Norwegian University of Life Sciences

Master's Thesis 2020 30 ECTS
Faculty of Environmental Sciences and Natural Resource Management (MINA)
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Greywater treatment to drinking water: challenges and technologies

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Master's Program in Environment and Natural Resources – specialization in Sustainable water and sanitation, health and development.

Greywater treatment to drinking water: challenges and technologies.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environment and Natural Resources - Specialization Sustainable Water and Sanitation, Health and Development

By

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May 2020

ACKNOWLEDGEMENT

I am thankful to all positive energies and to my family that have been there for me in every step of my life, and always encouraged me to continue my personal and professional growth, and not to give up on my goals. I am also so grateful with everybody that helped me to come to Norway, my friends Andreza Lisboa and Jemily Lisboa that supported me with every gesture, affection, suggestions, and even financial support during difficult moments.

I am gratefully thanks to my supervisor Petter D. Jenssen and my Co-supervisor Melesse E. Moges who gave me good suggestions with valuable guidance, support, and constructive criticism for me to fulfill my thesis on time. I am also obliged to Norwegian University of Life Sciences (NMBU) and especially Faculty of MINA for offering me the admission and providing me a good environment throughout this program.

I had planned to perform laboratory experiments but due to the outbreak of COVID-19, access to the laboratory was restricted. This made it impossible to conduct experiments. Thus, this thesis is based on a review of literature.

During these two years of the study program, there were many challenging moments, setbacks, financial problems, and jobs in the weekends to settle survival needs. I think that all these barriers contributed to make me stronger and believing in myself.

Rodolfo Rosario Klautau Araujo Gomes

Ås, May 27th, 2020

Abstract

Water is a vital source to human health and well-being and an important engine in ecosystem services and a precondition for economic prosperity and sustainable development. However, water scarcity is becoming a rising concern around the world due to a blend of population growth, consumption patterns and socio-economic development. Wastewater reuse and reclamation offers interesting possibilities to overcome water scarcity. How to find solutions to achieve equilibrium between demand and supply intensify in the scenario of increasing pressures on water resources. The wastewater management systems and sustainable sanitation can soften demand from agriculture, freshwater supply, industry, energy generation and ecosystem replenishment by saving the insert of freshwater into the system and by providing the water fraction of wastewater available for environmental release and safe use. Decentralized source separation systems, that handle grey- and blackwater separately, are an attractive alternative due to the potential of water saving and resource recovery, where greywater reuse has the capacity to reduce the demand for new water. The main objective of this thesis is to investigate the challenges and prospects of using greywater as a source of drinking water and potential applications of decentralized greywater technologies to achieve drinking water quality. This thesis provides a literature review based on principles, facts and discussions regarding greywater characteristics and its challenges for reuse as well as an overview of potential technologies for decentralized greywater treatment. The study revealed that greywater represents one interesting alternative source of potable water due to the lower contamination than mixed wastewater. Furthermore, greywater can present challenges regarding organic micro-pollutants, pathogens, public perception when using greywater as a source of producing drinking water. There is a wide variation in greywater characteristics and volume generation rates which it is dependent on the, lifestyle patterns and type of settlement. The available technologies have been developed to treat or remove specific pollutants, but they do not offer alone full treatment of the greywater to drinking water. Filtration systems have the potential of integration with other systems to achieve potable water quality. Membrane processes are compact technologies for upgrading greywater pretreated from mechanical / biological / chemical process to drinking water. Public perception of greywater reuse is important to consider for implementation of adequate methods for a specific context.

Keywords: greywater, reuse, drinking water, challenges, technologies, treatment, organic micro-pollutants, pathogens, public perception.

Abbreviation

APIS: Active pharmaceutical ingredients
BOD: Biological Oxygen Demand
BTEX: Benzene/toluene/ethyl benzene/xylene
cfu: coliform forming units
COD: Chemical Oxygen Demand
CW: Constructed wetland
DOC: Dissolved Organic Carbon
E. coli: *Escherichia coli*
EDCS: Endocrine disrupting chemicals
EPA: Environment Protection Agency
EU: European Union
FWSCW: Free water surface constructed wetland,
GAC: Granular Activated carbon
GROWCW: Green roof water recycle constructed wetland
GW: Greywater
HSFCW: Horizontal subsurface flow constructed wetland
Lpcd: liters per capita per day
MBR: Membrane Bioreactor
MF: Microfiltration
MPB: Methyl paraben
NF: Nanofiltration
NOM: Natural Organic Material
OMP: Organic micro-pollutant
PAC: Powered Activated Carbon
PAHS: Polyaromatic hydrocarbons
PFASS: Polyfluoroalkyl substances
PFRS: Phosphorus-containing flame retardants
PG: Propylene glycol
PPCP: Pharmaceutical and Personal Care Products
RO: Reverse Osmosis
SDS: Sodium dodecyl sulphate
SS: suspended solids
TCS: Triclosan
TDS: Total Dissolved Solids
TMA: Trimethyl amine
TN: Total Nitrogen
TOC: Total organic carbon
TP: Total Phosphorus
TSS: Total Suspended Solids
UK: United Kingdom
USA: United States of America
UV: Ultraviolet
VSFCW: Vertical subsurface flow constructed wetland
WHO: World Health Organization

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Water scarcity

Water is an important commodity and is vital to human health and well-being, an important engine in ecosystem services and a precondition for economic prosperity and sustainable development. It is, therefore, at the very core of the 2030 Agenda for Sustainable Development (ESCAP-UN, 2017). Water use and scarcity is, however becoming a rising concern around the world due to a blend of population growth, consumption patterns and socio-economic development (WWAP, 2018; Boretti and Rosa, 2019). This solid growth has principally been driven by heavy demand in developing countries and emerging economies, where per capita water use is simply achieving a similar demand in developed countries (WWAP, 2019).

According to Burek et al. (2016), it is expected that global water demand rises ongoing at a similar rate until 2050, representing an increase of 20 to 30% above the current level of water use. In a study in World Economic Forum's Global Risks Report 2016, water crises are one of the three biggest challenges we face (WEF, 2016). A recent study revealed that about 4 billion people, two-thirds of the global population, is facing water scarcity (Mekonnen and Hoekstra, 2016).

Water scarcity can be defined as the feature in which the combined impact of users affect the water supply and quality under prevailing institutional arrangements to the scope of the all demands cannot be satisfied fully (WWAP, 2012). Since water stress is a function of the availability of water resources, the concept of water scarcity is defined in terms of access to water (IWMI, 2007; WWAP, 2012). The figure 1 shows water scarcity by regions.

