TECHNICAL GUIDE FOR SPECIFYING DECENTRALIZED GREYWATER TREATMENT PROCESSES

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Climate Survival Solutions

Abstract

As temperatures rise, drought spreads, aquifers and water reservoirs empty, and freshwater sources such as lakes and rivers either empty or are contaminated, mostly as a direct consequence of the climate crisis, recycling water after use, provided it is not heavily contaminated, has become mandatory for survival in many parts of the world. Decentralized wastewater treatment systems (DEWATs), which offer on-site, on-demand recycling of greywater generated in households and residential complexes, institutions such as universities and government, corporations, and restaurants represent a class of solution which could ease some of the severity of the water crisis ahead if properly implemented. This paper shows how DEWAT systems operate, how greywater quality and production vary across the world. Configuring the optimum DEWAT system requires understanding both the characteristics of greywater as well as the different methodologies which can be used for proper treatment. The paper provides high-level guidance to those interested in deploying their own DEWAT systems under a variety of conditions.

Table of Contents

1 Introduction 5
2 What is Greywater 6
3 Physio-chemical and biological characteristics of greywater 7
Geographical variations in greywater characteristics 12
4 Greywater management and reuse technologies/process 16
Next generation of infrastructures: complementing grey with green 16
Dual plumbing system: a prerequisite for greywater recycling and reuse 19
Selection criteria for best greywater treatment system and processes 20
Conventional greywater treatment sequence 22
Various processes and methods involved in greywater treatment 23
Integrated biological treatments -- Nature based solutions 35
5 Greywater treatment models 36
6 Conclusions 38
7 Selected Readings 39

Table of figures

Figure 1. Specific sources and their general characteristics explain the complexities of the greywater. 8

Figure 2. Diagrammatic sketch of greywater storage tank showing different types of pollutants. The non-biodegradable pollutants remain as it is in the polluted water where as the biodegradable pollutants (brown circles) get degraded by aerobic bacteria (green shape) using dissolved oxygen (blue circles) during the biological treatment process. Both biodegradable (brown circles) and non-biodegradable (grey circles) pollutants are oxidized chemically using laboratory assay to measure the chemical oxygen demand (COD) of greywater. The biodegradation process in laboratory is assessed using microbiological assay to measure the biological oxygen demand either on day 3, day 5 or day 7 which are represented as subscript to abbreviated form (BOD). 10

Figure 3. The range of greywater produced in liters per person per day (L/P/D) in different parts of the world. (Piotrowska, Słyś, Kordana-Obuch, & Pochwat, 2020). 14

Figure 4. Next generation water management infrastructure ensures sustainable development. 18

Figure 5. An example of commissioning validation and verification monitoring requirements for the treated water intended for non-potable reuse in Australia. (Directorate 2011) 22

Figure 6. Various methods and the roles involved in the greywater treatment process. ...23

Figure 7. Schematic diagram showing the flow of greywater in alternative pattern of down and upward flow through the series of columns. 25

Figure 8. An example of simple filtration system fabricated for Indian household with COD, BOD and TSS removal efficiencies of 85.98%, 86.28% and 94.44% respectively. (Patil, Bhange, et al. 2022). 26

Figure 9. A pilot scale prototype filter design for treating laundry wastewater composed of sand filter, bio-char and teff straw media (Yaseen, et al. 2019). 27

Figure 10. Schematic diagram of an anaerobic baffled reactor showing the path and flow of greywater treatment process. 27

Figure 11. The various advantages and drawbacks of anaerobic baffled reactor system to treat greywater. 28

Figure 12. Schematic diagram of activated sludge reactor (ASR) system. 29

Figure 13. A commercially available membrane bioreactor for wastewater treatment. Source: AMTA 30

Figure 14. Physical adsorption and various types of chemical processes involved in the removal of pollutants using activated carbon material for physiochemical treatment of greywater. 33

Figure 15. Schematic diagram showing hybrid chemical treatment reactor for simultaneous electrocoagulation and ozonation..34

Table of tables

Table 1. Grey water from different sources show variations in the general characteristics. (Li, Wichmann and Otterpohl 2009). NTU- nephelometric turbidity unit; TSS- total suspended solids; TC- total coliform; CFU-colony forming unit; FC-fecal coliform.......11

Table 2. Physiochemical Characteristics of Greywater in Low and High- Income Nations. NTU- nephelometric turbidity unit; CFU-colony forming unit.......................................15

Table 3. Greywater effluent standards in different countries for discharge into surface water. (Morel and Diener 2006)...21

Table 4. Greywater effluent standards in different countries for reuse in unrestricted irrigation. (Morel and Diener 2006)...21

Table 5. Proposed models for recycling different strengths of greywater in DEWATS system of treatment. 37

1 Introduction

While the world is struggling with water pollution due to household, agricultural and industrial contaminants in freshwater resources, our freshwater aquifers are getting depleted due to the impacts of climate change.

One major source for water to replenish these supplies comes from what is known as "greywater", the water which has been lightly soiled by uses such as taking showers and yet is still useful for other purposes after sufficient treatment and filtration.

We generate more than 60% of greywater in our households. The volumes and characteristics of greywater generated differ in different parts of the world. In countries where the water shortage is still not an alarming issue, freshwater consumption in households is significantly higher than in the arid and semi-arid countries. This is an important factor which greatly affects the strength of greywater. The strength of greywater is determined by the amounts of organic and inorganic matter or contaminants suspended in a liter of polluted water. The concentrations of the greywater contaminants in water scarce regions (where water is costly and not enough available for the luxurious use) is so considerably higher that it exhibit the attributes of black water.

Depending upon the regions, usage of the various synthetic (contaminant) products in greywater is influenced by the social status, individual habits, and demographic status of the households. The greywater characteristics by class, such as low, middle, and high income show wide variations. The quality of greywater also depends on lifestyle, social status, water availability, personal hygiene habits, choice of cleaning methods and soaps, and other personal care products in a household.

In a water reuse system, various physical, biological and chemical methods of treatment are applied to remove, degrade and transform various forms of organic and inorganic pollutants in greywater. The selection of treatment model depends on the quality of greywater and the target end uses for the reclaimed water. We have discussed various types of treatment methods and processes that are designed to efficiently regulate the requirement for greywater reuse in non-potable applications such as toilet flushing, washing, restricted and unrestricted irrigation, and other outdoor uses where use of the potable water (fit for drinking purposes) is unsustainable.

2 What is Grey water

The transformation of fresh to contaminated water during various kinds of activities in our kitchen, laundry, and bathroom uses, such as the washing of food commodities and greasy utensils, household and garment cleaning, and taking of showers involving the use of synthetic products, is called the generation of the greywater footprints. Technically, greywater does not contain water from toilets and should be free from fecal matter and urine. Some definitions also exclude the kitchen wastewater as it contains the oily and greasy contaminants that require differential process of treatment. In this document we would consider the kitchen wastewater to address the treatment process for greywater reuse. Although greywater is less contaminated and polluted, it is generally deemed unsuitable for restricted non-potable reuse in its crude form.

Up to 80% of the total wastewater generated from the household is the greywater with variable compositions which depend on the culture, living status, locations and health conditions. The demands and consumption of the finite freshwater resource will soon outnumber the supply. The greywater recycling and reuse has tremendous potential to contribute towards the urban sustainability by increasing the capacity of clean water supply.

As the greywater is generated from bathroom and laundry, there are concerns regarding the presence of pathogenic microbes, an issue which became particularly of concern during the outbreak of the coronavirus in 2020 and beyond. When households have infected members, the daily activities of bathing, brushing, and washing of cloths pose environmental risk of pathogen transmissions through greywater contamination. These are additional concerns that demand due attention for the proper management of greywater with strict guidelines for its recycling and reuse.

3 Physio-chemical and biological characteristics of greywater

The composition and characteristics of greywater display spatio-temporal variations depending upon the habits of people, the kinds of products they use and their location. Generally, greywater is composed of high concentrations of easily biodegradable organic materials, and basic constituents (Oteng-Peprah, Acheampong and deVries 2018) such as that shown in Figure 1. The biodegradability of greywater is determined by the amount of organic matter or carbon, most of which is derived from kitchen wastewater.

