finally, this review summarizes resource recovery and sustainable resource reuse.

Key words: decentralized treatment system, environmental impacts, greywater management, resource recovery

HIGHLIGHTS

- Reusing untreated greywater causes difficulties for human health, the environment, and the installation.
- The decentralized wastewater treatment system can be considered a long-term solution for small societies by offering reliable and cost-effective wastewater treatment.
- Implementing decentralized treatment systems encounters barriers like public perception, unpleasant odor, and technological and economic challenges.

GRAPHICAL ABSTRACT



LIST OF ABBREVIATIONS

AD	Adsorption
BOD_5	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CWWTP	Centralized Wastewater Treatment plant
DGW	Dark Greywater
DGWTS	Decentralized Greywater Treatment System
DOC	Dissolved Organic Carbon
DWWTP	Decentralized Wastewater Treatment Plant
DWWTS	Decentralized Wastewater Treatment System
EC	Electrocoagulation
EO	Electro-Oxidation
FC	Fecal Coliform
GAC	Granular Activated Carbon
GW	Greywater
HPC	Heterotrophic Plate Count
HRT	Hydraulic Retention Time
LAS	Linear Alkylbenzene Sulfonate
LECA	Lightweight Expanded Clay
LGW	Light Greywater
LWW	Laundry Wastewater
MBBR	Moving Bed Biofilm Reactor
MBR	Membrane Bioreactor
NF	Nanofiltration
NP	Nonylphenol
OP	Octhylphenol
RSF	Rapid Sand Filtration

SAR	Sodium Adsorption Ratio
SRT	Sludge Retention Time
SSF	Slow Sand Filtration
TDS	Total Dissolved Solid
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solid
UF	Ultrafiltration
UV	Ultraviolet
WW	Wastewater
WWTS	Wastewater Treatment System
XOCs	Xenobiotic Organic Compounds

1. INTRODUCTION

Increased water consumption has resulted in a scarcity of high-quality water resources, necessitating wastewater treatment and reuse as a potable or non-potable water source. Environmental and economic concerns have been driving forces behind wastewater reuse. Due to the low levels of pathogenic contamination and nitrogen, greywater (GW) has received increased attention for recycling and reuse in recent decades. Greywater and blackwater are the two types of wastewater generated by households. GW accounts for 75–90 percent of household wastewater and includes wastewater from kitchen sinks, showers, bathtubs, hand basins, washing machines, and laundries (Leal *et al.* 2011). Light GW is wastewater generated by bathrooms, showers, and basins. The term 'dark greywater' refers to grey wastewater that contains more contaminated waste from laundry facilities, dishwashers, and kitchen sinks. Light GW, on the other hand, appears to be the easiest wastewater to recycle because it contains fewer pollutant loads. Toilet waste is managed in blackwater. Blackwater includes a high level of nitrogen, phosphorus, pathogens, hormones, and pharmaceutical residues, especially when using vacuum toilets (Chaillou *et al.* 2011; Leal *et al.* 2011).

Water recovery from wastewater has been debated for decades, but recently increasing awareness of resource scarcity has grown substantially. Greywater is an excellent resource for recycling to reduce water stress and has gained international attention as an alternative water source for reuse (Ghaitidak & Yadav 2013). Geographic location, climatic conditions, water abundance, water infrastructure, lifestyles, living standards, population structures (age, gender), culture, and habits influence the volume of GW generated. The released GW can range from 90 to 120 L per person per day in developed countries and as low as 20–30 L per day in low-income countries suffering from water scarcity (Li *et al.* 2009; Oteng-Peprah *et al.* 2018). This huge amount of generated wastewater (WW) can be used for indoor and outdoor non-potable applications. The most attractive applications are toilet water flushing, lawn watering, agriculture watering, irrigation of parks and recreational areas (Widiastuti *et al.* 2008).

Wastewater requires treatment before reuse or discharge to surface or groundwater. Currently, a substantial share of the WW has been treated by conventional large-scale centralized wastewater treatment plants (CWWTPs), in which WW is collected from various sources and transported through extensive pipeline networks to a CWWTP. However, employing the on-site decentralized treatment and reuse of WW, particularly grey wastewater, can achieve the dual benefits of reducing freshwater consumption while also managing GW sustainably, especially in rural and peri-urban areas. In developing countries, rural areas confront severe water shortage challenges and risk of groundwater contamination due to lack of water treatment. A decentralized greywater treatment system (DGWTS) for reuse is one solution to these issues (Subramanian *et al.* 2020).

This study provides an overview of the management of grey wastewater considering treatment and resource recovery with the decentralization concept. The review is arranged in the following sequence. First, a summary of the GW and its characteristics are given, followed by the environmental impacts and health risks of disposal or reusing the untreated GW. Next, the importance of decentralized wastewater treatment and the different decentralized treatment approaches are brought up. This discussion is followed by decentralized treatment of greywater and resource recovery and sustainable resource reuse in terms of water reclamation, nutrient, and energy recovery. Finally, the techno-economic aspects and critical challenges pertinent to the DGWTS and the recommendations to surmount the implementations are debated.

2. GREYWATER AND ITS CHARACTERISTICS

Greywater has different characteristics, depending on its source (e.g., kitchen, laundry, or bath), as well as the quality of water provision, type of distribution network (e.g., pipe structure and age), and household activities (Eriksson *et al.* 2002; Rakesh *et al.* 2020). The kitchen and laundry wastewater contain more organics and physical pollutants than the bathroom and mixed GW, according to the GW classification based on its origin. Furthermore, due to product usage and water consumption variations, the composition will change dramatically over time. Besides this, the WW properties may vary as a result of chemical compound degradation during transportation and storage (Eriksson *et al.* 2002; Li *et al.* 2009).

Greywater comprises a wide range of pollutants, including suspended and dissolved solids, alkaline and acidic compounds, fats, oils, and greases. Heavy metals, nitrates, phosphates, and xenobiotic organic compounds (XOCs) were also reported as pollutants. Surfactants are a primary chemical compound of cleaning chemicals in GW (Widiastuti *et al.* 2008; Rakesh *et al.* 2020). Grey wastewater also contains metals such as sodium, calcium, potassium, sulfur, magnesium, and aluminum (Palmquist & Hanæus 2005). Eriksson *et al.* (2002) reported that 900 potential XOCs could present in GW due to the consumption of household chemical products (Eriksson *et al.* 2002). Greywater has been found to contain microorganisms, biological microbes, pharmaceuticals, health and personal care products, and dyes (Oteng-Peprah *et al.* 2018). The presence of the substances above in GW demonstrates the complexities of GW composition. Table 1 summarizes the literature's data, relying on the properties of grey wastewater from urban and rural area that employed decentralized methods to treat.

As expected, the grey wastewater characteristics are highly dependent on the source of generation, which here is classified into light and dark GW. Wastewater generated by bathroom sinks, showers, and basins is considered light greywater (LGW). In contrast, GW discharged from laundry facilities, dishwashers, and kitchen sinks that are more polluted are referred to dark greywater (DGW). This differentiation has remarkably affected greywater treatment systems and the potential for reuse (Leiva *et al.* 2021). Light greywater mainly contains soaps, shampoos, body care products, toothpaste, shaving waste, hair, body fats, lint, and a trace of urine. On the other hand, DGW from laundry includes soap, bleaches, oils, paints, solvents, and non-biodegradable compounds, and from kitchen sinks contains food residues, high amounts of oils and fat, and detergents (Albalawneh & Chang 2015).

Literature has extensively discussed the physical and chemical characteristics of greywater. Results in Table 1 indicate that GW parameters are highly variable. Dark greywater is higher in both organics and physical pollutants compared to LGW (Halalsheh *et al.* 2008). Typically, the total suspended solid (TSS) values are in the range of 100–1,000 $mg \cdot L^{-1}$ in GW. However, the amount out of this range was also reported (Katukiza *et al.* 2014; Teh *et al.* 2015). TSS levels are generally higher in DGW compared to LGW due to washing clothes, dishes, fruits, and vegetables that may contain sand, clay, and other contaminants. The conventional WW parameters, such as biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD), have always been reported in terms of wastewater features. Probably, the high concentration of COD in DGW is caused by detergents in laundry powders and dishwashing liquids. COD and BOD_5 values in studies of Halalsheh *et al.* (2008) and Katukiza *et al.* (2014) in a rural area in Jordan and urban slums in Uganda were reported higher than the other studies (Halalsheh *et al.* 2008; Katukiza *et al.* 2014). According to Halalsheh *et al.* (2008), the low per capita water consumption in Jordan accounted for the high level of contaminations reported in their study (Halalsheh *et al.* 2008). Biodegradability refers to the ability of bacteria to decompose organic matter and convert it to carbon dioxide and water (Metcalf *et al.* 1991). It is determined by the BOD_5/COD ratios, and both LGW and DGW show good biodegradability (Albalawneh & Chang 2015). The average ratios in GW were reported to be in the range of 0.25–0.80, indicating that almost half of the organic matter in GW is biodegradable.

Due to kitchen activities and laundry detergent, DGW is typically higher in nutrients N and P (2.75–57.7 and 0.062–42 $mg \cdot L^{-1}$) than LGW (4.1–16.4 and 0.11–1.8 $mg \cdot L^{-1}$) (Boyjoo *et al.* 2013). Surprisingly, high concentrations were measured for nutrients in the GW in rural areas in Jordan, especially for LGW from ablution and hand basins. The author concluded that the high ammonia level was because children in some families do not use diapers in houses (Halalsheh *et al.* 2008). Therefore, by washing babies and their fecal-contaminated clothes in the hand basins, the concentration of nutrients in the effluent might increase. Another critical parameter in GW with kitchen sinks and showers in bathrooms is oil and grease. The literature has reported oil and grease concentrations of 50 to 100 $mg \cdot L^{-1}$ (Rakesh *et al.* 2020).