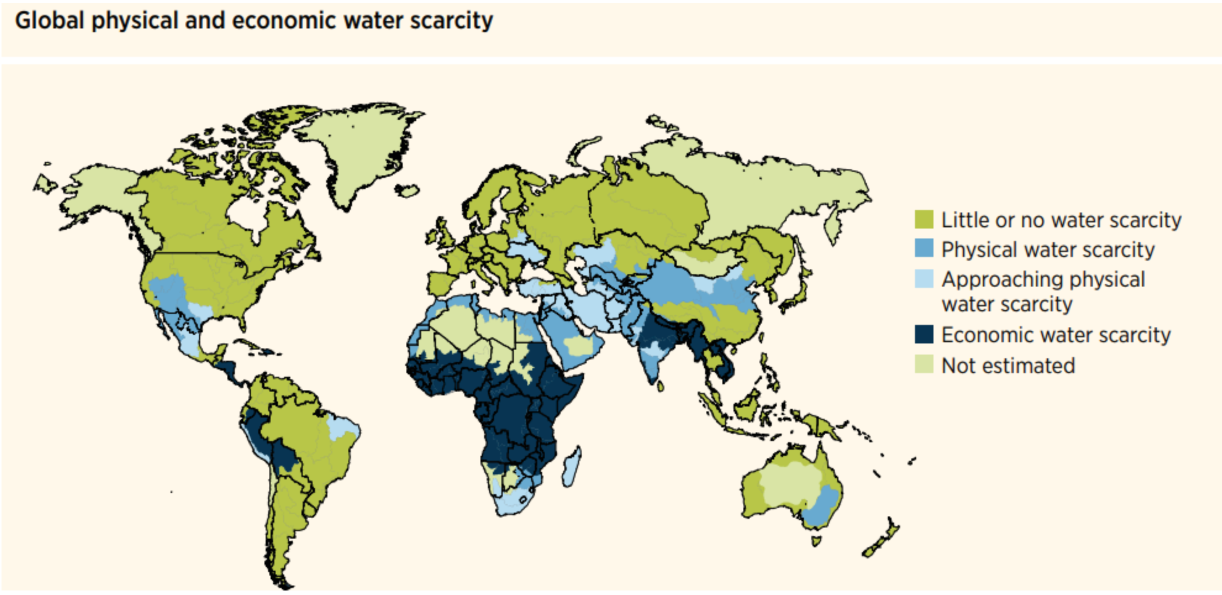

Figure 1: Global water scarcity (WWAP, 2012)

Regarding types of water scarcity, there are physical scarcity and economic scarcity. Whereas Physical scarcity is defined in a situation that there is not enough water to meet all demands, including environmental flows, the economic scarcity occurs by a lack of investment or human capacity to satisfy the demand (IWMI, 2007). Physical water scarcity exposes environmental degradation, declining groundwater, and water allocations that can disfavor some groups over others, and economic water scarcity displays scant infrastructure development in small or large scale, so that hinder people to get enough water for their needs (IWMI, 2007).

Regarding the largest water consumer, agriculture represents 69% of annual water withdrawals globally, industry contributes with 19% and households with 12% (AQUASTAT). The Figure 1 shows the water withdrawal ratios by sector among continents.

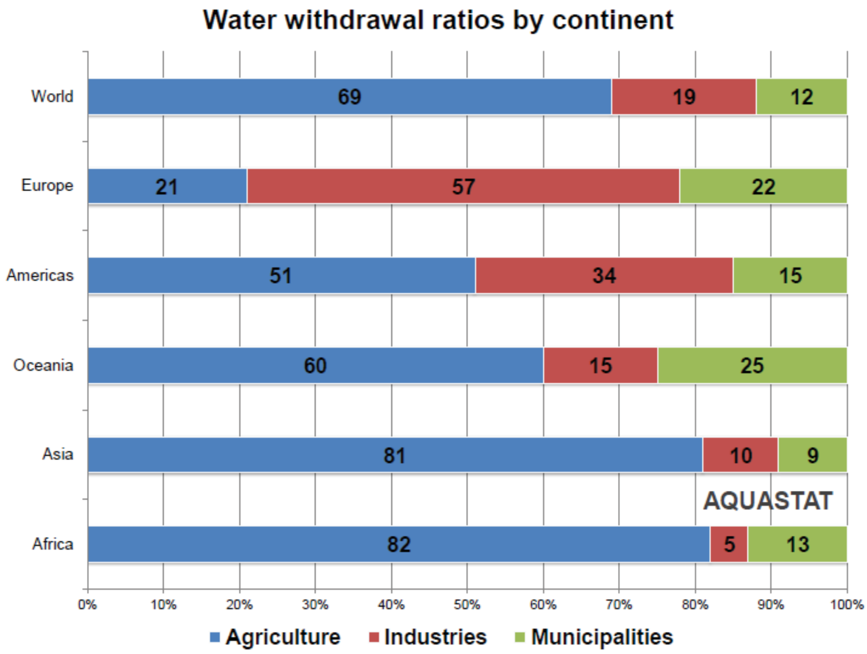

Figure 2: Water withdrawal ratios by continent. (FAO, 2016; AQUASTAT Main Database)

Some projections and facts in current years by principal international organizations about water crisis have been steadily alarming (Biswas and Tortajada, 2019). A prediction from GWI claimed that 700 million world's people could be dislocated by intense water scarcity up 2030 (GWI, 2013). By a report of the Water Working Group of the IRP, UNEP declared that nearly half of people worldwide 'will suffer from severe water stress by 2030' (UNEP, 2015). A report on Water and Sanitation by United Nations claimed that over 2 billion people live in countries undergoing high water stress, that hinders sustainability, and limits social-economic development (UN, 2018). A report by World Bank and UN in 2018 alleged that 36% of the global population already lived in water-scarce areas and projections suggested that world would 'face a 40% shortfall in water availability by 2030' (HLPW, 2018).

1.2. Wastewater reuse and management

Due to increasing population pressure, changing water consumption behavior, and climate change, the challenge of keeping water consumption at sustainable levels is projected to become even more difficult in the near future (Gosling and Amell,2016). To overcome this challenge, Target 6.4 of the SDG 6 deals with water scarcity, aiming to ensure there is sufficient water for the population, the economy and the environment by increasing water-use efficiency across socioeconomic sectors (SDG-UN, 2017). This includes addressing other aspects of water management such as reuse of treated wastewater. Concerning on how to find solutions to support the equilibrium within demand and offer arise in the scenario of increasing pressures on water resources, the wastewater reuse and reclamation is one of the main possibilities to overcome water scarcity (Salgot and Montserrat, 2018).

There is a promoting of reclaimed wastewater as a cheap and reliable form of water supply, which keep the water resources, besides allowing economically making use of sewage (Luckmann et al., 2016). The wastewater management systems and sustainable sanitation can soften demand from agriculture, freshwater supply, industry, energy generation and ecosystem replenishment that overtake availability by decreasing the insert of freshwater into the system and by providing the water fraction of wastewater available for environmental release and safe use (Andersson et al., 2016).

According to Andersson et al., (2016), the degree of centralization of collection services is one of important choices to consider in a sanitation or wastewater management system, where it is shown that a system can be centralized, partly decentralized or fully decentralized. In particular, the decentralized wastewater system can simply treat wastewater next to the source the source, using alternative technologies (Omenka, 2010; Chirisa et al., 2017). Alternatively, the approach of decentralized wastewater treatment which make use of a combination of on-site system is becoming more visible (Chirisa et al., 2017).

Moreover, decentralized source-separated systems are an attractive alternative as a possibility to enhance resource recovery, where wastewater is divided and treated separately, from toilets as blackwater and the remaining wastewater as greywater (Larsen et al., 2009; Ashok et al., 2018; Kobayashi et al., 2020). Greywater has the capacity to reduce the demand for new water, the energy and carbon footprint of water services, and to meet several social-economic needs (Allen et al., 2010). The treatment reuse of greywater can be an important aspect in converting a significant fraction of wastewater to a valuable water resource (Friedler and Hadari, 2006). In countries where water resources are expensive, the reuse of treated greywater can make economic benefits (Boano et al., 2020), as potentially saving around 9 – 47% of potable water (Hourlier et al., 2010; Fowdar et al., 2017).

2. Objective

The main objective of this thesis is to investigate the challenges and prospects of using greywater as a source of drinking water and potential applications of decentralized greywater treatments to achieve a drinking water quality.

3. Methodology

This research provides a literature review based on principles, facts and discussions found in online sources such as articles, manuscripts, books, and thesis regarding characteristics of greywater, challenges related to reuse of greywater and an overview of potential technologies for decentralized greywater treatment.

