DEVELOPMENT OF HYBRID SYSTEM FOR GREY WATER TREATMENT

A Thesis submitted to the
UPES

For the award of
Doctor of Philosophy
in
Electrical and Electronics Engineering

BY
Mukesh Chandra Kestwal

August 2024

SUPERVISOR

Dr Jitendra Kumar Pandey

School of Advanced Engineering
UPES
Dehradun-248007, Uttarakhand (Bharat)

DEVELOPMENT OF HYBRID SYSTEM FOR GREY WATER TREATMENT

A Thesis submitted to the
UPES

For the award of
Doctor of Philosophy
in
Electrical and Electronics Engineering

BY
Mukesh Chandra Kestwal
(SAP ID 500063535)

August 2024

Supervisor
Dr Jitendra Kumar Pandey
Professor
School of Advanced Engineering
UPES

School of Advanced Engineering
UPES
Dehradun-248007, Uttarakhand (Bharat)

Dedicated to my beloved mother

Late Smt. Shashi Kestwal

(23.12.1961 - 19.06.2023)

DECLARATION

I declare that the thesis entitled ***"Development of Hybrid System for Grey Water Treatment"***, has been prepared by me under the guidance of ***Prof. (Dr.) Jitendra Kumar Pandey***, Professor, School of Advanced Engineering, UPES Dehradun.

No part of this thesis has previously formed the basis for the award of any degree or fellowship.

Mukesh Chandra Kestwal

SAP ID: 500063535

Doctoral Research Fellow
UPES
Dehradun

Date: 29 Aug 2024
Place: Dehradun

UPES
UNIVERSITY OF TOMORROW

Great Place To Work® Certified FEB 2024-FEB 2025 INDIA ™

CERTIFICATE

I certify that **Mr. Mukesh Chandra Kestwal** has prepared his thesis entitled "***Development of Hybrid System for Grey Water Treatment***", for the award of PhD degree from the UPES, under my guidance.

He has worked at the Department of Electrical and Electronics Engineering UPES, Dehradun.

(Supervisor)

Prof. (Dr.) Jitendra Kumar Pandey
Professor, School of Advanced Engineering
UPES Dehradun
Date: 29th August 2024
Place: Dehradun

ABSTRACT

Amidst the escalating global challenges posed by freshwater scarcity, this experimental research embarks on a quest to explore alternative water sources as a promising solution. At the forefront of this exploration is greywater reuse, emerging as a potential alternative water source with the capacity for continuous exploitation and non-potable usage after treatment. The significance of this research is underpinned by its potential role in addressing climate change adaptation, enhancing food security, extending potable water supply, and mitigating environmental pollutants.

In an era where water scarcity intensifies, greywater reuse garners increasing interest, spanning across both industrialized and developing nations. This is primarily driven by the pressing issues of freshwater demand associated with population growth and the dual incentives of economic and environmental considerations. Greywater reuse not only conserves precious freshwater resources but also significantly reduces the costs associated with wastewater treatment.

This research shines a spotlight on greywater, which is defined as wastewater excluding contributions from toilets. Greywater sources encompass laundry, kitchens, showers, hand basins, and kitchen sinks across diverse settings, ranging from households to office buildings and schools. An extensive exploration of greywater's characteristics unfolds, considering critical factors that impact human health and the environment. Health aspects are scrutinized, focusing on the presence of microorganisms, while environmental perspectives delve into the accumulation of xenobiotic organic compounds (XOCs) and metals in soil and groundwater.

A significant outcome of this research is the revelation of greywater's potential applications. Greywater can be effectively reused for urinal and toilet flushing, irrigation, and construction purposes, all of which traditionally rely on freshwater of drinking quality. The impact is profound, with estimates indicating that reusing

greywater for toilet flushing alone could lead to a 30% reduction in total household water consumption. Successful international examples of greywater reuse are cited, underscoring the technical feasibility and its ability to meet health requirements. Intriguingly, the research casts a wide net over greywater's applications, extending to outdoor usages such as lawn irrigation, sports fields, cemeteries, parks, golf courses, and domestic gardening. Furthermore, the scope encompasses other potential applications, including vehicle and window washing, fire protection, boiler feedwater, concrete production, and the development and preservation of wetlands.

To safeguard against groundwater contamination arising from microbes and pollutants in greywater, the research emphasizes the need for innovative treatment and management strategies. This comprehensive experimental research reiterates the potential of greywater reuse and treats the quest for sustainable water resource management as paramount. Employing natural adsorbents and meticulous characterization and treatment, this research optimizes greywater's utility, particularly in the context of student accommodations. The study meticulously evaluates key parameters like Total Dissolved Solids (TDS), pH levels, turbidity, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and levels of nitrate and phosphorus.

The results of the treatment process are significant. The initial concentrations of key parameters in the greywater were reduced dramatically after the treatment process. For instance, Electrical Conductivity (EC) was reduced from 2480 µS/cm to 242 µS/cm, achieving a 90.2% removal rate. Total Dissolved Solids (TDS) were reduced from 1612 mg/l to 138 mg/l, achieving a 91.4% removal rate. Chemical Oxygen Demand (COD) saw a reduction from 554 mg/l to 24 mg/l, achieving a 95.6% removal rate, while Biochemical Oxygen Demand (BOD) was reduced from 120 mg/l to 8 mg/l, achieving a 93.3% removal rate. Phosphorus and Nitrate concentrations also saw significant reductions, with removal rates of 93.7% and 89.2%, respectively. Turbidity was reduced from 150 NTU to 9 NTU, achieving a 94% removal rate. These results confirm the effectiveness of the treatment methodology.

The research's most innovative aspect is its proposal of a household-level treatment approach. This pioneering method underscores the feasibility of sustainable greywater treatment and reuse. By merging environmentally conscious practices with technological advancements, this research contributes to the ongoing discourse on water resource optimization in an increasingly water-scarce world.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my PhD guide, mentor, and supervisor, ***Dr. Jitendra Kumar Pandey*.** His unwavering support, insightful guidance, and constant encouragement have been instrumental in helping me reach this significant milestone in my life. I am especially grateful for the opportunity to work on the DST-funded project under his mentorship, which has greatly enriched my research experience. Acknowledging ***Department of Science and Technology, (Government of India)*** generous support through the "Greywater Treatment Technology for Community Building" project has been essential in sponsoring my PhD program and advancing my research.

I extend my heartfelt thanks to ***Dr. Ram K. Sharma***, Vice Chancellor of UPES, for providing me with the opportunity to complete my PhD. His support and belief in my work have been vital in this journey.

I am profoundly thankful to the entire R&D Cell at UPES for their relentless support and facilitation of my research work. The IP Cell has been invaluable in assisting with the filing and granting of patents, which has greatly contributed to the success of my research.

My sincere appreciation goes to **Dr Sukdeb Pal**, Senior Scientist at CSIR - NEERI, and our collaborative partners, including IIT Roorkee, for their invaluable contributions to the DST-funded project. Their efforts have been crucial to my research.

Thankful to the support of IIT Ropar – Technology and Innovation Foundation, that has given me exposure to work on Technologies and Innovation in Agriculture and Water Domain as part of my professional journey, and to ***Dr Pushpendra Singh*** (Dean, R&D, IIT Ropar and Project Director, iHub – AwaDH) for the exposure and opportunity. Also, would like to thank ***Dr Vinay, Dr Vivek, Dr Manna*, *Ms Rakhi*** and other faculties and mentors for their unwavering support and guidance throughout my research. Your encouragement and insights have been essential to my progress. A special note of thanks to ***Dr Parag, Dr Ravi, Dr Surajit,*** **and** ***Dr Ajit*** for their continuous support, which has greatly enhanced the quality of my research work.

I am eternally grateful to my family. To my father, ***Shri Ghanshyam Kestwal***, an academician, and to my late mother, ***Late Smt. Shashi Kestwal***, whose dream was to see me complete my doctorate. To my both sisters, brothers, and in-laws, thank you for your constant support and encouragement.

Most importantly, I owe my deepest gratitude to my beloved wife, ***Renu Thapliyal***, for her unconditional support and for keeping my motivation high. Despite managing our 4-four-year-old daughter ***Avantika Kestwal*** and running her startup, *R2E Technologies*, Renu has been my pillar of strength through all the highs and lows. *Renu* and *Avantika*, you have been key to my success, and I dedicate this achievement to you both.

Thank you all for being a part of this incredible journey.

TABLE OF CONTENT

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

AL - Aluminum

BOD - Biochemical Oxygen Demand

COD - Chemical Oxygen Demand

DO - Dissolved Oxygen

DOC - Dissolved Organic Carbon

EC - Electrical Conductivity

E. COLI - Escherichia Coli

EU - European Union

FC - Fecal Coliforms

F/M - Food to Microorganism

GAC - Granular Activated Carbon Filter

GM - Grey Model

GW - Greywater

HRT - Hydraulic Retention Time

MLSS - Mixed Liquor Suspended Solids

MF - Microfiltration

MMF - Multimedia Filter

NF - Nanofiltration

NEERI - National Environmental Engineering Research Institute

N - Nitrogen

P - Phosphorus

PVC - Polyvinyl Chloride

PA - Pseudomonas Aeruginosa

QMRA - Quantitative Microbial Risk Assessment

SAT - Soil Aquifer Treatment

ST - Salmonella Typhi

TDS - Total Dissolved Solids

TOC - Total Organic Carbon

TP - Total Phosphorus

TSS - Total Suspended Solids

NTU - Turbidity

UF - Ultrafiltration

UV - Ultraviolet

USEPA - United States Environmental Protection Agency

XOCS - Xenobiotic Organic Compounds

CHAPTER 1

INTRODUCTION

CHAPTER 1

1.1 Introduction

The contemporary global water crisis is a paramount concern that extends beyond mere scarcity. Contrary to the prevailing narrative that attributes the crisis to insufficient water supplies to meet human demands, the core issue lies in the profound mismanagement of existing water resources. This mismanagement has precipitated dire consequences for billions of individuals and the natural environment alike. As highlighted in the World Water Vision Report, the crisis is fundamentally one of governance, characterized by inadequate policies, inefficiencies, and inequities in water distribution, exacerbating the plight of the most vulnerable populations. Addressing this crisis requires a multifaceted approach that includes sustainable management, equitable distribution, and robust infrastructural development to alleviate widespread suffering and safeguard our ecological heritage.

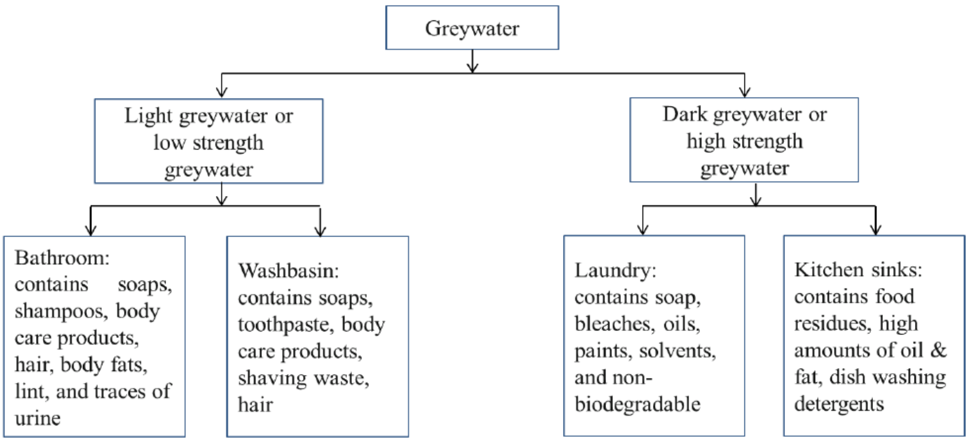


Figure 1.1: Greywater sources and their constituents

The residential, industrial, and energy sectors all use freshwater. Freshwater availability is reduced in both quantity and quality as a result of overuse of these resources and increased wastewater generation. (Boano et al., 2020; Manju & Sagar, 2017; Rajasulochana & Preethy, 2016). Furthermore, competition among various water users exacerbates concerns regarding the freshwater supply. In light of these challenges, water conservation has become paramount, necessitating the adoption of controlled, efficient consumption and wastewater reuse practices (do Couto et al., 2015a). In water-stressed areas in particular, recycled greywater has become a feasible source for non-potable or indirect potable uses, with the goal of lowering freshwater use and improving water sustainability. (Janeiro et al., 2020). The growing issues of water scarcity, resource depletion, ageing infrastructure, and inadequate facilities have spurred significant research into alternative water reuse technologies within the urban water sector, making sustainable management of water resources critical (Nas, 2016). (As Shown in Figure 1.2)

The study at IIT Madras examines, greywater characteristics and water consumption in households and analyzes water use across various activities, noting that bathing and toilet flushing is the most water-intensive. Greywater accounts for 55-61% of total consumption, with significant variation between different socio-economic classes. C Type households generate the most greywater (90 Lpcd), while the hostel generates the least (19.5 Lpcd). The findings highlight the influence of water availability and household characteristics on consumption patterns (Delhiraja, K., Philip, 2020).

Greywater (GW) refers to untreated wastewater generated from washrooms, laundry, and bathing activities in residential settings (Abu Ghunmi et al., 2011; Barzegar et al., 2019a; Li et al., 2009; Oh et al., 2018). Reusing GW can convert a substantial portion of wastewater from waste into a valuable water resource. In the European Union (EU) and other high-income countries, GW constitutes up to 75% of household wastewater production. In contrast, in low-income countries, it accounts for 75-90 litres per day (Ghaitidak & Yadav, 2013) compared to India. Residential wastewater's more polluting component needs to be properly treated, and GW source separation can lighten the strain on wastewater treatment facilities. (Boano et al., 2020; Larsen* et al., 2009; Remy & Jekel, 2008). Moreover, reclaimed GW can be reused locally for various applications such as toilet flushing, recreational activities, and gardening, which would otherwise require high-quality water, thereby promoting a circular economy (Liu et al., 2015; Masi et al., 2018).

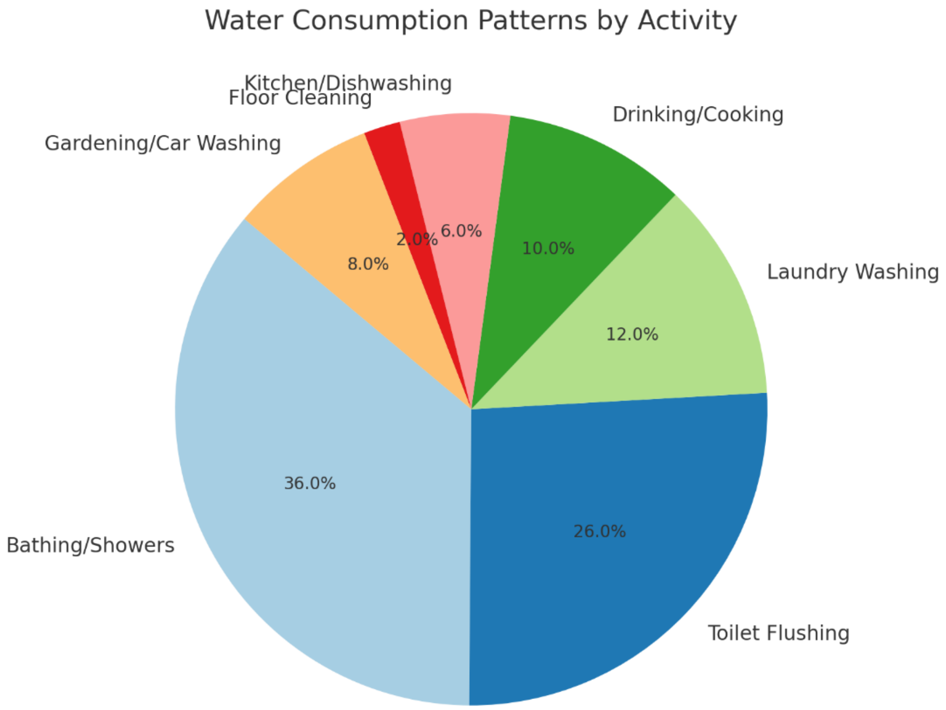


Figure 1.2: Water Consumption Patterns by Activity

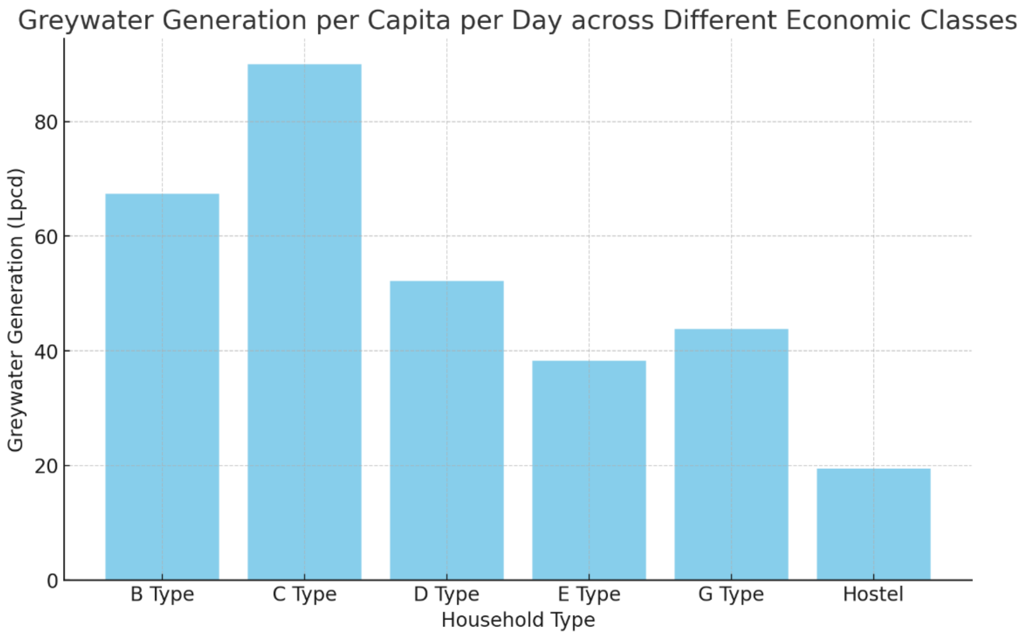


Figure 1.3: Greywater Generation across Different Economic Classes; compares greywater generation across different household types. C Type households produce the most greywater at 90 Lpcd, followed by B Type at 67.4 Lpcd. D Type, G Type, and E Type generate 52.2 Lpcd, 43.8 Lpcd, and 38.3 Lpcd, respectively. The hostel has the lowest greywater generation at 19.5 Lpcd

GW recycling represents a viable system-level strategy to enhance water sustainability and resilience (Liu et al., 2015) (Figure 1.3).

In response to escalating global challenges stemming from freshwater scarcity, the exploration of alternative water sources has become imperative. This thesis focuses on greywater treatment as a promising solution within the broader context of sustainable water resource management. Greywater, defined here as wastewater excluding that from toilets, originates from various domestic sources such as laundry, kitchens, showers, and hand basins.

Table 1.1: The microbiological properties of greywater derived from different sources (Edwin, G.A., Gopalsamy, P. & Muthu et al., 2014)

Parameter	Tap water	Shower	Wash basin	Kitchen	Laundry	Combined GW
Total coliform	1.72–1.87	3.95–6.28	2.94–6.95	3.38–5.11	3.04–5.6	6.99–7.71
E. coli	0.85–1.15	2.98–3.06	2.81–2.95	Not Detected	Not Detected	3.54–6.3

Greywater reuse presents a viable strategy to alleviate freshwater demand pressures exacerbated by population growth, industrialization, and urbanization. (As outlined in Table 1.1) By diverting greywater from traditional wastewater streams, significant reductions in freshwater consumption can be achieved. Moreover, the reuse of treated greywater for non-potable applications such as irrigation and toilet flushing not only conserves potable water but also mitigates the environmental impact associated with conventional wastewater disposal.