3. ENVIRONMENTAL IMPACTS AND HEALTH RISKS OF GREYWATER

Approximately half of the surface water has been reported to be contaminated by untreated wastewater discharge (Sabeen *et al.* 2018). Since this matter has affected our environment, attention was taken to protect the environment from primary

Table 1 | Characteristics of grey wastewater from the urban and rural area

Characteristics	Light greywater				Dark greywater			
Sampling location	Urban home in Malaysia (Teh *et al.* 2015)	School in rural India (Subramanian *et al.* 2020)	Rural areas in Jordan (Halalsheh *et al.* 2008)	Tourist facility in Spain (Zraunig *et al.* 2019)	School in rural India (Subramanian *et al.* 2020)	Rural areas in Jordan (Halalsheh *et al.* 2008)	Urban slums in Uganda (Katukiza *et al.* 2014)	Dormitory in Iran (Ghanbari & Martínez-Huitle 2019)
	Showers & bathroom sinks	Hand basins	Ablution and hand basins	showers & washbasins	Kitchen sinks	Kitchen sinks	bathroom, laundry and kitchen sinks	Washing machine
Temperature (°C)							24.3 ± 2.5	
Turbidity (NTU)		196 ± 112		68.4 ± 39.8	225 ± 118			
Conductivity (μS/cm)			1,836	767 ± 108		1,066	$2{,}097 \pm 135$	$2{,}170 \pm 100$
TSS (mg/L)	36–224	351 ± 223	573	63 ± 114	619 ± 237	644	$2{,}850 \pm 689$	
pH	5.94–6.40		7.6	7.08 ± 0.31		5.58	7.6 ± 1.2	6.7 ± 0.05
BOD_5 (mg/L)	168–673	344 ± 272	597	116 ± 67	445 ± 165	1,100	$1{,}354 \pm 389$	240 ± 50
COD (mg/L)	146–903	643 ± 387	1,489	158 ± 112	553 ± 267	2,244	$5{,}470 \pm 1{,}075$	480 ± 50
BOD_5/COD	0.80	0.53	0.40	0.73	0.80	0.49	0.25	0.5
TOC (mg/L)				39.0 ± 25.6			940 ± 161	202 ± 5
DOC (mg/L)							568 ± 102	
TN (mg/L)				10.4 ± 9.3				
TKN (mg/L)			105	10.3 ± 9.0		51	64.5 ± 15.7	
Nitrite (mg/L)				0.06 ± 0.39				
Nitrate (mg/L)		34 ± 6		0.02 ± 0.04	40 ± 6			
NH_4–N (mg/L)				4.88 ± 2.92			26.0 ± 6.9	
NH_3 (mg/L)			87			32		
TP(mg/L)		1.03 ± 0.68	26		4.53 ± 2.01	18.25	3.2 ± 0.4	
PO_4–P (mg/L)				0.34 ± 0.76				
Anionic surfactant (mg/L)			28			55		
Total coliforms (CFU/100 mL)	6.04×10^7–1.91×10^8						$7.5 \times 10^7 \pm 1.3 \times 10^7$	
Fecal coliforms (CFU/100 mL)		2.35×10^8			2.26×10^8			
Escherichia coli (CFU/100 mL)	0–5.2×10^6		3.0×10^4			7.0×10^5	$4.0 \times 10^6 \pm 2.4 \times 10^6$	
Other microorganisms (CFU/100 mL)	4.40×10^7–1.75×10^8							

pollution sources and prevent extensive expansion (Chrispim *et al.* 2019; Kong *et al.* 2019). The risks associated with untreated GW depend on the objectives of water recycling. For example, in agricultural irrigation, one of the main risks is determined by whether the water is reused in the short or long term (Vuppaladadiyam *et al.* 2019). More than 10% of the world's population consumes foods grown with wastewater irrigation. Low-income countries with arid and semi-arid climates have a much higher proportion. The main motivations for this type of water recycling are due to the increasing water scarcity and the recognition of the value of GW as a water resource (WHO 2006a). Recycling wastewater can contribute to environmental sustainability when performed safely. There was widespread use of partially treated or untreated wastewater for irrigation in agriculture because of its high nutrient content and availability (Adegoke *et al.* 2018). In most cases, GW irrigation could provide all of the nutrients needed for crop growth without incurring the costs associated with additional fertilizers (WHO 2006a). Although the practice offers many benefits, numerous adverse health outcomes have still been reported. Due to the presence of high organic matter concentrations, nutrient content, surfactants, and pathogen content, entering untreated GW causes irreversible damage to the soil and receiving water (Benami *et al.* 2016). Untreated GW irrigation has been shown in studies to alter soil chemistry and hydraulic properties. A study assessed the environmental effects of irrigating a farm using GW. Long-term irrigation with GW has been shown to cause salts, surfactants, and boron to accumulate in the soil, thereby changing the soil properties and causing plant toxicity (Gross *et al.* 2005). Greywater typically contains low concentration levels of persistent organic compounds. Eriksson *et al.* (2002) identified 900 potential xenobiotic organic compounds that might be presented in GW due to the usage of household chemical products in Denmark; however, the majority of these substances will be found at very low concentrations. (Eriksson *et al.* 2002). However, there is a growing trend toward utilizing GW for irrigation; treating the GW before reusing is strongly advised (Eriksson *et al.* 2006; Reichman & Wightwick 2013). Surfactants, oils, grease, sodium, and potentially pathogenic organisms in high concentrations can adversely affect human health and the environment (Siggins *et al.* 2016). Disposal and reusing untreated or partially treated GW has negative consequences for soil, plant, water resource, marine life, and human health. Table 2 illustrates the impacts and health risks while either rejecting untreated GW into the environment or reusing untreated GW.

3.1. Soil and plant

Greywater has a high concentration of organic matter, some of which are poorly degraded, such as surfactants and oils. The most common use of GW is to irrigate plants, which means plant health poses the immediate risks of pollutants in GW. Grey wastewater could be beneficial for plants, as its nutrients, mainly nitrogen and phosphorus, on the other hand, it can be harmful to some plant species with sodium and chloride (Organization 2006). Long-lasting soil exposure to untreated GW results in high surfactants, oils, and grease levels in the soil. As a result, it causes soil hydrophobicity, soil water resistance, a decline in soil characteristics, and adverse effects on plants (Siggins *et al.* 2016). Greywater tends to increase soil alkalinity and salinity while decreasing soil's ability to absorb and retain water. Anions and cations dissolved in water cause salinity. It causes an increase in the osmotic pressure of soil solutions, reducing the water and nutrient absorption by plants. Therefore, controlling salinity is necessary when using treated wastewater for irrigation. Water salinity is generally measured as its electrical conductivity or concentration of total dissolved solids. Electrical conductivity is an easy way to determine the suitability of water for irrigation (Shakir *et al.* 2017).

Alkalinity increases by the presence of sodium, potassium, or calcium salts, especially from the detergents, in GW (Rana *et al.* 2014). Sodium compounds are found in the majority of soaps and detergents. High sodium levels can contribute to an alkaline soil condition while also causing leaf discoloration and burning. The sodium adsorption ratio (SAR) is a parameter that quantifies the effect of sodium compounds on the soil's structure. The increase in SAR (13 or higher) can adversely influence soil properties, limit the plant species to be cultivated, and reduce crop yields due to toxic and osmotic effects. SAR can be calculated from the ratio of sodium to calcium and magnesium by Equation (1):

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}} \tag{1}$$

where Na^{+}, Ca^{2+} and Mg^{2+} are in meq/L (milliequivalents per liter). Furthermore, some sodium compounds interfere with the soil's ability to absorb water. In addition, high sodium levels can prevent calcium from reaching certain plants (WHO 2006d; Shakir *et al.* 2017).

Table 2 | Impacts and health risks while rejecting untreated GW into the environment or reusing untreated GW

Object	Action	Impact	Ref.
Soil & plant	Long-term (3 years) irrigation of arid loess soil with greywater	– Accumulating salts, surfactants, and boron in the soil caused changes in soil properties and toxicity to plants.	Gross *et al.* (2005)
	Long-term (8–18 years) greywater disposal	– Increases in soil chemical parameters such as pH, phosphate, and sodium adsorption ratio (SAR) and pathogen indicators such as *E. coli* might negatively affect soil and human health. – Increases in soil surfactants, oils, and grease levels resulted in soil hydrophobicity, soil water resistance, and adverse effects on plants. – Long-term irrigation may depress yields and crop quality.	Siggins *et al.* (2016)
	Irrigation with greywater	– The presence of elevated salinity and sodicity in greywater could damage soil structures. – The pores of soil can also be physically clogged by organic compounds and suspended solids. – A poorly buffered soil might experience a rise in pH, thereby interfering with the biochemical process.	Maimon & Gross (2018)
	Irrigation of lettuce and radish by greywater	– A high sodium concentration had a competitive effect on Ca, Mg, and K uptake. – Nutrient solubility and bioavailability could have been affected by a rise in soil pH. – Soil irrigation with greywater containing detergents impacted plant nutrition, soil enzyme activity, and worm avoidance.	Reichman & Wightwick (2013)
Water resource & marine life	Wastewater discharge into surface water in South Africa	– Degradation of the receiving surface water body – Aquatic ecosystems and consumers of surface water resources faced adverse health risks. – Nutrients like nitrites, nitrates, and phosphorus enter water bodies and caused eutrophication. – The organic load of wastewater contributed to the depletion of dissolved oxygen (DO) in surface water. – Aquatic life requires low BOD/COD values in surface water. The presence of high BOD and COD levels can pose a threat to marine life, especially fish.	Edokpayi *et al.* (2017)
	Irrigation with greywater	– Surface water and groundwater may be contaminated with GW pollutants like nitrogen, boron, and surfactants. – Specific GW components might adversely affect water biota, including toxic and endocrine-disrupting micropollutants.	Maimon & Gross (2018)
	Greywater containing alkylphenols	– Inhibit testicular growth in rainbow fish, carp, and flounder. – They also stimulate egg production in immature Japanese medaka fish. – Long-time exposure of fish to these compounds disrupts the liver architecture.	Abdulla Bin-Dohaish (2012)

(*Continued.*)

Table 2 | Continued

Object	Action	Impact	Ref.
Human	Through contact with greywater	– Presence of pathogens of indicator organisms that would negatively affect human health	WHO (2006d)
	Through vegetables, shellfish or other food products exposed to contaminated water or soil	– From the presence of pathogenic microorganisms	WHO (2006d)
	Greywater reuse for irrigation	– Micropollutants and metals that are present in GW might cause secondary human health risks. – Greywater is associated with microbiological risks due to pathogens originating from fecal contamination, skin, mucus, and food preparation, like E. coli, Rotavirus, Legionella spp., Pseudomonas aeruginosa, Staphylococcus aureus, Salmonella spp. etc.	Maimon & Gross (2018)
	Wastewater discharge into surface water in South Africa	– As a result of the eutrophication of water sources, cyanobacteria that produce toxins may also grow, and exposure to such toxins can present health hazards to humans.	Edokpayi *et al.* (2017)

Other chemicals harmful to plants, such as chlorides, peroxides, and boron, have also been found in detergent and laundry products. Bleaches often contain chlorides that can damage plants. The tendency to bleach new expanding leaves is a symptom of chlorine-related damage (Gross *et al.* 2005). Chloride is neither adsorbed nor retained by soils, so it moves readily with the soil-water, is taken up by the crop, passes via the transpiration stream, and accumulates in the leaves. Compared with crop tolerances to salinity, chloride tolerances are not so high (Shakir *et al.* 2017). Most plants, furthermore, are extremely sensitive to boron. Boron toxicity involves a burnt appearance to the edges of the leaves, leaf cupping, chlorosis, dieback of the branch, premature leaf fall, and decreased growth (Gross *et al.* 2005).

Microorganisms, particularly fecal indicator bacteria, present in wastewater, transmit disease to plants (Eriksson & Donner 2009). In addition, due to the use of GW with a pH higher than 8, the availability of certain micro-nutrients for plants may be reduced (Vuppaladadiyam *et al.* 2019).