4. Greywater

4.1. Characteristics of greywater

Greywater refers a fraction of household wastewater produced in showers, bathtubs, laundry, hand basins, kitchen sinks, but excluding toilet flushing (Eriksson et al., 2002; Edwin et al., 2014; Manna, 2018; Ashok et al., 2018; Boano et al., 2020). Greywater is usually divided in light greywater, where come from showers, baths, hand basins and laundry machines in some cases, and dark greywater which includes laundry facilities, dishwasher machines, and in some studies also kitchen sinks (Jefferson et al., 2004; Allen et al., 2010; Hourlier et al., 2010, Ghaitidak and Yadav, 2013, Leonard et al., 2016, Fowdar et al., 2017). While dark greywater may contain high concentrations of pollutants (Birks and Hills, 2007; Allen et al., 2010), light greywater has a low concentration of ones that may enable high potential for local treatment and reuse (Fowdar et al., 2017). Some studies name dark greywater as high strength greywater, and light greywater as low strength greywater (Winward et al., 2008; Li et al., 2009; Mainali, 2019). The figure 3 shows types of greywater and constituents.

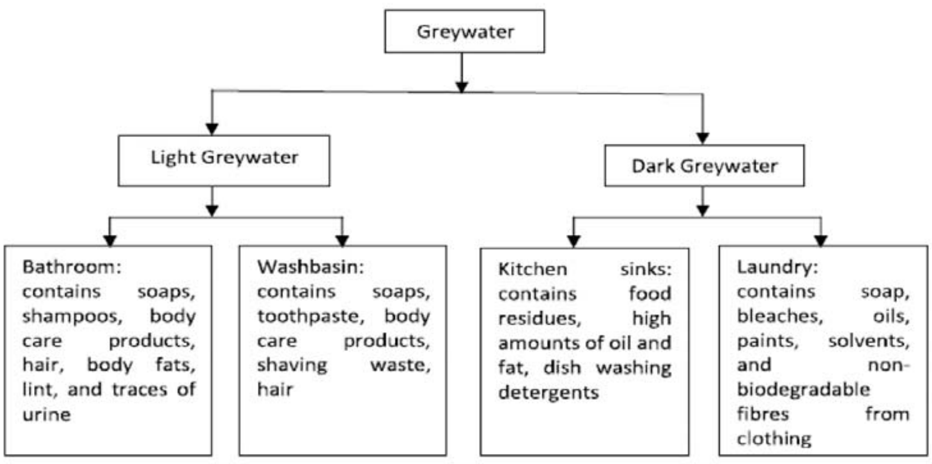

Figure 3: Types of greywater and their contaminants (Noah, 2002; Morel and Diener, 2006; QLD, 2008).

Several literatures agree that there is a variation of quality and quantity in greywater that depends on house facilities, characteristics of users, types of cleaning products, wastewater collection system and area type (Manna, 2018; Boano et al., 2020).

Greywater quality is commonly evaluated through the physical, chemical and biological parameters as shown in Table 1, where they are focused on their subcategories on previous studies by Eriksson et al., (2002), Leonard et al., (2016) and Fowdar et al., (2017). The analysis of pathogens is most assessed by indicator *Escherichia coli* (E. coli) and the identification of xenobiotic organic compounds, also known as organic micro-pollutants, is included surfactants, solvents, preservatives, fragrance flavors and others. The appendix A shows a comparison of physical and chemical properties of domestic greywater in several countries, by published reviews and articles investigated by Boano et al., (2020).

Table 1: Parameters for evaluation of greywater quality (Adapted from Boano et al., 2020)

Chemical parameter	**Unit**	**Physical parameter**	**Unit**
pH	-	Temperature	ºC
BOD	mg/l	Turbidity	NTU
COD	mg/l	Total solids	mg/l
TOC	mg/l	TSS	mg/l
DOC	mg/l	TDS	mg/l
Nitrate	mg/l	**Biological parameter**	
Ammonium	mg/l	Total coliforms	MPN/100 ml
Oxidized nitrogen	mg/l	Faecal coliforms	MPN/100 ml
TN	mg/l	*Escherichia Coli*	MPN/100 ml
TP	mg/l	F-RNA bacteriophase	MPN/100 ml
Phosphate	mg/l	Clostridium perfringes	MPN/100 ml
Heavy metals	mg/l	Bacterioidales	MPN/100 ml
Xenobiotic organic compounds	mg/l		

The figure 4 shows the average distribution of greywater production in household sources, where there is a high contribution from bath and shower, and kitchen. According to Boano et al., (2020), these values refer to sixteen countries (Australia, Brazil, Burkina Faso, Denmark, England and Wales, Greece, Holland, India, Israel, Jordan, North America, Oman, Yemen), calculated from twenty studies.

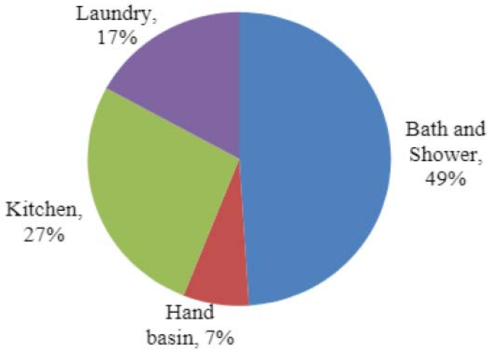

Figure 4: Contribution of main different sources in greywater. (Edwin et al., 2014)

Regarding greywater quantity of total domestic wastewater, this fraction can represent 55 - 75%, that it depends on total water consumption, people habits, living standards, climate and other factors (Hussain et al., 2002; Parjane and Sane, 2011; Ghaitidak and Yadav, 2013; Albalawneh et al., 2015; Karnapa, 2016). In EU and high- income countries, greywater represents around 100–150 L/PE/day of the total wastewater (Ghaitidak and Yadav, 2013), and it represents to 70 – 90 L/PE/day in India (Karnapa, 2016). In rural areas, greywater corresponds to 94lL/PE/day in Syria (Mourad et al., 2011), and 14 L/PE/day in Jordan (Halalsheh et al., 2008).

5. Quality standards

Quality requirements to reuse greywater depend on its origin, type of reuse and scope of human contact with recycled water (Eriksson et al., 2002; Hourlier et al., 2010; Ghunmi et al., 2011; Ghaitidak and Yadav, 2013; Leonard et al., 2016; Boano et al., 2020). In addition, there are many available quality requirements from regulations and guidelines to greywater reuse among several countries. Categorization of greywater reuse standards has been provided in previous studies by Li et al., (2009), Edwin et al., (2014), De Gisi et al., (2016), and Al-Ismaili et al., (2017).

Several mandatory standards reviewed by Boano et al., (2020), where they pointed out that standards limits have been proposed by existing guidelines for some quality parameters among countries. However, no standard limits or regulations and recommendation is available for reuse of greywater for direct potable use. Table 2 shows some guidelines for GW reuse.

Table 2: Overview of guidelines sources for GW reuse

Standards	Applicability	BOD_5 mg/L	Tot P mg/L	TSS mg/L	E.coli MPN/100 ml
US standard (NSF/ANSI 350-2012)	reuse of greywater	10	-	10	14
Australian Guideline (2011)	reuse of greywater	<20		<30	<30
EC 2018	Class A reclaimed water quality for agriculture	<10		<10	<10
EPA (2004)	Unrestricted urban reuse	<10			Not detected
	Restricted reuse	<30		<30	<200

Concerning regulations to drinking water, there are several standards limits from different institutions. But there are guidelines for drinking water quality from EPA and WHO that produce international norms on water quality worldwide, as shown in table 3. Some quality parameters are more restricted or follow similar ranges between standards.