This research endeavours to comprehensively assess the characteristics of greywater, focusing on key factors influencing human health and environmental integrity. Critical aspects under scrutiny include the presence of microorganisms, xenobiotic organic compounds (XOCs), and metals, which can potentially impact soil and groundwater quality upon disposal or reuse. Addressing these concerns is essential to ensure that treated greywater meets rigorous health and environmental standards.

The adoption of greywater treatment technologies varies globally, influenced by regional water stress levels, regulatory frameworks, and technological capabilities. (As shown in Table 1.1) For instance, developed regions like Europe exhibit higher rates of treated wastewater recycling compared to developing regions where infrastructure and resource constraints pose significant challenges. Bridging these disparities requires tailored approaches that consider local contexts and resource availability.

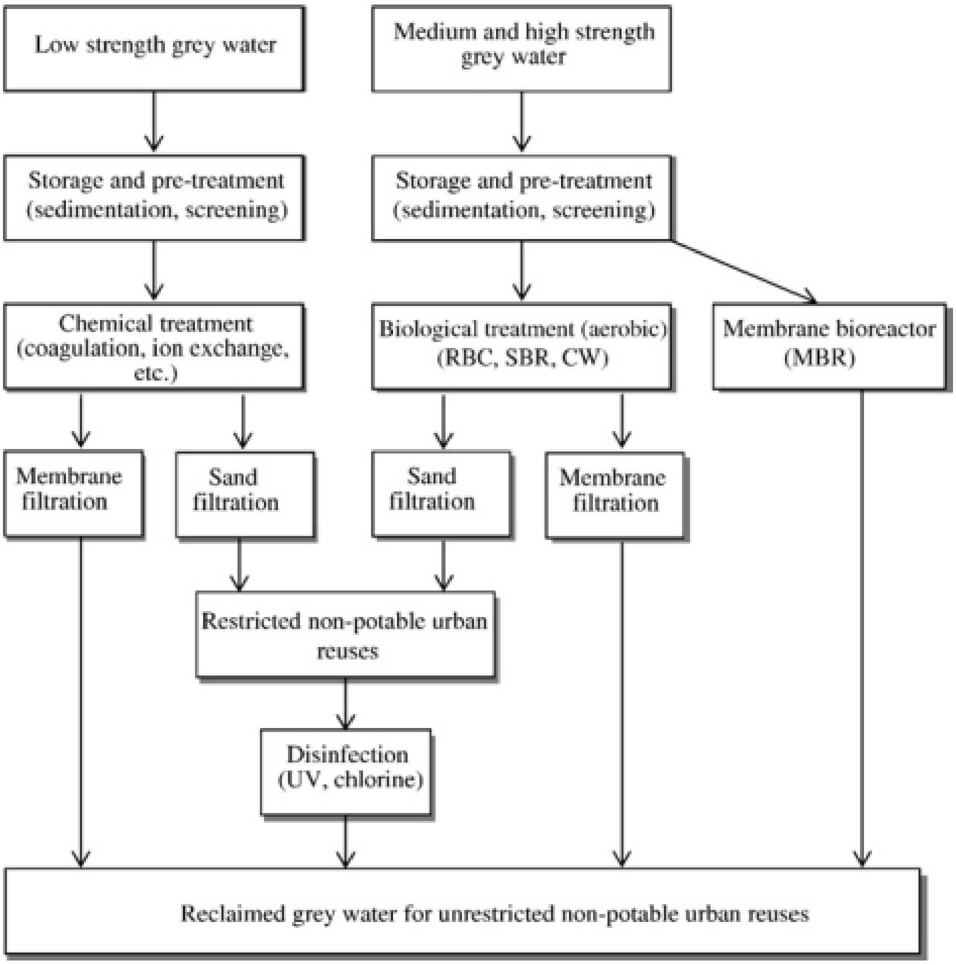


Figure 1.4: The grey water recycling schemes for non-potable urban reuses (Li, Fangyue, Knut Wichmann, and Ralf Otterpohl, 2019)

Furthermore, the societal and economic benefits of greywater reuse extend beyond immediate water conservation. By integrating treated greywater into water resource management frameworks, decision-makers can optimize water allocation, reduce wastewater treatment costs, and enhance overall water sustainability. This paradigm shift underscores the transformative potential of viewing wastewater as a valuable resource rather than a mere byproduct of human activities.

Greywater, defined as untreated household wastewater excluding toilet wastes, presents a viable resource for sustainable water management in regions like India. Unlike the United States, where its primary use is for landscape irrigation, greywater reuse practices in India encompass broader applications due to water scarcity and sanitation challenges (Figure 1.4).

1.1.1. Composition and Sources of Greywater

Greywater, a subset of domestic wastewater, is defined as untreated household wastewater that has not been contaminated by toilet discharges. In the context of India, the primary sources of greywater include:

- *Showers and Bathtubs:* Water used for personal hygiene, which generally contains soap residues, body oils, hair, and minimal amounts of organic matter.
- *Hand Basins:* Water from washing hands and face, often containing soap, skin particles, and minor traces of cosmetics.
- *Laundry Activities:* Water discharged from washing machines and laundry tubs, typically containing detergents, dirt, fibres, and residual chemicals from cleaning agents.

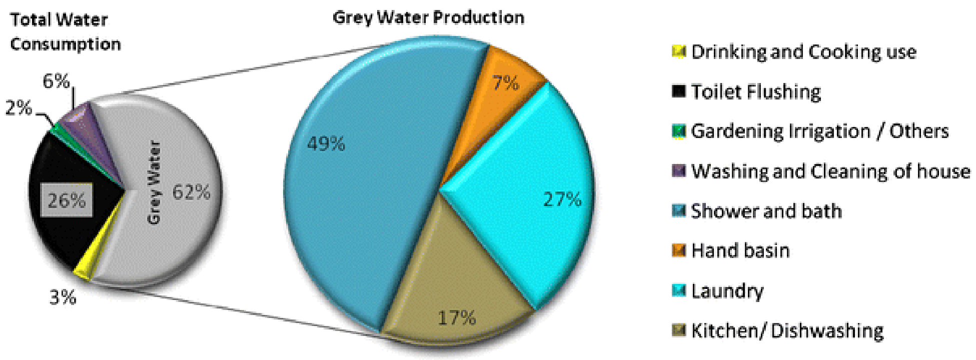


Figure 1.5: Relative distribution of total water consumption and GW production

Figure 1.5 displays the relative distribution of GW production and total water use. When compared to published statistics from other Indian cities, the mean total water use is noticeably higher, according to the findings. This indicates that the water use of urban families is higher than that of rural ones. On average, 62% of GW is produced, with the bathroom accounting for the largest portion (49%) and being followed by the kitchen, laundry, and wash basin sources. (Edwin, G.A., Gopalsamy, et al., 2014)

Greywater's composition is characterized by its relatively lower levels of contaminants compared to blackwater. The key components include:

- *Organic Matter:* Greywater contains biodegradable organic substances, though in significantly lower concentrations than blackwater. This includes skin cells, oils, and food particles from washing.
- *Suspended Solids:* Particles such as lint, hair, and soap scum, which can be removed through basic filtration processes.
- *Nutrients:* Low levels of nutrients like nitrogen and phosphorus, originate from soaps and detergents, which can benefit plant growth when used in irrigation.
- *Pathogens:* While greywater typically contains fewer pathogens than blackwater, it may still harbour bacteria and viruses from bodily fluids and soil.
- *Chemical Residues:* Residual amounts of personal care products, detergents, and cleaning agents contribute to the chemical load in greywater. These include surfactants, phosphates, and other synthetic compounds.

The composition and sources of greywater highlight its potential for reuse in non-potable applications. With appropriate treatment, greywater can be repurposed for irrigation, toilet flushing, and industrial processes, thereby conserving precious freshwater resources. Understanding the specific characteristics of greywater from different household activities is crucial for designing effective treatment systems and ensuring safe and sustainable reuse practices.

1.1.2. Technologies for Treatment of Greywater

The treatment of greywater in India employs a range of technologies, from basic filtration methods to more sophisticated biological and physical processes. The selection of a treatment system is typically based on the intended reuse of the greywater, the quality of the influent, and the local environmental conditions. The primary technologies used in greywater treatment are detailed below (Figure 1.6):

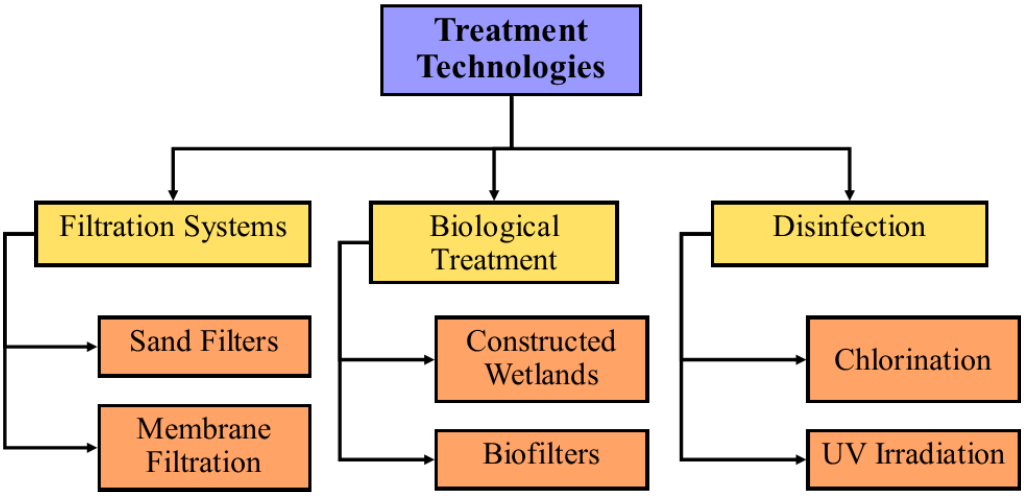


Figure 1.6: Greywater treatment technologies

1.1.2.1. Filtration Systems

Sand Filters:

Sand filters are a cost-effective and straightforward method for removing suspended solids from greywater. The process involves passing greywater through layers of sand, which trap particles and impurities. The key components of sand filters include (Figure 1.7):

- *Coarse Gravel Layer:* Positioned at the bottom to support the sand layers and facilitate drainage.
- *Fine Sand Layer:* The main filtration medium, captures finer particles and organic matter.
- *Maintenance:* Periodic backwashing or replacement of the top sand layer to prevent clogging and maintain efficiency.

Membrane Filtration:

Membrane filtration offers a more advanced approach to greywater treatment by using semi-permeable membranes to remove contaminants at the microscopic level. This technology includes:

- *Microfiltration (MF):* Removes suspended solids, bacteria, and some viruses using membranes with pore sizes between 0.1 and 10 micrometres.
- *Ultrafiltration (UF):* Employs membranes with smaller pore sizes (0.01 to 0.1 micrometres) to retain viruses and finer particles.

- *Operation and Maintenance:* Regular cleaning and periodic replacement of membranes are essential to maintain performance and prevent fouling.

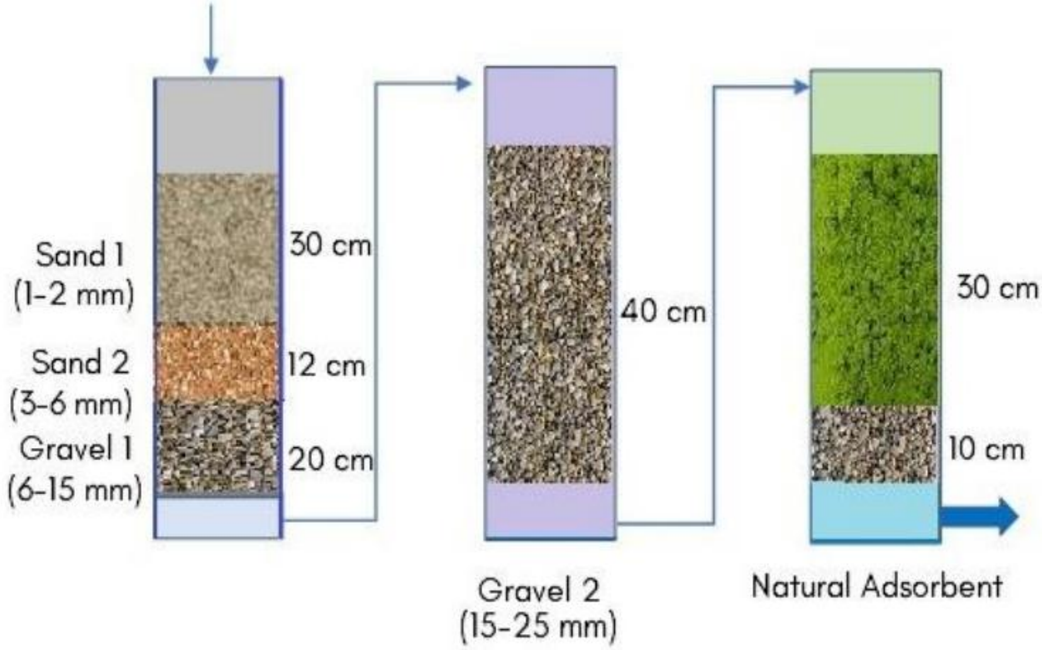


Figure 1.7: Schematic diagram of the Sand and Natural Adsorbent process

1.1.2.2.Biological Treatment

Constructed Wetlands:

Constructed wetlands mimic natural wetland ecosystems to treat greywater through biological processes. The key elements include:

- *Vegetation:* Plants such as reeds and cattails provide a surface for microbial growth and contribute to nutrient uptake.
- *Substrate:* Layers of gravel or soil support plant roots and facilitate the filtration of greywater.
- *Treatment Mechanisms:* Microbial degradation, plant uptake, and sedimentation reduce organic matter, nutrients, and pathogens.
- *Design Considerations:* Proper design ensures adequate hydraulic retention time and prevents short-circuiting of water flow.

Biofilters:

Biofilters use a combination of biological and physical processes to treat greywater. They consist of:

- *Filter Media:* Layers of sand, gravel, or synthetic media support microbial communities that degrade organic contaminants.

- *Aeration:* Adequate oxygen supply enhances microbial activity and ensures effective treatment.
- *Maintenance:* Routine cleaning and occasional media replacement are necessary to sustain performance.

1.1.2.3. Disinfection

Chlorination:

Chlorination is a widely used disinfection method that involves adding chlorine or chlorine compounds to greywater to kill pathogenic microorganisms. Key aspects include:

- *Chlorine Dose:* The concentration of chlorine must be carefully controlled to ensure effective disinfection without producing harmful byproducts.
- *Contact Time:* Sufficient contact time between chlorine and greywater is crucial for microbial inactivation.
- *Residual Chlorine:* Monitoring residual chlorine levels ensures ongoing disinfection and safety.

UV Irradiation:

Ultraviolet (UV) irradiation disinfects greywater by exposing it to UV light, which inactivates microorganisms by damaging their DNA. Key features include:

- *UV Lamps:* Special lamps emit UV-C light (200-280 nm) that effectively inactivates bacteria, viruses, and protozoa.
- *Reactor Design:* The design of the UV reactor ensures uniform exposure of greywater to UV light.
- *Maintenance:* Regular cleaning of UV lamps and periodic replacement are necessary to maintain disinfection efficacy.

Over the years, various studies have explored and documented different methodologies for greywater (GW) treatment. These research efforts focus on achieving efficient and sustainable reuse of greywater for non-potable applications. Below (Table 1.2) is a detailed overview of notable research contributions in this field, accompanied by a comprehensive table summarizing the key findings and technologies.

Table 1.2: Summary of Greywater Treatment Technologies

Particulars	**Salient Features**
Greywater Dam Design for Single and Multiple Households (Gleick, 2003)	- Designed for homesteads shared by 5 households - 2000 L/D treatment capacity - Aerobic breakdown of organic matter - Controlled supply and vertical pipes for efficiency - Hydraulic equation for seepage path determination
GW Recycling: Treatment Options and Application (Tiruneh, 2014)	- 40% water and cost savings for 200 dwellings - >90% removal of BOD5, COD, TSS, ammonia - Effluent meets WHO 2006 guidelines (BOD5 <10mg/L)
Constructed Wetland Treatment (Pidou et al., 2007; Vymazal, 2011)	- Removal of BOD, suspended solids, heavy metals, toxic substances - Utilizes physical, chemical, biological processes - Efficiency dependent on surface loading rate, electron acceptors
Hybrid Treatment Process (Halalsheh et al., 2008; Parjane & Sane, 2011a)	- Lab-based model with 180 lit/hr capacity - Four-stage treatment: primary settling, aeration, agitation, filtration - 83% organic load reduction - 46% and 49% adsorption of anions and cations - Removal of potassium, magnesium, calcium
Filtration Characteristics for Domestic Wastewater Reclamation (Parjane & Sane, 2011a)	- 95% removal of TOC, BOD - 50% removal of TN - 85% removal of TP
Monitoring of Indoor Plants for GW Reuse (Seo et al., 2007)	- Reductions in turbidity (18%), pH, suspended solids (28%), TOC (20%), TN, COD (25%)
Lab-Based GW Treatment System (Gual et al., 2008)	- 99% removal of turbidity, pH, colour, COD, and suspended solids
Performance of GW Treatment (Kim et al., 2009a)	- Reductions in hardness (60%), COD (91%), TDS (81%), TSS (90%), oil and grease (98%), nitrates (75%), nitrites (100%), cations (49%), anions (46%)

These studies collectively underscore the diverse and effective approaches to greywater treatment, offering valuable insights into optimizing water reuse strategies in various contexts, including high-density urban environments and decentralized settings. Extensive literature supports the premise that conducting treatment experiments on a laboratory scale yields controlled and enhanced results. Notably, the adoption of filtration techniques, particularly membrane-based methods, has demonstrated significant promise in reducing overall turbidity, total suspended solids (TSS), and concentrations of nitrates and phosphorus.

The selection of appropriate treatment methodologies is often constrained by considerations of economic feasibility and cost-effectiveness in practical implementation. Therefore, it is essential to evaluate treatment approaches that not only ensure sustainability and resilience but also meet the critical criteria of economic viability. This evaluation must consider the local context, including available resources, technical expertise, and regulatory frameworks, to implement the most efficient and effective greywater reclamation systems.

1.2 Important Applications of Treated Greywater

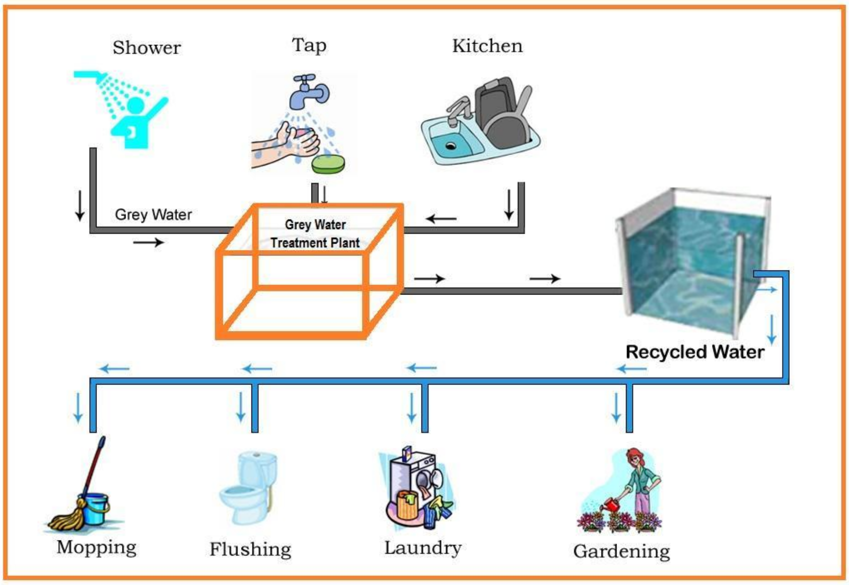


Figure 1.8: Flow Diagram of Greywater generation and possible opportunities

1.2.1. Urban Landscaping

Treated greywater is increasingly being utilized for the irrigation of urban landscapes, including parks, gardens, and green spaces, particularly in water-scarce regions of India (Figure 1.8; 1.4). This application helps conserve valuable freshwater resources. The key advantages and considerations include:

- *Water Conservation:* Utilizing greywater for irrigation significantly reduces the demand for potable water, aiding in water conservation efforts.
- *Nutrient Supply:* Greywater often contains low levels of nutrients such as nitrogen and phosphorus, which can benefit plant growth.
- *System Design:* Efficient distribution systems, such as drip irrigation, ensure that treated greywater is used effectively while minimizing evaporation and runoff.
- *Health and Safety:* Proper treatment and monitoring are essential to prevent any potential health risks associated with pathogens or contaminants in greywater.