3.2. Water resource and marine life

Irrigation with wastewater results in an indirect effect of aquifer recharge. The impact on groundwater quality is determined by a variety of factors such as the irrigation rate, the irrigation water quality, the treatment of water by the soil, the vulnerability of an aquifer, the method of irrigation, the rate of artificial recharge compared to natural recharge, the initial quality of the underground water and its potential use, the period of irrigation, and the type of crops being irrigated (WHO 2006b). Groundwater contamination is one of the most severe environmental risks associated with untreated GW recycling. Some substances found in GW can reach the groundwater reserves behind the reuse area (WHO 2006d). Greywater used for agriculture may adversely affect groundwater, so it is essential to monitor groundwater characteristics regularly, promote wastewater quality, and use the wastewater in zones where aquifers are less vulnerable (WHO 2006b).

Greywater use in agriculture is also affecting surface water bodies since they receive water from drainage and runoff. However, there are fewer effects than if wastewater is discharged directly into them; effects are still experienced. There are varying impact levels based on water body type, usage, hydraulic retention time, and the role played within the ecosystem (WHO 2006b). The presence of nitrogen and phosphorus in GW causes eutrophication when discharged to surface water, especially in large quantities. Eutrophication reduces water transparency, reduces dissolved oxygen levels, depletes fish and other aquatic life forms, degrades water quality, and increases the occurrence of toxic phytoplankton. Microbial growth could be facilitated by the high temperature of GW entering surface water (Carey & Migliaccio 2009; Edokpayi *et al.* 2017). Besides, an excessive amount of biodegradable organic matter in surface waters can deplete dissolved oxygen, affecting aquatic organisms and contributing to unpleasant odors (WHO 2006b).

Grey wastewater causes toxicity in water sources, as it contains heavy metals and XOCs. Surfactants such as LAS, nonylphenol-, and other alkylphenol-ethoxylates, also have adverse environmental impacts (Eriksson *et al.* 2002). Even at extremely low concentrations, they are incredibly toxic to aquatic organisms (Benami *et al.* 2016; Shah 2017). For instance, alkylphenol ethoxylates are unstable in the environment, resulting from the use, discharge, and biodegradation, nonylphenol (NP) and octhylphenol (OP) emerge. NP and OP have become a global environmental concern due to long-distance transportation, persistence against biological degradation, and an inclination for bioaccumulation in fatty tissues (Priac *et al.* 2017). Several studies have demonstrated the estrogenic effects of alkylphenols that inhibit testicular growth in rainbow fish, carp, and flounder. They also stimulate egg production in immature Japanese medaka fish. Furthermore, long-time exposure of fish to these compounds disrupts liver architecture (Abdulla Bin-Dohaish 2012).

3.3. Human health

Greywater contamination by microorganisms and chemicals may endanger human health. While GW generally contains fewer pathogens than wastewater, some pathogens are introduced into it as a result of washing diapers, doing laundry, using personal hygiene, etc. (WHO 2006a). Greywater consists of high content of readily degradable organic compounds, which contribute to the growth of fecal indicators. Besides, mishandling of food in the kitchen can sometimes introduce enteric pathogenic bacteria, such as *Salmonella* and *Campylobacter* (WHO 2006c). Pathogens enter the human body through various routes, including direct contact with GW, drinking contaminated water, and eating vegetables, shellfish, or other food products exposed to contaminated water or soil. In order to reduce health risks and minimize the inconvenience caused by the reuse of GW, it is recommended to avoid human contact with GW, limit the connection of GW with potable water, avoid GW's direct contact with edible vegetables, and prevent irrigation by sprinklers (WHO 2006d).

Moreover, contaminated groundwater, runoff to surface water, and sprinkler irrigation can further affect the local community (Adegoke *et al.* 2018). It is reported that children and immunocompromised individuals have a higher risk than immunocompetent adults do. The most common skin and intestinal infections were found among people infected via occupational exposure and ingestion. Besides, the use of partially or untreated wastewater to irrigate crops (fruits and vegetables) has been widely reported as a source of food-borne outbreaks (Adegoke *et al.* 2018).

The untreated GW might have an adverse effect on other elements like installation and pipeline. The presence of particles and colloids in GW might lead to systems clogging. The combination of colloids and surfactants could cause the solid phase to be stabilized. A pre-treatment procedure, therefore, is required to remove solids (Eriksson *et al.* 2002).

However, untreated GW is becoming common in applications such as home garden irrigation; due to potential problems associated with GW, it is not recommended that the GW be discharged into water resources and reuse without pre-treatment. Guidelines have been established to ensure public health and produce the full benefits of GW reuse or discharge. Although these guidelines for safe WW reuse exist, it may still be questionable whether the reuse of treated WW causes adverse health effects or not. The complexity of contaminants, treatment, and remediation of grey wastewater seems critical for controlling potentially detrimental health effects and environmental impacts.

4. WHY DECENTRALIZED GREYWATER TREATMENT?

When designing a water treatment system, one of the significant decisions is whether the system will be centralized or decentralized. In the areas where establishing a sewage collection/treatment system is not economically feasible, decentralization is more popular. For instance, 25% of the population in the US is already assisted by small, decentralized wastewater treatment plants (DWWTPs). A decentralized system emphasizes on-site treatment/recycling of domestic wastewater, bio-energy, and nutrients such as nitrogen and phosphorus. These systems are designed to provide optimal water management for homes, businesses, and industrial centers. Decentralization could therefore promote environmental sustainability and retreating loss of environmental resources. This approach is in accordance with global tendencies towards water management paradigms change, from a waste-oriented approach to resource-recovery and water reuse. In many arid areas of a country, recycling can support water resource management goals (Capodaglio *et al.* 2017).

Establishing consistent and feasible wastewater treatment in rural/remote areas is challenging, mostly in developing countries. The issues and restrictions of the centralized wastewater treatment systems can be the high cost of building and operating, specifically in the regions with low population densities and dispersed households. Alternatively, by applying on-site and/or cluster systems, the decentralized system has more advantages in flexibility in management and simplicity.

The decentralized system can be considered a long-term solution for small societies and more reliable and cost-effective (Massoud *et al.* 2009). Through the avoidance of significant capital costs, reduced operating and maintenance costs, and the promotion of business and employment, decentralized treatment may be a cost-effective and economical solution for many communities. Furthermore, it is green and sustainable because it provides clean water, uses energy and land efficiently, permits growth while preserving green space, and uses the natural treatment abilities of the soil. The final benefit is that it will protect the environment, public health, and water quality by offering reliable wastewater treatment, reducing pollutants, and mitigating contamination and health risks posed by wastewater (Tooke 2015).

It should be noted decentralized systems require proper design, maintenance, and operation to provide optimal benefits like any other system. Although decentralized treatment systems have many advantages, the implementation and operation of these systems face many challenges, which are described in detail in the final section of the review. Therefore, management systems must propose practical recommendations concerning wastewater treatment methods, such as financial aspects, public involvement and awareness, system design and selection processes, and inspection, monitoring, and program evaluation (Massoud *et al.* 2009).

The restrictions of centralized wastewater treatment systems, such as land availability, cost-effectiveness, and complexity, lead to employing economically and environmentally sustainable wastewater treatment systems, such as decentralized wastewater treatment systems (DWWTSs). DWWTSs are typically composed of two steps, primary and secondary processes. Heavy solids and flocs settle at the bottom of the tank during primary treatment, while other substances such as oil are separated from the surface. The pre-treated WW is generated once the settled particles and floating materials have been taken away from the tank. Secondary treatment is applied to enhance the treated water quality by removing the suspended and dissolved solids. Generally, a primary and a secondary treatment will be followed by disinfection in order to meet the water quality requirements of GW reuse (Matos *et al.* 2014). Control of pathogens in GW systems is typically achieved through a combination of removal from the primary and secondary process and final disinfection with chlorine or ultraviolet (UV) (Larsen *et al.* 2013). In this case, disinfection prior to reuse is generally accepted as a critical step that requires a robust, simple, safe, affordable, and low maintenance system (Friedler & Gilboa 2010).

Decentralized approaches aim to save freshwater, reduce water pollution, reuse water on-site, and recover resources (Bajpai *et al.* 2019). A significant feature of such a decentralized system is separating the resources as far as necessary. The low strength, but large GW, can be separated from high strength and a small amount of blackwater, thus simplifying and efficient water remediation (Wang *et al.* 2010). When GW is treated to the required standard, it can be reused for several purposes such as agriculture, landscaping, and toilet flushing.

4.1. Primary treatment

There are different on-site wastewater treatment systems (WWTSs). The septic tank treatment is the most frequent approach as a primary treatment method for on-site WW treatment due to eliminating most settleable solids and partially digesting organic matters like anaerobic bioreactor (Massoud *et al.* 2009). A septic tank consists of simple concrete, fiberglass, or polyethylene tank to be buried in the house courtyard. Gravity is typically the driving force in this system, with water running down from the house to the tank and then to the drainage area.

The tank is divided into three layers, scum, water, and sludge. Scum is generated in the layer of scum, while the water layer consists of a partially treated liquid that is free of solids but contains chemicals and bacteria. Moreover, solids are collected and digested by anaerobic bacteria in the sludge layer (Ahmed & Arora 2012). This system works well in a hotter climate and can remove up to 50% of organic load but is less effective in pathogens removal (Bajpai *et al.* 2019). Just the unsuitability of the soil and the site characteristics is the disadvantages. This system should be improved with an effluent filter vault which can prevent some solids from releasing into the effluent and clogging in the system (Massoud *et al.* 2009).

The less common approach would be the Imhoff tank can be considered as another primary treatment process that can regulate higher flow rates than the septic tank. Both mentioned systems are relatively inexpensive and simple to operate and maintain. However, the produced sludge may lead to an odor problem, and it needs to be handled. As known, the conventional on-site WWTSs cannot effectively remove the nitrate, phosphorus compounds, and pathogenic organisms. Therefore, this kind of treatment can be applied prior to further treatment. Suppose the anaerobic septic tank is not suitable for a region or WW type (in places where the soil is poor, the groundwater is high, the land available is small, or the site is sensitive). In that case, an aerobic system can be used alternatively (Massoud *et al.* 2009).

4.2. Secondary treatment

Several secondary treatment methods can be applied for on-site treatment. For example, sand filtration is one of the suggested systems. In the areas with deep, permeable soils, soil absorption systems can be used. While, in the regions with shallow, highly slowly permeable, or extremely permeable soils, the other complicated options must be considered (Massoud *et al.* 2009). Here, some prevalent treatment systems are discussed.