Table 3: International drinking water standards (Adapted from WHO, 2011; EPA, 2018)

Drinking water standards			
Parameters	**Unit**	**WHO**	**EPA**
pH	-	6.5 – 8.5	6.5 – 8.5
TDS	mg/l	1000	500
Turbidity	NTU	5	5
Ammonia	mg/l	1.5	-
Nitrite	mg/l	0.1	1
Nitrate	mg/l	10	10
Total Nitrogen	mg/l	NA	NA
Total phosphorus	mg/l	NA	NA
Total coliforms	Cfu/100ml	-	0
E. coli	Cfu/100ml	Must not be detected in any 100 ml sample.	0
Odor	-	NA	NA

6. Challenges of using greywater as source of drinking water

6.1. Organic micro-pollutants

The organic micro-pollutants (OMPs), are aromatic compounds, which are divided into three groups: polyaromatic hydrocarbons (PAHS), benzene/toluene/ethyl benzene/xylene (BTEX) and the synthetic-substituted aromatics represented by the chlorophenols (Harvey and Thurston, 2001). In addition, OMPs include pesticides, polyfluoroalkyl substances (PFASS), pharmaceuticals and personal care products (PPCPS), endocrine disrupting chemicals (EDCS), active pharmaceutical ingredients (APIS), phosphorus-containing flame retardants (PFRS), preservatives, plasticizers, softeners, emulsifiers, dyes and pigments (Noman et al., 2019). A completed list of OMPs is presented in Appendix B.

The source and accumulation of OMPs in greywater commonly result, from PPCPs, shampoos, hair conditioners, oils, foodstuffs, moisturising oils and the food additive (Noman et al., 2019). PPCPS that are a class of micropollutants which include frequently used as medicinal, cosmetic and personal hygiene products (Wang et al, 2018), and they may be widely detected in coastal, ground, surface and even drinking water (Kim et al., 2007; Vieno et al., 2007; Luo et al., 2014;

Pessoa et al., 2014). PPCPs include a great and different group of organic compounds, that emerge substantial concerns due to their potential adverse impacts on the human health and environment (Chtourou, 2018; Wang et al., 2018).

Although most of the pharmaceutical products are found in human excreta, some products such as anti-inflammatory pharmaceuticals usually used externally (e.g. skin), can also be found in greywater (Butkovskyi et al., 2016). However, there is a possibility of pharmaceutical disposal in the greywater system.

Chtourou, (2018) pointed out that triclosan (TCS) and preservatives are antimicrobial agents used in PPCPs, where TCS is an endocrine disruptor, and the preservative is used in pharmaceutical preparations. TCS can combine with chlorine in water and then, forming a carcinogen such as chloroform (Sioufi et al. 1977). The preservative methyl paraben (MPB) is used in cosmetic and toiletries consumer products, and TCS can be widely used in many consumer care products such as toothpaste, mouthwash and soaps, shampoo, deodorant, disinfectants and even in textiles (Dann and Hontela 2011; Chtourou, 2018).

TCS has already been a concern agent for scientific communities and regulatory authorities (Chtourou, 2018), where its use was disapproved by European Union (EU) in biocidal products due to its non-acceptable environmental risk (EU 2016). In USA, the consumption of antiseptic washing products containing TCS can no longer be sold without a prescription (FDA 2016). In addition, the Official Journal of the EU announced MPB has been restricted by Cosmetic Directive (Chtourou, 2018), and MPB free labels are emerging on beauty products recently (Steter et al. 2016).

Surfactants, which are surface active agents, represent the major greywater, applied in the production of detergents (amphoteric, cationic, anionic and non-ionic detergents) and hygiene products which are used extensively for laundry and showers (Noman et al.,2019). Phenols such as UV stabiliser, antioxidants for hydrocarbon-based products, pigments, and dyes such as p-phenylenediamine, toluene- 2,5-diamine and 2,5-diaminoanisole in hair colorants (Grčić et al. 2015). Moreover, dyes have acquired attention in studies, because they have high tectorial values and their discharge of less than 1 ppm into the water might cause changes in its physical characteristics (Noman, et al.,2019).

6.2. Pathogens

Pathogens in greywater come from body surface, nose and mouth, as well as residual traces of faeces (diapers and anal cleansing), where estimations indicate a fecal load of around 0.04 g-p.d discharged in greywater sources (Ottosson and Stenström 2003). In general, fecal coliform contamination in greywater presents similar levels to those found in treated effluent (Jefferson and Jeffrey, 2013). Moreover, greywater can be exposed to enteric pathogens such as Campylobacter and Salmonella, washed from cleaning practices and food preparation (raw meat or vegetables) from kitchen sources (Ottosson and Stenstrom, 2003; Jefferson and Jeffrey, 2013; Maimon et al., 2014).

In addition, opportunistic pathogens (that do not normally harm the host, but can cause disease if host has low resistance) such as Pseudomonas aeruginosa and Staphylococus aureus are identified in greywater, as well as pathogens transmitted by faeces such as Cryptosporidium spp, Giardia spp., and Salmonella spp. (Winward et al. 2008). However, pathogens transmitted with faeces are much less common, because they require the contribution of an affected person and, therefore, are more likely in larger samples and in those containing children or the elderly people (Jefferson and Jeffrey, 2013).

There are concerns about regrowth or die-off pathogens in greywater during storage, because indicator organisms have been revealed to rise by as much as 2 $\log_{10}$ units within 24-48 hours during storage while enteric pathogens do not show up to regrow but can persist for days (Rose et al. 1991).

6.3. Aesthetics and Reuse Perceptions

Presence of characteristics such as taste, color and odor are some challenges to treat greywater to drinking water quality. Greywater can easily turn anaerobic and thus provoke an undesirable odor, that might outcome that greywater is health hazard (Ridderstolpe, 2004). In addition, WHO recommend that the drinking water should not have unwelcome taste and odor (Bruchet and Laine, 2005).

Another challenge regarding to use greywater is reuse perceptions. The harsh public opposition that interpose many potable water reuse projects, has been assigned to the close association of greywater with sewage which creates a judgment of repugnance (De Sena, 1999); Hurliman and Dolnicar, 2013; Meehan et al., 2013; Oteng-Peprah et al., 2018). In addition, a study by Marks (2004) detected low public support and acceptance to reuse greywater for potable purposes in developed countries such as Australia, USA, and UK.

There are other studies that identify language of the names given to recycled water as one of the barriers affecting reuse plans (Dolnicar and Saunders 2006). Moreover, there is a severe public opposition for recycled water projects due to a low trust in the implementing body, even in spite of the most relevant advanced technology (Friedler et al., 2006; Omerod and Scott, 2013; Russell et al., 2008).

7. Technologies for decentralized greywater treatment to achieve a drinking water quality

7.1. Filtration system

Filtration systems are normally made up of various types of porous media that have a possibility to act as a support medium for biofilms. The filtering or straining efficiency increases with decreasing filter media size (Affam and Ezechi, 2020). Filtration systems reduce pollutants such as SS and turbidity, COD, BOD, and bacteria from greywater, and efficiency also depends on pH, temperature as well as characteristics of the raw material used in the design of the filter (Noman et al., 2019). Depending on the surface chemistry of the porous media, sorption of substances as heavy metals and phosphorus can occur. These filtration systems can be composed by material such as charcoal, gravel, peat, sand, limestone, clamshell, ceramics, wetland bed and volcanic ash (Mohamed et al. 2014; Wurochekke et al. 2014).

The clamshell is the raw materials ,in a form of calcium carbonate ($CaCO_3$), which switch calcium atoms in favor of heavy metals locking them into a solid form, that tender an efficiency of removing of arsenic metal ions from water in individual households (Köhler et al. 2007). Limestone is an alkaline agent available in different crystal forms of $CaCO_3$ and composed by mineral calcite and aragonite, where is highly effective for removing Fe and Mn ions from the water (Ghaly et al. 2007). Ceramic is an inorganic and non-metallic material, commonly used in filtration methods due to the efficiency to remove protozoa, bacteria and even microbial cysts (Plappally et al. 2011).