1.2.2. Toilet Flushing

Toilet flushing is a major application of treated greywater, contributing to substantial water savings in both residential and commercial buildings. The benefits and technical requirements include:

- *Water Savings:* By substituting treated greywater for potable water in toilets, overall water demand is significantly reduced, which is critical in areas facing water scarcity.
- *Infrastructure:* The implementation requires a dual plumbing system to separate potable and non-potable water supplies, along with backflow prevention mechanisms to avoid contamination.
- *Treatment Standards:* Ensuring that greywater meets specific quality standards for non-potable use is essential to maintain hygiene and safety.

1.2.3. Industrial Use

Industries in India are increasingly adopting treated greywater for cooling and process water, recognizing the cost and environmental benefits. Key aspects include:

- *Process Water:* Treated greywater can be used in various industrial processes where high-purity water is not essential, reducing reliance on freshwater sources.

- *Cooling Systems:* Using greywater for cooling towers and other cooling applications can significantly lower industrial water consumption.
- *Economic Benefits:* Industries benefit from reduced water procurement costs and potential subsidies or incentives for sustainable water use practices.
- *Regulatory Compliance:* Industries must ensure that the quality of treated greywater complies with regulatory standards to prevent any adverse effects on equipment or processes.

1.2.4. Agricultural Irrigation

In peri-urban and rural settings, treated greywater can be used for agricultural irrigation, providing a reliable water source for crop production. Key considerations include:

- *Irrigation Efficiency:* Efficient irrigation techniques, such as drip or subsurface irrigation, maximize water use efficiency and minimize contamination risks.
- *Soil and Crop Health:* Regular monitoring of soil and crop health is necessary to prevent the accumulation of salts and other potential contaminants from greywater.
- *Local Guidelines:* Adhering to local guidelines and regulations ensures that the use of greywater in agriculture is safe and sustainable.

1.2.5. Road and Construction Site Dust Control

Treated greywater can be used for dust control on roads and construction sites, helping to manage dust emissions and improve air quality. Key points include:

- *Application Methods:* Spraying treated greywater on roads and construction sites helps to bind dust particles and reduce airborne dust.
- *Environmental Impact:* Using greywater for dust control minimizes the need for potable water, promoting sustainable water use practices.
- *Quality Requirements:* Ensuring that the treated greywater is free from harmful contaminants is crucial to prevent any adverse environmental impacts.

The diverse applications of treated greywater in India demonstrate its potential to significantly contribute to water conservation and sustainability. By addressing the technical, regulatory, and health aspects of greywater reuse, India can effectively harness this valuable resource to mitigate water scarcity challenges and promote sustainable development.

1.3 The Motivation of the Research

Water scarcity is an escalating global challenge, particularly acute in developing countries like India. Rapid urbanization, population growth, and climate change exacerbate the stress on existing freshwater resources, necessitating innovative and sustainable solutions to meet the increasing water demand. In this context, greywater reuse presents a promising approach to alleviate water scarcity by supplementing non-potable water supplies.

Greywater, comprising wastewater from showers, bathtubs, hand basins, and laundry activities, constitutes a substantial portion of domestic water usage. Its relatively low contamination levels, compared to blackwater, make it a viable candidate for treatment and reuse in various applications such as irrigation, toilet flushing, and industrial processes. However, the current practices for greywater treatment in India are often limited by technological, regulatory, and social barriers.

The development of a hybrid system for greywater treatment addresses these limitations by integrating multiple treatment technologies to enhance efficiency, cost-effectiveness, and adaptability to varying water quality conditions. A hybrid system combines the strengths of biological, physical, and chemical treatment methods, offering a robust solution capable of treating greywater to a high standard suitable for diverse reuse applications.

The motivation for this research stems from several key factors:

i) *Water Resource Management:* Efficient greywater treatment and reuse can significantly reduce the demand for freshwater, easing the burden on overexploited water sources and contributing to sustainable water resource management.

ii) *Environmental Protection:* Proper treatment of greywater minimizes the discharge of pollutants into natural water bodies, thereby protecting ecosystems and reducing environmental degradation.

iii) *Technological Innovation:* Developing a hybrid treatment system provides an opportunity to advance current technologies, optimizing them for local conditions and improving their effectiveness and reliability.

iv) *Economic Benefits:* Implementing greywater reuse systems can result in considerable cost savings for households, industries, and municipalities by reducing the need for freshwater and decreasing wastewater treatment costs.

v) *Public Health Improvement:* Effective greywater treatment mitigates the risk of waterborne diseases by ensuring safe reuse, particularly in regions with inadequate sanitation infrastructure.

vi) *Regulatory Compliance:* Developing standardized and efficient treatment systems can aid in establishing regulatory frameworks and guidelines for greywater reuse, facilitating broader adoption and acceptance.

This research aims to develop a hybrid system for greywater treatment that is technically adaptable, economically viable, and environmentally sustainable. By addressing the specific challenges and opportunities within the Indian context, this study seeks to contribute to the global body of knowledge on sustainable water management and promote the widespread implementation of greywater reuse practices.

1.4 Problem Statement

Despite the advantages of hybrid greywater treatment systems, the technical, economic, and environmental impacts of their implementation have been insufficiently studied in the literature. Current methods often inadequately address challenges such as health risks, impacts on soil chemistry and microbiology, landscape plant health, and groundwater quality. This highlights the need for a comprehensive investigation to promote the widespread adoption of efficient, safe, and easily implementable greywater treatment solutions.

1.5 Research Questions

The study seeks to develop a comprehensive understanding of the technical, economic, and environmental aspects of hybrid greywater treatment systems (Figure 1.10) to facilitate their safe and effective implementation in residential settings. This research is driven by the need to address several critical questions that ensure the system's efficiency, safety, and environmental sustainability.

- *Maximizing System Efficiency:* How can the efficiency of the hybrid system be maximized for different household greywater sources?
- *Pathogen and Chemical Removal:* How effective is the hybrid treatment system in removing pathogens and harmful chemicals from greywater?
- *Impact on Soil Health and Fertility:* How does the use of treated greywater affect soil health and fertility compared to freshwater irrigation?
- *Monitoring and Control of Water Quality Parameters:* What are the most effective techniques for monitoring and controlling turbidity and dissolved oxygen in the hybrid treatment system?
- *Environmental Comparison:* How does the hybrid system compare environmentally to conventional water use and treatment practices?

1.6 Major Research Contribution

This research makes significant contributions to the field of sustainable water management by developing and evaluating a novel hybrid greywater treatment system (Figure 1.9).

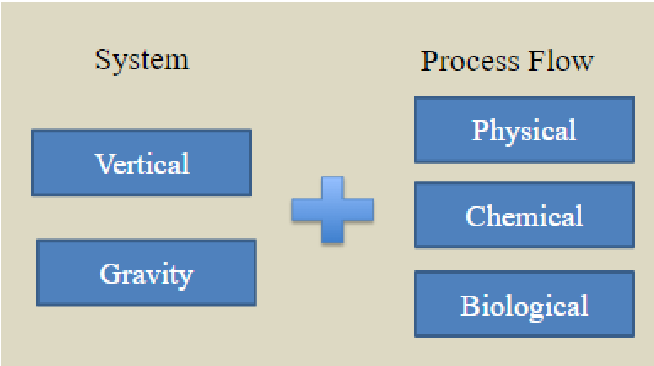


Figure 1.9: Hybrid Greywater treatment system (the proposed approach used for the research work)

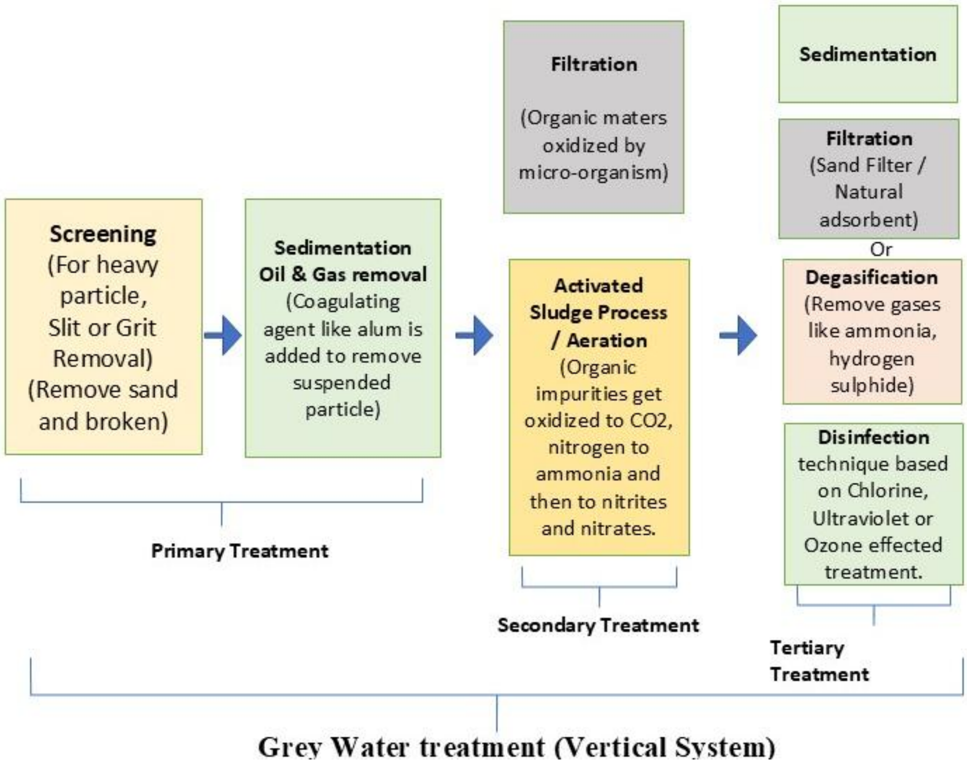


Figure 1.10: Methodology for Treatment Process of the Research Work.

The major research contributions are as follows (Figure 1.10):

- Identified and evaluated the suitability and effectiveness of various treatment technologies for greywater reuse, laying the groundwork for future research and development in this field.
- Introduced design innovations that optimize the treatment process, contributing to the advancement of greywater treatment technologies.
- Performed a comprehensive examination of the untreated greywater's physical, chemical, and microbiological properties, offering important baseline data.
- Proven the viability and efficacy of the hybrid greywater treatment system by evaluating its performance at a pilot scale with success.
- Presented a robust case for the adoption of hybrid greywater treatment systems in residential societies, contributing to sustainable water resource management practices.

1.7 Objectives of the Research

The primary aim of this thesis is to assess the technical, economic, and environmental feasibility of a hybrid greywater treatment system employing a combination of vertical and horizontal pipe-based mechanisms. The specific objectives of this research are:

1. *Literature Review and Technology Assessment:*
    - To assess the state of knowledge about hybrid greywater treatment systems and greywater recycling.
    - To assess the suitability and effectiveness of various treatment technologies for greywater reuse.
2. *Characterization of Untreated Greywater :*
    - To identify the actual, untreated greywater's physical, chemical, and microbiological properties.
    - To analyze the impact of turbidity and dissolved oxygen on greywater quality.
3. *Design of a Hybrid Treatment System:*
    - To design a hybrid structure that enhances water treatment efficiency through the integration of vertical and horizontal pipe-based mechanisms.
4. *Pilot-Scale System Evaluation:*
    - To assess the hybrid greywater treatment system's performance while it is in trial operation.
    - To develop a decision support technique for evaluating turbidity and dissolved oxygen in greywater.

These objectives aim to provide a comprehensive understanding of the feasibility and effectiveness of hybrid greywater treatment systems, thereby contributing to sustainable water resource management.

1.8 Overview of Thesis

This Thesis has been divided into six chapters, which discuss from the introduction to the research problem of the thesis. The overall outline of the chapters is shown in Figure 1.11.

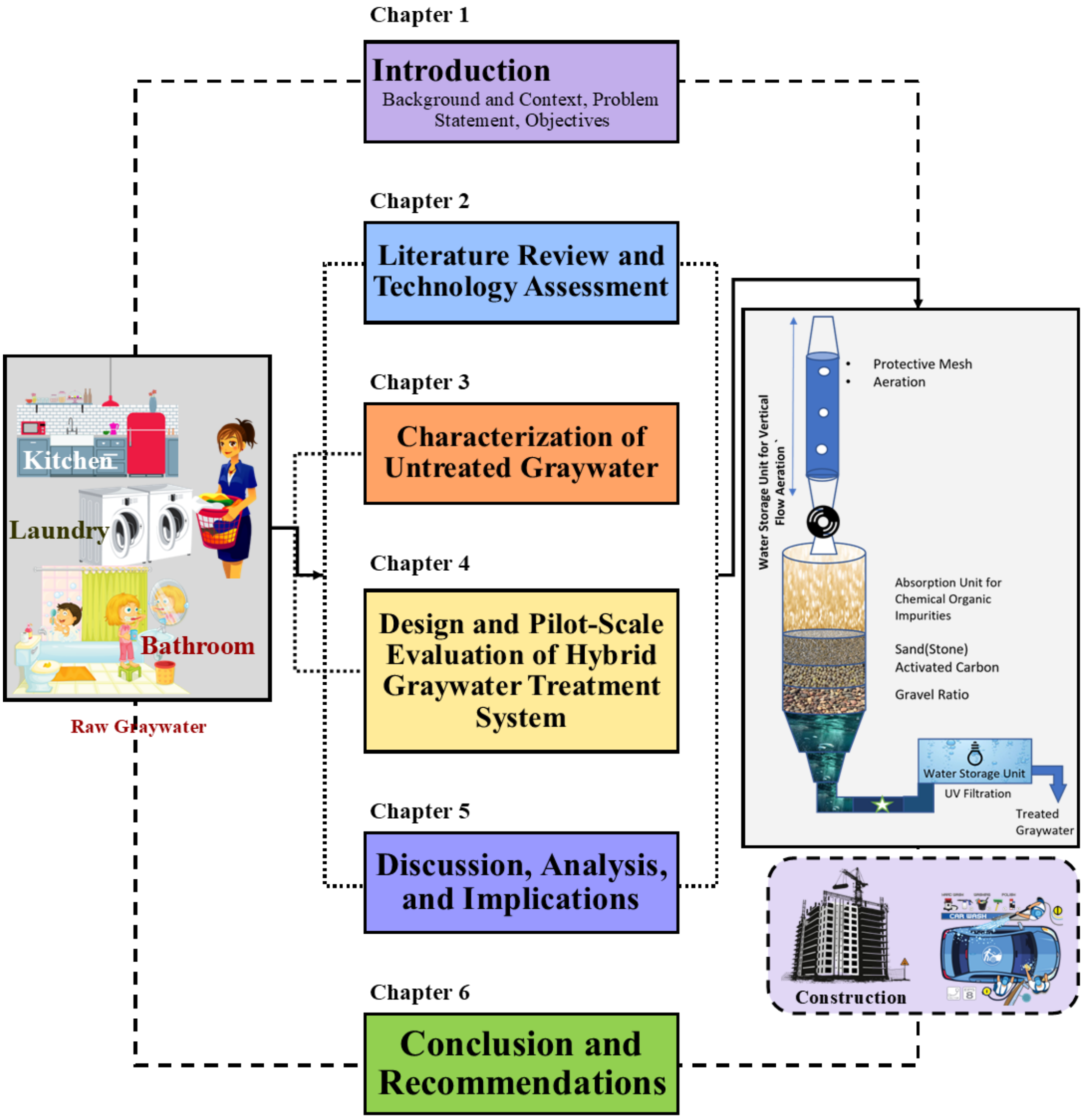


Figure 1.11: Graphical outlines of the overall thesis and research report

A brief description of each chapter is as

As the thesis's introduction, ***Chapter 1*** gives readers a basic overview of the important problems related to water shortage and the crucial part that greywater reuse plays in sustainable water management techniques. It establishes the scene by outlining the worldwide context of growing water shortages brought on by the effects of urbanization, population expansion, and climate change. The chapter elucidates the specific challenges inherent in greywater treatment, emphasizing the necessity for systems that are both efficient and effective in mitigating water scarcity challenges. Furthermore, it outlines the overarching objectives of the thesis, which encompass evaluating the technical, economic, and environmental feasibility of hybrid greywater treatment systems. This introductory framework establishes the rationale and scope of the research, laying the groundwork for subsequent chapters that delve deeper into each aspect of greywater treatment and system development.

Chapter 2, provides a comprehensive analysis of greywater recycling practices and treatment technologies. It begins with a thorough review of the current literature on greywater recycling, encompassing a wide array of treatment methods and technologies employed globally. The chapter evaluates various hybrid greywater treatment systems, examining their respective advantages, limitations, and applicability in different contexts. Furthermore, it critically assesses the suitability and effectiveness of biological, physical, and chemical treatment technologies for greywater reuse, offering insights into their performance metrics and operational parameters. This chapter serves as a foundational exploration essential for understanding the state-of-the-art in greywater treatment and guiding the development of innovative approaches towards sustainable water management solutions.

Chapter 3, the untreated greywater undergoes comprehensive analysis to delineate its physical, chemical, and microbiological attributes. The physical examination focuses on key parameters such as turbidity, colour, and temperature, providing insights into the clarity and visual properties of the water. Chemical characterization entails a thorough investigation of nutrient concentrations, metal content, and the presence of contaminants, elucidating potential risks and environmental impacts associated with untreated greywater. Microbiological analysis involves identifying microbial species and pathogens present in the water and assessing potential health hazards and microbial diversity. Additionally, the chapter delves into the impact of turbidity and dissolved oxygen levels on greywater quality, exploring how these factors influence its suitability for reuse and environmental compatibility. This detailed characterization serves as a foundational step in understanding the baseline quality of greywater and informs subsequent chapters on treatment strategies and system design.

Chapter 4, focuses on the comprehensive design and pilot-scale evaluation of a hybrid greywater treatment system. Initially, a conceptual framework is developed, integrating vertical and horizontal pipe-based mechanisms with detailed considerations of engineering principles to enhance water treatment efficiency. Strategies for optimizing system performance are explored, aiming to achieve effective removal of contaminants while maximizing resource efficiency. Subsequently, the experimental setup for pilot-scale evaluation is described, including protocols for assessing system performance metrics such as treatment efficiency, water quality parameters, and operational challenges. The chapter also includes the development and implementation of a decision support tool for real-time monitoring of turbidity and dissolved oxygen in greywater, ensuring robust performance assessment and informed decision-making in system operations.

Chapter 5, the thesis delves into the nuanced interpretation of results derived from comprehensive literature reviews, meticulous characterization studies of untreated greywater, detailed design considerations of a hybrid treatment system employing vertical and horizontal pipe-based mechanisms, and rigorous evaluation of its performance at a pilot scale. By critically assessing the alignment of findings with predefined research objectives, this chapter provides insightful reflections on the efficacy and limitations of various treatment technologies utilized for greywater recycling. Furthermore, it explores the broader implications of these findings for sustainable water resource management, offering strategic insights and recommendations aimed at informing policymakers, practitioners, and stakeholders in the field.