4.2.1. Constructed wetlands

Constructed wetland (CW) is an artificial wetland built using environmental technology to mirror natural wetland conditions. This technology is identified as a nature-based method due to the use of natural media, soil, and plants. Reed grass, cattails, and bulrushes are some of the most widely known plant types employed in constructed wetlands. The three criteria that must be considered before choosing constructed wetlands as a GW treatment process are water availability over the year, horizontal slopes, and impermeable layers to surround a system (Ahmed & Arora 2012). Typically, constructed wetlands are classified as subsurface flow, free water surface, and floating treatment wetlands. The most widely used constructed wetlands are subsurface flow systems divided into vertical flow constructed wetland and horizontal flow constructed wetland (Kivaisi 2001; Oteng-Peprah *et al.* 2018). The performance and efficiency of each type of CW are unique. For instance, the vertical flow CW was investigated and demonstrated to be more effective in removing pathogens than the horizontal flow system CW and green roof water treatment (Boamah 2020). Various studies confirmed that CWs remove contaminates by a combination of physical (filter media), biological (aerobic and anaerobic) as well as chemical processes. CW is an inexpensive and proper treatment method; however, it typically needs pre-treatment and can be deliberated as a secondary treatment alternative. Similar waste stabilization ponds, this system has high pathogens removal, although controlling the disease vectors, specifically mosquitoes and odors, should be considered (Parkinson & Tayler 2003). This method is recognized to remove organic pollutants and suspended solids effectively. A study showed that slugs and earthworms in the Kanuma soil contributed to eliminating solid food particles from the kitchen wastewater. Furthermore, the phosphorous concentration was removed from the GW by soil adsorption, and the biological process has helped reduce the concentration of nitrogen (Itayama *et al.* 2006). Although the removal efficiency varies but CWs are always capable to take away high amounts of GW contaminates.

Despite the advantages mentioned above, the limitations are periodically maintaining the units, the need for regular water supply, and influencing by seasonal weather variations. They can also be destroyed by overloads of ammonia and solids levels (Massoud *et al.* 2009).

4.2.2. Waste stabilization ponds

Another common, simple, and old form of DWWTSs are waste stabilization ponds (WSPs), including anaerobic ponds, optional ponds that combine aerobic and anaerobic treatments, and purely aerobic maturation ponds (Parkinson & Tayler 2003). For more than 3,000 years, WSPs have been used for wastewater treatment (EPA 2011). Its long residence time results in higher pathogen removal. The effluent has adequately high algae concentrations; thus, it is a valuable resource for irrigation (Parkinson & Tayler 2003). WSPs are simple in design, cost-effective, and have low energy consumption. These ponds can also provide other economic advantages since they can provide an environment for fish like tilapia to grow (Bajpai *et al.* 2019). These plants grow in nitrogen-rich soils and can be harvested, composted, and used as a fertilizer. The cultivation of these plants leads to the removal of nutrients and reduces the possibility of eutrophication in the watercourse. Its drawback is requiring a relatively large land area, especially when reusing water is considered (Parkinson & Tayler 2003).

4.2.3. Aerobic treatment

Aerobic WW treatment is a biological process that uses oxygen utilized by microorganisms to degrade organic contaminants into the degradation products like carbon dioxide and water. These systems have a small footprint in comparison to nature-based methods, but they consume more energy. In contrast to natural systems, aerobic systems can produce high-quality effluents that easily meet effluent discharge standards. The main benefit of aerobic systems is that they only require semi-trained personnel, making them an excellent choice of WW treatment process in low-income countries.

These systems can be classified as attached growth processes, suspended growth processes, and hybrid processes. Extended aeration process, moving bed biofilm reactor (MBBR), oxidation ditches, membrane bioreactor (MBR), submerged aerobic fixed film reactor, rotating biological contactor, and sequential bioreactor are some prevalent and full-scale aerobic treatment systems. These systems are used to treat WW with COD less than 1,000 mg·L^{-1}. Its significant drawbacks include plugging aeration equipment during operation, complicated scale-up, and mechanical failures (Singh *et al.* 2015).

4.2.4. Anaerobic treatment

These treatment systems govern the biological treatment where microorganisms degrade organic contaminants in the absence of oxygen into biogas based on hydrolysis, acidogenesis, acetogenesis, and methanogenesis mechanisms (Singh *et al.* 2015). Anaerobic treatment is typically less expensive than most aerobic treatment processes since this process can produce energy and, consequently, be independent of external power sources or reduce external energy consumption. It can simply include a septic tank, which settles suspended solids and digests some settled solids. The other processes include anaerobic waste stabilization ponds, anaerobic filters, and upward-flow anaerobic sludge blanket reactors can be added as well (Parkinson & Tayler 2003). In addition, these systems have been used to treat high-strength WW (with COD more than 4,000 mg·L^{-1}) (Singh *et al.* 2015).

Nevertheless, there are some obstacles, including insecurity in implementing new technologies and limitations from the legislation regarding the quality of treated effluent discharges. Generally, anaerobic systems are followed by aerobic systems for removing the remaining COD, nutrients, and pathogens. The other limitations are associated with low temperatures zones, long HRT, slow start-up, and potential odor and corrosion problems (Singh *et al.* 2015).

4.2.5. Membrane system

Membrane technology (like MBR) is suitable for DWWTSs and water recycling. In general, the following points need to be taken into account for utilizing membrane systems for on-site treatment: reducing costs and increasing affordability, minimizing energy consumption, enhancing nutrient removal, considering disposal approaches, developing monitoring and control system at low cost, effective, and designing remote management systems.

Membrane systems lead to high removal efficiencies. For instance, microfiltration (MF) and ultrafiltration (UF) could eliminate 2 to 5 log for virus contamination, respectively, and 5 log removal of protozoa can be expected. Thus, membrane separation is beneficial for decentralized and sustainable WW treatment/reusing. The membrane systems are typically attached with other processes to attain the appropriate clarification. A pre-treatment stage could be screening, and a combined membrane process, like MBR followed by oxidative treatment/ high retention membrane separation, can be used to yield water for reuse (Fane & Fane 2005).

4.2.6. Filtration

Filtration removes suspended solid matter from a liquid mixture using a filter medium that allows the fluid to pass through but traps the solid particles. Quartz sand, silica sand, anthracite coal, gravel, garnet, magnetite, paper, fabric, cotton-wool, asbestos, glass, and other materials could be used to produce the filter. Filtration in WW treatment removes the majority of solid particles from the water. Physical as well as biological processes remove solids from the filtration systems (Ahmed & Arora 2012).

Filtration is straightforward in terms of technology (simple equipment) and adaptable to various treatment formats. Another benefit of this method is its low investment and operational cost. Sand is the most common filter medium. In different water management stages, a sand filter might be used as a pre-treatment, side-stream filtration, or polishing filter. A sand filter often provides an effluent with the potential for reuse. However, for highly contaminated WW, this method is ineffective. Other drawbacks of this approach include its non-selectivity and filter clogging (Crini & Lichtfouse 2019).

Sand filtration can be categorized into slow and rapid sand filtration. It is critical to differentiate between slow and rapid sand filtration in this context. The disparity between the two is not just a matter of filtration speed but also a matter of the treatment process's underlying definition. Rapid sand filtration (RSF) is a physical treatment procedure, whereas slow sand filtration (SSF) is basically a biological process. The establishment of a microbial population on the top layer of the sand substrate, also known as 'schmutzdecke', makes the top layers of the sand biologically active. These microbes typically enter the system via the source water and form a population within a few days. Slow flow rates of 0.1–0.3 m^3/h per square meter of surface are typical for SSFs. Slow sand filtration is effective for turbidity less than 10–20 NTU. Pre-treatment may be needed if this is not the case. RSF, on the other hand, removes relatively large suspended particles quickly and effectively. This method can handle high filter rates (4,000–12,000 L.h^{-1}.m^{-2}) while requiring small land facilities (WHO(n.y) 2009; Verma *et al.* 2017).

Clogging of the bed is an issue associated with filtration. In the case of clogging, separating the top layer of sand is a widely suggested solution. Overall, scraping the top layer and wetting and drying cycles can minimize sand filter clogging (Verma *et al.* 2017). Backwashing the filter is performed at the end of the operation to clean it. Backwashing SSF is not typically required, but it would be achieved if the influent turbidity and suspended solids become higher than the recommended values. RSF, on the other hand, generally requires regular cleaning and backwashing every 24–72 hours (Tyagi *et al.* 2009; WHO(n.y) 2009).

4.2.7. Electro-technology

Electrochemical **treatment** schemes, like electrocoagulation (EC), electro-oxidation (EO), and electroflotation are appropriate techniques for WW treatment. For instance, the EC has some advantages over chemical coagulation, owing to its compactness, no need for chemicals, less sludge production, and cost-effectiveness, which nominate this technology as a trustable alternative for decentralization. Different operating conditions, such as current density, pH, electrode type, electrolysis time, and supporting electrolyte concentration, can be considered for optimum conditions (Barışçı & Turkay 2016). A study on EC treatment on GW revealed that the optimum operating condition is a current density of 12.5 $mA.cm^{-2}$, operation time of 30 min, and inter-electrode distance of 0.5 cm. Results of contaminants removal efficacy and electrical energy consumption lead to the possibility of the EC method in the treatment of GW. However, the proposed technology needs to be investigated in continuous mode at an industrial scale (Nasr *et al.* 2016).

4.3. Disinfection

Greywater recycling systems must generally include additional disinfection steps to comply with proposed guidelines and avoid contamination by microorganisms that cause disease (Bakheet *et al.* 2020). A final step in the reuse process is disinfection, depending on the reuse application. When high-quality effluent and low pathogen levels are demanded, disinfection is necessary (Boyjoo *et al.* 2013). In spite of the fact that, by definition, GW streams do not have contact with toilet waste, they may still be contaminated with fecal microorganisms like *salmonella veltereden* and *Giardia* have both been detected in GW. Disinfection after treatment is thus often required before particular reuse applications (Birks & Hills 2007). Greywater must be disinfected to meet microbial standards and avoid health risks associated with its storage and reuse.

As a disinfection procedure, chlorination by sodium hypochlorite (NaOCl) is the most commonly used to treat GW. There is some concern that the presence of coliforms would lead to effluents not suitable for re-use. However, post-treatment by chlorine should effectively eliminate any remaining pathogens and ensure that there is residual chlorine that prevents further contamination (Cecconet *et al.* 2019). The chlorination process does, however, have a few drawbacks. As GW contains organic compounds, they can react with chlorine and produce carcinogenic chloroforms or other harmful halogenated organic compounds. Chlorine requirements vary based on the treatment process, so conducting studies to minimize disinfectant dosage is essential. As warnings against reusing chlorinated GW for irrigation, research should also be undertaken since residual chlorine is toxic to plants (Boyjoo *et al.* 2013).

However, chlorine disinfection produces potentially harmful by-products; it was employed in several decentralized GW treatment processes. Greywater systems that were first introduced for commercial use relied on filtration and chlorine disinfection. For example, one hotel in Spain had a GW recycling system for flushing-toilet that included sedimentation, filtration, and disinfection by hypochlorite (March *et al.* 2004). Besides, in another project, an automatic membrane bioreactor (MBR) prototype has been designed and installed to treat LGW (from showers and bathroom sinks) to be reused in the flushing-toilet application. A final disinfection step with sodium hypochlorite led to an effluent with high microbial parameter quality that met Spanish legislation for urban water reuse (Santasmasas *et al.* 2013).