Dalahmeh et al. (2014) developed a filter system made of activated charcoal, pine bark and sand to treat greywater and remove of organic matter and nitrogen, where the study exhibited higher removal of BOD_5 with efficiency of 97% in charcoal, 98% in bark and 75% in sand filter. Mohamed et al. (2014) found that the filtration system made up of charcoal, peat and gravel also showed efficiency for the greywater treatment, as shown in figure 5, where charcoals were applied to remove the color and odor of greywater. Charcoal filter can also remove micropollutants of greywater (Hernández-Leal et al., 2011).

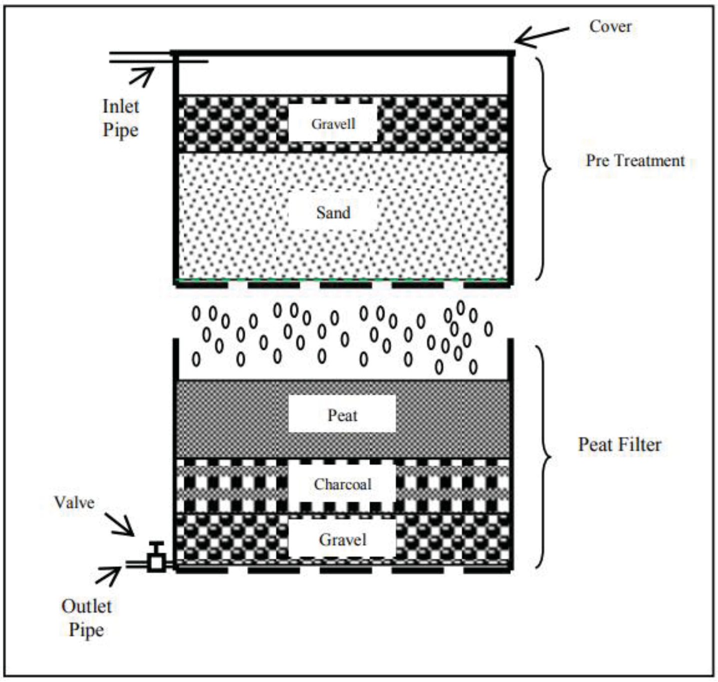

Figure 5: Diagram of filter media (Mohamed et al., 2014)

Mohamed et al. (2016) inquired a multicomponent filter of clamshell, limestone, steel slag and sand media for the treatment of greywater in the village houses, where the study revealed high efficiency for household greywater with removal of 74% of COD, 88% of BOD_5, 98% of turbidity and 96% of TSS. Moreover, a study on the performance of biochar and filtralite as polishing step for on-site greywater treatment plant showed improved the effluent quality of the system with biochar removing 96% of organic matter, 99% of turbidity and odor (Moges et al. 2015). The contribution of the polishing step in removing total coliform bacteria and E. coli was also remarkable.

The use of natural materials such as the charcoal bed sand bed, fine particles, course size bricks bedded, the bed of coconut shell cover and wooden sawdust bed have been applied in a development of natural filter system for individual users (Lalander et al. 2013; Mohamed et al. 2014).

Another filtration system by adsorbent process is the use of activated carbon in form of powdered activated carbon (PAC) and granular activated carbon (GAC). These filter systems reported an efficiency nearly of 90% and more of carbamazepine, caffeine, diclofenac, trimethoprim, bisphenol A, nonylphenol and triclosan (Grover et al. 2011; Hernández-Leal et al. 2011; Yang et al. 2011; Kovalova et al. 2013).

Many studies have also indicated that the pretreatment of adsorbent by chemical or physical process might enhance the adsorption process of OMPs (Al-Gheethi et al. 2017a; 2017b), such as the use of carbon nanotubes with high adsorption capacity for PPCPs (Ji et al. 2009; Liu et al. 2014; Wang et al. 2016). The use of natural zeolite in the removal of cationic surfactants has also been reported by Schulze-Makuch et al. 2002 and Schulze-Makuch et al. 2007.

7.2. Constructed Wetlands

Constructed wetland (CW) is one of the alternatives for decentralized greywater treatment which has less construction and maintenance cost, low energy consumption and simple operation (Massoud et al., 2009; Kadlec and Wallace; 2009; Parjane and Sane, 2011; Garfí et al., 2017, Wu et al., 2015). CW apply an ecological technology that simulate conditions that occur in a natural wetland (Oteng-Peprah et al., 2018) and then it provide one of the most eco-friendly options for greywater treatment (Li et al., 2009, Dominguez et al., 2018).

Constructed wetlands are classified under hydraulic flow scheme: free water surface constructed wetland (FWSCW), green roof water recycle constructed wetland (GROWCW), horizontal subsurface flow constructed wetland (HSFCW), vertical subsurface flow constructed wetland (VSFCW) and combined constructed wetland system (Arden and Ma, 2018).

CWs uses materials such as sand and gravel, besides the use of aquatic plants (duckweed or hyacinths) to reduce organic matter (Oteng-Peprah et al., 2018; Noman et al., 2019). This technology has been recognized as a reliable treatment technology for wastewater around the world including North America and Europe (Vymazal, 2011). The figure 6 shows the most commonly configurations of subsurface flow constructed wetlands.

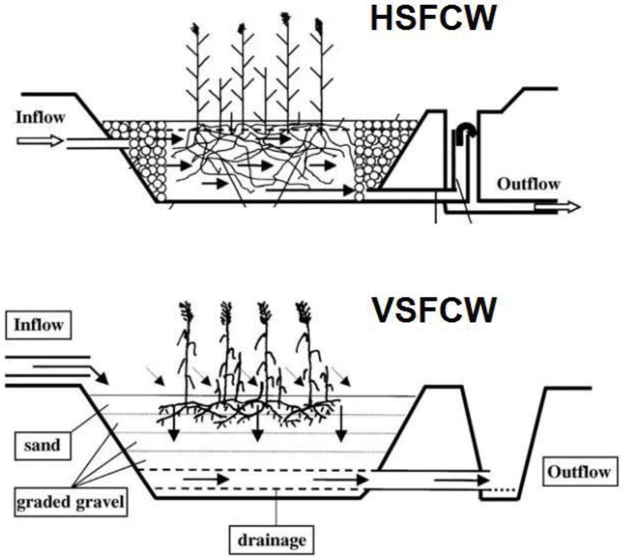

Figure 6: Schematic of subsurface flow constructed wetlands (modified from Vyzamal, 2007)

CW also provide a satisfactory removal efficiency of BOD and TSS (Arden and Ma, 2018), and removal efficiency of 85-89 % for sodium dodecyl sulphate (SDS) and 95-98% for propylene glycol (PG) and trimethyl amine (TMA) (Ramprasad and Philip, 2016). In a study of a novel CW using a shallow HSFCW was developed for small scale decentralized system in tropical countries, where the efficiencies were 90.8% for BOD, 92.5% for COD, 91.6% TSS, 83.6% nitrate, 87.9% total phosphate, 91.7% total nitrogen, 91.4% fecal coliform, 85.7% SDS, 93.4% PG and 88.9% TMA (Ramprasad et al., 2017).

However, CWs also present a high performance in cold climate regions, where this system is based on the use of a septic tank followed by an aerobic vertical down-flow biofilter succeeded by a subsurface horizontal-flow constructed wetland (Jenssen et al., 2005).