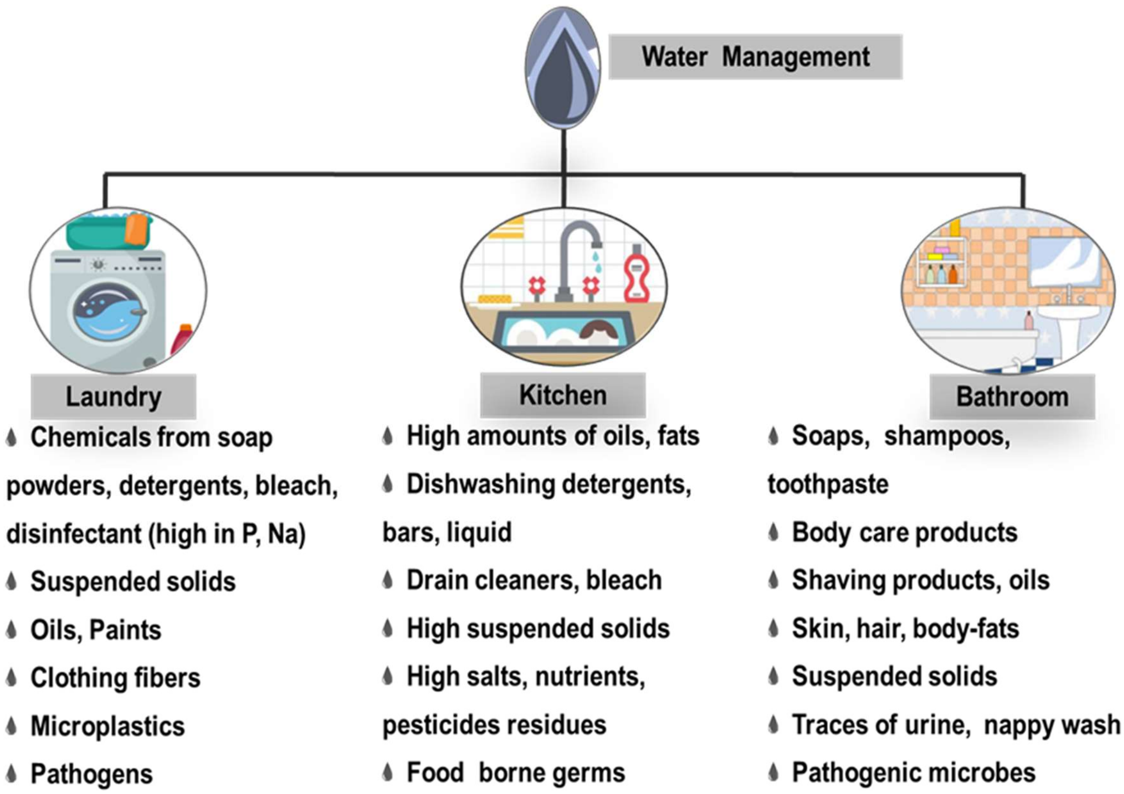

Figure 1. Specific sources and their general characteristics explain the complexities of the greywater.

The amounts of freshwater used and the types of synthetic products consumed in the household vary among the urban and rural households of the low-middle income countries and the developed countries. Household users in developed countries like Europe and North America tend to use freshwater leisurely for washing and so also their usage of diverse body care products. The culture habits and the water usage greatly determine the biodegradability and the pollution levels of the greywater discharge.

The physical, biological, and chemical constituents of greywater are solid suspended inorganic and organics particles such as food, sand, soil, fiber, synthetic compounds, microbes, nutrients and dissolved oxygen (Figure 2). The degradation of water pollutant occurs either biotic using microorganisms and/or abiotic by means of photolysis or chemical oxidation. The microbes present in the greywater decompose and transformed biodegradable organic pollutants, either in the presence or absence of oxygen, are respectively referred to as aerobic and anaerobic processes. The selection criteria for aerobic and anaerobic treatment processes depend on the organic loads of the polluted water. Very high loads of organic material require more oxygen supply to break down, which would neither be cost effective, profitable, nor within the limits of tolerance of the aerobic bacteria. On other hand, anaerobic treatment methods, which do not require oxygen input, will enable transformation of the organic pollutant to a source of bioenergy such as biogas or methane.

The organic load of greywater is measured chemically using oxidants such as potassium permanganate, using standardized laboratory assays involving high strength inorganic acids. This rapid method to measure the total amount of oxygen required to break down the organic compounds or pollutants is called chemical oxygen demand or COD. As the chemical oxidants cannot differentiate between the biodegradable and non-biodegradable, the oxygen demand for biodegradable pollutants is measured microbiologically using aerobic bacteria grown in specific nutrient medium during an incubation period of 3 to 5 days. The microbiologically determined change in the dissolved oxygen content is referred to as the biological oxygen demand or BOD.

As the breakdown of organic pollutant by bacteria is a slow process, the routine measurements for organic pollutant loads prior to and during the greywater treatment process is mainly done chemically by measuring the COD. However, the measurement of BOD is important for designing the bioreactors and for assessing the efficiency of the biological treatment process.

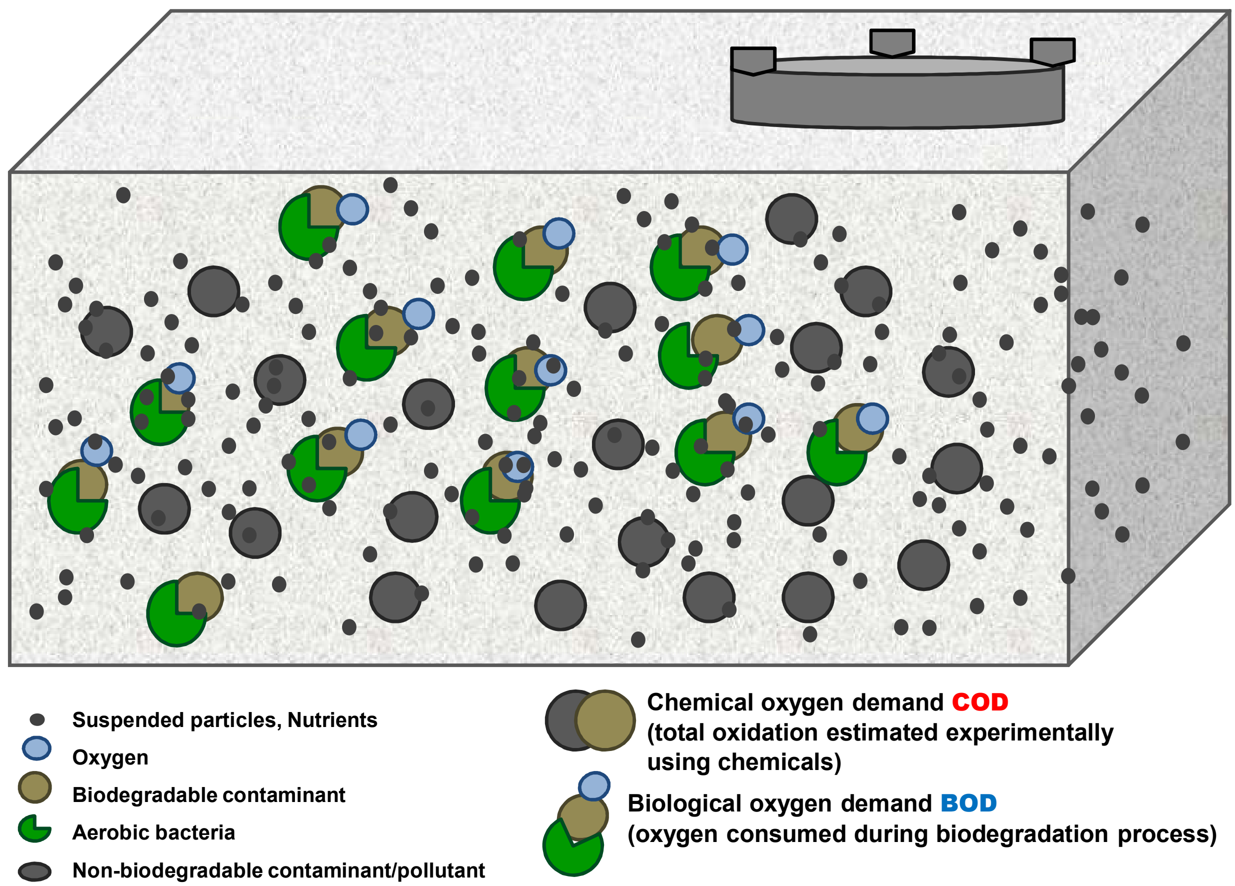

Figure 2. Diagrammatic sketch of greywater storage tank showing different types of pollutants. The non-biodegradable pollutants remain as is, in the polluted water where as the biodegradable pollutants (brown circles) get degraded by aerobic bacteria (green shape) using dissolved oxygen (blue circles) during the biological treatment process. Both biodegradable (brown circles) and non-biodegradable (grey circles) pollutants are oxidized chemically using laboratory assay to measure the chemical oxygen demand (COD) of greywater. The biodegradation process in laboratory is assessed using microbiological assay to measure the biological oxygen demand either on day 3, day 5 or day 7 which are represented as subscript to abbreviated form (BOD).

In general, the biodegradability of wastewater is determined by the BOD and COD ratios (Table 1). On an average, half of the organic matter (BOD:COD of 0.45) in greywater is available for degradation by different microorganisms (Albalawneh and Chang 2015) including bacteria, fungi and algae. As BOD and COD are measured in mg/L, the concentration values are greatly affected by the amounts of freshwater utilization by humans. In Middle Eastern countries, where overall water consumption is relatively lower, the greywater has high concentrations values of BOD and COD.

The range of organic matter, nutrients and suspended solids differ in greywater and are subject to daily and seasonal fluctuations. Solid particles from soil, dirt and food particles from the kitchen, hairs and fibers from the bathroom, and laundry make greywater turbid and has a tendency for clogging sewer systems. Similar to BOD and COD values, the concentrations of suspended solids equally depend upon the usage of water.