Chemical oxidants have been widespread for many decades in water treatment, mainly for disinfection and for removing color, taste, odor, and iron and manganese. Conventional oxidation with chemical oxidants and advanced oxidation processes have also found broader application in the last two decades in removing micropollutants from drinking water and, recently, wastewater effluents (Larsen *et al.* 2013). Ronen *et al.* (2010) reported hydrogen peroxide plus (a recently developed, stabilized H_2O_2-based compound) as a possible alternative to chlorination for GW disinfection in small communities. The chemical oxidants do not produce toxic by-products, making them an attractive option. Hydrogen peroxide was found to be a feasible and comparable disinfectant for small systems compared to chlorine (Ronen *et al.* 2010). In another study in Malaysia, a combined approach including aerobic digestion and hydrogen peroxide (H_2O_2) disinfection unit was evaluated to treat GW from showers and drains of bathroom sinks for the purpose of nonpotable usage. Hydrogen peroxide disinfection achieved a 2 log reduction in bacteria. Furthermore, the assessment of the microbial quality of stored GW revealed that hydrogen peroxide concentrations of more than 1 mL/L are able to inhibit bacteria regrowth up to 3 days after storage, resulting in more efficient use of GW (Teh *et al.* 2015).

A range of in-situ generated oxidants has been developed and tested in recent years to make sophisticated electrochemical disinfection methods effective (Martínez-Huitle *et al.* 2015). It has been demonstrated that electrochemical processes are more effective than using chemicals because they produce highly reactive hydroxyl radicals (•OH), which have a high level of disinfection efficiency. An electrochemical process is a more sustainable option since it prevents the costs and risks associated with transport, storage, and the addition of chemicals (Bakheet *et al.* 2020). Disinfection by a TiO_2-based photocatalytic oxidation process has also been reported (Li *et al.* 2004). Additionally, a study investigated a method of disinfection using an electrochemical system with Boron-doped diamond (BDD) electrodes and a solid polymer electrolyte (SPE). This process was claimed to be a low-energy disinfection system for GW recycling. According to the results, *E. coli* and total coliforms were reduced by 3.5 log with just 0.63–0.83 kWh/m^3 energy consumption after 10 and 15 minutes for 2 L and 4 L GW, respectively (Bakheet *et al.* 2020).

Ozonation is also another alternative process employed for GW disinfection. The ozonation process in treatment plants eliminates odors, colors, and micropollutants and enhances disinfection capabilities. Even though ozonation is more expensive than chlorination, it has fewer health impacts. Additionally, ozonation has also been known to cause an increase in dissolved oxygen levels because oxygen is a by-product of ozone degradation. In a study, this process was combined with screening, sand biofiltration, anaerobic sludge bioreactor, aeration, and ozonation to treat GW released from a governmental school in a rural area in India and was operated for over 12 months. The treated water was then used for toilet flushing at the school. Study results demonstrated that DGWTS could be implemented effectively and economically in rural India (Subramanian *et al.* 2020).

An ultraviolet light (UV) is another alternative to chlorine in disinfecting. UV light offers several advantages over chlorination, making it especially suitable for small treatment plants. No dosage or storage units are required, and there is no need to replenish chemicals. Besides not generating unwanted by-products, it is safer for operators. It effectively eliminates a wide range of pathogens, even chlorine-resistant ones (Friedler & Gilboa 2010). When reuse standards do not require chlorine residual, UV light disinfection may be an excellent option due to its simplicity (Cecconet *et al.* 2019). Ultraviolet disinfection was employed to treat and reuse GW in an airport in Brazil. According to reuse criteria, the results were satisfactory, and a cost-benefit analysis revealed that the investment would be repaid in five years (do Couto *et al.* 2015). In another study, UV disinfection was reported very effective at decreasing fecal coliforms and *Staphylococcus aureus* in GW. Inactivation of Heterotrophic Plate Count (HPC) and *Pseudomonas aeruginosa*, on the other hand, was less effective. Besides, a regrowth of HPC was observed in the reuse system, probably due to the emergence of UV resistant bacteria that faced less competition from other bacteria eliminated by UV disinfection. Consequently, some measures were recommended to enhance the microbial quality of GW for reuse, like adding a residual disinfectant or increasing the UV dose. Alternatively, a second UV disinfection unit may be installed nearby the reuse point, or the UV unit may be relocated closer to the reuse point (Friedler & Gilboa 2010).

Based on the amount of water treated per day, there is a variation in the cost estimate of disinfecting wastewater using chlorine, ozone, and UV light. For 1 m^3 of wastewater, the treatment cost was estimated at USD 0.02− 4.0, 0.18–11.7, and 0.02–8.0 $ for chlorine, ozone, and UV methods, respectively (Subramanian *et al.* 2020).

Finally, it is worth noting that irrespective of the type of disinfectant used, the removal of suspended solids from GW is critical to optimize disinfection process since particles act as shields against microorganisms. Total coliforms were shielded from inactivation by larger particles, and disinfection efficiency declined as particle size increased (Winward *et al.* 2008).

4.4. Combined treatment system (multi-stage processes)

The most promising methods for almost complete removal of pollutants from WW are combined technologies such as integrating physical/biological or physical/chemical methods (Bajpai *et al.* 2019). Since conventional technologies fail to eliminate refractory and non-biodegradable substances, combining these methods with other treatment technologies like advanced oxidation processes improves the quality of the effluent and produces treated water with the possibility of reuse. Different treatment methods can be combined and carried out sequentially or hybridized and fused into one process (Garcia-Segura *et al.* 2018). The objective of both methods is to enhance the treated water quality. Table 3 summarizes the literature's data relevant to efficiency of multi-stage processes for the treatment of greywater.

Table 3 | A summary of multi-stage processes for treatment of greywater

Type of greywater	Objective	Processes	Removal efficiency	Ref.
Laundry wastewater (LWW)	Treatment of industrial LWW and removal of $NPEO_{3-17}$, COD and turbidity to reuse in washing process	Ultrafiltration & adsorption Ultrafiltration & nanofiltration Ultrafiltration & electrooxidation	1.Resin: 40% < COD < 45%, NPEO = 95% 1.AC: 40% < COD < 45%, NPEO = 80% 2.COD = 80%, NPEO = 80% 3.COD = 80%, NPEO = 90%	Mostafazadeh *et al.* (2019)
Laundry wastewater	Treatment of industrial LWW and reuse in the laundry process	Bioreactor, UV/O_3, & ultrafiltration/nanofiltration	Effluent of biological treatment: non-ionic surfactant = 97%, anionic surfactant = 96%, COD = 95% Post-treatment was necessary before possible reuse of the wastewater	Mozia *et al.* (2016)
Laundry wastewater	Treatment of industrial LWW and reuse in the laundry process	MBBR, microfiltration, & nanofiltration MBBR, UV/O_3, microfiltration, & nanofiltration	Effluent of MBBR: BOD_5: 95–97% COD = 90–93%, surfactants = 89–99% Post-treatment was necessary before possible reuse of the wastewater	Mozia *et al.* (2020)
Laundry wastewater	Treatment of real LWW and reuse in the laundry process	Extended aeration activated sludge (EAAS), UV/O_3, microfiltration/ultrafiltration, & chlorination	•*Pseudomonas spp.* and *Bacillus spp.* were the dominant detergent degrading bacteria. •UV/O_3 process was effective for the complete mineralization of residual detergents. • Microfiltration/ultrafiltration was used to remove any remaining suspended solids.	Benis *et al.* (2021)
Laundry wastewater	Treatment of LWW and reuse in laundry industry (comparison of two processes)	Conventional methods: precipitation/coagulation, flocculation, and adsorption on AC Membrane filtrations: ultrafiltration and reverse osmosis processes	1. COD = 93%, BOD_5 = 95%, anionic surfactant = 95% (emission into water) 2. COD = 98.9%, BOD_5 = 99.2%, anionic surfactant = 99.2% (reuse in the laundry industry)	Šostar-Turk *et al.* (2005)
Synthetic grey-water	Treatment of greywater (GW)	Hybridized system including adsorption with granular activated carbon (GAC) and electrooxidation	COD = 88% ; TOC: 85%	Garcia *et al.* (2016)
Mixed greywater	Treatment GW from an airport and reuse for non-potable activities	Anaerobic filter followed by UV disinfection	BOD_5 = 73% ; TSS = 77% ; Turbidity = 88%	do Couto *et al.* (2015)
Baths, showers & washbasins wastewater	Treatment and reuse of greywater for toilet flushing	Rotating Biological Contactor (RBC), sedimentation basin, & UV disinfection Membrane Bioreactor (MBR) & UV disinfection	1. BOD = 96% ; Turbidity = 95% 2. BOD = 99% ; Turbidity = 99% UV disinfection was reported very effective at decreasing fecal coliforms and *Staphylococcus aureus* in GW.	Friedler & Gilboa (2010)

(*Continued.*)

Table 3 | Continued

Type of greywater	Objective	Processes	Removal efficiency	Ref.
Showers & bathroom sinks wastewater	Treatment of greywater to reach non-potable usage standards	Hybridized system including aerobic digestion unit & hydrogen peroxide disinfection	COD = 68% ; TSS = 88% Complete elimination of all bacteria after one day of storage.	Teh *et al.* (2015)
Showers & bathroom sinks wastewater	Treatment of greywater to reach urban water reuse standards	Screening, biological oxidation, filtration &disinfection by chlorination.	BOD_5 = 95% ; surfactant = 98% Disinfection step led to achieve satisfactory removal efficiency of microbial contamination.	Santasmasas *et al.* (2013)
Hand wash & kitchen wash wastewater	Treatment and reuse of greywater for toilet flushing	Screening, sand biofiltration, anaerobic sludge bioreactor, aeration, & ozonation	BOD_5 = 98% ; COD = 96% ; TSS = 98% ; fecal coliform > 99.99%	Subramanian *et al.* (2020)

AC: activated carbon; MBBR: Moving bed biofilm reactor.