7.3. Membrane processes

Membrane processes implies the use of technology for the separation of biomolecules and particles for the concentration of process fluids, where a semipermeable membrane acts as a selective barrier retaining the molecules/particles bigger than the pore size, while allowing the smaller molecules to permeate through the pores (Mukherjee, 2019). The range of membrane filtration processes is shown in figure 7. There are several range of membrane filtrations such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Membrane technologies can be used in decentralized greywater treatments, as they are very compact, do not depend on gravity separation and provide consistent product quality (Leslie and Bradford-Hartke, 2013).

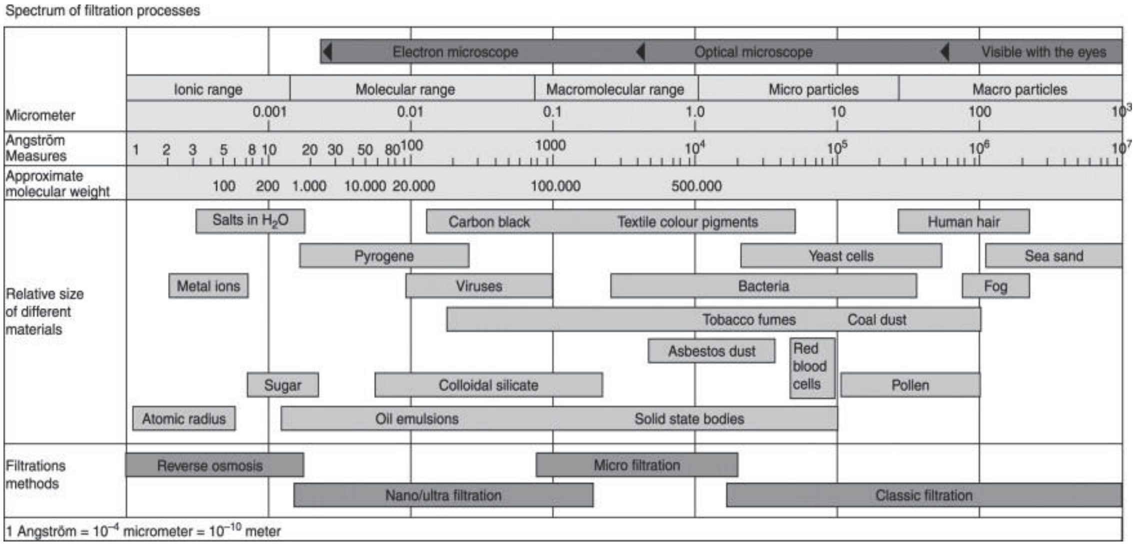

Figure 7: Ranges of membrane filtration processes. (Graff, 2012)

MF and UF may be used as clarifier to remove microorganisms and suspended solids, reducing effluent turbidity and providing some disinfection, and RO and NF can be placed to remove residual carbonaceous, nitrogenous and phosphorous nutrients, and monovalent, divalent and trivalent ions (Leslie and Bradford-Hartke, 2013)

Among membrane processes, membrane bioreactor (MBR) is also a promising technology for greywater treatment (Cashman et al., 2018; Cecconet et al., 2019), where it display advantages such as small footprint, process stability, low sludge production and high quality effluent for water reuse (Li et al., 2009).

Some studies regarding membrane technologies have reported high performance to remove OMPs. Boleda et al. (2011) and Sahar et al. (2011) have reported that UF - RO double membrane process has an efficiency removal of 90% on PhACs and EDCs. Kimura et al. (2004) have investigated RO effect on 11 EDCs and PhACs, where it exhibited that the polyamide membrane has achieved a good removal effect on 2-naphthol, 4-phenylphenol, caffeine, bisphenol A, sulfamethoxazole and 17β-Estradiol with a rate between 51% - 91%.

Regarding MBR, this technology has a better effect (>80%) on most pharmaceuticals (naproxen 99.3%, ofloxacin 94.0%, bezafibrate 95.8%, and paroxetine 89.7%), compared to conventional activated sludge (Radjenovic et al., 2007). Dolar et al. (2012) gave attention to the study of MBR-RO process's efficiency on twenty multiple-class pharmaceuticals, where the treatment has showed excellent overall removal rates of above 99%. A study with 40 trace organics, using MBR-NF treatment process, has demonstrated removal efficiency of above 95% (Alturki et al., 2010).

7.4. Oxidative Processes

The solar treatment based on the photo-oxidation and photocatalysis processes might have efficiency in the degradation of OMPs such as dye and their derivatives, surfactants, and fragrances compounds (Santiago-Morales et al. 2012). Grčić et al. (2015) reported the possibility of hair colorants removal by solar photocatalysis and flocculation, where household greywater was placed in a reactor with the photocatalytic layer (TiO_2-coated textile fibers) and then exposed to direct sunlight.

The degradation of OMPs by solar radiation is explained as a result of the destruction of chemical bonds by UV waves called photolysis (Wang and Wang 2016). However, some of OMPs are resistant to UV destruction and then some studies propose the combination of oxidative agents and UV, called advanced oxidation process (Noman et al., 2019).

Moreover, studies reported that the disinfection of greywater might be performed simultaneously using the natural processes of solar disinfection with effectiveness of reduction of pathogenic bacteria to less than detection limits when there is a sunlight intensity between 5.2 and 6.8 $kWh/m^2/day$ (Al-Gheethi et al., 2015).

There are chemical disinfection techniques such as bromine chloride, chlorine, calcium hypochlorite, hydrogen peroxide and ozone (Al-Gheethi et al., 2019). Chlorination is a common process used for the disinfection due to the low cost, the simple usage and effectiveness for the inactivation of most of the infectious agents (Ottosson 2003), but a non-effectiveness of previous treatment steps of greywater can lead to a formation of disinfection by-products.

7.5. Combined treatment system

A research by Mainali (2019), greywater was treated for drinking water purpose, where the sample was retrieved from the municipality of Nesodden. The greywater treatment followed the same sequences system as in Kaja student housing located at campus Ås from Norwegian University of Life Sciences (NMBU) and in a small scale way at Klosterenga in Oslo, where the on-site treatment system consists of: septic tank (ST), vertical flow aerobic biofilter (VFAB) and HSFCW, as shown in figure 8.

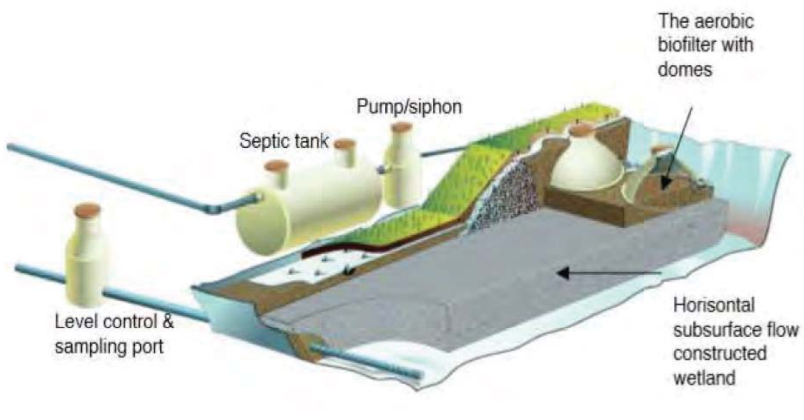

Figure 8: Greywater treatment in Norway (Jenssen and Vråle, 2003)

During laboratory tests, Mainali (2019) demonstrated the potential of a compact post-treatment system to treat effluent from a constructed wetland using nano filter (pore size 0.3 µm) and GAC filter through two different filtration sequences, as shown in figure 9.