Besides organic matter, greywater contain many other forms of nutrients (P, N, Na) that come from the use of soaps and detergents for cleaning, and during the washing of food items in the kitchen (see Figure 1 and Table 1). Greywater has generally low concentrations of nitrogen, with main sources from that coming from meat, vegetables and household products which contain ammonia. Some countries such as Vietnam have high ammonium-nitrogen concentrations in the groundwater aquifers, originating from the mineralization of peat; in those locations the water supply offers a higher natural source of nitrogen.

Parameters	Kitchen	Laundry	Bathroom	Mixed
COD (mg/l)	26-2050	231-2950	100-633	100-700
BOD (mg/l)	536-1460	48-472	50-300	47-466
Turbidity (NTU)	298	50-444	44-375	29-375
TSS (mg/l)	134-1300	68-465	7-505	25-183
N (mg/l)	11.4-74	1.1-40.3	3.6-19.4	1.7-34.3
P (mg/l)	>74	>171	>48.8	0.11-22.8
pH	5.9-7.4	7.1-10	6.4-8.1	6.3-8.1
TC (CFU/100ml)	$>2.4 \times 10^8$	$200.5\text{-}7 \times 10^5$	$10\text{-}2.4 \times 10^7$	$56\text{-}8.3 \times 10^7$
FC (CFU/100ml)	-	$50\text{-}1.4 \times 10^3$	$0\text{-}3.4 \times 10^5$	$0.1\text{-}1.5 \times 10^8$

Table 1. Grey water from different sources show variations multiple characteristics. (Li, Wichmann and Otterpohl 2009). NTU- nephelometric turbidity unit; TSS- total suspended solids; TC- total coliform; CFU-colony forming unit; FC-fecal coliform.

Other elements like phosphates, which are often present in cleaning products, account for high P concentrations in greywater originating from dishwashers, laundry and bathroom.

Countries such as Thailand and Israel, (Morel and Diener 2006) where phosphate detergents have not been banned, concentrations can reach as high as 280 mg/L.

These inorganic elements of greywater provide a nutrient source for the growth of algae in natural waters. In some developing and economically weak countries around the world, greywater treatment is given the least preference; therefore, its direct discharge into the aquatic bodies leads to eutrophication and water pollution. The rivers in many low and middle income countries are polluted to such a great extent that they can be reasonably compared to open sewers. Many rivers in India are threatened and are vanishing due to the untreated and uncontrolled discharge of the greywater.

The biological components of greywater include microbes such as fecal coliform, thermo-tolerant coliform, bacteria, viruses and protozoa. Demographic factors such as age of the household residents and their health status determine the microbial loads and compositions in greywater at a particular time. A high contamination of microbes in greywater is expected from households with young children, aged and sick members. The high organic matter in the greywater supports the re-growth of enteric bacteria which could lead to overestimation of the fecal loads (Morel and Diener 2006). In addition, the presence of antibiotics in the greywater results in the growth of resistant bacterial strains.

Other important constituents of greywater are the oil and greases coming from the kitchen wastewaters, either through direct disposal of waste cooking oils or during the washing of greasy utensils. The oil and grease concentrations in the greywater from restaurants are extremely high of the order 1000- 2000 mg/L (Morel and Diener 2006).

Geographical variations in greywater characteristics

There are multiple factors which affect the composition of greywater. The source of freshwater and its availability are different across various parts of the world.

Economic status is one such factor which has a major impact on what makes up greywater. High-income nations, for example, mainly utilize surface freshwater sources. Low-to-middle income countries make broader use of groundwater as a source.

The degree of water scarcity varies widely across the world, and that variability also greatly affects the physio-chemical composition and concentrations of the various constituents within the greywater.

We have done a comparative analysis of the greywater availability for different countries of the world, a factor which depends upon the abundance of freshwater resources and its usage by region Figure 3. The range of greywater produced in liters per person per day (L/P/D) in different parts of the world. .. (Figure 3). Much of the variations are observed in BOD and COD, which in turn are influenced by the levels of water pollution. In arid and semi-arid regions where the water resources are scarce and costly, water pollution as determined from COD values are extremely high.

It is important to determine the quantity and quality of the greywater generated by households and other institutions such as hotels, hostels, restaurants, and schools, in order to assess the economic feasibility of the reclamation and treatment processes for a given region. Greywater quality improvement via a reclamation process primarily depends on its physio-chemical characteristics. The aim is to bring the concentrations of various contaminants in the reclaimed greywater within and under the acceptable and environmentally safe limits by choosing the right and sustainable options for its treatment.

In the last section, we have categorized the greywater based on the range of different concentrations of its constituents obtained from different countries of the world (Table 2). Understanding of greywater is critical in order to determine what are the necessary and efficient treatment practices and technologies which should be used.

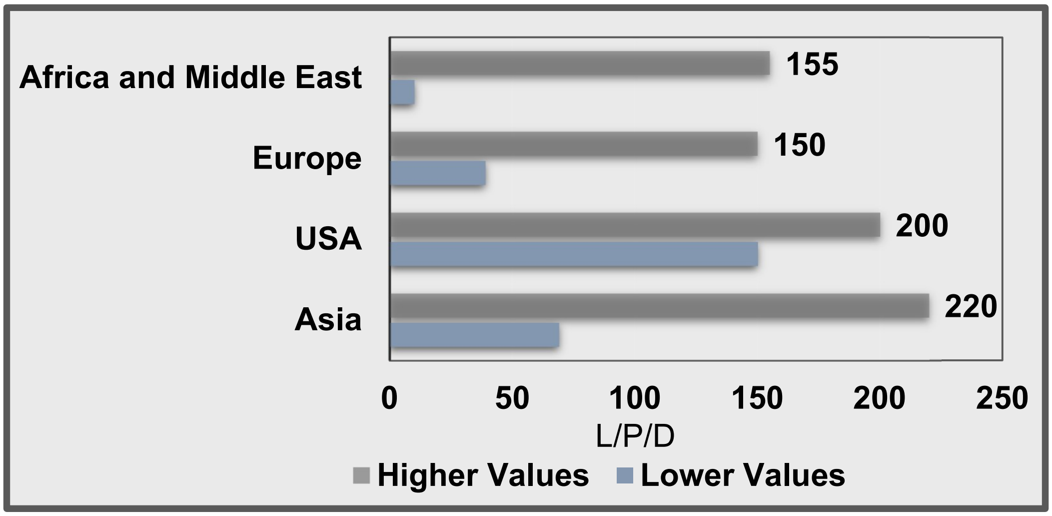

Figure 3. The range of greywater produced in liters per person per day (L/P/D) in different parts of the world. (Piotrowska, Słyś, Kordana-Obuch, & Pochwat, 2020).

	Low Income Countries				High Income Countries				
Parameters	India (Paranje & Sane, 2011)	Pakistan (Pathan, Mahar, & Ansari, 2011)	Niger (Hu, et al., 2011)	Yemen (Al-Mughalles, Rahman, Suja, Mahmud, & Jalil, 2012)	USA (Jokerst, Sharvelle, Hollowed, & Roesner, 2011)	UK (Birks & Hills, 2007) (Pidou, et al., 2008)	Spain (March & Gual, 2007) (March, Gual, & Simonet, 2004)	Germany (Merz, Scheumann, El Hamouri, & Kraume, 2007)	Australia ((Albalawneh and Chang 2015)
pH	7.3-8.1	6.2	6.9	6	6.4	6.6-7.6	7.6	7.6	6.4-10
Turbidity (NTU)	-	-	85	619	31.1	26.5-164	20	29	50-240
TSS (mg/l)	100-283	155	-	511	17	37-153	32	-	48-250
BOD_5 (mg/l)	100-188	56	106	518	86	39-155	-	59	48-290
COD (mg/l)	250-375	146	-	2000	-	96-587	151-177	109	-
Nitrate (mg/l)	0.67	-	-	98	-	3.9	-	-	0.05-0.31
TN (mg/l)	-	-	-	-	13.5	4.6-10.4	10-11	15.2	1-20.0
TP (mg/l)	0.012	-	-	-	4	0.4-0.9	-	1.6	-
FC (CFU)	-	-	-	1.9×10^5	-	-	-	1.4×10^5	$110\text{-}3.3 \times 10^3$
E. coli (CFU)	-	-	-	-	5.4×10^5	$10 – 3.9 \times 10^5$	-	-	$79\text{-}2.4 \times 10^3$

Table 2. Physiochemical Characteristics of Greywater in Low and High- Income Nations. NTU- nephelometric turbidity unit; CFU-colony forming unit.

4 Grey water management and reuse technologies/process

There are many different means of treatment, recycling, and management of greywater, ranging from the simple to advanced.

Depending on the levels of advancement of the implemented technologies, the reclaimed greywater can be put to non-potable or potable uses. Basically, the treatment methods are used to ensure the reduction in various toxic and harmful contaminants through multistep processes. These processes involve both physio-chemical and biological treatment methods such as sedimentation, filtration, adsorption, reverse osmosis and microbial driven biodegradation.

Filtration, activated sludge process, membrane bioreactors and upflow anaerobic sludge blankets (UASBs) are most often used greywater treatment systems in most developing countries.