Chapter 6, covers the thesis and consolidates the key findings derived from the evaluation of a hybrid greywater treatment system. The summary succinctly recaps the significant contributions of the research, emphasizing insights gained into the technical, economic, and environmental feasibility of employing vertical and horizontal pipe-based mechanisms for greywater treatment. Practical recommendations are offered to enhance the efficiency and effectiveness of hybrid systems, suggesting avenues for future research and development. The potential of hybrid greywater treatment systems to advance sustainable water management practices is affirmed in the chapter's conclusion, tackling important water scarcity issues with cutting-edge technology solutions.

CHAPTER 2

LITERATURE REVIEW AND TECHNOLOGY ASSESSMENT

CHAPTER 2

Reusing greywater has attracted a lot of interest as a viable way to alleviate water scarcity and lessen the harm that wastewater discharge does to the environment. Greywater is a feasible alternative for non-potable uses including toilet flushing and irrigation. It is made up of wastewater from showers, bathtubs, hand basins, and laundry operations. However, in order to create efficient treatment systems, trustworthy statistics on the formation and quality of greywater are required due to its complicated composition. This literature review explores the current state of knowledge on greywater generation, quality, and treatment technologies, emphasizing the need for efficient, cost-effective, and sustainable solutions tailored to diverse local contexts. The review covers various studies that have investigated the presence of xenobiotic organic compounds (XOCs), evaluated the performance of different treatment systems, and analyzed the impact of greywater reuse on environmental and human health. These insights provide a foundation for the development of advanced greywater treatment systems aimed at optimizing water reuse while ensuring safety and sustainability.

Utilizing greywater for urinals, toilet flushing, irrigation, and construction could be a highly effective solution, as the water used for these purposes is typically freshwater and of drinking water quality. It is estimated that reusing greywater for toilet flushing alone could reduce total household water consumption by up to 30%. (Karpiscak, Foster, & Schmidt, 1990). In Germany, the reuse of grey wastewater from bathrooms has been successfully implemented, demonstrating that it is both technically feasible and compliant with health regulations. Significant volumes of water can be recycled by employing a dual treatment system. (Nolde, 2000). An analysis of the water demands of major buildings today reveals that in addition to using greywater from restrooms, stormwater and wastewater from washing machines must also be used to meet the demand for recycled water for non-potable uses. (Surendran & Wheatley, 1998). Greywater can be used for outdoor applications such as irrigating lawns on college campuses, athletic fields, cemeteries, parks, and golf courses, as well as for domestic gardens. (Okun, 1977). Greywater can also be used for fire prevention, boiler feed water, concrete manufacture, and car and window washing. (Okun, 1977; Santala et al., 1998). Based on the literature, authors have defined greywater based on the outcome of the water coming from the household, mainly the kitchen (Table 2.1)

Table 2.1: Definitions of greywater used in the Literature

Definition	**Kitchen Included**	**References**
Greywater, which is wastewater produced in the kitchen, laundry, and bathroom, is made up of elements that did not come from the toilet.	Yes	(Greywatersafer.com, 2004)
wastewater, with the exception of food waste from garbage grinders and toilet waste	Partially	(Greywater.com, 2004)
Wastewater from showers, bathtubs, washing machines, and cleaning, mostly including detergents	No	(Wilderer, 2003)
wastewater from laundry facilities, showers, bathtubs, hand basins, and kitchen sinks that does not contain toilet waste.	Yes	(Ottoson and Stenstrom, 2003)
Wastewater created in bathtubs, showers, hand basins, laundry machines, and kitchen sinks in homes, offices, and schools is equivalent to wastewater produced without any input from toilets.	Yes	(Eriksson et al., 2002)
the waste from bathrooms, showers, sinks, laundry rooms, and kitchens; waste from water closets and urinals is particularly excluded. Unless dirty clothes or baby napkins are rinsed in washing tubs or basins, greywater often does not contain human feces.	Yes	(Queensland, 2002) (Australian/ New Zealand Standard AS/NZS 1547: 2000 "On-site domestic wastewater management")
wastewater from laundry rooms, kitchen sinks, dishwashers, washing machines, and showers.	Yes	Ledin et al., 2001a
All wastewater produced in the home, excluding toilet waste, is referred to as graywater. It may originate from a home's washing machine, shower, tub, or sink.	Yes	(Casanova et al., 2001)
Wastewater from washing, dish, bath water and the like.	Yes	(Gunther, 2000)
Bathtub, shower, washbasin, laundry tub, clothes	Yes	(Del Porto and

washer, kitchen sink, and dishwasher water are all sources of graywater.		Steinfeld, 2000)
Grey wastewater (grey water) from bathrooms, washing machines and kitchens with little nutrients.	Yes	(Otterpohl et al., 1997)
Wastewater from buildings excluding that fraction discharged from the WC.	Yes	(Dixon et al., 1999)
All wastewater from non-toilet plumbing devices in the house is referred to as greywater. It is not advised to use kitchen greywater as a source of greywater.	No	(Christova Boal et al., 1996)

In addition to this, greywater could be used to develop and preserve wetlands (Otterpohl, Albold, & Olgenburg, 1999). Infiltrating grey wastewater into the earth is an alternate approach of manage it, which essentially creates a shortcut in the urban hydrological cycle. However, it is essential to minimize groundwater contamination caused by microbes and pollutants present in greywater. Table 2.1 shows the greywater sourced from different origins used for characterization and treatment.

The characteristics of greywater are shaped by the quality of the water supply, the distribution system, and the various uses of the water. These characteristics can differ based on the source, local conditions, and lifestyle factors, such as the use of household chemicals. The composition of greywater also varies with location and over time due to variations in water usage and the effects of chemical and biological degradation within the plumbing network. Greywater treatment can be categorized based on the principles of its treatment methods, which include physical, chemical, and biological systems. These methods can be used individually or in combination, with varying proportions of each depending on the specific treatment needs. (Li *et al.*, 2009; Ghunmi *et al.*, 2011; Boyjoo *et al.*, 2013). Most of the time, treatments are done in a set of steps which include pre-treatment, main treatment, and post-treatment as explained in Figure 2.1.

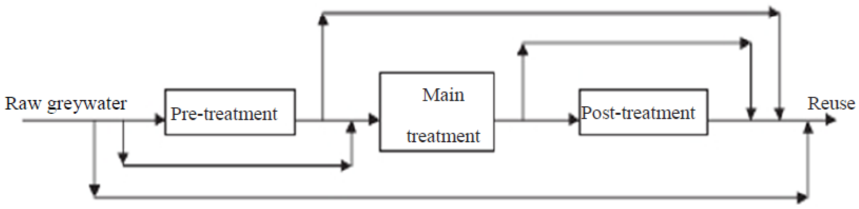


Figure 2.1: Greywater recycling and treatment: possible steps and tracks [Ghunmi *et al.* (2011)]

Greywater's primary physical characteristics are its color, temperature, turbidity, and suspended particles. Warm temperatures have the potential to promote microbial development and precipitation, while particulates from sources like restrooms and kitchens may clog treatment or transportation systems. Greywater's alkalinity, hardness, and the soil's inherent buffering ability all affect the pH and buffering capacity of the soil. Conventional wastewater measurements such as nutrient levels, COD (chemical oxygen demand), and BOD (biochemical oxygen demand) provide crucial information about the organic matter in greywater and its ability to produce sulfur dioxide (Figure 2.2).

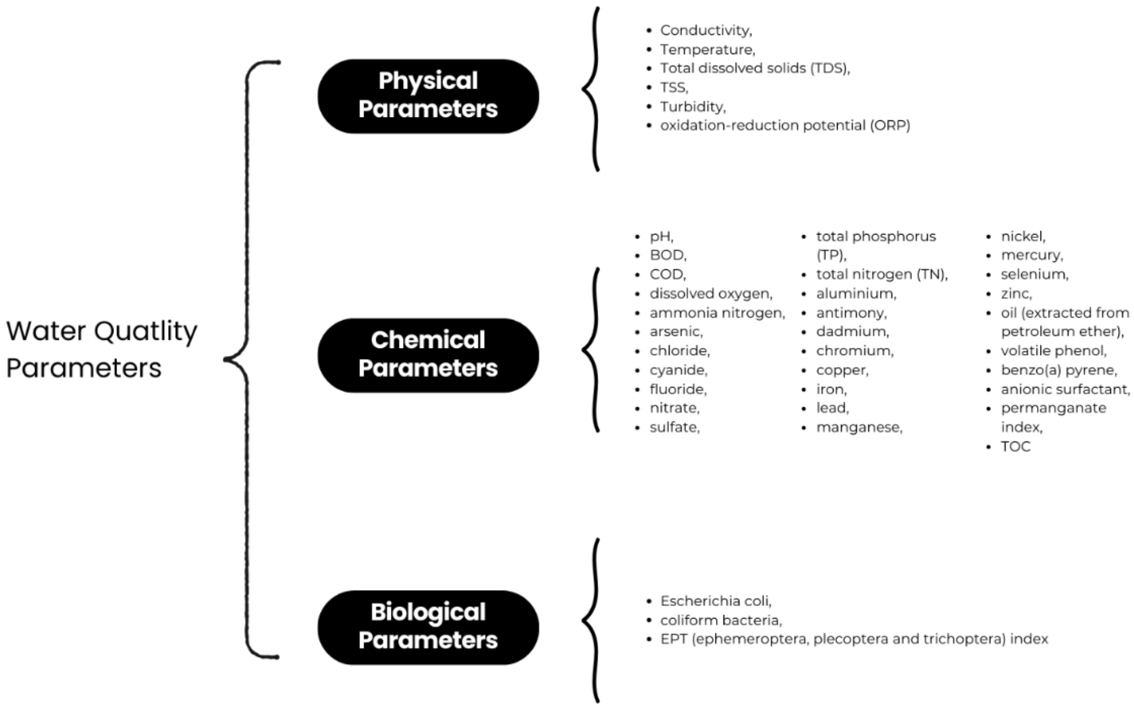


Figure 2.2: The most prevalent water quality standards for all general designated use categories

Figure 2.3 (Li et al., 2009) reports the number of research and scientific articles on the treatment, reusability, and application of greywater, highlighting a range of technologies varying in complexity, performance, and efficiency. Over the past 17 years, the number of publications on this topic has steadily increased, with greywater treatment accounting for nearly 69% of all research in the field, according to data from the Web of Science database. Despite the growing interest from the scientific community, there are still very few technologies available for evaluating the performance of these systems (Li et al., 2009). Additionally, cost-effective treatment methods remain underdeveloped, with no new technologies emerging in this area so far (Jabornig and Podmirseg, 2015).

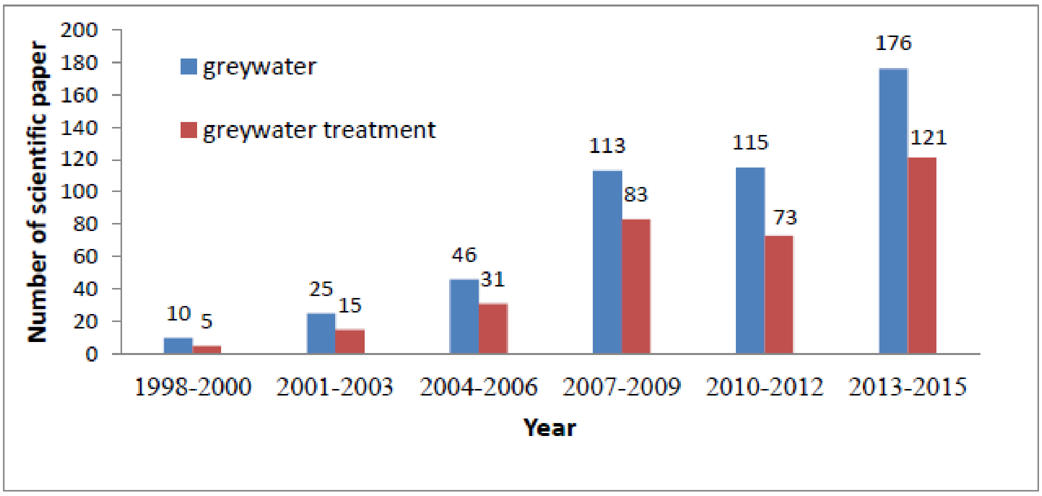


Figure 2.3: Number of published papers in the Web of Science database

2.1 Greywater Management: Assessing Quality and Treatment Strategies

Reliable data on greywater generation and quality is essential for determining appropriate treatment systems and reuse options. Using content tables from common household chemicals, a study by Eriksson et al. (2002) identified nine hundred distinct xenobiotic organic compounds (XOCs) that may be present in grey wastewater. This underscores the complexity of greywater composition and the necessity for tailored treatment approaches. (Jamrah et al., 2006) evaluated the potential for greywater availability and identified various components constituting greywater sources in Amman. The study investigated multiple water quality parameters of greywater to assess its reuse potential, providing critical insights into the local context. Commercial and custom-constructed greywater systems have been reported, with commercial systems often being prohibitively expensive for small-scale applications. (Ahmed et al., 2008) aimed to develop a cost-effective, low-maintenance treatment system for small to medium-sized mosques, highlighting the need for affordable solutions in resource-constrained settings. (Aizenchtadt et al., 2009) analyzed the long-term performance of three pilot-scale greywater treatment systems using novel statistical methods, emphasizing input-output deviation statistics crucial for on-site reuse. This analysis offers useful information about the performance and dependability of the system over long stretches of time. The utilization of two distinct up-flow anaerobic sludge blanket reactors as a primary treatment step was examined by (Abdel-Shafy et al., 2009). Constructed wetlands were then used to treat greywater and blackwater independently. The study found that total suspended solids (TSS), biological oxygen demand (BOD), and chemical oxygen demand (COD) were all removed at high rates.recommending this combination as an effective treatment system. (Comino et al., 2013) presented a study designing, realizing, and analyzing a functional hybrid phytoremediation pilot platform. The vegetated system demonstrated significant COD reduction at an organic loading rate of approximately 31 g COD/m²/d, indicating the potential of vegetation to enhance treatment efficiency. (Ushijima et al., 2013) evaluated the performance of a slanted soil system for greywater treatment in terms of water quality requirements for irrigation reuse. The study found that fine soil (1–4 mm) effectively reduced Escherichia coli and MS2 phage, while coarse soil did not. However, fine soil experienced clogging after 3–5 weeks, which could be extended to 8 weeks by combining coarse and fine soil chambers.

Table 2.2: Physical and chemical properties of greywater and their reasons for concern

Constituent	**Reasons for Concern**
Suspended solids	Absorbs heavy metals and organic pollutants Protect microbes from UV and other disinfectants Overdosing may result in systems plugging in.
BOD, COD, TOC	Give microorganisms nourishment, and their population will grow. Color and odor issues might result from food degradation.
Nutrients (N, P)	In surface waters, excessive discharge can cause eutrophication.
pH	Water pH affects disinfection, coagulation, metal solubility as well as soil alkalinity
Heavy metals (e.g., Cd, Zn, Ni and Hg)	Can accumulate in the environment and are toxic to flora and fauna
EC/total dissolved solids (TDS) (due to specific elements	Specific ions such as chloride, sodium and boron are toxic to some plants When EC <500 – no detrimental effects on plants

such as Na, Ca, Mg, Cl, and Ba)	When EC ¼ 500–1,000 – can affect sensitive plants When EC ¼1,000–2,000 – can affect many crops and careful management practice should be followed When EC >2,000 – can be used only for tolerant plants on permeable soils
Residual chlorine	Excessive amounts of free residual chlorine (<0.05 mg L1) can be damaging to some sensitive crops (leaf burn) Chlorination of high organic loads of water can form carcinogenic chloroforms or other halogenated organics

Several studies have explored various treatment methods for greywater to ensure it meets regulatory standards for reuse in irrigation. (Abdel-Shafy et al., 2014) demonstrated that using a sand filter as a secondary treatment step for primary sedimented effluent was effective. (As highlighted in Table 2.2) During their study, gravel filters operating in both down flow and up flow configurations were used with an influent flow rate of 173 $m^3/m^2/d$. The final effluent, treated with both gravel and sand filters, complied with the National Regulatory Standards for treated effluent reuse in irrigation. (do Couto et al., 2015b) investigated greywater reuse in airports, presenting a case study from Brazil. They evaluated an anaerobic filter system followed by ultraviolet disinfection. Their findings underscored the feasibility of such systems in high-traffic environments. (Zipf et al., 2016) studied the efficiencies of simplified treatments for greywater reuse using slow sand and slow slate waste filtration over a 28-week monitoring period. Parameters analyzed included pH, turbidity, apparent colour, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and surfactants. The average removal efficiencies for turbidity, apparent colour, COD, and BOD were 61%, 54%, 56%, and 56%, respectively, for the sand filter. Both systems were effective in removing surfactants (approximately 70%) and maintaining a pH of around 7.80. Statistical analysis indicated no significant differences between the performance of the two systems. (Lam et al., 2017) developed an eco-efficiency analysis framework integrating life-cycle assessment and economic analysis to evaluate different water systems in Hong Kong. Their results identified the anaerobic fluidized bed membrane bioreactor for greywater reuse as the most ecoefficient option. This system not only facilitated energy recovery and water recycling but also reduced sewage treatment loadings.