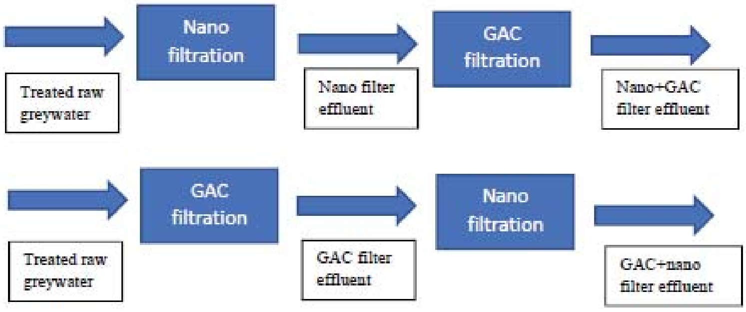

Figure 9: Filtration sequences proposed for greywater treatment (Mainali, 2019)

The experiment revealed the potential of producing drinking water quality water from treated greywater. Both combination of NF-GAC filter or GAC-NF have shown good performance as post-treatment of constructed wetland. The GAC-NF sequence was, however, found to be more effective as it reduces early clogging of the NF filter. In addition, Mainali, (2019) suggested the adoption of sand-filter along with NF and GAC, to remove ammonia up to desirable level of drinking water quality. Although several studies have shown the removal of most PPCPs using GAC, further study is required to affirm the potential of this post-treatment system on the removal of PPCPs and viruses.

8. Discussion

The segregation process of greywater from blackwater might improve the treatment efficiency to remove organic matter as well as infectious agents. Many treatment processes focus on removing agents that might cause the growth of pathogenic microorganisms and contaminate the environment.

There is a concern of OMPs bioaccumulation in the environment that reach humans via food chain and drinking water sources, that may cause unknown health effects. However, it is necessary to use different reuse strategies such as suitable treatment process in order to achieve physical, chemical and microbial requirements.

There are several technologies with their efficiency and effectiveness to produce high quality of treated greywater. However, the main concern in the greywater is the occurrence of pathogens and toxicity of OMPs that their removal by traditional methods is difficult. Therefore, many studies have showed effective decentralized treatment technologies that can treat greywater in small scale.

The aerobic and anaerobic treatment system has been used as greywater treatment for lower energy consumption, but they need additional process to inhibit the growth of infectious agents. It is recommended the use of aerobic treatment for greywater due to the high reduction of COD and consequently the re-growth of microorganisms and odor are avoided (Li et al., 2009).

The constructed wetland is a cost-effective alternative and more flexible in operation and maintenance to operate the treatment system, which is relatively affordable and practical for the household (Halalsheh et al. 2008). Constructed wetland can achieve good performances regarding the removal of the biodegradable organic matter. However, this technology may require a large footprint and it is not able to treat greywater to a high quality for drinking water without additional processes, such as membranes processes, filter system and/or disinfection.

Filtration systems has showed a good effectiveness against pathogens, heavy metals, BOD, COD, turbidity and TSS in the greywater treatment. However, a major challenge for filters is clogging and the necessity to replace filter materials.

Membrane filtration system has also provided good performance to remove organic matter and micropollutants in general, besides to be a very compact, they are easily coupled with other processes and require no use of chemicals. However, membranes are prone to fouling effects which lead to decrease in permeate flux and some membrane technologies thus can have high maintenance cost.

In general, all decentralized treatment system reviewed in this study proved good removal of several pharmaceuticals, surfactants, detergents, and others micro-pollutants. But it is necessary to combine different type of technologies so that greywater treatment can achieve a desirable drinking water quality.

Another challenge to use greywater as drinking water is reuse perception, where there is a judgment that recycled water is associated to human waste and then it causes a repulsive public's point of view. Some studies reported that the main barrier of using greywater for potable purpose, is related to its perceived health risk in activities that involve direct contact (washing, cooking and drinking) of the user (Oteng-Peprah et al., 2018). Furthermore, public authorities need to stimulate social learning processes with specific actions and build trust among users in the new governance network in order to increase acceptance of alternative water supplies (Domènech and Saurí, 2010).

9. Conclusion

Greywater represents one of alternative source raw water for production of potable water due to the low contamination compared with mixed wastewater. Furthermore, several reviewed studies revealed that greywater can present challenges in terms of organic micro-pollutants and microbial contaminants when used as a source of drinking water.

There is a wide variation in greywater characteristics and volume generation rates which it is dependent on the water use, lifestyle patterns and type of settlement. This must be taken into consideration when designing a treatment system for producing drinking water from greywater.

There are technologies developed to treat or remove specific pollutants, but one single system or technology do not alone offer full treatment of the greywater to produce potable water. Filtration systems seem feasible and have the potential of integration with other systems to achieve a desirable greywater quality. Membranes processes are compact technologies for greywater treatment that combined with other treatment steps can upgrade greywater to drinking water standards for households.

Regarding perception reuse, the most users have preferred to reuse greywater for activities that do not involve direct contact. In general, public perceptions as well as support from authorities are important in order to select implementation of adequate methods for a specific context.

10. Recommendations for further studies

This study focuses on challenges in using greywater as a raw water source for drinking water and discuss potential technologies that can achieve sufficient treatment performance. Further studies are required to test how these technologies can be combined and especially achieve a satisfactory degree of removal of organic micro-pollutants. Therefore, the applicability and compatibility of these systems must be understood in context of the requirements of different regions.

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Appendix

Appendix A: Comparison of physico-chemical parameters of domestic greywater in different countries (Boano et al., 2020)

Physico-chemical features of domestic greywater in different countries. All values are reported as minimum-maximum (average), depending on available data.