Different treatment methods which vary by complexity, maintenance, efficiency, and performance can be selected according to the characteristics of the greywater. The main considerations in most cases involve cost, maintenance, purpose of reuse of the reclaimed water, the latter of which of course must conform with the guidelines of the specific geographical region.

In the proceeding sections, we will discuss the various levels and types of the greywater treatment methods and processes.

Next generation of infrastructures: complementing grey with green

After understanding the characteristics of greywater sources, the next important step is to build an infrastructure for their treatment which is cost effective, sustainable, and has reduced environmental footprints. To ensure that we reduce our greywater footprint we must be careful to avoid creating another environmental problem in the process. To address this challenge, we present different categories of water management infrastructures that allow us to have low carbon footprints and ensure sustainability. To address the complex challenges of today's world, ideally greywater should be tapped not just as a water source but also for its value as a renewable energy and nutrient resource. To make the recovery of nutrients and energy from greywater a sustainable process, we must build next generation infrastructures which bring together a balance of engineered and nature-driven processes and systems. Sustainable growth of economies is possible to accomplish by complementing conventional human-engineered infrastructures with appropriate natural systems, services and processes.

One of the drivers of integrating grey and green infrastructures (

Figure 4) is the water security. During the process of adopting various methods of greywater treatment, we must also navigate through the possible risks of water shortages, flash droughts and flooding. When the motto of greywater reclamation is reuse to address water scarcity, relying solely on storage tanks, reservoirs and treatment plants is not sufficient. We must employ nature based systems to ensure extraction of resources from the wastewater and to energize it for further downstream applications.

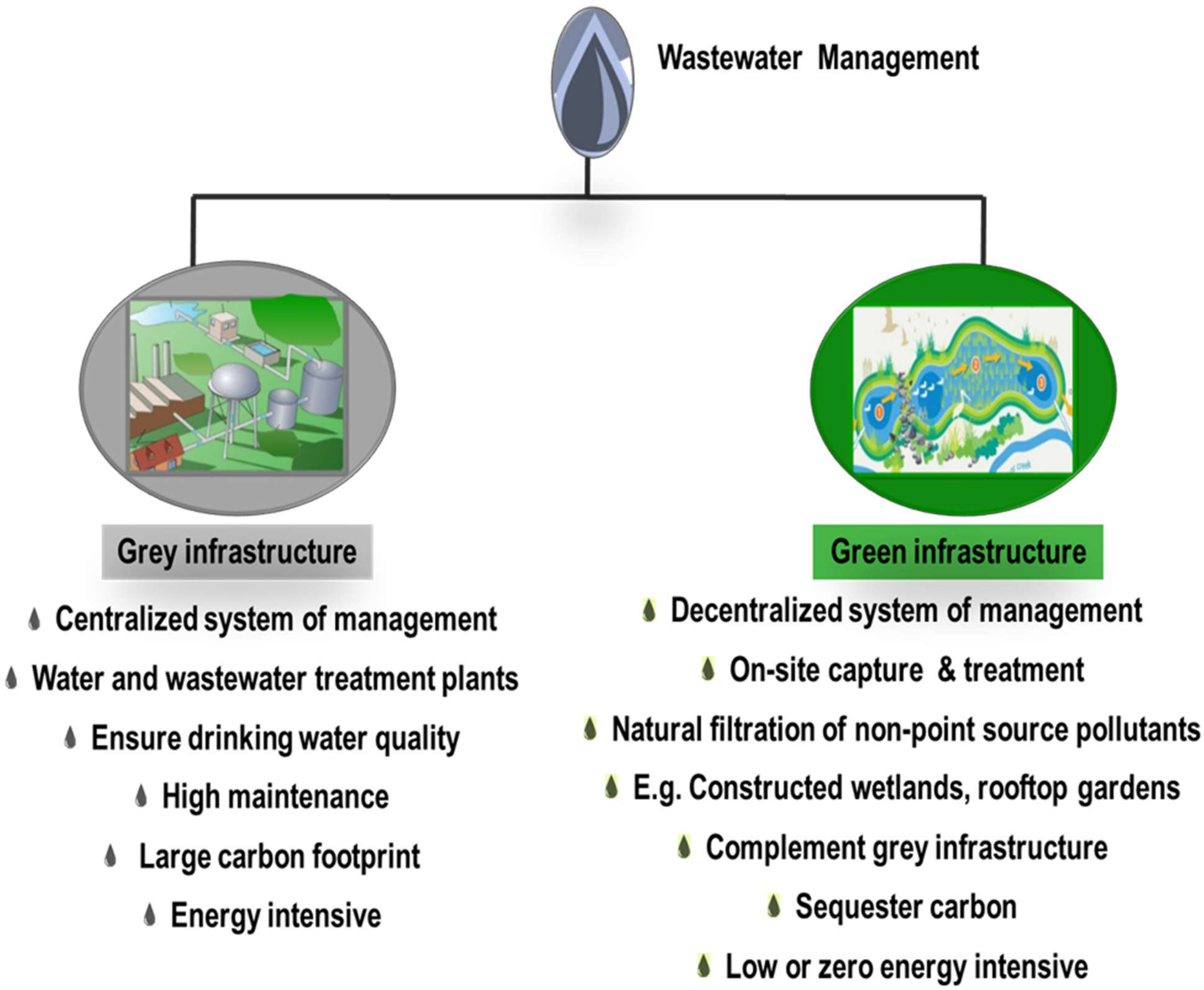

Figure 4. Next generation water management infrastructure ensures sustainable development.

We propose an integrated approach of management to support implementation of effective, robust and sustainable strategies for recycling and reuse of differentially polluted greywater.

Dual plumbing system: a prerequisite for greywater recycling and reuse

Collection

Greywater treatment systems include subsystems for collection, storage and treatment. Greywater must not come in contact with toilet discharges that contain feces and urine. Thus, it is a mandatory requirement to have a separate plumbing system for collection of greywater coming from kitchen, laundry and bathroom. The collection of greywater occurs either through gravitational force or using pumps.

Storage

The requirement for storage of greywater prior to the treatment depends on the on-site treatment methods. If storage of greywater is unavoidable, it must not be stored for more than 24 hours. The longer the storage of untreated greywater, the higher the chances it could become septic; due to microbial decomposition it would also create fouling smells.

The material for greywater storage should not encourage the growth of microbes and should be anti-corrosive. Concrete and fiber reinforced polymer (FRP) are among the most common durable materials used for this purpose. Opaque materials are favored where possible, to avoid growth of algae. In case of overflow there should be provisions for outlet to the sanitary sewage system. Greywater storage should also strictly follow appropriate regional guidelines. One example is for regions where dangerous vector-borne diseases are common; in those cases the greywater storage must be configured to minimize the risk of leakage or seal damage, to avoid any mosquito breeding.

Selection criteria for best greywater treatment system and processes

Quality requirements for greywater recycling and reuse for different purposes generally include hygiene, environmental safety, efficiency and economic feasibility at the top of the list. Within these criteria, the safety of greywater is of course largely determined on the levels of pathogenic microbes within it.

Safety guidelines for recycled greywater vary in different parts of the world, and for the most part entirely depend on the end use of the recycled water. (See Tables 3 and 4.)

We have determined various factors as described below toallow us to implement the best treatment method for a particular greywater resource.:

- Pollutant levels and type of greywater
- Levels of exposure to the end users of treated greywater
- Potential end uses
- Legislative guidelines set by each state of different country
- Cost effectiveness and the space available for setting up the infrastructure

There are broadly three different stages of greywater treatment. Each stage of the process involves different methods which in turn vary from region to region; it is also greatly determined by the potential end use of the reclaimed water. The guidelines for the treated greywater (effluent compliance value) are set in accordance to the potential end uses and the levels of exposure to humans. Underestimation of treatment levels required to comply with legislative guidelines can lead to failure of the process and could, without appropriate attention, lead to the system not being approved by local authorities.

Surface water discharge standards	Costa Rica	India	Israel	Sri Lanka
pH	5.0-9.0	5.5-9.0	7.0-8.5	6.0-8.5
BOD (mg/l)	40	30	10	30
COD (mg/l)	-	250	70	250
TSS (mg/l)	-	100	10	50
Oil & Grease (mg/l)	30	10	1	10
NH_4-N (mg/l)	-	50	1.5	50
TN (mg/l)	-	-	10	-
TP (mg/l)	-	-	0.2	-

Table 3. Greywater effluent standards in different countries for discharge into surface water. (Morel and Diener 2006).

Unrestricted irrigation standards	India	Israel	Thailand
pH	5.5-9.0	6.5-8.5	6.5-8.5
BOD (mg/l)	100	10	20
COD (mg/l)	-	100	-
TSS (mg/l)	200	10	30
Oil & Grease (mg/l)	10	1	5
NH_4-N (mg/l)	50	20	-
TN (mg/l)	-	20	-
TP (mg/l)	-	5	-

Table 4. Greywater effluent standards in different countries for reuse in unrestricted irrigation. (Morel and Diener 2006).