In a study, the treatment and reusability of laundry wastewater (LWW) by a novel sequential coupled system including UF of raw LWW at first step and treatment of filtrate (permeate effluent) by the use of either adsorption processes (AD) (granular activated carbon or polymeric resin) or nanofiltration (NF) system, or EO has been investigated to remove mainly TSS, turbidity, COD, and surfactants such as nonylphenol ethoxylates (NPEO3-17) to meet the environmental rejection and reusability standards. Concentrate (retentate effluent) of UF and NF were also treated using EC and EO methods, respectively. Optimum conditions to obtain the best results were determined in each case. The UF separated the raw LWW into a filtrate with a low organic pollutant content (300–400 $mg \cdot L^{-1}$ of dissolved COD) and a concentrate with a total COD of 700–1,200 $mg \cdot L^{-1}$ and TSS of 140–200 $mg \cdot L^{-1}$. Following UF application, NPEO3-17 were found not only in the concentrate but also in the filtrate and subsequently were treated using mentioned techniques that were effectively removed by NF and AD (Mostafazadeh *et al.* 2019). In another study, a comparison of EC and biological treatment process have been presented for LWW treatment. In the biological treatment step, the WW is treated with a *Bacillus* strain of aerobic bacteria, which is especially suitable for degrading fats, lipids, protein, detergents, and hydrocarbons. The EC process was carried out by using aluminum metal under controlled voltage. The efficiency of each methodology was evaluated by measurement of surfactant concentration, COD, and total dissolved solids. A noteworthy decrease was detected after 12 hours of biological treatment, while the remarkable reduction in surfactant was observed within the first 30 min by the EC process, attributed to the fast generation of aluminum hydroxyl species (Ramcharan & Bissessur 2017).

A hybridized system implemented for decentralized GW treatment is adsorption with granular activated carbon (GAC) and EO. This system was carried out to remove pollutants from synthetic GW. It was found that the 3D reactor hybrid system is capable of eliminating color. However, the AD could reach the removal efficiency by 71%. Therefore, color removal was evaluated by using the 2D reactor hybrid system and obtained 12%. The combination of (electro)sorption and EO at the surface of GAC makes an improvement in the treatment performance of 3D compared with the performance of AD with GAC and 2D systems. Besides, the results showed that 88% of the adsorbed COD and 85% of the adsorbed total organic carbon (TOC) were degraded when a current density of 15 $A \cdot m^{-2}$ was applied. As a result, the electrochemical regeneration of the GAC bed was achieved that led to extending the lifetime of the GAC bed (Garcia *et al.* 2016).

In another hybridized study, gray wastewater was treated with an aerobic digestion unit integrated with the hydrogen peroxide disinfection to achieve the treated water quality based on non-potable usage standards. In the optimum operation conditions of 5 h hydraulic retention time and an organic loading rate of 2.16 $gCOD \cdot L^{-1} \cdot day^{-1}$, the system successfully removed 88% of TSS and 68% of COD. Besides, the disinfection with hydrogen peroxide at a concentration of 1 $mL \cdot L^{-1}$ led to the complete elimination of all bacteria after one day of storage (Teh *et al.* 2015).

Table 4 | Recent studies on the decentralized wastewater treatment systems

Action	Country	Process	Results	Ref.
Performance evaluation	India	Settler, anaerobic baffled reactor + anaerobic filter, anaerobic filter, planted gravel filter	Further treatment like conditioning ponds would be required to promote the safe reuse of treated wastewater. This technology has environmental benefits due to its low cost, less energy demand, and simple operation. In addition to the technical and economic issues, the environmental and social aspects should also be considered in the decision-making process.	Singh *et al.* (2019)
Cost-benefit analysis	Indonesia		The decentralized system was more feasible economically for this case study. Further assessment on environmental, health, social and institutional aspects are recommended.	Prihandrijanti *et al.* (2008)
Bench-scale DWWTS	China	Microbial fuel cell techniques	Simultaneous removal of nitrogen compounds and organic matters in wastewater with electricity production.	Feng *et al.* (2013)
Full-scale DWWTS	Brazil	Septic tank + anaerobic filter filled with green coconut husks + intermittent sand filter	The quality of the effluent generated by this combination is in accordance with Brazilian and European legislation and even allows for its reuse in agricultural activities.	de Oliveira Cruz *et al.* (2019)
Process performance and alternative management strategies; nitrogen control	USA	Review	Only one of the 20 DWWTSs approaches the reliability and stability of centralized plants and can comply with less than 10 mg/L TN effluent standard with a 99% probability. Further N removal in the immediate vicinity of the discharge zone can be enhanced with shallow trenches and subsurface drip distribution/irrigation systems	Oakley *et al.* (2010)
Implementation of a new approach	Jordan	Assessment of local lowest-cost wastewater solutions	A decentralized wastewater management solution is more feasible compared to a centralized approach, with cost savings of up to 40%	van Afferden *et al.* (2015)

The combined decentralized treatment systems have been employed to achieve high-quality treated water that can be reused on-site. In other words, this type of system leads to obtaining the reclaimed water that meets the standards of reuse in the various applications based on the quality.

5. GREYWATER TREATMENT AND DECENTRALIZATION

Due to the lack of water and WWTSs in rural and peri-urban areas in developing countries, water scarcity and the risk of groundwater contamination are two possible challenges. An option to deal with these challenges is a DGWTS. Several studies were conducted to evaluate the DWWTSs in various criteria. Table 4 shows some of these carried out recently.

A study was performed on a decentralized GW treatment and reuse system in rural India. The hand wash and kitchen wash wastewater effluents were treated separately in that study. The treatment processes included pre-treatment by screens and grease traps, followed by slow sand biofiltration integrated with anaerobic sludge bioreactor, then aeration, and finally disinfection by ozone. The results demonstrated that the pre-treatment could successfully decrease the TSS and turbidity to avoid clogging the subsequent filtration system. The filtration could efficiently diminish the TSS, turbidity, BOD_5, and COD. In addition, the ozonation system could remove the high fecal coliform (FC) values. The treated GW met the effluent discharge reuse standards for toilet-flushing in the school. The treatment method exhibited removal of 99% in turbidity, 98% TSS, 66% nitrate, 73% total phosphorus (TP), 98% BOD_5, 96% COD and >99.99%, and FC, respectively (Subramanian *et al.* 2020).

Very high COD, BOD, and TSS concentrations with average values of 2,568 mg·L^{-1}, 1,056 mg·L$^{-1,}$ and 845 mg·L^{-1}, respectively, characterize grey wastewater in rural areas Mafraq governorate, Jordan. To find the most suitable treatment system for this high-loaded GW, three treatment options were evaluated: septic tank followed by the intermittent sand filter; septic tank followed by wetlands; and UASB-hybrid reactor. The results showed the most appropriate system considering compactness and simplicity would be the UASB-hybrid reactor with a volume of 0.268 m^3 and surface area of 0.138 m^2 for each house with ten inhabitants and an average GW generation of 14 L·c^{-1}·d^{-1}. The treated water characteristics met Jordanian standards in irrigating fruit trees (Halalsheh *et al.* 2008).

Green wall installation for the GW treatment is another nature-based method employed in an office building in Pune, India. In this study, the green wall was filled with lightweight expanded clay (LECA) plus sand and lightweight expanded clay plus coconut fiber as the porous media. The COD removal was obtained 14–86% and 7–80% for LECA-coconut and LECA-sand, respectively. The reclaimed water quality has complied with Indian irrigation and toilet-flushing guidelines (Masi *et al.* 2016).

Eshetu *et al.* (2017) evaluated the performance of a combined system including a fixed-film biofilter and soil infiltration for on-site treatment GW from at cottages and small households in Norway. This system was achieved 95% overall removal efficiency in COD, BOD, TSS, total nitrogen (TN), and TP and up to 5 log reduction of coliform bacteria. This system could generate effluent with quality that meets Norwegian discharge requirements in sensitive areas such as drinking water sources with minimum risk to the environment and health (Moges *et al.* 2017).

In another study, a horizontal flow wetland in a vertical set-up with four cascading stages was employed to treat the low load GW (from the showers and washbasins) of a hotel in Lloret de Mar, Spain. They used 15 various plant species in LECA at three different hydraulic retention times (1.9, 1.4, and 1.0 days). The results showed the removal efficiency of the system was more than 90% for COD, BOD_5, TSS, volatile suspended solids, and turbidity. Alongside the said standard parameters, several organic micropollutants, including pharmaceutical organic compounds and endocrine-disrupting compounds, were observed over 22 months. This system succeeded in removing many organic micropollutants like acetaminophen, ibuprofen, salicylic acid, caffeine, estradiol, etc., with high efficiency. However, more persistence was demonstrated in other compounds such as ketoprofen, naproxen, carbamazepine, metoprolol, sulfamethoxazole, and hydrochlorothiazide. The effluent in all three HRTs complied with the standard of Spanish legislation for various reuse applications (Zraunig *et al.* 2019).

Another combined system applied to degrade organic matter in GW, released from 223 inhabitants in Berlin, Germany, included a multistage MBBR followed by sand filtration and UV disinfection. The removal efficiency of the system reached up to 94, 99, and 91% for COD, BOD, and dissolved organic carbon (DOC), respectively. The MBBR system was designed in series to designate a particular treatment function for each reactor and enhance the overall performance of the system. Because of the reactor operation conditions, a specialized biofilm was developed within the reactor that improved the degradation of the less biodegradable organic matter. The decentralized recycling system was so effective that the treated water met the reuse standard for toilet-flushing (Saidi *et al.* 2017).

Several other DGWTS have been employed to produce high-quality treated water (Katukiza *et al.* 2014; Dos Santos *et al.* 2018; Ghanbari & Martínez-Huitle 2019). In all these systems, the goal was to generate the purified water to reuse in different applications with the least harmful effect on the health and environment and reduce water consumption. Although they have made outstanding achievements by decentralized systems, there have been some challenges. Obstacles include not being accepted by the public, unpleasant odor in the vicinity of the treatment plant, the potential health risk associated with using treated GW to irrigate crops, the alteration of soil properties, etc. Therefore, before implementing a treatment system, it is necessary to anticipate the possible challenges and address them as much as possible.

6. RESOURCE RECOVERY FROM GW

A sustainable DWWTS emphasizes on-site WW treatment as well as recycling and reuse of resources in the neighborhood. The said resources comprise reclaimed water, nutrients (mainly nitrogen and phosphorus), and energy (primarily from transforming organic materials, even recovering the remaining heat in the wastewater). Local reuse of recovered elements is beneficial to move from the conventional linear economy toward the circular economy. The circular economy approach seeks to recycle the resources to reduce the stress on limited sources, ameliorate their sustainability, and protect the environment (Capodaglio 2017; Corona *et al.* 2019).

The implementation of an efficient WWTS mainly depends on sustainability. To design a new WWTS or improve an existing plant, sustainability is defined in various criteria, including health and hygiene, environment and natural resources, technology, financial and economic issues, and socio-cultural and institutional aspects (Capodaglio *et al.* 2017).

6.1. Water reclamation

A transition to a circular economy leads to handling the unbalance between water supply and demand. Various DDWTS systems have been implemented worldwide to recycle and reuse GW for different applications. It is worth noting that the required quality of reclaimed water entirely depends on its application. In order to protect the environment and human health, several countries have imposed different standards and guidelines for reclaimed water reuse. Therefore, the treated GW should comply with four principles: hygienic safety, aesthetics, environmental tolerance, and economic feasibility for reuse (Nolde 2000; Bajpai *et al.* 2019).