Table 2.3: Tertiary Treatment: Current and potential applications of technology in water and wastewater treatment

Applications	**Representative nanomaterials**	**Desirable nanomaterial properties**	**Enabled technologies**
Adsorption	Carbon nanotubes	Many interactions between contaminants and CNTs, a sizable specific surface area, readily evaluable adsorption sites, modifiable surface chemistry, and convenience of reuse	Contaminant pre-concentration /detection, adsorption of recalcitrant contaminants
	Nanoscale metal oxide	Compressible without significantly reducing surface area, easy to reuse, high specific surface area, short intra-particle diffusion distance, more adsorption sites, and some superparamagnetic properties	Adsorptive media filters, slurry reactors
	Nanofibers with core-shell structure	Short internal diffusion distance, reactive core for degradation, and tailored shell surface chemistry for selective adsorption	Reactive nano-adsorbents
Membranes and membrane processes	Nano-zeolites	Molecular sieve, hydrophilicity	High permeability thin film nanocomposite membranes
	Nano-Ag	Strong and wide-spectrum antimicrobial activity, low toxicity to humans	Anti-biofouling membranes
	Carbon	Antimicrobial activity	Anti-biofouling

	nanotubes	(unaligned carbon nanotubes)	membranes
		Small diameter, atomic smoothness of inner surface, tunable opening chemistry, high mechanical and chemical stability	Aligned carbon nanotube membranes
	Aquaporin	High permeability and selectivity	Aquaporin membranes
	Nano-TiO2	Photocatalytic activity, hydrophilicity, high chemical stability	Reactive membranes, high-performance thin film nanocomposite membranes
	Nano-magnetite	Tunable surface chemistry, superparamagnetic	Forward osmosis
Photocatalysis	Nano-TiO2	Low human toxicity, great stability, low cost, and photocatalytic activity in the UV and perhaps visible light range	Photocatalytic reactors, solar disinfection systems
	Fullerene derivatives	High selectivity and photocatalytic activity in the sun spectrum	Photocatalytic reactors, solar disinfection systems
Disinfection and microbial control	Nano-Ag	Strong and wide-spectrum antimicrobial activity, low toxicity to humans ease of use	POU water disinfection, anti-biofouling surface
	Carbon nanotubes	Antimicrobial activity, fibre shape, conductivity	POU water disinfection, anti-biofouling surface
	Nano-TiO2	Photocatalytic ROS generation, high chemical stability, low human toxicity and cost	POU to full-scale disinfection and decontamination
	Quantum dots	wide absorption range, narrow, steady, bright emission that varies with the chemical component and	Optical detection

Sensing and monitoring		particle size	
	Noble metal nanoparticles	Enhanced localized surface plasmon resonances, high conductivity	Optical and electrochemical detection
	Dye-doped silica nanoparticles	High sensitivity and stability, rich silica chemistry for easy conjugation	Optical detection
	Carbon nanotubes	Large surface area, high mechanical strength and chemical stability, excellent electronic properties	Electrochemical detection, sample pre-concentration
	Magnetic nanoparticles	Tunable surface chemistry, superparamagnetic	Sample pre-concentration and purification

In mesocosm-scale stabilization ponds in Salford, artificially produced ochre pellets were utilized to treat synthetic greywater that was both highly and minimally contaminated. (Abed and others, 2017). Two large-scale greywater recycling systems were used to monitor the untreated greywater quality. Referred to in Table 2.3. The efficacy of a decentralized hybrid treatment system that combines greywater and rainwater was evaluated in the study. With its multimedia filter (MMF), granular activated carbon filter (GAC), and ozone disinfection, this pilot-scale system exceeded Malaysia's allowable limits for total coliforms in irrigation waters (Class IV) and recreational waters with body contact (Class IIB). Furthermore, it was commonly discovered that untreated greywater was tainted with faecal particles, since 20 out of 32 samples had positive Escherichia coli tests. (Leong and others, 2018). In a peri-urban area of a developing country, the amount and quality of greywater from families with an internal water supply and those depending on external sources were examined. The findings showed that the average water consumption for households with in-house access was 82.51 ± 12.21 litres per person per day. (Oteng-Peprah et al., 2018a). A proposed method was tested in the Rio Mannu Basin (Sardinia, Italy) for evaluating durum wheat production. The Soil and Water Assessment Tool (SWAT) model was used to assess the fraction of nutrients entering the river and groundwater. Significant uncertainty was observed, with 60% for dissolved inorganic nitrogen and 18% for total phosphorus (TP). The environmental sustainability of durum wheat production across the basin was also evaluated. (De Girolamo et al., 2019). (such as those detailed in Table 2.4) Greywater was treated naturally using ornamental plant species, which can be vertically integrated into green building designs. Column experiments were conducted to test various regional ornamental plants and growing media. The results showed that the choice of media played a more significant role in treatment performance than plant selection. The removal rates of hydrophilic and hydrophobic organics were evaluated, and specific ultraviolet (UV) absorbance measurements of the effluent indicated that more toxic compounds were effectively removed from the system. (Pradhan et al., 2019) The treatment of light greywater using *Chlorella vulgaris* was investigated. Microalgae were cultivated in both raw greywater and samples diluted by 30% with tap water. After 19 days of cultivation, the microalgae were removed from the media through centrifugation. (Table 2.3) The removal efficiencies for COD, BOD_5, TN, and TP were determined. The results indicated maximum remediation efficiencies of 92.3% for chemical oxygen demand (COD), 91.9% for BOD_5, 85.6% for total nitrogen (TN), and over 97% for total phosphorus (TP). Microbiological analysis also confirmed that the treated water could be safely used for toilet flushing. (Oktor & Çelik, 2019).

2.2 Technological Innovations in Grey Water Disinfection

Greywater reuse offers a promising solution to alleviate water scarcity in regions globally. This section provides a comprehensive review of recent studies and advancements in greywater treatment technologies, emphasizing their effectiveness, challenges, and potential applications. (Winward et al., 2008) conducted a critical assessment of common pathogens present in greywater and evaluated the performance of various treatment technologies in removing these pathogens. Their study highlighted chlorine as a primary disinfectant for greywater, focusing on its effectiveness in inactivating total coliforms. The findings underscored the impact of organic matter and particles on chlorine disinfection efficiency, crucial for ensuring the safe reuse of greywater. (Chong et al., 2010) introduced a multi-variable optimization approach to enhance the performance of photooxidation processes in greywater treatment. Their research explored photomineralization and photo-disinfection kinetics, providing detailed models to optimize operation parameters.

This approach represents a significant advancement in maximizing process efficiency and ensuring the effective removal of contaminants through photocatalytic water treatment technologies. (Ghunmi et al., 2011) investigated efficient treatment strategies for greywater, focusing on characteristics, reuse standards, technology performance, and costs. They recommended a combined anaerobic-aerobic process as an effective, simple, and economically viable solution for greywater treatment. The study highlighted that integrating disinfection as an optional step further enhances the safety and quality of treated greywater for reuse purposes.

The aim of (De Gisi et al., 2016a) is to provide an overview of the state-of-the-art in greywater reuse at the building level, addressing (i) greywater characteristics and the quantities produced, (ii) relevant recycling guidelines, (iii) treatment systems and reuse technologies, including the removal of micropollutants such as xenobiotic organic compounds, and (iv) a review of case studies from developed countries. By adopting an integrated water-energy approach, it becomes possible to enhance water efficiency for energy applications, such as cooling and heating systems.

The technology employed demonstrated satisfactory performance, significantly reducing the BOD and COD of the effluent to 69 mg/L and 98 mg/L, respectively. The objective of the system was to (Debnath et al., 2019) The objective of the system is to recycle and reuse the treated effluent for purposes such as washing and toilet flushing. (Figure 2.4) Enhancing drinking water quality in rural areas of developing countries necessitates a paradigm shift towards unconventional, innovative water disinfection strategies that are cost-effective, easy to implement and maintain, and require minimal infrastructure. (Chu et al., 2019). Give an explanation of the physicochemical characteristics and molecular disinfection mechanisms of the four types of disinfectants that can be produced by sunlight harvesting: strong oxidants, gentle oxidants, heat, and germicidal UV radiation. Greywater, which accounts for a large amount of domestic wastewater, is a viable alternative water supply when handled appropriately. (Prajapati et al., 2019) The objective was to test a full-scale version of a novel compact greywater treatment technology, which utilizes passive aeration and particle trapping in multiple layers. Other notable work includes... (Collivignarelli et al., 2017).

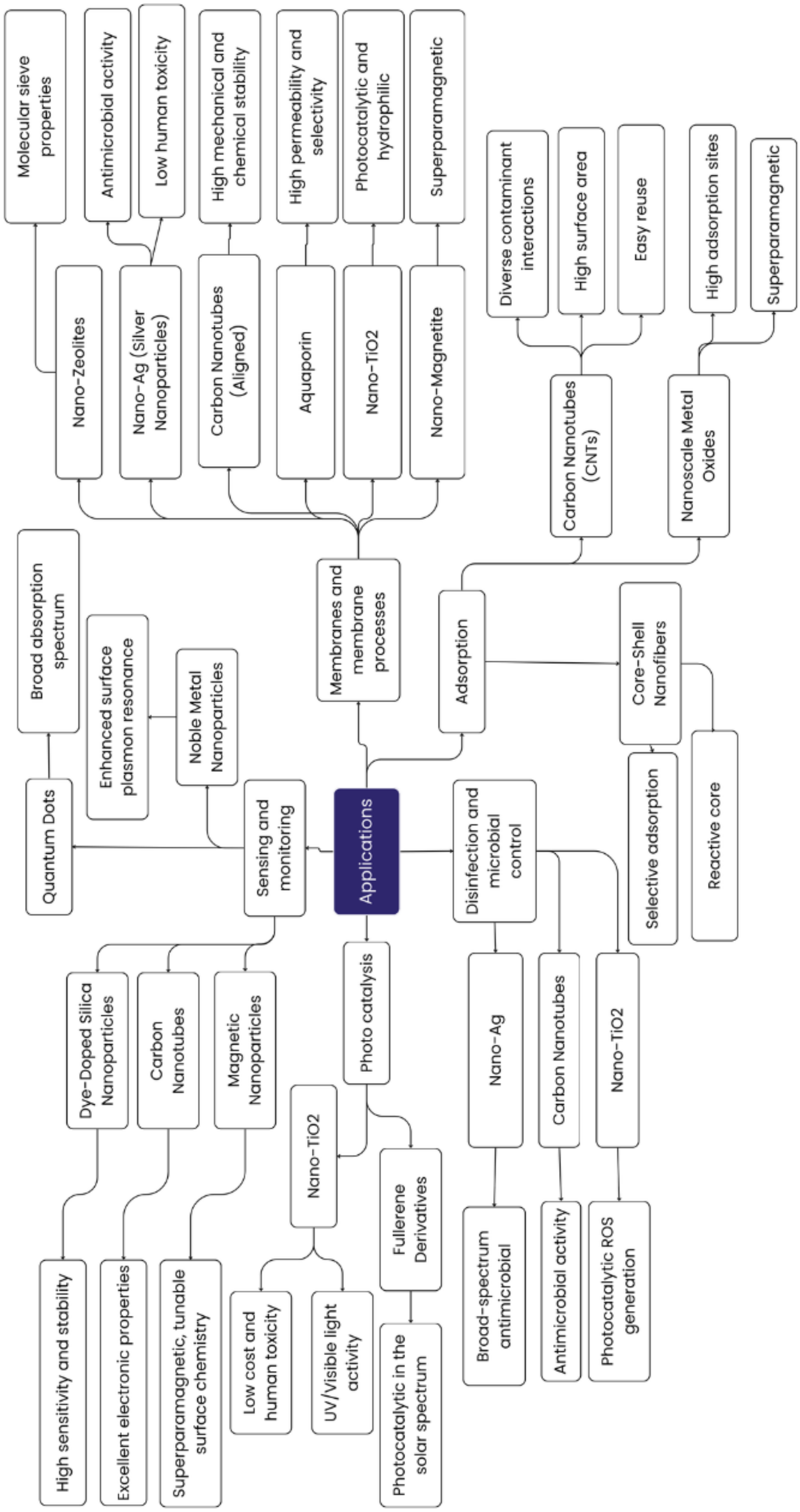


Figure 2.4: Examples of GW treatment systems being used around the world

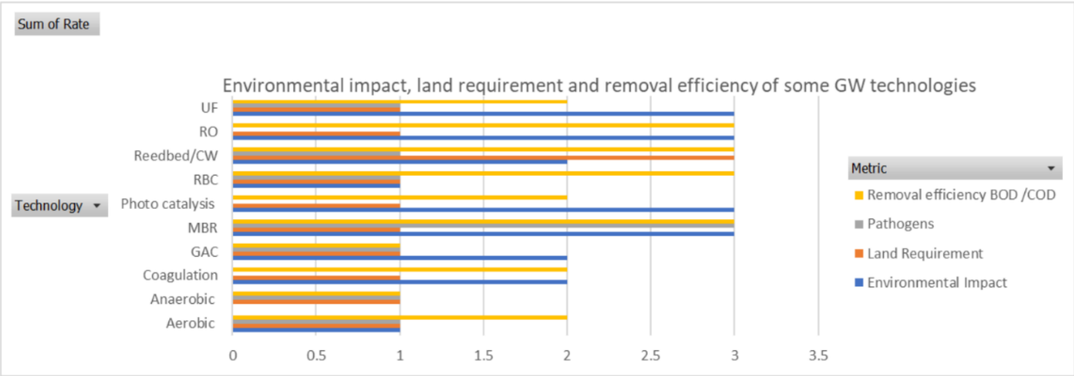


Figure 2.5: Some GW technologies' effects on the environment, land requirements, and removal efficiency..+: <50%, ++: 50–80%, +++: >80%, NDL: Non-Detectable Limits reached in effluent [Ghaitidak and Yadav, 2013]

2.3 Evaluating the Feasibility of Integrated Greywater Management Systems

The feasibility analysis of greywater treatment has been a focal point of numerous studies, reflecting its growing significance in sustainable water management. (Otterpohl et al., 1997) conducted a pioneering pilot project in Germany, demonstrating the practicality of an integrated system that utilized vacuum toilets and specialized pipes for blackwater collection. This study challenged the conventional reliance on centralized wastewater treatment plants, suggesting alternative sanitation solutions. (Nnaji et al., 2014) evaluated the performance and economic viability of a straightforward greywater treatment system. Their findings indicated substantial savings in water expenditures, supporting the financial benefits of such installations. Similarly, (Molinos-Senante et al., 2010) underscored the critical role of economic research in water resource management, as advocated by the European Water Framework Directive, highlighting the need for cost-effective water management strategies. (Dakua et al., 2016) focused on the potential of greywater recycling in urban areas facing water scarcity. Their study utilized constructed wetland processes for quantitative analysis of greywater recycling, demonstrating its feasibility in mitigating urban water shortages. (Abdalla et al., 2021) performed an eco-efficiency analysis of integrated grey and blackwater management systems, comparing various treatment alternatives to assess both financial feasibility and environmental impacts. Their research emphasized the need to balance economic and environmental considerations in the evaluation of water treatment systems. Further expanding on this theme, (Liang et al., 2018) discussed the importance of comprehensive risk assessment in large engineering projects, including water treatment facilities. Their work on risk evaluation for waste incineration projects provided valuable insights into the necessity of rigorous risk management practices in the development and operation of water treatment infrastructures. (Hashim et al., 2020) developed a strategic decision framework aimed at sustainable wastewater treatment and management in oil-producing regions (Table 2.4). Their study highlighted the imperative for sustainable alternatives in water and wastewater treatment, particularly in regions with significant industrial activity.

Table 2.4: Summary of Case Studies on Feasibility of Integrated Greywater Management Systems

Study	Focus	Key Findings	Applications
(De Gisi et al., 2016b)	Greywater reuse in buildings	- Mini-review of guidelines, technologies, and case studies related to greywater reuse. - Characteristics of greywater, recycling guidelines, and treatment systems. - Highlighted limited use of non-conventional technologies for water recycling in buildings.	Greywater recycling in residential and commercial buildings.
(Alvisi & Franchini, 2010)	Calibration of water distribution systems	- Proposed a calibration procedure using grey numbers to estimate pipe roughness under uncertain conditions. - Assumed nodal head measurements under different demand conditions.	Optimization of water distribution system performance.

		- Utilized grey numbers to account for uncertainty in the calibration process.	
(Zhou et al., 2006)	Forecasting electricity demand	- Introduced a trigonometric grey prediction approach for electricity demand forecasting. - Combined traditional grey model GM(1,1) with trigonometric residual modification. - Enhanced accuracy of electricity demand forecasts and provided a reasonable grey prediction interval.	Electricity demand forecasting and decision-making.
(Wu et al., 2014)	Grey system theory and modelling	- Presented a non-homogeneous discrete grey model with fractional-order accumulation. - Demonstrated superior performance in terms of model fitting and forecasting through real case studies. - Contributed to the advancement of grey system theory with a novel modelling approach.	Diverse applications in grey system theory, including practical case studies.
(Jeong et al., 2018)	Greywater Reclamation System	Reduced non-potable water demand in single-family houses (17-49%) and multi-family apartments (6-32%). Reduced electricity consumption by 17-49% in single-family houses and 32-	Single-family houses, multi-family apartments, water and energy conservation.

		41% in multi-family apartments.	
(Marinoski et al., 2018)	Potable Water Savings	Potential potable water savings of 21% with greywater recycling, up to 42.9% when combined with water-efficient equipment and rainwater collection. Greywater and water-efficient equipment significantly reduced domestic water use by 36.8%.	Potable water conservation, domestic water use reduction, sewage reduction.
(Kobayashi et al., 2020)	Greywater Reuse and Treatment Systems	High-quality effluent from membrane bioreactors is suitable for multiple non-potable applications. Constructed wetlands outperformed membrane bioreactors at community and neighbourhood scales.	Non-potable applications, community and neighbourhood scale greywater treatment.
(Coutinho Rosa & Ghisi, 2020)	Financial Analysis of Rainwater Tanks	Achieved 51.6% potable water savings with a 5,000-liter rainwater tank. Estimated payback period of five years and three months.	Rainwater harvesting, potable water savings, financial feasibility.
(Leong et al., 2019)	Hybrid Rainwater-Greywater Systems	Hybrid systems achieved the highest mains water savings (55.3%) and lowest environmental impact scores. The financial viability of decentralized rainwater harvesting at USD 2.00/m3, is not financially attractive at a	Decentralized rainwater harvesting, environmental impact reduction, financial analysis.

		6% discount rate over 50 years.	

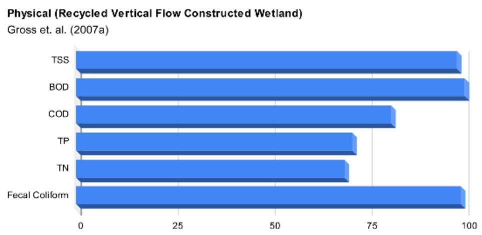
2.4 Gray Water Reuse: Innovations, Applications, and Future Prospects

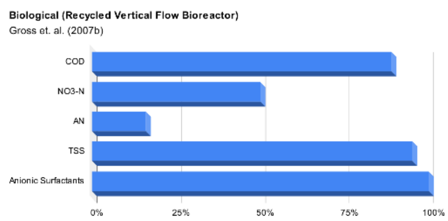
Greywater reuse has been identified as a potential solution to alleviate water scarcity issues in various regions. Studies have shown that overdependency on groundwater resources can lead to excessive pressure on aquifer systems and the deepening of groundwater tables (Drewes et al., 2012). To address this issue, research has been conducted on the reuse of grey water generated from different domestic sources to reduce daily water demand in cities like Dhaka (Biswas et al., 2012). Furthermore, the integration of greywater reuse with other alternative water resources, such as seawater, has been explored to maximize water availability in coastal areas. For example, a study conducted at the Hong Kong International Airport examined the feasibility of integrating seawater toilet flushing with greywater reuse to create a sustainable triple-water supply system (Leung et al., 2012). In addition to domestic applications, greywater reuse has also been studied for agricultural purposes. A survey conducted in the Jordan Valley revealed insights into community attitudes towards using greywater for irrigation, highlighting motivations, practices, and concerns related to greywater treatment and reuse (Al-Mashaqbeh et al., 2012). Moreover, research has focused on the quality of reclaimed water and compliance issues in the context of increasingly stringent regulatory requirements. Studies have explored innovative approaches, such as membrane treatment followed by managed aquifer recharge, for indirect potable reuse in countries like Belgium (Drewes et al., 2012; Malek & Nor, 2013). Overall, the literature emphasizes the importance of greywater reuse as a sustainable water management strategy, offering potential solutions to water scarcity challenges in various regions. Studies have highlighted the need for innovative approaches, regulatory compliance, and community engagement to promote the effective implementation of greywater reuse systems (Table 2.5).