The compliance values for intended reuse of treated greywater have significant variations among different countries of the world. As an example, compliance requirements for effluent waters in countries like India and Sri Lanka are significantly higher than others. (See Tables 3 and 4.) On the other hand, technologically advanced countries such as Israel (Table 4) and Australia have stricter guidelines regarding the use of treated greywater with a significantly lower range of compliance values (Figure 5) for effluents.

High exposure risk

Potential end uses

1) Internal use,
2) External surface irrigation
3) Agriculture irrigation (salad crops)
4) Urban irrigation with unrestricted access
5) Communal uses- flushing toilets, washing machine

Parameter	Compliance value
pH	6.5-8.5
SS	<10 mg/l
BOD	<10 mg/l
Turbidity	<5 NTU
E.coli	<1 cfu/100 ml

Medium exposure risk

Potential end uses

1) Urban irrigation with some restricted access
2) Fire fighting
3) Fountains
4) Industrial use with human exposure
5) Dust suppression

Parameter	Compliance value
pH	6.5-8.5
SS	<30 mg/l
BOD	<20 mg/l
Turbidity	<5 NTU
E.coli	<10 cfu/100 ml

Low exposure risk

Potential end uses

1) Communal sub-surface irrigation
2) Urban irrigation with high restriction access
3) Agriculture irrigation for non-edible crops

Parameter	Compliance value
pH	6.5-8.5
SS	<30 mg/l
BOD	<20 mg/l
Turbidity	-
E.coli	1000 cfu/100 ml

Figure 5. An example of commissioning validation and verification monitoring requirements for the treated water intended for non-potable reuse in Australia. (Directorate 2011).

Conventional greywater treatment sequence

As discussed in detail in the previous chapters, greywater can be thought of as consisting of physical, chemical and biological components, with treatment methods based on specific physio-chemical and biological processes. It is also important to note that significant physical and chemical changes in the composition of greywater may occur within short period of time after "capture", an issue which can pose some difficulties during the treatment process (Patil, et al. 2022). The main objective of treatment methods is the removal and reduction of the various and diverse forms of contaminants before the eventual reuse or discharge into the natural environments. The conventional treatment sequences as described in the proceeding sections adopt physiochemical (filtration, adsorption, reverse osmosis) and biodegradation and biotransformation methods (Figure 6).

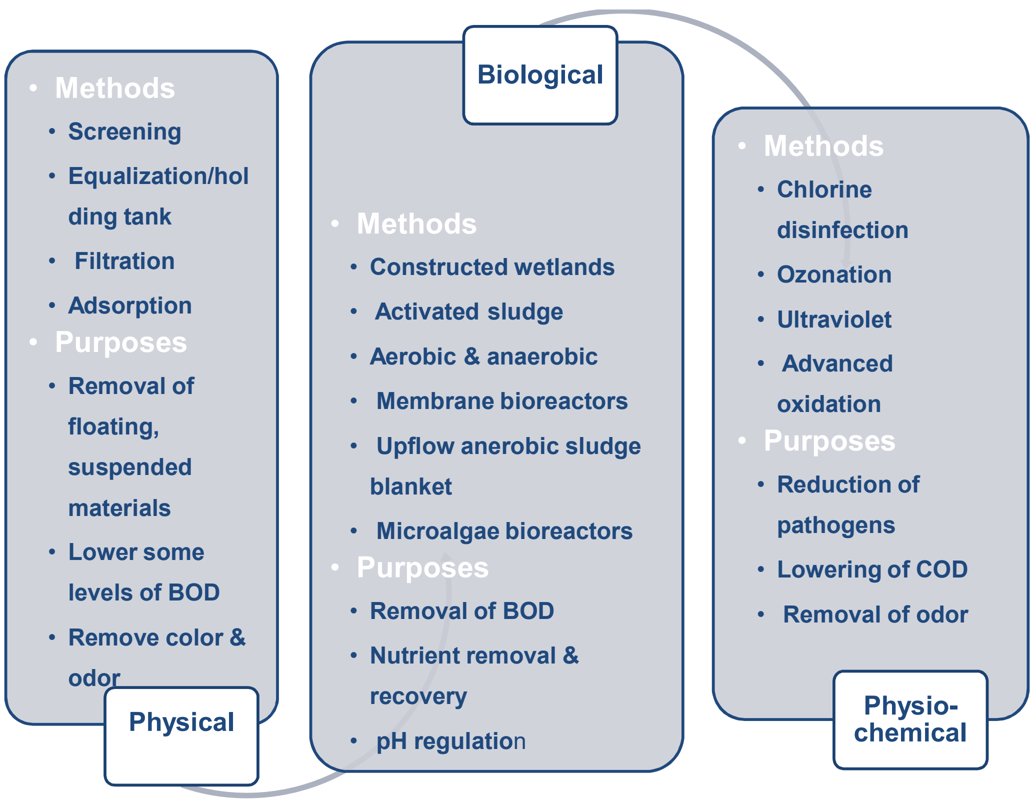

Figure 6. Various methods and the roles involved in the greywater treatment process.

Various processes and methods involved in greywater treatment

The pretreatment part of the process has the aim of preventing coarse debris, oil, grease, solid particles to enter the effluent discharge (in case of lowly polluted grey water) and to the proceeding post treatment steps. It basically involves the physical separation of coarse pollutants using different types of screens that prevent the entry of solid particles to enter the greywater collection system. These are drain screens used in the kitchen and bathroom to prevent the entry of food particles, hairs and other large debris. To further prevent the entry of laundry fibers, oil and grease, different types of filtration systems are used. The criteria for selecting the type of filtration system are cost, efficiency, environmental friendliness and maintenance.

Physical methods: Filtration

Among the primary treatments, filtration is favorable for low income countries where locally available natural materials can be utilized to make easy to operate filters which have low cost and low maintenance. Additionally, filtration does not require energy inputs and can still offer better quality of greywater which can be used in countries where the effluent compliance values are high for restricted applications.

We will present different examples of the filtration system which allow treatment of the various scales of greywater inputs used particularly in developing countries where low cost is an important parameter for designing treatment method.

Upflow-downflow filter

An upflow-downflow filter typically consists of a series of four columns. The filtration process starts by the entry of greywater through the bottom of first column which is made up of big gravels of 40-60 mm size. The subsequent flow of water occurs as shown in the diagram (Figure 7) across the channel of gravel of 20-40 mm size, coarse (1-5 mm) and fine (0.1-1 mm) sand particles (Diwan 2022). The gravel allows filtration of biological contaminants such as helminth eggs, protozoa cysts and sand, and can remove viruses.

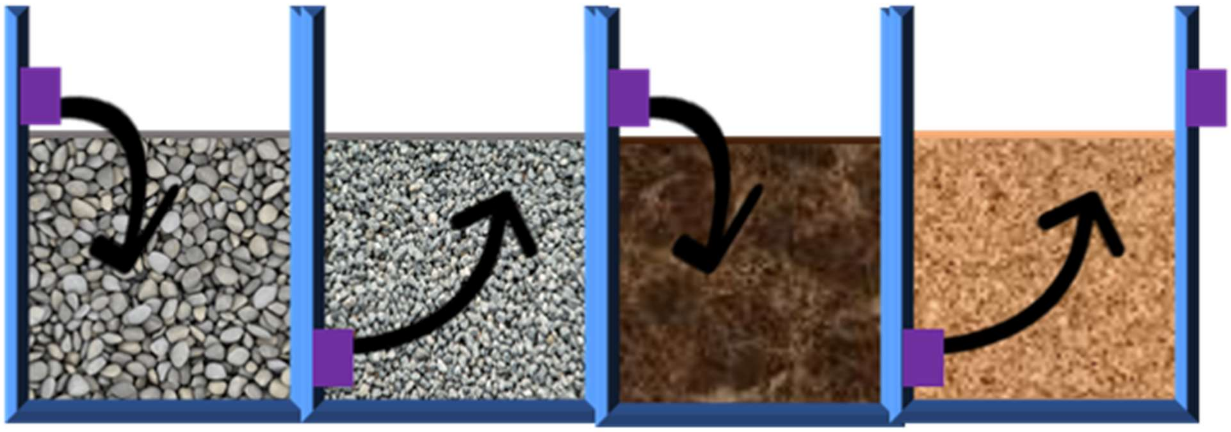

Figure 7. Schematic diagram showing the flow of greywater in alternative pattern of down and upward flow through the series of columns.

Low cost hybrid filters

A low cost and simple filtration system to treat household greywater can be collected manually by gathering fine sand, banana peel, wood chips, coconut husks, different size of gravel and crushed fly ash bricks (Figure 8), and placing it in the path of the greywater flow. This is an example of a low cost fabricated eco-friendly filtration system intended for indoor (toilet flushing) and outdoor greywater reuse applications such as gardening, car washing, construction of roads and buildings, imitation fountains and fire fighting (Patil, Bhange, et al. 2022).