Reducing freshwater requirements and reducing sewage generation are two main objectives of reusing the treated GW. Based on these purposes, the reclaimed GW can be used in different applications that can be seasonal or non-seasonal. The most appealing non-seasonal usages of treated GW are toilet-flushing since the water used for toilet-flushing in many countries has drinking water quality. Flush water consumption accounts for 25% of the total household water consumption (Widiastuti *et al.* 2008). The next most popular worldwide application is crop irrigation. This type of irrigation is usually a seasonal application for the treated GW. Other popular ways are surface storage and landscape irrigation like sporting facilities, golf courses, private gardens, and roadside vegetation. When seasonal irrigation is not required, surface storage of partially treated water can be utilized to add aesthetic value in rural and pre-urban neighborhoods. The subsequent non-seasonal usage is non-irrigation urban applications like street washing, fire protection, air conditioning cooling, car washing, and commercial laundering. The treated water can be used for environmental applications such as restoring habitats such as

Table 5 | Overview of regulations and guidelines for wastewater reuse

Country	**USA (EPA) (EPA 2004)**		**USA (NSF) (NSF350 2011)**	**Canada (HealthCanada 2010)**	**Italy (Chaillou *et al.* 2011)**	**Australia (New South Wales) (NSWhealth 2000)**	
	Application						
Parameter	**Agricultural reuse**	**Landscape impoundments**	**Restricted indoor and unrestricted outdoor use**	**Toilet flushing**	**Irrigation; urban reuse**	**Irrigation**	**Toilet flushing & laundry use**
pH	6–9		6–9		6–9.5		
TSS (mg/L)		≤ 30	10	≤ 20	< 10	30	30
Turbidity (mg/L)	≤ 2		5	≤ 5			
BOD_5 (mg/L)	≤ 10	≤ 30	10	≤ 20	< 20	20	20
COD (mg/L)					< 100		
TN (mg/L)					< 15		
TP (mg/L)					< 2		
Total chlorine residual (mg/L)	≥ 1	≥ 1		≥ 0.5			
E. coli (CFU/100 mL)			14	≤ 200			
Thermotolerant coliforms (CFU/100 mL)				≤ 200		30	10
Fecal coliforms(CFU/100 mL)	ND	≤ 200					

Table 6 | Overview of regulations and guidelines for wastewater reuse (continued table 4)

Country	**Israel (Inbar 2007)**	**Jordan (WHO 2006e)**		**China (CHINA 2002; IWA)**			**Japan (Tajima *et al.* 2007)**	
	Application							
Parameter	**Unrestricted irrigation**	**Agricultural irrigation cooked vegetables**	**Agricultural irrigation tree crops**	**Toilet flushing**	**Urban landscaping**	**Irrigation fiber crops**	**Toilet flushing**	**Landscape**
pH	6.5–8.5	6–9	6–9	6.0–9.0	6.0–9.0	5.5–8.5	5.8–8.6	5.8–8.6
TSS (mg/L)	10	50	150			100		
Turbidity (mg/L)		10		≤ 5	≤ 10		≤ 2	≤ 2
BOD_5 (mg/L)	10	30	200	≤ 10	≤ 20	100		
COD (mg/L)	100	100	500			200		
TN (mg/L)	25	45	70					
Ammonia nitrogen (mg/L)				≤ 10	≤ 20			
TP (mg/L)	5							
Total chlorine residual (mg/L)	1			≥ 0.2	≥ 0.2	1.5	Combined ≥ 0.4	
Total coliforms (CFU/100 mL)				≤ 3	≤ 3			
E. coli (CFU/ 100 mL)		100	1,000				ND	$\leq 1,000$
Fecal coliforms(CFU/ 100 mL)	10							

marshes, wetlands, or fens for recreational benefits and groundwater recharge, which are non-seasonal. The tertiary-treated GW might be used for potable water (Capodaglio 2017).

Considering the reuse application, various standards and guidelines for reclaimed water reuse were established by several countries. The water reuse regulation or guideline varies from country to country and, in some cases, from state to state. Tables 5 and 6 present some of the policies based on the application.

A case study for the treatment and reuse of GW to landscaping water ponds, gardening, and sprinkling was carried out in a residential area in Xi'an, China. Since Xi'an is located in a water-deficient area, treatment and reuse of water, at least for non-potable applications, seems necessary. A combined process was employed in this study comprised of a fluidized pellet bed separator followed by ozone-enhanced flotation. The system was achieved both technical and economic approval because the quality of the reclaimed water met the standard of reuse, and the treatment cost was obtained less than the cost of fresh-water (Wang *et al.* 2010).

In another study, a decentralized MBR prototype including four stages, screening, biological oxidation, filtration, and final disinfection by chlorination, was utilized to treat low-load GW. This study aimed to identify the treated water characteristics that comply with the Royal Spanish Decree for water reuse. The results showed the effluent with outstanding quality in organic, surfactants, and microbial parameters used in the flushing-toilet application (Santasmasas *et al.* 2013).

Water recovery is the main aim of DGWTS, especially in remote and arid areas. Based on the quality of the reclaimed water, the regulation imposed for reusing water, and requirements, the application can be changed over time. Sometimes, by adding a disinfection unit, the treated water can meet potable water standards, which can be valuable in a dry region.

6.2. Nutrient recovery

A decentralized wastewater treatment system is one of the primary nitrogen sources entering into body waters, while strict TN effluent standards are regulated in N-sensitive regions (limitations of <10 mg/L TN). The DWWTSs show limited capacity for meeting the guidelines based on effluent concentrations at the point of discharge into the environment. The alternatives to significantly removing nitrogen are proposed, such as passive, natural systems like denitrifying bioreactors and drip irrigation.

The former offers a more vigorous approach, consumes the least amount of energy, and has the equal performance of centralized plants (like the postanoxic SPSF/DB). The drawback of such a system is the requirement for a large area footprint. The latter offers further nitrogen removal in the immediate vicinity of the effluent by shallow trenches and subsurface drip distribution/irrigation systems considered to enhance denitrification in the carbon-rich root zone and nitrogen uptake by plant roots, and the setting up the solid carbon denitrification walls/layers. The sustainable use of resources in WWTS includes nutrient recovery, material usage, energy consumption, and greenhouse emissions. DWWTSs can enhance the chances for the reclamation of sewage components. Regarding the nutrients in wastewater, phosphate, is a non-renewable resource, which must ultimately be recycled. In fact, decentralized systems can minimize the contamination of nutrient residuals by metals or other toxins (Oakley *et al.* 2010).

In a study, a decentralized treatment system including a septic tank followed by the submerged spiral wound membrane filtration was carried out to evaluate the performance and suitability of resources and nutrients recovery from GW. The results indicated that the permeate consisted of 16.7 and 6.7 mg·L-1 TN and TP, respectively. This water could be used for gardening and crop irrigation due to its fertilizing properties. Besides, it could be used for toilet-flushing after disinfection. TP and TN increased continuously in the retentate at the end of each filtration cycle and reached 40 and 140 mg·L-1. It was suggested the generated retentate mixed with blackwater and kitchen waste and treated in an anaerobic digester to produce biogas or compost (Li *et al.* 2008).

Decentralized wastewater treatment systems can comply with the requirements for local water reuse. Besides, the reclaimed water and nutrient content can improve the productivity of agriculture.

6.3. Energy recovery

Large-scale wastewater treatment plants can benefit in terms of energy regeneration. This energy can be recovered by biosolids management, hydropower generation, and thermal energy recovery (Diaz-Elsayed *et al.* 2020). However, in decentralized systems, energy recovery is mainly related to the transformation of organic materials (Capodaglio 2017).

In a study, bioflocculation of GW was performed in a lab-scale MBR to concentrate the GW for the recovery of energy. To evaluate the reclaimed COD in concentrate, three concentration factors were assessed based on the ratio of sludge retention time (SRT) to hydraulic retention time (HRT): 3, 8, and 12. The recovered COD in the concentrate was obtained 57, 81, and 82% at SRT/HRT ratios of 3, 8, and 12. This high recovered efficiency indicated a strong bioflocculation of GW. The concentrate generated from the bioflocculation process can be added to the anaerobic treatment of blackwater. It claimed that the GW concentrate leads to an increase of 73% methane production (Leal *et al.* 2010). Therefore, by recovering the COD of GW in DWWTS, energy can be generated without requiring an additional anaerobic reactor or mixing wastewater streams.

7. TECHNO-ECONOMICAL ASPECTS

Generally, wastewater treatment plants have been employed at full-scale across the world. Capital costs comprise the cost incurred in land acquisition, construction, and design cost of facilities. The survey displayed that performance is independent of the size of the plant, while total cost is directly proportional to the size of the system. Limited information on the economic analysis of decentralized wastewater management systems in developing countries is available, but some information can be found for developed countries. Typically, anaerobic and combined treatment systems for small communities are used in developing countries. This system results in better quality for organics and nutrients removal and is applicable in a smaller zone. On the other hand, natural systems need a larger area and have lower efficiency, particularly in nutrient removal (Singh *et al.* 2015). Evaluating and selecting a proper wastewater treatment approach must consider the life cycle cost of design, construction, operation, maintenance, repair, and replacement. Cost estimations on a general and national basis are challenging mainly because of the variation of each area's circumstances, like population density, land costs, and local expenses. A study exposed that decentralized systems, such as clusters or on-site are normally more cost-effective in rural zones than centralized systems (Massoud *et al.* 2009).

In the last decade, the costs of membrane processing have fallen significantly. As a result of the construction of submerged systems, for instance, installation costs of some MF hollow-fiber systems have declined by a factor of 30 since 1990. Membrane technology remains, however, relatively costly for a large population. Membrane systems are generally economically preferred for medium-size (cluster) plants (Fane & Fane 2005).