Country	pH Min-Max (Avg)	TSS (mg/L) Min-Max (Avg)	BOD_5 (mg/L) Min-Max (Avg)	COD (mg/L) Min-Max (Avg)	TN (mg/L) Min-Max (Avg)	TP (mg/L) Min-Max (Avg)	TC (MPN/100 mL) Min-Max (Avg)	FC (MPN/100 mL) Min-Max (Avg)	*E. coli* (MPN/100 mL) Min-Max (Avg)
Australia[a]	–	(74)	(104)	–	(5.3)	(3)	–	–	–
Canada[b]	6.7–7.6	–	–	278–435	–	0.24–1.02	–	4.7E+04–8.3E+05	–
Egypt[e]	6.05–7.96 (7)	70–202 (116)	220–375 (298.6)	301–557 (388)	–	8.4–12.1 (10.54)	–	–	–
France[d]	6.46–7.48 (7.28)	23–80 (59)	85–155 (110)	176–323 (253)	–	–	1.7E+08–1.4E+09 (4.9E+08)	4.0E+03–5.7E+06 (1.3E+06)	–
Germany[e]	(7.6)	–	(59)	(109)	(15.2)	(1.6)	–	(1.4E+05)	–
Ghana[f]	5.00–9.00 (6.89)	192–414 (296.8)	87–301 (204.1)	207–1299 (643.8)	–	1–3 (2.3)	2.5E+06–4.9E+06 (3.7E+06)	0–6.9E+06 (1.80E+06)	–
India[e,g,h,i,j]	5.90–8.34 (7.4)	53.80–788.00 (337.2)	17.10–290.00 (244.2)	43.90–733.00 (705.4)	17.00–28.82 (17.8)	0.01–3.84	–	5.0E+01–1.2E+02	–
Indonesia[k]	(6.85)	(18.00)	(8.50)	(15.00)	–	–	–	–	–
Israel[e]	6.3–8.2	30–298	74–890	840–1340	10–34.3	1.9–48	–	3.5E+04–4.0E+06	(5.0E+04)
Japan[e]	–	–	–	(675)	(25.6)	(1.1)	–	–	8.5E3-1.2E4
Jordan[e]	6.4–9	23–845	36–1240	58–2263	6.44–61	0.69–51.58	250–1.0E+07	1.3E+01–3.0E+05	(2.0E+05)
Malaysia[m,n]	6.5–7.2 (6.85)	19–175 (114.4)	1.1–309 (188.85)	16–1103 (328.9)	–	(4.5)	–	0–1.9E+06 (2.9E+05)	0–6.7E+03 (1.1E+03)
Niger[e]	(6.9)	–	(106)	–	–	–	–	–	–
Norway[o,p]	(7.1)	(39)	(129)	(241)	(10.61)	(1.03)	(6.8E+06)	–	(4.9E+06)
Oman[e]	6.7–8.5 (7.5)	11–505	25–562	58–486	–	–	2.0E+02–3.5E+03	(2.0E+02)	(2.0E+02)
Pakistan[e]	(6.2)	(155)	(56)	(146)	–	–	–	–	–
Palestine[q]	5.8–8.26 (7.8)	304–4952 (1290)	407–512 (470.6)	863–1240 (995)	111–322 (199)	5.8–15.16 (10.45)	–	–	–
Republic of Korea[e]	(7.4)	(2180)	(255)	–	–	–	–	–	–
Spain[e,r,s]	(7.39)	(336.09)	(130.32)	151–177 (409.11)	10.00–11.00 (16.17)	–	–	(1.0E+03)	(1.0E+03)
Sweden[e]	(7.8)	–	(425)	(890)	(75)	(4.2)	–	(1.7E+05)	–
Taiwan[e]	6.5–7.5	(29)	(23)	(55)	–	–	(5.1E+03)	–	–
Tunisia[e]	(7.5)	(33)	(97)	(102)	(8.1)	–	–	–	–
Turkey[e]	–	(54)	(91)	190–350	(7.6)	(7.2)	–	(1.1E+04)	–
UK[e,t]	6.6–7.8	37–153	8.7–155	33–587	4.6–10.4	0.4–0.9	1.8E+03–2.2E+07	1.0E+01–2.2E+05	1.0E+01–3.9E+05
United Arab Emirates[u]	–	–	–	(1020)	–	–	(1.0E+07)	–	–
USA[e]	(6.4)	(17)	(86)	–	(13.5)	(4)	–	–	(5.4E+02)
Western Europe [v]	6.1–9.6 (7.5)	20–361 (89)	20–756 (221)	25–1583 (362)	3–75 (14)	0–11 (4)	–	–	–
Yemen[e]	(6)	(511)	(518)	(2000)	–	–	–	(1.9E+07)	–

Appendix B: Organic micro-pollutants in greywater (Noman et al., 2019).

Xenobiotic organic compounds (XOCs) in greywater

Source	Xenobiotic organic compounds (XOCs)
Skin care products, hair conditioners, shampoos, food additives, moisturising oils	Hydrocarbons
Oils and foodstuffs, skin cleaners, fragrance, food flavouring agents	Alcohols/ethers
Disinfectants; flavouring substance in foodstuffs, UV stabiliser and antioxidant for hydrocarbon-based products	Phenols
Foodstuffs and essential oils, Fragrance	Aldehydes and ketones
Soap, emulsifier for facial creams and lotions, shaving cream formulations, mould cheese	Carboxylic acids
fragrances, household dust, PVC floor wipes, food additive, emollient	Carboxylic acid esters
Flame retardant	Phosphoric acid ester
Cough syrup, dishwashing agents, body care, baby care, toiletries, artificial and natural jasmine oil, coffee, tobacco	Nitrogenous organics
Emulsifier	Deceth-3, Oleth-30, Lauric acid, Glycol distearate Ceteareth-25, Glamorous
Fragrances	Tonalide, Galaxolide, HCA, Hexyl cinnamic, aldehyde, flavours AHTN, HHCB, Styrene, Benzene-1,3-diol, p-Cresol
UV filters	BP, 4-methylbenzylidene-camphor (4MBC), octocrylene, octrocrylene, 2-ethylhexyl-4-methoxycinnamate (EHMC), avobenzone, 2-phenyl-5-benzimidazolesulfonic acid (PBSA), 2EHS, benzophenone-3 (BP3), 4-tert-Butyl-4′-methoxy-dibenzoylmethane (avobenzone) and 2-ethylhexyl salicylate (2EHS)
Softeners	Bis-(2-ethylhexyl)phthalate (DEPH), Diisononylphthalate (DNP) 1, Ethylenediaminetetramethylenephosphonate (EDTMP), Dibutylphthalate (DBP) 2, Diethylphthalate (DEP) 3, Nitrilotriacetic acid (NTA)
Solvents	Heptane, 1,2,4-Trichlorobenzene, Propylene glycol Diethanolamine, Ethanolamine, Glycerin, Isopropanol, Phenol, Xylene
Plasticizer	Bisphenol-A, Butylbenzyl phthalate, Di-(2-ethylhexyl) phthalate, Dibutyl phthalate, Diethyl phthalate, Di-isobutyl phthalate, Dimethyl phthalate

(continued)

(continued)

Source	Xenobiotic organic compounds (XOCs)
Preservatives	Methylparaben, Ethylparaben, Propylparaben, Butylparaben, Bronopol, Bronidox, 5-Chloro-2-methyl-4- isothiazolin-3-one, Imidazolidinyl urea Triclosan, Quaternium
Biocide/surfactants	Triclosan, BaCl, Nonylphenol
Endocrine disrupting chemicals (EDCs)	Bisphenol-A (BPA), nonylphenol (NP) and triclosan (TCS)
Pharmaceutical products	Acetaminophen, Salicylic acid, Hormones, Antibiotics, Lipid regulators, Nonsteroidal anti-inflammatory drugs, Beta-blockers, Antidepressants, Anticonvulsants, Antineoplastics, Diagnostic Contrast Media
Food additives/stimulants	Caffeine
Personal care products	Benzophenone, Galaxolide, Tonalide, Triclosan
Surfactants (Amphoteric detergents)	4-Nonylphenol, 4-Octylphenol, Cetearyl alcohol Trideceth-2 carboxamide MEA, Cocamidopropyl betaine, Alkylamide betaines, Alkylamidopropyl betaines, Alkyl betaines, Amidopropyl betaines Amphoglycinates, Lauriminodipropionates, Lauroamphodiacetates
Surfactants (Anionic detergents)	-Methylestersulphonate, a-Olefinsulphonate Alkyl benzene sulphonates, Sulphonates Alkane sulphonates, Alkyl ether sulphates Alkyl sulphates, Alkyl sulphosuccinates Isotridecanolethoxylates, Panthenol
Surfactants (Cationic detergents)	Benzalkonium chloride, N-Hexadecyltrimethyl ammonium chloride, DHTDMAC, DSDMAC DTDMAC, Alkyltrimethylammonium, Chloride
Surfactants (Non-ionic detergents)	Alkylphenolethoxylates (APEO), Nonylphenol (NPE), Alcohol ethoxylates (AEO), Alkyl amide ethoxylates, Alkyl amine ethoxylates, Fatty alcohols (EO/PO) polymers, Fatty alcohol ethoxylates(AEO) Coconut diethanolamide, Ethylene glycol
Dyes and pigments	3,30-Dichlorobenzidine, 4,40-Methylenebis-(2-chlorobenzenamine), o-Aminoazotoluene Benzidine, o-Anisidine, CI77891 (TiO_2), CI77491 (iron oxides), Mica

Source Adams and Kuzhikannil (2000), Eriksson et al. (2002), Straub (2002), Simonich et al. (2002), Eriksson et al. (2003), Seo et al. (2005), Palmquist and Hanaeus (2005), Kupper et al. (2006), Andersen et al. (2007), U.S. EPA (2009), Pal et al. (2010), Deblonde et al. (2011), Luo et al. (2014), Etchepare and Van der Hoek (2015), Grcic et al. (2015)

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