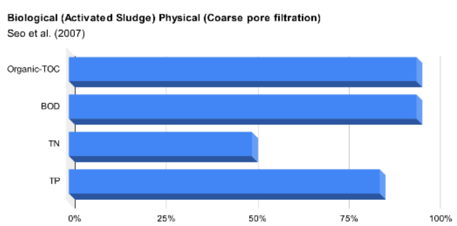
Table 2.5: Summary of Case Studies on Gray Water Reuse

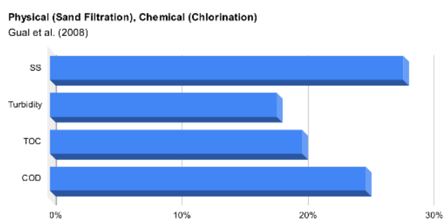
Authors & Year	Description and Contribution of the Research	Focus	Key Findings	Applications
Santos et al. (2012)	Experimental greywater treatment systems showed potential for recovery due to simplicity, low cost, and easy maintenance. High reduction in SS, COD, and BOD; no coliforms detected in treated samples.	Greywater treatment system	High reduction in SS, COD, and BOD; absence of coliforms in treated greywater samples.	Residential, institutional, and small-scale applications
Khor et al. (2020)	The approach resulted in approximately 57% savings in freshwater compared to nominal requirements.	Water conservation	Significant freshwater savings (57%) compared to traditional usage patterns.	Residential and commercial water conservation practices
Wheatley & Surendran (2008)	Recycled water quality achieved 3 mg/L BOD; UV disinfection ensured compliance with UK guidelines for microbial indicators. Users couldn't differentiate recycled water from mains water after 5 years.	Recycled water quality	Low BOD levels (3 mg/L); successful compliance with UK microbial guidelines; user acceptance after long-term use.	Urban landscaping, non-potable water supply

Aizenchtadt et al. (2009)	Light greywater quality was found unsuitable for direct reuse, highlighting the need for treatment. High variability in raw greywater quality. Removal efficiency is high for turbidity, BOD, and TSS.	Greywater treatment and variability	Unsuitability of untreated light greywater for reuse; significant variability in raw greywater quality.	Treatment systems for light greywater, emphasizing variability management
Pinto & Maheshwari (2010)	Growing adoption of greywater reuse in Western Sydney. Concerns include plumbing costs and health risks to people, plants, and soil.	Public perception and environmental awareness	Increasing adoption of greywater reuse; concerns over plumbing costs and health risks.	Household and community-level greywater reuse, environmental education initiatives









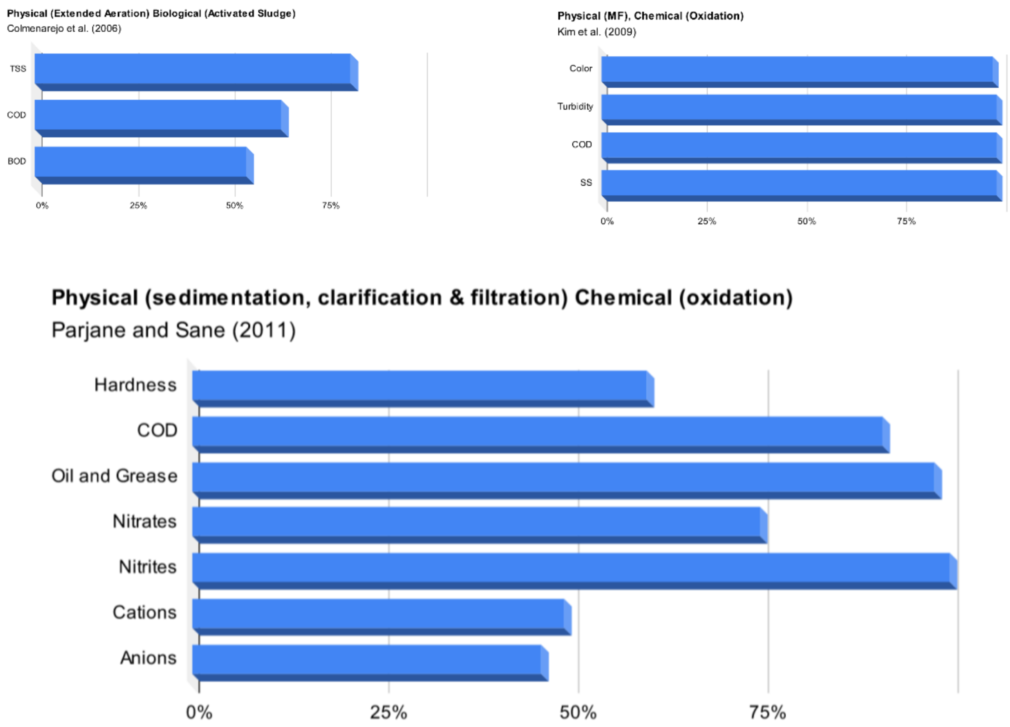


Figure 2.6: Comparison of the performance of the Greywater Treatment Technology and their efficiency for the removal of various parameters

2.5 Economic Viability of Grey Water Reuse: Global Case Studies

Grey water, which refers to wastewater generated from domestic activities such as hand-washing, showering, and laundry, has gained attention as a potential resource for reuse in various applications, particularly irrigation. Several case studies have been conducted to explore the feasibility and effectiveness of reclaiming and reusing grey water. (Khan et al., 2013) investigated the biological effects of hand-washing grey water for reuse in irrigation on an urban farm.

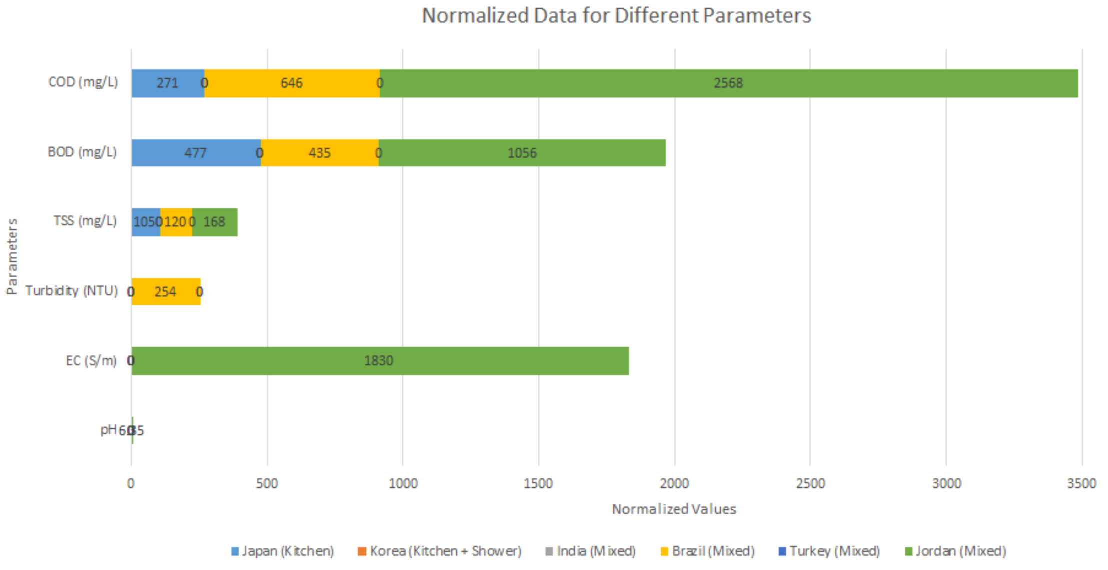


Figure 2.7: Comparative Analysis of Greywater Characteristics Across Global Regions

The study provided useful information for designing a future water treatment system for the reuse of greywater in irrigation and illustrated a novel method for evaluating the biological impact of greywater. Similarly, (Gabarró et al., 2013) focused on greywater treatment at a sports centre for reuse in irrigation using sequencing batch reactor (SBR) technology. The study highlighted the applicability of SBR technology in producing effluent suitable for irrigation purposes. (Keely et al., 2015) characterized the bacterial composition of grey water from various sources, shedding light on the relative importance of human- and infrastructure-associated bacteria in grey water. This study utilized high-throughput sequencing to identify the bacterial composition of greywater, contributing to a better understanding of greywater quality. (Gharbia et al., 2016) evaluated wastewater post-treatment options for reuse in agriculture, emphasizing the importance of sand filtration and Soil Aquifer Treatment (SAT) systems. The study ranked sand filtration with textured geo-membrane higher than the SAT system for wastewater reuse in agriculture. (Wang et al., 2016) focused on alleviating water scarcity in rural arid areas through grey water treatment and reuse, with a specific case study in Palestine. The study highlighted the potential of greywater treatment and reuse in mitigating water scarcity in arid regions. (Martínez-Alcalá et al., 2018) addressed the pharmaceutical grey water footprint, accounting for the grey component of the water footprint for common pharmaceutical compounds. The study emphasized the importance of wastewater treatment plants and direct reuse of treated wastewater in irrigation. Overall, these case studies provide valuable insights into the reclaiming and reusing of grey water for various purposes, including irrigation and water scarcity alleviation. By exploring different treatment technologies and assessing the quality of grey water, these studies contribute to the sustainable management of water resources and the promotion of water reuse practices.

Further section provides an extensive overview of recent research and developments in the field of greywater reuse and management, highlighting various studies and their findings from different geographical locations. (Figure 2.7) In Jordan, Faruqui & (Faruqui & Al-Jayyousi, 2002) conducted a pilot project in Tufileh, Jordan, allowing the use of untreated household greywater for house gardens. They assessed the quality of untreated greywater and its impacts on soil and crops through an environmental impact assessment, suggesting potential changes with larger volumes of greywater use. In Brazil, (Ghisi & Ferreira, 2007a) evaluated the potential for potable water savings in multi-storey residential buildings in Florianópolis, Brazil, using rainwater and greywater. Their study utilized questionnaires and water flow measurements to assess water end use, alongside an economic analysis to determine the cost-effectiveness of rainwater and greywater use. Kuwait, (Abusam, 2008) discussed the current status and potential for greywater reuse, highlighting economic and political considerations. The study emphasized the potential shift towards greywater reuse amidst challenges such as oil reserve depletion and high desalination costs. In China, (Zhang et al., 2009) studied water management at Tianxiu Garden in Beijing, focusing on decentralized approaches. They explored the feasibility of substituting drinking water with rainwater harvesting and demonstrated the efficiency of recycling treated greywater for toilet flushing. In Indonesia, (Henriques & Louis, 2011) developed a capacity factor-based classification for technology options in Cimahi, Indonesia, validating their findings through requirements analysis. Their study was published in the International Journal of Water Economics, contributing to technology selection for greywater management. In Syria, (Mourad et al., 2011) proposed artificial wetlands and commercial biofilters for treating greywater in Sweida, Syria, highlighting economic analyses that showed significant drinking water savings through treated greywater use. In China (Daxing New City, Beijing), (Zeng et al., 2013) presented a centralized greywater reuse system for Daxing New City, Beijing, using separate greywater and black-water discharge pipes. Their water supply balance analysis indicated a potential conservation of 28.5% of freshwater resources. In Brazil (University of São Paulo), (Chrispim & Nolasco, 2017a) evaluated a greywater collection and treatment system for non-potable reuse at the University of São Paulo, focusing on washing machines, showers, and other sources. Their pilot system provided insights into the collection and characterization of greywater. In Brazil (Southern Brazil), (Marinoski & Ghisi, 2019a) applied Life Cycle Analysis to assess the environmental performance of hybrid rainwater-greywater systems in residential buildings in southern Brazil. Their methodological approach contributed to understanding the sustainability of integrated water systems. In China (Life Cycle Impacts), (Liao et al., 2019) quantified China's electricity demands' life-cycle impacts on water quality using the Grey Water Footprint indicator. Their findings provided crucial insights for policymakers in managing water resources associated with energy production. In Canada (Niagara Region, Ontario), (Johnson & Mehrvar, 2019) presented a method for assessing the grey water footprint associated with winery wastewater co-treated with municipal wastewater in Ontario's Niagara Region.

Table 2.6: Summary of Case Studies on Economic Viability of Grey Water Reuse

Authors & Year	Focus	Key Findings	Applications
(Ghisi & Ferreira, 2007b)	Cost-effectiveness of water reuse systems	The greywater system demonstrated the shortest payback period (less than 8 years) compared to rainwater systems. Cost savings were significant, making greywater the most cost-effective option.	Residential, commercial, and institutional buildings; Cost-effective water reuse systems.
(Marinoski & Ghisi, 2019b)	Environmental and resource savings	Hybrid rainwater-greywater systems offered potential potable water savings (41.9%), domestic sewage reduction (40%), and energy consumption	Residential buildings in southern Brazil; Sustainability assessment of integrated water

		reduction (36.1%) compared to conventional systems.	systems.
(Chrispim & Nolasco, 2017b)	Microbial and organic pollutant removal	Showers exhibited higher E. coli concentrations, while lavatories had higher total coliform concentrations. Removal efficiencies were 59% for BOD and 70% for chemical oxygen demand in greywater.	Pilot studies; Characterization and treatment of greywater from showers and lavatories.
(Faruqui & Al-Jayyousi, 2002)	Socio-economic impacts of greywater reuse	Households in Jordan reduced food expenditures by using greywater for garden irrigation, saving up to 44% of income for the poorest families.	Jordanian households; Socio-economic benefits of greywater reuse in garden irrigation.
(Ahmed et al., 2008)	Compliance and economic feasibility	Both custom-made and commercial greywater treatment systems met government regulations. Internal rates of return (IRR) for mosque installations were 14.9% and 19.06%, respectively, indicating economic feasibility.	Institutional buildings (mosques); Compliance with regulations and economic viability of systems.

(Zhang et al., 2009)	Rainwater harvest(Zhang et al., 2009)ting for water substitution	Rainwater harvested from residential rooftops substituted 25.4% of toilet-flushing water in buildings. Limited savings potential due to seasonal rainfall patterns in Beijing (85% rainfall from June to September).	Residential buildings in Beijing; Effectiveness of rainwater harvesting for toilet-flushing water.
(Mourad et al., 2011)	Greywater production and reuse in urban areas	Average greywater production in Syrian urban areas was 46% of total water consumption. Significant adoption of untreated greywater (laundry water) for irrigation and house cleaning. Savings up to 600 m3/year for residential blocks.	Urban areas in Syria; Utilization and potential savings from greywater reuse in residential blocks.

2.6 Research Gaps

Despite significant advancements in the study and application of greywater reuse systems, several critical research gaps remain. These gaps highlight the need for further investigation to optimize the performance, safety, and applicability of greywater treatment systems in diverse settings.

Key research gaps identified from the literature include:

1. *Pollutant-Specific Removal Processes:* The literature highlights the significant influence that a pollutant's physical, chemical, and biological characteristics have on the predominant removal process associated with it. (Revitt et al., 2011). However, there is a lack of comprehensive studies

detailing the specific removal mechanisms for a wide range of common pollutants found in greywater. This understanding is crucial for designing effective treatment systems tailored to varying pollutant profiles.

2. *Impact on Domestic Wastewater Quality and Quantity:* Studies like (Penn et al., 2012) have shown that light greywater reuse can reduce household wastewater flows by 25–40%, predominantly during peak usage times. Nonetheless, there is limited research on the long-term impacts of greywater reuse on domestic wastewater characteristics, particularly concerning the proportional concentration increase of pollutants and the overall balance of wastewater composition.
3. *Sewer System Modifications:* While (Penn et al., 2013) demonstrated that greywater reuse could lead to decreased flow, velocity, and proportional depth in sewers, primarily during peak hours, further research is needed to understand the implications for sewer system design comprehensively. Specifically, there is a need for detailed guidelines on constructing new sewer systems with smaller pipe diameters to accommodate reduced flow rates without increasing blockage risks.
4. *Health Risks and Epidemiological Studies:* (Busgang et al., 2015) conducted an epidemiological survey revealing no significant difference in the prevalence of water-related diseases between greywater and potable water users. However, additional longitudinal studies are required to confirm these findings across different populations and environmental conditions. The need for robust, long-term health monitoring to validate the safety of greywater reuse practices remains critical.
5. *Quantitative Microbial Risk Assessment (QMRA):* (Shi et al., 2018) employed QMRA to estimate public health risks associated with greywater reuse for toilet flushing and food-crop irrigation. Despite these efforts, there is a gap in integrating these risk assessments into regulatory frameworks effectively. More research is needed to refine QMRA methodologies, incorporating a broader range of exposure scenarios and behavioural patterns to ensure comprehensive risk mitigation.
6. *Comprehensive Field Studies:* Most studies to date have relied on simulation models and controlled experiments. There is a paucity of large-scale, real-world implementations and field studies that can provide empirical data on

the performance and impact of greywater reuse systems under diverse environmental and operational conditions. Such studies are essential to validate theoretical models and refine practical guidelines for greywater reuse.

7. *Economic and Environmental Trade-offs:* While several studies have explored the economic feasibility of greywater systems (e.g., (Ghisi & Ferreira, 2007b)), there is a need for more integrated assessments that consider both economic and environmental trade-offs. This includes evaluating the lifecycle costs and benefits, energy consumption, and broader environmental impacts to inform sustainable decision-making.

Summary

This chapter delves into a comprehensive literature review and technology assessment of greywater management, focusing on various facets such as quality assessment, treatment strategies, technological innovations, feasibility studies, economic viability, and research gaps. The chapter begins with an in-depth exploration of greywater quality and the different strategies employed for its treatment. This section outlines the various contaminants typically found in greywater and reviews the effectiveness of existing treatment methods, including physical, chemical, and biological processes.

The discussion then shifts to technological innovations in greywater disinfection. This segment highlights cutting-edge technologies that have emerged in recent years, such as advanced oxidation processes, membrane bioreactors, and electrochemical treatments. These innovations are critically assessed for their efficiency, scalability, and applicability in different contexts, providing a clear understanding of the current state-of-the-art in greywater treatment technologies.

Following the technological assessment, the chapter evaluates the feasibility of integrated greywater management systems. This involves examining the integration of greywater treatment with other water management practices, such as rainwater harvesting and blackwater treatment. The feasibility study considers both technical and logistical aspects, offering insights into the potential benefits and challenges of implementing such integrated systems in urban and residential settings.

The chapter also reviews the latest innovations and applications of greywater reuse, exploring various real-world implementations and their outcomes. This section highlights successful case studies from around the world, showcasing diverse applications of treated greywater, including irrigation, toilet flushing, and industrial processes. Prospects for greywater reuse are discussed, emphasizing the need for continued research and development to enhance the efficiency and sustainability of these practices.

Economic viability is another crucial aspect covered in this chapter. By analyzing global case studies, the chapter provides a detailed examination of the cost-effectiveness of greywater reuse systems. It discusses the initial investment, operational costs, and potential savings, offering a balanced view of the economic implications of adopting greywater reuse practices.

Finally, the chapter identifies key research gaps in the field of greywater management. Despite the advancements and successful implementations, there are still areas that require further investigation. These gaps include the long-term performance of treatment systems, the impact of greywater reuse on public health, and the development of standardized guidelines and regulations. By highlighting these gaps, the chapter sets the stage for future research directions and underscores the importance of continued innovation and policy development in greywater management.

CHAPTER 3

CHARACTERIZATION OF UNTREATED GREYWATER

CHAPTER 3

This chapter provides an in-depth analysis of untreated greywater to understand its physical, chemical, and microbiological characteristics. Greywater, which includes wastewater from showers, bathtubs, hand basins, and laundry activities, contains various constituents that influence its treatment and reuse potential. Understanding these constituents is essential for designing effective greywater treatment systems (Figure 3.1).

The qualities of the water source, the kind of greywater and drinking water distribution system, and the particular applications of the water all affect the features and attributes of greywater. Depending on where it comes from, local lifestyles, customs, and the use of chemical household goods all have an impact on the content of greywater. Due to variations in water intake and the release of different compounds, its composition might vary greatly depending on the time and place. Additionally, chemical and biological degradation of compounds can occur within the transportation network and during storage (Figure 3.2).

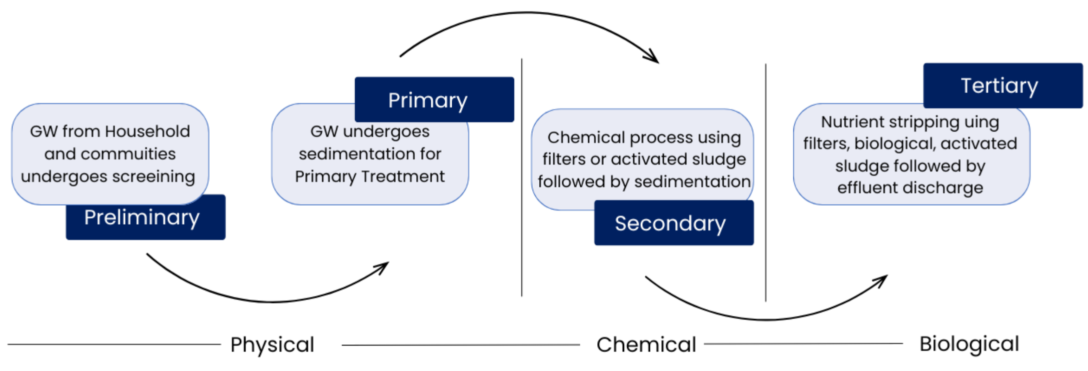


Figure 3.1: Greywater treatment process (Primary, Secondary and Tertiary Treatment)

Relevant physical parameters include temperature, colour, turbidity, and suspended solids content. High temperatures can be problematic as they promote microbial growth and may lead to precipitation (e.g., calcite). Suspended particles from kitchen, laundry, and bathroom sources contribute to greywater in the form of hair, soil particles, fibres, etc. Measurements of turbidity and suspended solids provide insights into the presence of particles and colloids that may cause clogging in systems such as piping or sand filters used for treatment. Although the amount of solids in greywater is generally lower than in combined wastewater, the risk of clogging issues should not be overlooked. Additionally, the impact of infiltrating greywater on soil pH and buffering capacity will depend on the alkalinity, hardness, and pH of the water being infiltrated.