In a world where water prices increase steadily, GW reuse on-site proved economically viable. In addition, the unit cost of GW reuse was found to be highly sensitive to the size of the system, particularly on small systems. For instance, Friedler

Table 7 | Treatment cost of typical GW decentralized systems

Region	Type of treatment	Application	Cost	Ref.
Rural public schools in Chile	School 1: 3 sections of filters in series, two sections composed of modified activated carbon and one section composed of zeolite. School 2: two sections of activated carbon in series. School 3: two activated carbon filter sections	Irrigation of recreational areas and services	The installation, operating, maintenance, water quality control, and noise pollution cost for 10 years: School 1 (420 members): USD 2.11/m^3 School 2 (121 members): USD 12.01/m^3 School 3 (133 members): USD 17.51/m^3	Rodríguez *et al.* (2020)
REMOSA facilities in Barcelona, Spain	An automatic membrane bioreactor prototype comprises screening, biological oxidation, filtration, and disinfection by chlorination	Toilet flushing	The installation, operating and maintenance cost for 1.15 m^3/day treated water was estimated at €1.8/m^3.	Santasmasas *et al.* (2013)
Mallorca Island, Spain	Filtration, sedimentation and disinfection by chlorination	Toilet flushing	The operation, and maintenance cost for 5.2 m^3/day treated water was estimated at € 0.75/m^3.	March *et al.* (2004)
Negev Desert, Israel	Vertical flow constructed wetland and disinfection with the hydrogen peroxide plus	Irrigation	Annual cost of the disinfection unit for 5 m^3/day treated water was estimated at USD 0.16/m^3.	Ronen *et al.* (2010)
Israel	Equalization basin, an rotating biological contactor unit, a sedimentation basin, and disinfection by chlorination	Toilet flushing and garden irrigation	USD 1/m^3 for 9 m^3/day treated water USD 2/m^3 for 3 m^3/day treated water	Friedler (2008)
Residential area in Xi'an, China	Fluidized-pellet-bed bioreactor and dispersed-ozone flotation	Landscape and environmental purposes	The direct operation and maintenance cost: Yuan 1.35/m^3 for 60 m^3/day Yuan 0.82 /m^3 for 100 m^3/day	Wang *et al.* (2010)
Industrial laundry facility in Turin, Italy	Pre-treatment, sand filtration, ozonation, adsorption by activated carbon, and ultrafiltration	Washing processes	Total operating cost of the system for 15 m^3/h treated water was estimated € 0.81/m^3	Ciabattia *et al.* (2009)
A mosque in the Kingdom of Saudi Arabia	Filtration, activated carbon adsorption, and disinfection by chlorination	Toilet flushing	Capital and operating cost for the lifetime of 30 years was estimated USD 0.67 to 1.0/m^3 for 20 to 1.4 m^3/day treated water.	Alharbia *et al.* (2019)

(2008) reports by increasing the design flow from 3 to 9 m^3/day; the cost decreased from 2 to 1 USD/m^3 (Friedler 2008). Table 7 presents the costs (capital, operational, and maintenance) for some DGWTS.

It is worth noting the DWWTS should be economically affordable, technically sustainable, environmentally protective, and socially acceptable to be implemented. In general, decentralized systems are compact and flexible under different operating conditions. However, other local impacts such as odor should be taken into account (Capodaglio *et al.* 2017).

8. CHALLENGES AND RECOMMENDATIONS

Like other wastewater treatment processes, a decentralized wastewater treatment system for small volumes of GW must provide advanced waste treatment; it must be cost-effective, easy to operate, robust, and simple to maintain (Wilderer & Schreff 2000). Generally, decentralized solutions can meet local water use and reuse requirements. For example, locally treated water can be used to support agricultural productivity or can be used to supplement drinking-quality water supply (Capodaglio 2017). However, there are some challenges and concerns on utilizing decentralized systems to treat GW, which requires more assessments.

- A barrier is that in some areas, the household piping system does not separate the collection of GW from blackwater or sewage. A dual piping system must be installed or modified to transfer GW to a separate tank before implementing a GW treatment system (Oh *et al.* 2018). As a result, the cost of implementing the plant increases. In many cases, the high cost of GW treatment and management prevents such projects from being implemented.
- Furthermore, the acceptance of GW reuse by the public plays a big role in its success. Many reasons contribute to public opposition, including cultural bias, aesthetics, etc. The lack of trust in the quality of GW treatment and concerns about health risks are other barriers. Furthermore, religious considerations may also present a limitation to the successful reuse of GW (Oh *et al.* 2018).
- Another obstacle to implementing a decentralized system is legal constraints, particularly in developing countries. Despite the Malaysian government's interest in recycling GW, Mah *et al.* (2009) reported that minimal experience running and maintaining GW recycling systems prevented the ministry from approving the system. The Malaysian government continues to prioritize the development of centralized wastewater treatment systems (Mah *et al.* 2009).
- Selecting the appropriate treatment technology for GW recycling is a tough challenge. Choosing the appropriate treatment technology will achieve high energy efficiency, lower capital and operating costs, and higher quality of treated GW, resulting in improved public acceptance of GW recycling (Oh *et al.* 2018).
- In most cases, the beneficiaries are supposed to supervise and maintain the plants. However, they may not have the essential knowledge and experience in operation and maintenance, nor do they have the motivation to ensure the system works appropriately (Wilderer & Schreff 2000). Hence, residents of the areas that use these treatment units should be trained to

Table 8 | Challenges on utilizing decentralized greywater treatment systems

Challenge	Example	Impact	Ref.
Monitoring and maintenance	The company that manufactures the DWWTP do not dispatch specialist regularly to the site to inspect and maintain the system or train the beneficiaries.	– It causes beneficiaries' dissatisfaction.	Wilderer & Schreff (2000)
Legal constraints	Failure to get approval of the DWWTS by the relevant ministry due to the lack of experience in maintaining greywater recycling systems.	– The development of CWWTS even if it is not cost-effective compared to implementing a DWWTS.	Mah *et al.* (2009)
Public perception	Public opposition due to cultural bias, aesthetics, the lack of trust in the quality of GW treatment, concerns about health risks, religious considerations and etc.	– Residents resist reusing treated greywater.	Oh *et al.* (2018)
Health risk	Using treated GW to irrigate crops.	– A lack of proper control over irrigation with treated water can depress yields and crop quality.	Shakir *et al.* (2017); Thaher *et al.* (2020)
Unpleasant smells	Odor emission and insect infestation in the vicinity of the treatment plant.	– Cause nuisance for the local residents	Thaher *et al.* (2020)
Altering of soil properties	Long-term use of reclaimed water increased salinity, SAR, and organic content of soil.	– Depress soil quality. – In the long-term irrigation depress yields and crop quality.	Al-Hamaiedeh & Bino (2010)
Retrofitting in existing homes	Install or modify piping system to separate GW from black water to transfer GW to a separate tank	– The cost of implementing the plant increases.	Oh *et al.* (2018)
Low water price	The cost of the treated greywater is more expensive than drinking water.	– Recycling greywater is not economical.	Vuppaladadiyam *et al.* (2019)

handle minor problems. Moreover, companies that install these units must regularly dispatch specialists to the site to inspect and maintain the system.

- The release of unpleasant odor in the vicinity of the treatment plant is another limitation of on-site greywater treatment systems which is a nuisance for the local residents. A survey by Thaher *et al.* (2020) stated that the first and most significant barriers to GW reuse in Palestinian rural communities are odor emission and insect infestation (Thaher *et al.* 2020). Others also identified plants emitting unpleasant odors (Redwood 2008; Shakir *et al.* 2017). Strong odors could be a result of poor quality treated GW or any wastewater being sucked from the anaerobic areas of a treatment plant's reservoir (Shakir *et al.* 2017).
- Another challenge is the health risk associated with using treated GW to irrigate crops. A lack of proper control over irrigation with treated water can depress yields and crop quality (Shakir *et al.* 2017; Thaher *et al.* 2020).
- Other barriers hindering successful implementation of GW reuse that can be mentioned are low water prices at particular locations and the alteration of soil properties (Vuppaladadiyam *et al.* 2019). Table 8 summarizes challenges on utilizing DGWTS.

Future approaches in research into DGWTS to surmount the existing shortcomings are demonstrated as follows:

- Developing a GW reuse strategy to minimize freshwater consumption requires more than just technological advances; it also entails people's attitudes towards its reuse. This is an area where education plays an essential role, especially when understanding the advantages of GW recycling (Vuppaladadiyam *et al.* 2019). Social issues surrounding the use of reclaimed water are public perception, public trust, and public acceptance. The social aspects of wastewater treatment must be given more significant consideration if greater reuse is to be achieved. Public perceptions largely determine public acceptance of reuse projects. Public confidence in the operating agency is often lacking as they do not trust it to treat water consistently and on time while meeting all applicable requirements. In order to address the issues, more extensive monitoring will be required to demonstrate that DGWTS built and designed adequately will perform and be reliable over the long term (Tchobanoglous *et al.* 2004). In this sense, the local community and government need to raise public awareness of the importance of reusing GW, a water-saving measure.
- The government can help promote a decentralized wastewater treatment system by creating a conducive learning environment and encouraging technologists to get involved. Governments can also make new regulations and governance to facilitate the use of these frameworks. The government should support and be more aware of the possible application of DGWTS in rural communities at the policy level. The government should be more active in rural wastewater management (Hafeez *et al.* 2021).
- Since governments in developing countries have more pressing demands, such as resolving conflicts, providing health care, and ensuring food security, wastewater management is typically pushed to the bottom of the priority list (Oh *et al.* 2018). As a result, financial assistance from international organizations and developed countries is critical.
- Occasionally, construction projects cost millions, and collecting reliable design data costs just a few dollars. Two reasons for project failure are adopting inappropriate technologies and the inability to consider the local conditions. Identifying the receiving environment is critical for technology selection and should be performed by a thorough site assessment. Successful projects should be replicated, but they should be tailored to the local requirements, especially the climatic conditions. The low-cost technology often wins out without consideration of any other factors. Sustainable wastewater management necessitates a comprehensive, long-term approach that involves substantial planning and execution phases (Massoud *et al.* 2009).
- Operation and control of the treatment systems must be performed by personnel specially trained for the job (Wilderer & Schreff 2000).
- The necessity of the follow-up process and practical training in operation and maintenance as part of project implementation is one of the essential suggestions to the implementing agencies (Thaher *et al.* 2020). Municipal employee training programs are critical for the effective operation and maintenance of equipment and facilities and wastewater quality monitoring (Massoud *et al.* 2009). Ascertain that the treated water meets local requirements for reuse and whether the quality of the treated water is stable (Thaher *et al.* 2020).

9. CONCLUSION

Due to decreased freshwater resources and scarcity, water consumption and wastewater management patterns have changed. Separation at the source of greywater contributes to efficiently treating it since it is less polluted than black water. Considering this matter, many countries have set guidelines and standards for reusing greywater. Furthermore, it is essential to learn and assess how untreated greywater can negatively affect soil, plant life, water resources, marine life, and human health.

Water recovery has increased at the small community scale. Decentralization concerns the reuse or disposal of the effluent in relatively close vicinity to its generation source. The region's remoteness and lack of road access to many communities increase the costs of GW treatment and make timely maintenance, repairs, and monitoring difficult. The decentralization approach aims to protect public health and the natural environment by substantially reducing health and environmental hazards. Northern regions (extreme conditions), remote areas, and rural/pre-urban areas in which constructing a CWWTP are difficult or impossible and chemical transportation is challenging could have benefits of decentralized greywater water treatment. Recycled greywater in these regions can be used for irrigation applications and toilet flushing. DGWTSs can provide a long-term and cost-effective solution for communities by avoiding significant capital costs, lowering costs for new infrastructure, reducing operation and maintenance costs, and promoting business and job opportunities. Apart from the advantages of DGWTS, it is necessary to do more investigation on process selection, evaluation of the performance, and economic aspects of decentralized treatment systems. Moreover, studies regarding the energy and nutrient recovery from on-site GWTS are required.

Various GW treatment technologies can be adopted and used in low-income rural and peri-urban communities that are suitable for decentralized management systems. However, most of these have not been widely used and remain in pilot projects. In order to achieve widespread implementation, it is necessary to overcome the obstacles by raising awareness, developing suitable policies, institutional strengthening, and training.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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