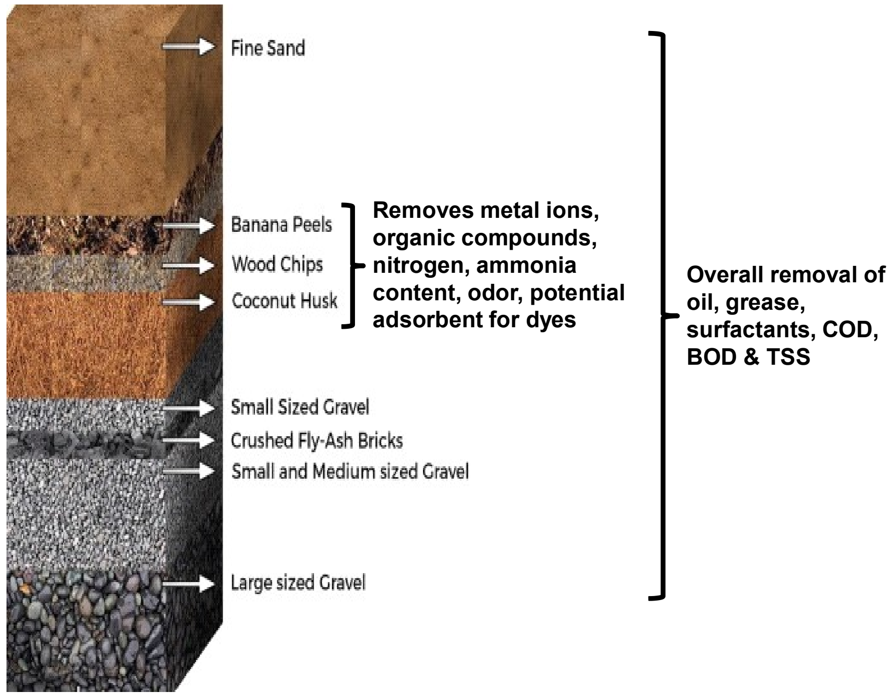

Figure 8. An example of a simple filtration system fabricated for Indian household with COD, BOD and TSS removal efficiencies of 85.98%, 86.28% and 94.44% respectively. (Patil, Bhange, et al. 2022).

Another example where locally available absorbent materials such as sand, biochar, and teff straw are sometimes used for making a low cost and indigenous filter system is shown in (Figure 9). The removal rates for COD, BOD and total alkalinity displayed by this inexpensive filter varied from 79% to higher than 83%; the same system also provided greater than 99% removal efficiency for the total suspended solids (Yaseen, et al. 2019).

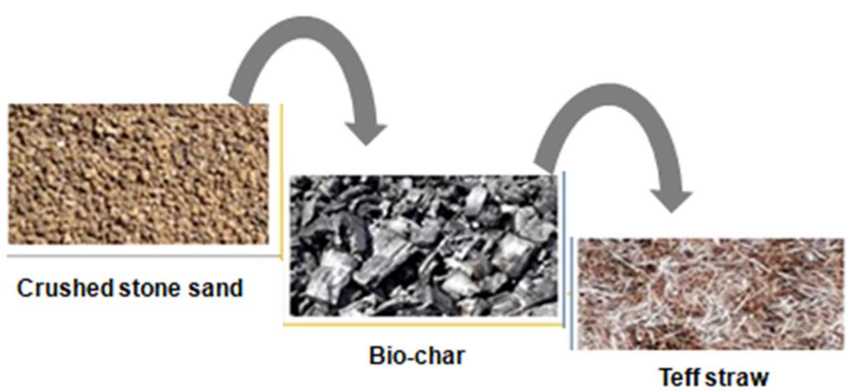

Figure 9. A pilot scale prototype filter design for treating laundry wastewater composed of sand filter, bio-char and teff straw media (Yaseen, et al. 2019).

Biological methods- Aerobic and anaerobic treatments

For a high strength greywater with COD >1000 mg/l, the primary treatment is initiated using biological method involving the use of anaerobic and aerobic microorganisms. Principally, the aerobic bacteria cannot efficiently handle the heavy loads of biodegradable pollutants or in other words, very high values of COD. For aerobic degradation of high COD which are above 2000, high oxygen inputs would be required; that would not be cost effective for household greywater treatment systems. To overcome these drawbacks of the use of aerobic systems to handle dark greywaters, households generally use septic tanks that operate on the principal of anaerobic microbial biodegradation.

Anaerobic baffled reactor

Recent development of high-rate anaerobic reactors designed to separate the hydraulic retention time (HRT) from the solid retention time (SRT), allow slow growing bacteria to remain within the reactor irrespective of the wastewater flow. One example of a high-rate anaerobic reactor is anaerobic baffled reactor (ABR) as shown in the diagram (Figure 10).

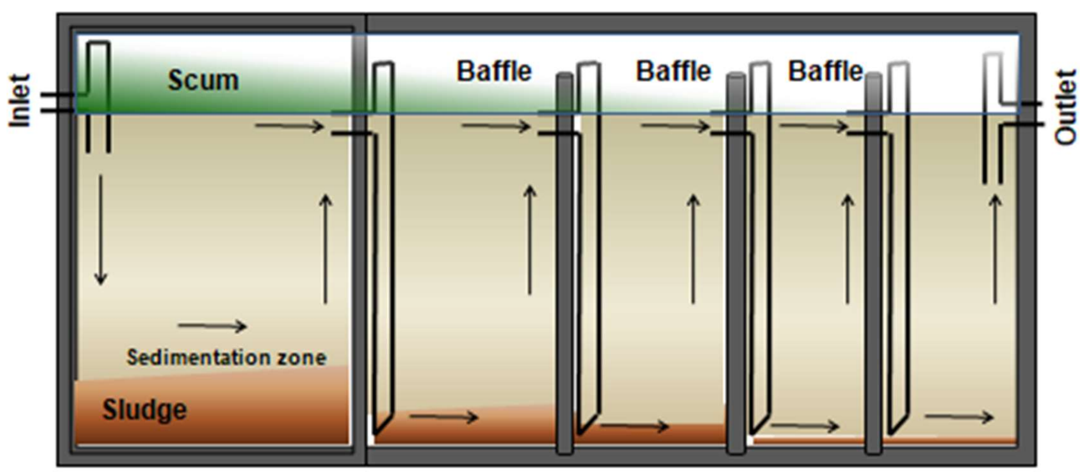

Figure 10. Schematic diagram of an anaerobic baffled reactor showing the path and flow of greywater treatment process.

The ABR was conceptualized as series of upflow anaerobic sludge blanket reactors (UASBS), compartmentalized using baffles which allow both upward and downward movement of greywater from inlet to outlet. The design and the typical flow of water allow ABR to retain active bacteria which otherwise show vertical movement with gas production but show slow horizontal movement across the reactor, thereby increasing the SRT. Due to the slow microbial movement, the water tends to have a continuous contact with active microbes and as a result, the HRT is shortened. The advantages and drawbacks of ABR are listed in (Figure 11).

Advantages of Anaerobic baffled reactor (ABR)

- Simple design
- Economical
- No mechanical mixing required
- Not prone to clogging
- Reduced expansion of sludge bed & low sludge formation
- Ability to separate acidogenesis and methanogenesis longitudinally across reactor
- Different bacteria can grow under different suitable conditions
- Low hydraulic retention time
- Stable to hydraulic shock loads
- Capable of treating greywater in range of 450 to >1000 mg/l

Drawbacks

- Nitrogen & Phosphates are not treated/removed
- Partial removal of pathogenic microbes
- Post treatment required for complete removal of COD and TSS

Figure 11. The various advantages and drawbacks of anaerobic baffled reactor system to treat greywater.

Activated sludge process

The activated sludge process is a type of biological treatment in which the activity of aerobic microbial degradation of soluble organic pollutants is supported and enhanced with oxygen input through optimized aeration methods. The aerobic degradation of organic matter takes place in an activator sludge reactor (ASR), which is usually associated with sedimentation or clarifier for sludge recycling (bacteria culture) as shown in (Figure 12).

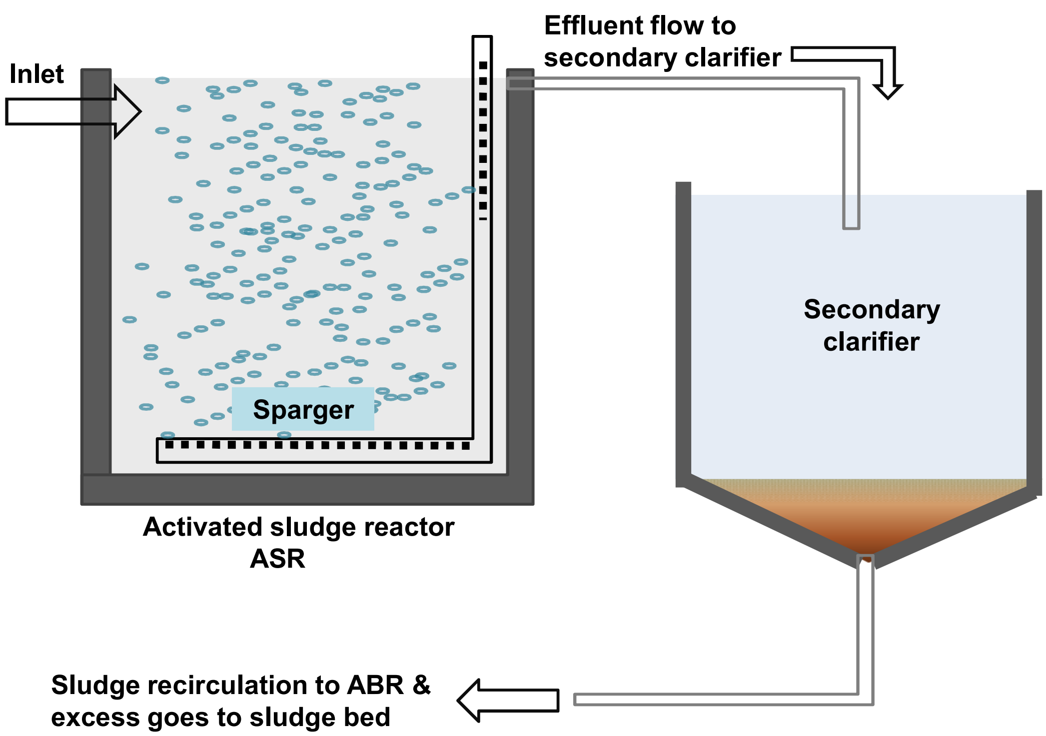

Figure 12. Schematic diagram of activated sludge reactor (ASR) system.