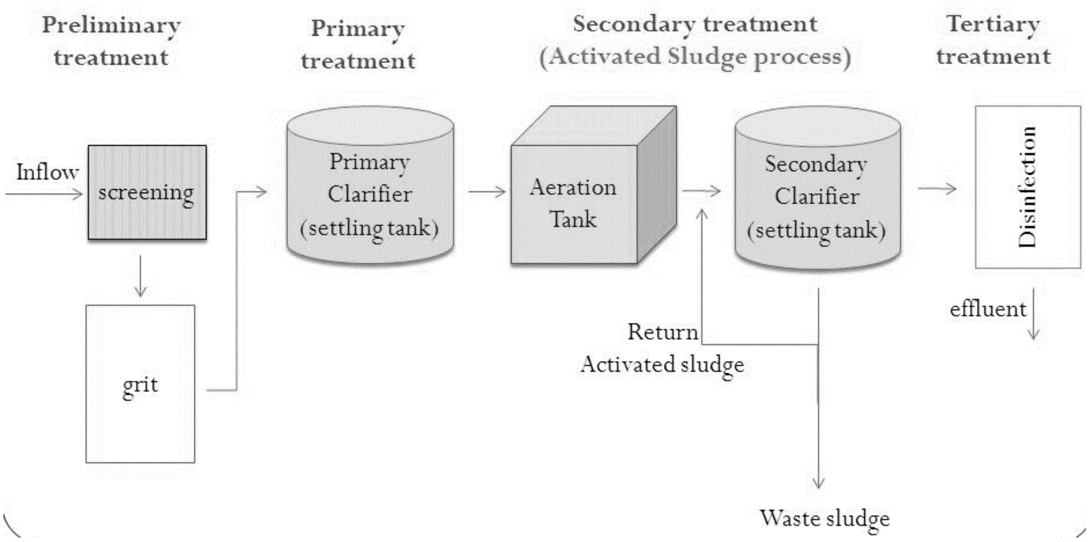


Figure 3.2: Greywater Treatment System (Primary, Secondary and Tertiary Treatment)

The soil's innate ability to act as a buffer will, however, also have an impact on the consequences that are detected. As a result of infiltration, soil characteristics pertaining to pollutant sorption capacity will shift. In addition, alkalinity and hardness measurements, like suspended particles and turbidity, might reveal information about the likelihood of clogging. The quality of the drinking water has a major role in determining these characteristics, and the addition of chemicals during water usage usually has a little effect. Measurements of traditional wastewater parameters, such as BOD, COD, and nutrient concentrations (N and P), are also valuable. The BOD and

COD levels in greywater indicate the amount of biochemically and chemically oxidizable organic matter, which affects the risk of sulfide production during transport and storage. These parameters are essential for the proper categorization of greywater (Figure 3.3)

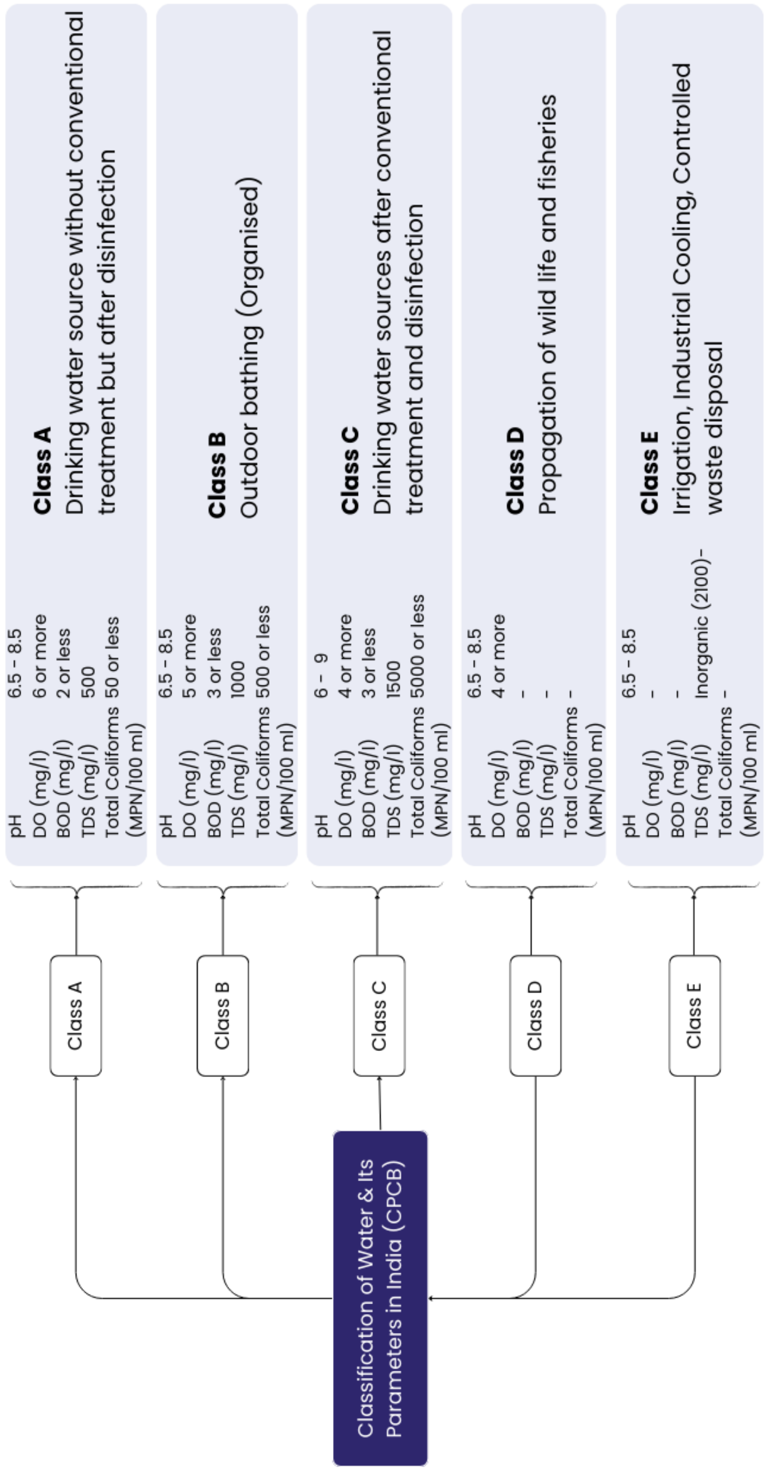


Figure 3.3: Classification of Waters & Its Parameters in India: CPCB

Table 3.1: Physical and chemical properties of greywater and their reasons for concern

Constituent	Reasons for Concern
Suspended solids	Absorbs heavy metals and organic pollutants Protect microbes from UV and other disinfectants Overdosing may result in systems plugging in.
BOD, COD, TOC	Give microorganisms nourishment, and their population will grow. Color and odor issues might result from food degradation.
Nutrients (N, P)	In surface waters, excessive discharge can cause eutrophication.
pH	Water pH affects disinfection, coagulation, metal solubility as well as soil alkalinity
Heavy metals (e.g., Cd, Zn, Ni and Hg)	Can accumulate in the environment and are toxic to flora and fauna
EC/total dissolved solids (TDS) (due to specific elements such as Na, Ca, Mg, Cl, and Ba)	Certain ions, including sodium, boron, and chloride, are harmful to certain plants • When EC <500, plants are not negatively impacted • When EC ¼ 500–1,000–may have an impact on delicate plants • When EC is between 1,000 and 2,000, it might impact numerous crops, hence cautious management techniques need to be used. Use only for tolerant plants on permeable soils when the EC is more than 2,000.
Residual chlorine	Certain crops that are susceptible to high levels of free residual chlorine (<0.05 mg L1) may suffer harm, such as leaf burn. Chlorinating water with high organic content can produce halogenated organic compounds, such as hazardous chloroforms.

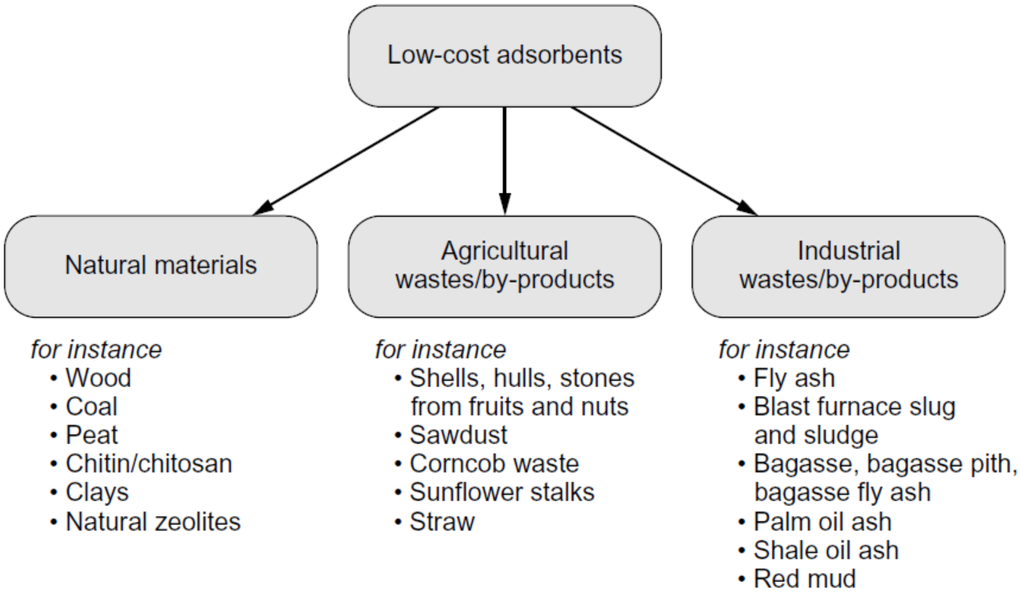


Figure 3.4: Low-cost adsorbents for the GW Treatment process.

The analysis is structured into three main categories:

1. *Physical Constituents:* This section examines the physical properties of greywater, such as turbidity, temperature, colour, and suspended solids. These attributes affect the initial treatment processes and the overall efficiency of the treatment system.
2. *Chemical Constituents:* This section focuses on the chemical composition of greywater, including organic and inorganic compounds. Parameters such as pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), nutrients (nitrogen and phosphorus), and the presence of detergents and other household chemicals are analyzed to understand their impact on treatment processes and potential environmental effects.
3. *Microbiological Constituents:* This section explores the microbiological profile of greywater, identifying the types and concentrations of microorganisms present. Pathogenic bacteria, viruses, and other microorganisms are assessed to evaluate the health risks associated with greywater reuse and to inform necessary treatment measures to ensure safety.

Table 3.2: Characterization of GW based on physical, chemical, and biological constituents of greywater

S. No	Types of Constituents	Parameters	Range	Description	References
1	Physical Constituents	Temperature	18–35 °C	Influences biological activity and chemical reactions in greywater treatment.	(Prabhakar et al., 2019)
		Turbidity	19–444 NTU	Indicates the presence of suspended particles; affects light penetration and treatment	(Sushmitha et al., 2019)

				efficiency.	
		Electrical Conductivity	14–3000 μS/cm	Reflects the ion concentration in greywater, indicating the presence of dissolved salts.	(Ciabattia et al., 2009)
		Suspended Solids	190–537 mg/L	Particles suspended in water; higher levels can hinder treatment processes.	(Oteng-Peprah et al., 2018b)
2	Chemical Constituents	pH	7.3–8.1	Measure of acidity or alkalinity; essential for maintaining optimal conditions for biological treatment processes.	(Boyjoo et al., 2013)
		Alkalinity	-	Capacity of water to neutralize acids; affects chemical stability and treatment processes.	-
		Nitrates	0.67 mg/L	Nutrients that can cause eutrophication; are important for assessing environmental	(Parjane & Sane, 2011b)

		impact.	
Phosphates	0.131 mg/L	Key nutrient; excessive levels can lead to algal blooms and eutrophication.	(Parjane & Sane, 2011a)
BOD	100–188 mg/L	Indicates the amount of organic matter; higher values require more oxygen for decomposition.	(Oteng-Peprah et al., 2018b)
COD	250–375 mg/L	Measures the total quantity of oxygen required to oxidize organic and inorganic compounds.	(Rakesh et al., 2020)
Chlorides	53 mg/L	Contributes to salinity; affects soil and plant health when used for irrigation.	(Prabhakar et al., 2019)
Oil and Grease	7 mg/L	Indicates contamination from kitchen and personal care products; hinders biological treatment processes.	(Elhegazy & Eid, 2020)
Calcium	32–50 mg/L	Affects water hardness; which is important for plant health when used for	(Sushmitha et al., 2019)

				irrigation.	
3	Biological Constituents	Total Coliforms	1.2×10^3–8.2×10^8 counts/100 mL	Indicator of fecal contamination; important for assessing health risks.	(Alsulaili & Hamoda, 2015), (Dwumfour-Asare et al., 2017), (Mandal et al., 2011a)(Masi et al., 2018)
		E. coli	Up to 6.5×10^6 counts/100 mL	Specific indicator of faecal contamination; crucial for evaluating microbial safety of treated water.	(Atanasova et al., 2017), (Friedler et al., 2006), (Khalaphallah & Andres, 2012), (Kim et al., 2009b), (Oteng-Peprah et al., 2018b)
		Fecal Coliforms	Up to 1×10^6 counts/100 mL	Indicates the presence of pathogenic bacteria; important for health risk assessments.	(Halalsheh et al., 2008), (Mandal et al., 2011b)
		Pseudomonas aeruginosa	1.4×10^4 counts/100 mL	Opportunistic pathogen; relevant for assessing health risks in treated greywater.	(Benami et al., 2015), (Khalaphallah & Andres, 2012)
		Staphylococcus aureus	1.2×10^2–1.8×10^3 counts/100 mL	Pathogenic bacteria; are important for evaluating the microbiological	(Benami et al., 2015),(Benami et al., 2015), (Shoults & Ashbolt, 2017)

		quality of greywater.	
Salmonella typhi	5.4×10³ counts/100 mL	Pathogenic bacteria causing typhoid fever; critical for health risk assessment.	(Kim et al., 2009a)
Salmonella spp.	3.1×10³ counts/100 mL	Pathogenic bacteria; are significant for determining the safety of greywater reuse.	(Oteng-Peprah et al., 2018a)

Table 3.3 provides a detailed summary of the physical, chemical, and biological constituents of greywater, serving as a reference for understanding the comprehensive analysis presented in this chapter.

3.1 Physical Constituents

Greywater, which is generated as a result of cleaning or washing activities, contains various physical constituents such as surfactants. Additionally, greywater can contain volatile solids and contribute to turbidity, chemical oxygen demand (COD), and total suspended solids. Studies have shown that greywater is suitable for concrete production, as it meets the allowable mixing water limits for concrete. Greywater quality is an important factor to consider for reuse potential, as it can impact the physical and mechanical properties of soil when used for irrigation. The physical properties of greywater, such as pH, conductivity, and suspended material, can pose hazards if not properly managed. Different sources of greywater, such as kitchen, laundry, and bathing, have been independently assessed for their physical and chemical properties. It is important to consider the general ranges of common physical, chemical, and microbial water quality constituents for greywater when evaluating its reuse potential. Overall, understanding the physical constituents of greywater is crucial for assessing its reuse potential and ensuring that it does not pose risks to human health or the environment. Studies have shown that greywater can be effectively treated and reused for various applications, contributing to sustainable water resources management.

Researchers (Kim et al., 2009a) conducted experiments to evaluate greywater treatment using a microfiltration and oxidation process at a laboratory scale. The study involved sampling from 170 apartments and accounted for seasonal variations. The treatment system employed an A2O membrane configuration comprising anaerobic, anoxic, and aerobic submerged microfiltration (MF) membranes. Specific reactor volumes included a 2.5 L anaerobic bioreactor, connected via circular columns to an anoxic bioreactor (2 L) and an oxic bioreactor (8 L). Recirculation from the oxic to the anoxic bioreactor was maintained at a 1.5Q internal recycle ratio using a pump. Throughout the 60-day experiment, the total Hydraulic Retention Time (HRT) was controlled at 6 hours (1.2 h for the anaerobic reactor, 0.96 h for the anoxic reactor, and 3.84 h for the oxic reactor). The Food to Microorganism (F/M) ratio ranged from 0.11 to 0.17 kg BOD/MLVSS/d, while Mixed Liquor Suspended Solids (MLSS) were maintained at 4500 mg/L. The membrane module utilized hollow fibres with a pore size of 0.4 µm made from polyvinyl difluoride. Disinfection was achieved through an ozone reactor system incorporating an ozone generator, detector, acrylic reactor, bubble removal equipment, KI solution, and ozone destruction equipment. Optimization experiments were conducted at different ozone contact times (10, 20, and 30 minutes), determining that 2.5 LPM and 7kV were optimal for O2 flow rate and output voltage, respectively, based on efficiency in colour, turbidity, and organic matter removal across nine trials.

In another study conducted by (Ahmadpari et al., n.d.), greywater treatment using a slow sand filter was investigated at Azad University of Behbahan. Greywater samples collected weekly from bathroom sinks were allowed to enter the filter, where they remained for a week before the outlet was opened to discharge treated water at varying loading rates. The results indicated a substantial reduction in suspended solids by 72.8% and turbidity by 67%. The concentration of Chemical Oxygen Demand (COD) in the outlet ranged from 19.15 to 71.45 mg/l, averaging 45.86 mg/l, with a maximum removal efficiency of 71.85% observed in the filter. Biological Oxygen

Demand (BOD) was also significantly reduced, achieving an 89% removal, resulting in a BOD5 measurement of 6.76 mg/l at the filter outlet. The study comprehensively analyzed the characteristics of greywater over several months, plotting graphs that demonstrated the attainment of quality suitable for agricultural use standards in the treated wastewater. The slow sand filter used in the experiment consisted of a fine sand layer with an effective size of 0.3 mm and a thickness of 400 mm, housed in a cylindrical vessel with a diameter of 10 cm and a height of 2 meters. Additionally, a protective layer of coarse sand measuring 300 mm in thickness was positioned beneath the sand bed to safeguard the filter particles during operation.

(Ramona et al., 2004) conducted a study focusing on the physical and chemical characterization of greywater using direct membrane filtration techniques for onsite reuse applications. The research utilized both Ultrafiltration (UF) and Nanofiltration (NF) modules to assess the quality of greywater samples. UF experiments employed a dead-end bench-scale laboratory module featuring a flat sheet membrane sealed with an o-ring on a fret support within a stainless steel module. The module had dimensions of 100 mm outer diameter and 60 mm inner diameter. Results indicated that UF treatment achieved significant reductions in Chemical Oxygen Demand (COD) and turbidity concentrations, ranging from 45-70% and 92-97%, respectively. However, Biochemical Oxygen Demand (BOD) values remained above regulatory limits in all cases. NF permeates demonstrated high quality with rejection rates exceeding 90% for soluble organic matter and 50% for ionic species. Greywater samples were sourced from a public sports centre shower with Total Suspended Solids (TSS) of 29.8 mg/L and COD of 170.3 mg/L. The study concluded that direct dense-membrane filtration, particularly NF, shows promise as an effective method for treating greywater to meet quality standards suitable for unrestricted reuse. The research was based on samples collected from a 200 L holding tank.