The variations in design to upgrade the ASR process are achieved using membrane technologies which increase the populations of aerobic microorganisms in the reactor to improve latter's efficiency. An integrated fixed-film activated sludge (IFAS) includes both suspended and attached microbial growth which provides an option where there are limitations in the availability of land. In addition, IFAS offers increased nitrogen and phosphorous removal efficiencies (Eslami, et al. 2018).

Membrane Bioreactors

In activated sludge process, the solid-liquid separation is achieved using secondary clarifiers (Figure 12) followed by a filtration process. In complete and integrated systems, the solid-liquid separation is performed through the use of low pressure microfiltration (MF) and ultrafiltration (UF) membranes. A commercial MBR unit (Figure 13) consists of combined series of modules that house individual submerged membranes which filter out the pollutants degraded by the aerobic microbial process.

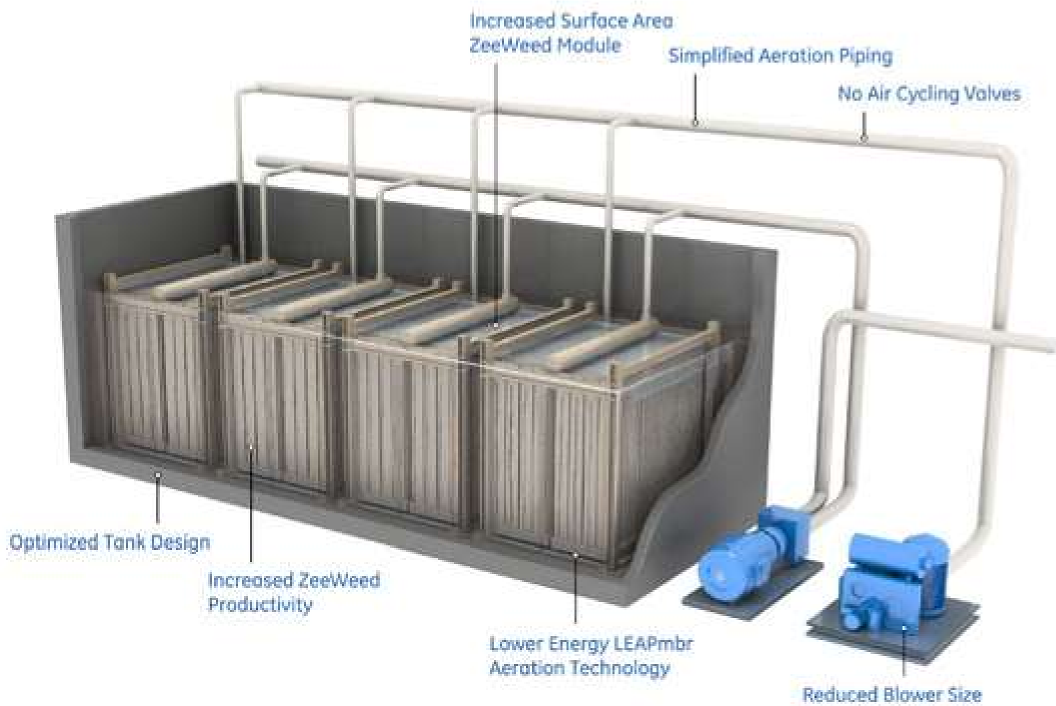

Figure 13. A commercially available membrane bioreactor for wastewater treatment. Source: AMTA (American Membrane Technology Association), amtaorg.com.

Treatment of micro pollutants using microorganisms

The organic pollutants in greywater are relatively easy to treat using physical and biological processes. However, daily uses of a wide variety of synthetic personal care hygiene products that contain toxic compounds need chemical methods for treatment. Some of the synthetic compounds, such as propyl- and butyl paraben, nonylphenol, triclosan, bisphenol-A, BaCl, are more readily removed using aerobic treatment than anaerobic methods. Biodegradation and adsorption to sludge make up the most efficient removal process for the various synthetic inorganic compounds in aerobic digester.

There are different kinds of microorganisms that also play significant roles in reduction and removal of various kinds of micropollutants. Among them are the consortium of bacteria from the genera of *Vibrio, Flavobacterium, Klebsiella, Pseudomonas, Enterobacter, Bacillus, Escherichia, Shigella, Citobacter, Proteus,* and *Anaebena* (Okpokwasili & Olisa, 1991). This consortium enables high degradability of some commonly utilized detergents and shampoos such as SDS detergent, Rainbow shampoo, Flex shampoo, Apollo detergent, Triton X- 100 detergent, and Teepol detergent, ust to give some examples.

Sodium dodecyl sulphate (SDS), also known as sodium lauryl sulphate (SLS), is one of the principal surfactants present in detergents and is used in high amounts in detergent products such as shampoos and utilized as a foaming agent in shaving foams, toothpaste, and bubble bath. It is an anionic surfactant with the chemical formula - $C_{12}H_{25}OSO_3Na$. It consists of a hydrocarbon chain and a sulphate group attached to the chain.

Degradation of SDS forms a significant challenge for microorganisms because this surfactant solubilizes the microbial cellular membrane and denatures the proteins. However, microorganisms form few resistant mechanisms against these anionic surfactants like diffusion barriers or multidrug efflux pumps. Several microbial enzymes such as alkylsulphatases and dehydrogenases are involved in optimal SDS degradation processes.

The bacterial strain *Pseudomonas aeruginosa* MTCC 10311, isolated by the soil enrichment technique, illustrated the high biodegradability of SDS (Ambily, 2010). Several physiological parameters such as pH, substrate concentration, temperature, incubation time, aeration, carbon sources, and nitrogen sources along with plasmid are thought to be responsible for the high biodegradability of the SDS by this strain.

A few more bacteria illustrating varying degrees of SDS degradation include; *Acinetobacter calcoacetiacus*, *Klebsiella oxytoca, Acinetobacter johnsoni, Pseudomonas beteli,Citrobacter Sp., Pseudomonas agglomerans, Pseudomonas aerugiosa* MTCC 10311*, Pantoea agglomerans, Citrobacter braakii.* (Ambily, 2010)*, Staphylococcus aureus WAW1 and Bacillus cereus WAW2* (Adekanmbi & Usinola, 2017)*, P. nitroreducens (DSM 14399^T)*(Paulo, Plugge, García-Encina, & Stamsa, 2013).

However, shampoos or detergents allowing luxurious growth of the microbes are not necessarily more easily biodegradable. Builders like sodium tripolyphosphate present in detergent and shampoos can likewise act as a source of nutrients for microbial growth. The relationship between the surfactant and microbes is intricate. Under several conditions, surfactants can also act as bactericides and bacteriostats.

The relationship between the surfactant and microbes is intricate. Under several conditions, surfactants can also act as bactericides and bacteriostats. Therefore, the complete removal of these chemical compounds can further be achieved using advanced chemical treatment methods. In addition, some pathogenic microbes also require chemical disinfection methods for their removal from effluent water.

Chemical treatment methods and processes

Certain compounds such as 2-phenyl-5-benzimidazolesulfonic acid (PBSA) and 2-Ethylhexyl-4-methoxycinnamate (EHMC) in UV-filters are not degraded in biological systems due to their hydrophobicity (PBSA) or conditions in these systems are not very favorable (EHMC). Chemical oxidation, activated carbon adsorption methods present some chemical treatment methods for the removal of persistent chemicals from greywater. Activated carbon and biochar are preferred materials for the removal of different types of inorganic chemicals through physical adsorption and various forms of chemical interactions and reduction reactions (Figure 14).

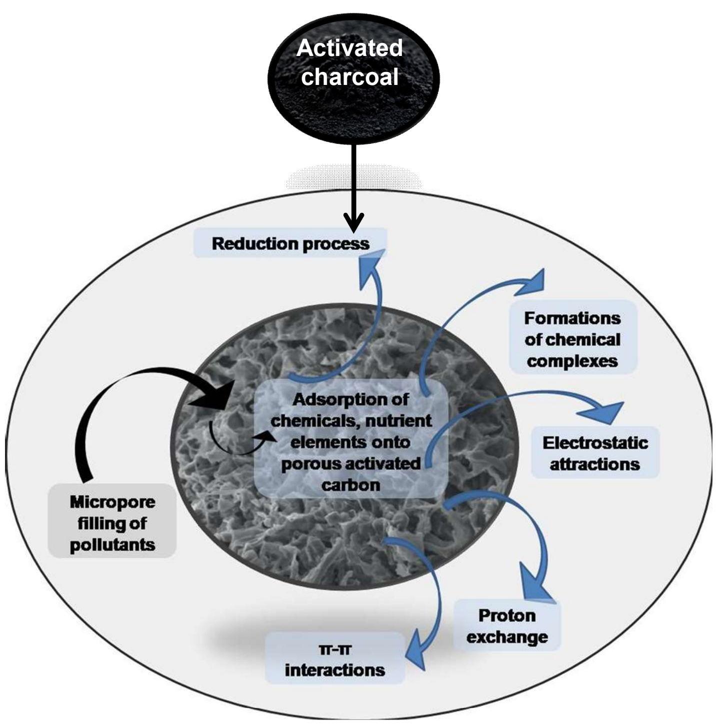

Figure 14. Physical adsorption and various types of chemical processes involved in the removal of pollutants using activated carbon material for physiochemical treatment of greywater.

Various hybrid chemical processes such as ozonation with coagulation, adsorption with ozonation also prove to be beneficial during the treatment of synthetic chemicals. The inorganic and organic compounds can be separated in greywater by electrocoagulation using chemical coagulants like Fe and Al, which are in turn electrochemically generated in a reactor cell. In the advanced oxidation method, ozone, which is a powerful oxidant, can be activated in an integrated electrocoagulation system (Figure 15) to produce free OH radicals. Such hybrid treatment methods achieve for higher degradation efficiencies in comparison to the standalone systems (Barzegar, Wu and Ghanbari 2019).

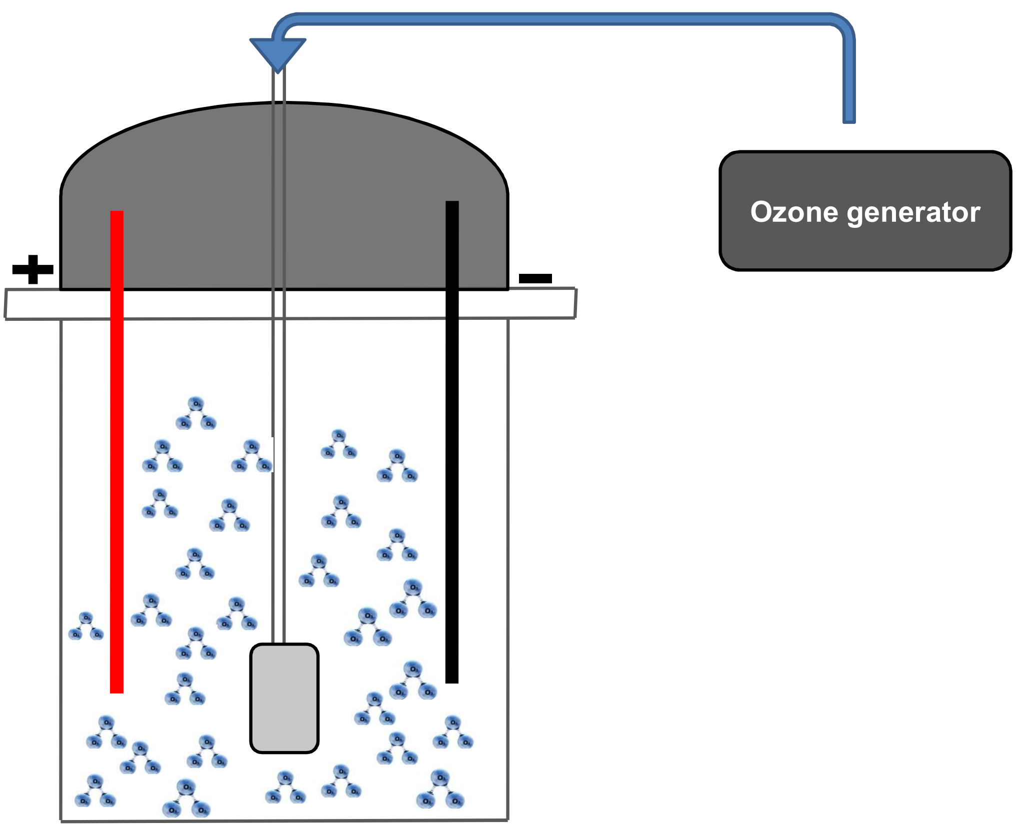

Figure 15. Schematic diagram showing hybrid chemical treatment reactor for simultaneous electrocoagulation and ozonation.

Integrated biological treatments- Nature based solutions

The effluents from anaerobic baffled reactor are rich in nutrients and carry pathogen loads that make it unsuitable for surface water discharge or downstream reuse of treated water. The nutrients are thus recovered during post treatment methods such as constructed wetlands and other nature based remediation systems. The further treatment of greywater effluents from anaerobic reactors can be integrated with the construction of wetlands that offer a practical model for the decentralized wastewater treatment systems (DEWATS). The constructed wetland systems namely horizontal-flow constructed wetland and vertical-flow constructed wetlands assist in the nitrogen and phosphorous removals. These natural systems are cost-effective and environmental friendly solutions for greywater treatment and recycling.

Nutrient recovery using algae photobioreactors

The drawbacks of low nutrient recovery from the microbial (anaerobic and aerobic) processes can be overcome using the photosynthetic microorganisms namely microalgae. Microalgae and cyanobacteria have high demands for nutrients like nitrogen and phosphorous and thus they cause blooms in eutrophicated water bodies in which the untreated or undertreated effluents are discharged in unrestricted manner. The aerobic membrane bioreactor can efficiently reduce the organic carbon loads up to 99% and the negative feedback would in turn limit the growth of bacteria due to resource competition. The low carbon and low bacterial loads obtained in the membrane bioreactor generate favorable effluents which can sequentially be fed to the algae membrane reactors (Nguyen, et al. 2020).

5 Greywater treatment models

Based on the different greywater profiles, we have developed an assessment method to determine the most suitable treatment process system for a given scenario. Various factors need consideration to adopt an efficient and cost effective greywater DEWAT system. These factors are listed as following:-

- Greywater characteristics and inputs
- Availability of land and cost effectiveness
- Environmental friendliness
- Efficient to process specific kind of pollutant (more laundry chemicals, surfactants, high oil and grease)
- Reuse applications
- Local or regional guidelines for effluent parameters

Based on greywater characteristics and different methods of treatment discussed in previous sections, we have developed some selected models for greywater DEWAT system (Table 5). Advanced models may need to be developed for the region where the primary water source has particular kind of pollutants such as Fe and other heavy metals.

Parameters (mg/l)	**Greywater strength**		
	Low	Medium	High
COD	<100-500	500-2000	>2000
BOD	50-250	250-500	>500
TN	1-5	5-10	>10
TP	<0.5	0.5-1.0	>1.0
Treatment models			
• **Toilet flushing, car washing, laundry**	***Model 1:*** Filtration (Figure 8,Figure 9) ↓ Chlorination/Ultraviolet	***Model 1:*** ASR/MBR (Figure 12/Figure 13) ↓ Constructed wetlands	***Model 1:*** Anaerobic baffled reactor (Figure 11) ↓ Aerobic treatment (Figure 12) ↓ Chemical treatment (Coagulation/Advanced oxidation/ozonation)
• **Restricted agriculture irrigation**	***Model 2:*** Filtration (Figure 7) ↓ Algae photobioreactor	***Model 2:*** MBR (Figure 13) ↓ Algae bio reactor ↓ Chemical treatments	***Model 2,3:*** Anaerobic baffled reactor (Figure 11) ↓ Aerobic treatment (Figure 12) ↓ Constructed wetlands ↓ Algae cultivation
• **Unrestricted agriculture irrigation**	***Model 3:*** Filtration (Figure 7) ↓ Reef bed, Phycoremediation	***Model 3:*** Anaerobic baffled reactor (Figure 11) ↓ Aerobic treatment (Figure 12) ↓ Constructed wetlands	

Table 5. Proposed basic models for recycling different strengths of greywater in DEWATS system of treatment.

6 Conclusions

Decentralized wastewater treatment systems for greywater recycling and reuse represent the best current sustainable solutions to address the water scarcity in various regions of the world.

Based on the availability of resources for developing grey and green infrastructures, different types of treatment methods can be employed for on-site greywater treatment. Hybrid processes which integrate different types of physical, chemical and biological methods are gaining momentum worldwide. There is also much advancement in physio-chemical processes and the adoption of nature-based solutions. With appropriate planning, one can also ensure compliance with the regulations and requirements for usage of treated greywater in wide range of non-potable applications.

Many chemical treatment methods such as some oxidation processes may be disadvantageous, as they may generate secondary pollutants. For these reasons, the combination of nature- and algae-based photo and phytoremediation solutions are proving beneficial for achieving sustainable development goals and for addressing the challenges of water-energy nexus.

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