Their study, (Al-Jayyousi, 2003) investigated greywater reuse in Jordan, focusing on water sourced from dishwashing, sinks, and laundry, which constitutes approximately 50% of residential wastewater. They observed significant variability in greywater quality, influenced greatly by residence time within systems, which alters its characteristics substantially. The authors implemented simple two-stage filtration and chemical disinfection methods, effectively reducing coliform levels while retaining high turbidity and organic content. However, advanced filtration systems demonstrated improved removal of all greywater components, though achieving consistent compliance with water recycling standards remained a challenge. The decentralized management approach highlighted by the study offers enhanced opportunities for maximizing greywater recycling. Furthermore, the study noted a high Chemical Oxygen Demand (COD) to Biochemical Oxygen Demand (BOD) ratio of up to 4:1, indicating substantial organic pollution in the greywater. The findings underscore the complexities and ongoing efforts in managing and improving greywater quality for effective reuse.

(Pinto et al., 2010) conducted greenhouse experiments to investigate the impact of greywater irrigation on the growth of silver beet plants. Their study compared the effects of irrigating with 100% potable water, 100% greywater, and a 1:1 mixture of greywater and potable water. The greywater used in the experiments had pH and EC values of 10.5 and 1358 μS/cm, respectively. Post-harvest analysis revealed that greywater irrigation did not significantly affect the total nitrogen (N) and total phosphorus (P) content of the soil. However, notable effects were observed on soil pH and electrical conductivity (EC) values, indicating the influence of greywater on these soil properties.

(Mandal et al., 2011c) conducted a comprehensive study on greywater characteristics, focusing on a system implemented in an urban household with a per capita daily water requirement of 165 litres. The system addressed a greywater generation rate of 80 litres per capita per day, employing both upflow and downflow treatment plants comprising screening, sedimentation, filtration, and disinfection processes. The study site, Nagpur, situated at an altitude of 310 meters above sea level (21°06'N latitude, 79°03'E longitude), experiences a predominantly dry and slightly humid climate throughout most of the year, with a severe summer season from March to June where temperatures often exceed 45°C for approximately 30 days. Despite an annual rainfall of about 1200 mm, occurring mainly during the monsoon months from July to September, Nagpur faces water scarcity issues during summer. Water demand for various household purposes was quantified: 96 lpcd for bath and laundry, 17 lpcd for kitchen activities, and 22 lpcd for toilet flushing. The study recommended a design flow rate for filtration of 0.15 m3/m2/h. Mandal et al. estimated potential annual savings of Rs. 2,80,320 lakhs in water charges by utilizing treated recycled greywater for gardening, irrigation, and toilet flushing in the NEERI (National Environmental Engineering Research Institute) colony. The research underscores the critical role of water recycling and conservation in urban settings as a vital contribution to future sustainability efforts.

The temperature of grey wastewater was found to range between 18–38°C, with the higher temperatures attributed to the use of warm water for personal hygiene. This elevated temperature can pose issues by promoting microbiological growth and potentially leading to $CaCO_3$ precipitation, as the solubility of $CaCO_3$ and other inorganic salts decreases at higher temperatures.

Turbidity measurements in laundry water show significant variation throughout the laundry cycle, with the wash cycle exhibiting much higher turbidity (39–296 NTU) compared to the rinse cycle (14–29 NTU). Christova-Boal et al. (1996) observed that the highest turbidity during the wash cycle came from households with extensive outdoor activities. For other sources of greywater, turbidity values ranged from 15.3–240 NTU. Notably, there is a lack of literature on turbidity values for greywater from kitchen sinks. The highest total solids content is found in greywater from kitchen sources.

Table 3.3.: Summary of Physical Constituents

Study Citation	Treatment Method	Key Findings	Experimental Setup
(Ahmadpari et al., n.d.)	Slow Sand Filter	- 72.8% reduction in suspended solids - 67% reduction in turbidity - COD outlet: 19.15-71.45 mg/l (average 45.86 mg/l) - Maximum COD removal efficiency: 71.85% - 89% removal of BOD	- Greywater collected from the bathroom sink - Filter: Fine sand (effective size 0.3 mm, thickness 400 mm) - Cylinder dimensions: Diameter 10 cm, Height 2 meters - Coarse sand layer:

		- BOD5 of 6.76 mg/l at outlet	Thickness 300 mm
(Ramona et al., 2004)	Ultrafiltration (UF) and Nanofiltration (NF)	UF reduced Chemical Oxygen Demand (COD) by 45-70% and turbidity by 92-97%, but Biochemical Oxygen Demand (BOD) remained above regulatory limits. NF achieved >90% rejection of soluble organic matter and >50% rejection of ionic species.	UF: Dead-end bench-scale lab module with flat sheet membrane (100 mm OD, 60 mm ID) in stainless steel module, o-ring sealed, free support. NF: Dense-membrane filtration. Greywater is sourced from the public sports centre shower (TSS: 29.8 mg/L, COD: 170.3 mg/L). Samples were collected from a 200 L holding tank.
(Kim et al., 2009b)	Microfiltration and oxidation process for greywater treatment at laboratory scale.	- Evaluated greywater treatment using A2O membrane configuration (anaerobic, anoxic, aerobic). - Conducted experiments with 170 apartment samples, considering seasonal variations. - Used hollow fibre MF membranes (0.4 µm PVDF) and ozone reactor system for disinfection. - Optimized ozone contact times and operational parameters for efficient colour, turbidity, and organic matter removal.	- Treatment system: A2O membrane configuration (anaerobic bioreactor 2.5 L, anoxic bioreactor 2 L, oxic bioreactor 8 L). - Recirculation: 1.5Q internal recycle ratio from oxic to anoxic bioreactor. - Hydraulic Retention Time (HRT): Total 6 hours (1.2 h anaerobic, 0.96 h anoxic, 3.84 h oxic). - Food to Microorganism (F/M) ratio: 0.11-0.17 kg BOD/MLVSS/d. - Mixed Liquor Suspended Solids (MLSS): 4500 mg/L. - Disinfection: Ozone reactor with optimized O2 flow rate

			(2.5 LPM) and output voltage (7kV).
(Al-Jayyousi, 2003)	Two-stage filtration, chemical disinfection	Greywater from dishes, sinks, and laundry comprises 50% of residential wastewater. Variability in greywater quality noted. Advanced filtration reduces components but challenges in meeting recycling standards.	Greywater quality was assessed under different residence times. Two-stage filtration and chemical disinfection methods were applied. Decentralized management studied. COD ratio up to 4:1.
(Pinto et al., 2010)	100% potable water, 100% greywater, 1:1 mixture of greywater and potable	Greywater irrigation had no significant effect on soil total N and total P after plant harvest.	Greenhouse experiments; Silver beet plants; Greywater with pH 10.5 and EC 1358 µS/cm; Soil pH and EC values affected by greywater irrigation.
(Mandal et al., 2011b)	Upflow and downflow treatment plant including screening, sedimentation, filtration, and disinfection.	Greywater from an urban household with a per capita water requirement of 165 lpcd and a generation rate of 80 lpcd. Nagpur's climate is predominantly dry with severe summers exceeding 45°C for 30 days. Despite 1200 mm annual rainfall, water scarcity occurs during summer. Estimated annual	The study was conducted in Nagpur, located at 310m altitude (21°06'N, 79°03'E). The experimental design included quantification of water demand: 96 lpcd for bath and laundry, 17 lpcd for kitchen, and 22 lpcd for toilet flushing. Design flow rate for filtration set at 0.15 m3/m2/h.

		water charge savings of Rs. 2,80,320 lakhs by using recycled greywater for gardening, irrigation, and toilet flushing.	

3.2 Chemical Constituents

A variety of basic to sophisticated chemical processes, such as precipitation, electromagnetic resin ionization, catalytic degradation, activated granulated carbon, electrode-enhanced UV, and electrolysis, are covered in the literature on greywater (GW) treatment and recycling. This review highlights key research findings to illustrate the evolution of these technologies. (Pidou et al., 2008) investigated the efficacy of precipitation and electromagnetic resin ionization using GW from student residences at Cranfield University, UK. For the coagulation test, 1 L of greywater was added to a container, followed by a coagulant. The sample was emulsified, allowed to settle, and after an hour, the appropriate dosage was determined. The greywater was then mixed with the prepared electromagnetic resin and rinsed with deionized water. While these methods achieved significant organic removal, they did not meet certain national greywater reuse regulations. (Sanchez et al., 2010) conducted a study on hotel greywater using a cylindrical glass photoreactor with a low-pressure mercury lamp in a quartz sleeve, surrounded by a water jacket. The treatment utilized a titanium dioxide (TiO2) photocatalyst, which was effective due to the low dissolved organic carbon (DOC) content in the greywater. (Vuppaladadiyam et al., 2019) explored the use of various metal electrode systems to enhance electrolysis efficiency. Their study evaluated different electrode combinations for removing turbidity (TD), chemical oxygen demand (COD), and biological oxygen demand (BOD) from greywater. The Al–Fe electrode combination demonstrated removal efficiencies of 95% for TD, 85% for COD, and 90% for BOD. The researchers concluded that inter-electrode distance, electrode areas, and electrode couplings (Al–Fe and Fe–Al) are crucial parameters influencing electrode performance.

(Chopra & Sharma, 2013) conducted experiments using a 5L reactor and discovered that optimizing electrode spacing and surface area significantly improved pollutant removal. They determined that a 160 cm2 region with 2.5 cm between electrodes would be the optimal electrode layout, with a system cost of $0.25 per cubic meter. Similar research was conducted in 2014 by Vakil et al., who looked at an electrochemical reactor with aluminum electrodes that removed 70% of COD and 99.9% of microorganisms at 0.3 kWh/m³ of greywater with a potential variation of 12V. The aluminium electrodes demonstrated significant potential for household-scale applications to eliminate pathogens, turbidity, and COD from greywater. Expanding on this research, (Ozay et al., 2018) performed comprehensive tests with various electrode combinations, including aluminum-aluminum (Al–Al), iron-iron (Fe–Fe), aluminum-iron (Al–Fe), and iron-aluminum (Fe–Al). The hybrid Al–Fe electrode configuration was the most effective for COD removal. They evaluated several operational parameters, such as current density, pH, and supporting electrolyte content, to determine optimal conditions. The study reported a reduction in COD from 87.9 to 29.4 mg/L at pH 7 using a current density of 1 mA/cm². Under these optimum conditions, the Al–Fe–Fe–Al electrode configuration consumed 9.46 kWh/m³ of energy. (Barzegar et al., 2019b) demonstrated significant reductions in Total Organic Carbon (TOC) and Chemical Oxygen Demand (COD) from greywater using an electrocoagulation process. They combined electrocoagulation with ozone (EC + O3) and with ozone and ultraviolet light (EC + O3 + UV) electrodes. Their results showed a COD and TOC removal of approximately 70–85% within 60 minutes at pH 7.0 and a current density of 15 mA/cm2. Ozone, when used in conjunction with the electrochemical technique, outperformed other chemical oxidants such as peroxidisulfate (Na2S2O8) and hydrogen peroxide (H2O2). The addition of UV irradiation significantly enhanced the performance of the EC/ozone process, achieving TOC and COD removals of 87-95%. Moreover, the EC + O3 + UV method effectively eliminated 4 logs of Total Coliforms (TC) and 96% of E. coli, with costs calculated at $1.9/m3 for EC + O3 and $4.03/m3 for EC + O3 + UV.

Recent advancements in chemical treatment methods have been noted. (Çalışkan et al., 2021) investigated a UV-A-enhanced electrocoagulation technique using aluminium and iron electrodes in a hybrid reactor. Their study reported an 88–97% elimination of COD and turbidity with aluminium electrodes at pH 7.4 and 3 mA/cm2 in the presence of 1 g Na2SO4/L electrolyte within a 40-minute reaction time. Under optimal conditions, iron electrodes achieved 79% COD removal and 99% turbidity reduction. The study also examined the presence of total nitrogen, phosphate, suspended solids, and BOD5, highlighting the effectiveness of the method. The study demonstrated removal efficiencies of 62-88% with aluminium (Al) electrodes and 78-98% with iron (Fe) electrodes. Conversely, UV-A irradiation had a negligible impact on the treatment process. Chemical oxygen demand (COD) and turbidity were effectively reduced, while biological oxygen demand over five days (BOD) was rapidly decreased to meet the reclaimed water standards established by the United States Environmental Protection Agency (USEPA). These findings are crucial for advancing simple, mobile, and low-cost greywater treatment systems, particularly for onsite use in small dwellings, rural areas, and military settlements. Improvements in existing chemical treatment methods, including alternative electrode combinations or the use of innovative nanomaterials, could further enhance greywater reclamation efforts. The separate collection and treatment of greywater present a sustainable long-term strategy to prevent the contamination of potable water sources, especially in remote areas, commercial and residential establishments, and during emergencies. Table 3.2 provides an overview of the major chemical treatment technologies employed for greywater treatment.

Table 3.4: Comparative Analysis of chemical treatment technologies for greywater for Various Parameters

Chemical Treatment Technologies	**Parameter**	**Inlet Concentration**	**Outlet Concentration**	**Reduction**	**References**	**Additional Notes**
Photocatalytic oxidation	COD (mg/L)	139–660	30–60	Significant	(Badawy et al., 2009)	High efficiency in COD reduction.
	Total coliform (CFU/100 mL)	10^6	ND	Complete		Effective disinfection capability.

Electrocoagulation + disinfection	COD (mg/L)	55	22	Moderate	(Altenbaher & Turk, 2009)	Combination treatment for enhanced performance.
	BOD (mg/L)	23	9	Significant		
	TSS (mg/L)	29	9	Significant		
	Turbidity (mg/L)	29	9	Significant		
	Total coliform (CFU/100 mL)	5100	ND	Complete		
Coagulation + sand filter + GAC	COD (mg/L)	280	20	High	(García & Moreno, 2009)	Multi-stage treatment process.
	BOD (mg/L)	195	10	High		
	TSS (mg/L)	–	–	–		
	Turbidity (mg/L)	35	<5	Significant		
	Total coliform (CFU/100 mL)	–	–	–		
Magnetic ion exchange resin	COD (mg/L)	791	272	Moderate	(Mergen et al., 2008)	Effective for specific contaminants.
	BOD (mg/L)	205	33	Significant		

	TSS (mg/L)	–	–	–		
	Turbidity (mg/L)	46.6	8.1	Significant		
Coagulation with aluminium salt	COD (mg/L)	791	272	Moderate	(Pidou et al., 2008)	Similar performance to magnetic ion exchange resin.
	BOD (mg/L)	205	33	Significant		
	TSS (mg/L)	–	–	–		
	Turbidity (mg/L)	46.6	8.1	Significant		
	Total coliform (CFU/100 mL)	–	–	–		
Electrocoagulation + submerged membrane bioreactor	COD (mg/L)	463	51	High	(Bani-Melhem & Smith, 2012)	Enhanced treatment with combined technologies.
	BOD (mg/L)	–	–	–		
	TSS (mg/L)	78	ND	Complete		
	Turbidity (mg/L)	133	4.1	Significant		
	Total coliform (CFU/100 mL)	43×10^4	ND	Complete		

Electrocoagulation with Al (anode)–Fe (cathode) electrode	pH	7.4	7.25	Slight	(Chopra & Sharma, 2013)	Minimal impact on pH, effective contaminant reduction.
	Conductivity (µS/cm)	727.8	–	–		
	TDS (mg/L)	472.5	50	High		
	Turbidity (NTU)	16.34	9.74	Moderate		
	BOD (mg/L)	53.31	27.71	Moderate		
	COD (mg/L)	106.69	60.23	Moderate		
Electrocoagulation with Al electrode	COD (mg/L)	380	160	Moderate	(Vakil et al., 2014)	Simple and effective electrocoagulation setup.
	Turbidity (mg/L)	104	15.6	Significant		
	Total coliform (CFU/100 mL)	9100	<10	Complete		
Al–Fe–Fe–Al	TP (mg/L)	1.07	0.088	Significant	(Sharif et al., 2020)	Effective for multiple parameters.
	TN (mg/L)	11.1	1.87	Significant		
	PO4-P (mg/L)	0.311	0.262	Moderate		

	NO3-N (mg/L)	0.375	0.062	Significant		
	NO2-N (mg/L)	0.067	0.0015	Significant		
	TSS (mg/L)	33.5	0.0012	Significant		
	Turbidity (NTU)	53.4	0.45	Significant		
Photocatalytic fuel cell (PFC)	pH	9.76	–	–	(Kee et al., 2018)	Advanced photocatalytic system for high efficiency.
	ZnO/Zn photoanode COD (mg/L)	1325	55	High		
	CuO/Cu photocathode BOD5 (mg/L)	133	55	Significant		
	Turbidity (NTU)	28.2	88	Increase		Unusual turbidity increase needs investigation.
	NH4+	4.9	75	Increase		An increase in ammonium ions needs attention.
EC/ozone	pH	7.2	7.8	Slight	(Barzegar et al., 2019a)	Combined advanced oxidation

						process.
	COD (mg/L)	460	53	Significant		
	BOD (mg/L)	180	20	Significant		
	TOC (mg/L)	185	53.4	Moderate		
	TDS (mg/L)	3150	2650	Moderate		
	Cl− (mg/L)	780	702	Moderate		
	SO42− (mg/L)	120	107	Slight		
	Anionic surfactant (mg/L)	4.3	<0.05	Significant		
	Turbidity (NTU)	242	20.2	Significant		
	Ammonia (mg/L)	1.1	1.1	None		
	NO3− (mg/L)	5.6	5.5	Slight		
	Total coliforms (CFU/100 mL)	2–5×10^7	1.9–4.1×10^4	Significant		
	E. coli (CFU/100 mL)	2–2.8×10^3	200–500	Significant		
EC/ozone/UV	pH	7.2	8	Slight	(Barzegar et al., 2019b)	Enhanced performance with UV addition.

	COD (mg/L)	460	20	High		
	BOD (mg/L)	180	20	Significant		
	TOC (mg/L)	185	23.4	Moderate		
	TDS (mg/L)	3150	2700	Moderate		
	Cl− (mg/L)	780	712	Moderate		
	SO42− (mg/L)	120	104	Slight		
	Anionic surfactant (mg/L)	4.3	<0.05	Significant		
	Turbidity (NTU)	242	21.3	Significant		
	Ammonia (mg/L)	1.1	0.1	High		
	NO3− (mg/L)	5.6	5.1	Slight		
	Total coliforms (CFU/100 mL)	2–5×10^7	1.5–3×10^3	Significant		
	E. coli (CFU/100 mL)	2–2.8×10^3	50–100	Significant		
UV-A enhanced electrocoagulation (with Al electrode)	pH	7.4	–	–	(Çalışkan et al., 2021)	UV-A enhancement improves performance.
	Conductivity (µS/cm)	571	–	–		

	Turbidity (NTU)	60.2	97	Increase		Unusual turbidity increase requires further study.
	COD (mg/L)	207	182	Slight		
	BOD5 (mg/L)	111	97.68	Moderate		
	TSS (mg/L)	28.7	62	Increase		An unusual increase in TSS needs investigation.
	TN (mg/L)	11	44	Increase		The increase in TN needs further evaluation.
	TP (mg/L)	1.12	98	Increase		Significant increase in TP.
	E. coli (count/100 mL)	2000	100	Significant		
UV-A enhanced electrocoagulation (with Fe electrode)	Conductivity (µS/cm)	571	–	–	(Çalışkan et al., 2021)	UV-A enhancement with Fe electrode.
	Turbidity (NTU)	60.2	99	Increase		Significant increase in turbidity.
	COD (mg/L)	207	79	Moderate		

3.3 Microbiological constituents

Microbiological constituents systems have been extensively employed for greywater (GW) treatment, both as standalone Since the late twentieth century, processes combined with various physical treatment techniques have been increasingly used for greywater management. These methods often integrate biological, chemical, and mechanical systems to enhance the efficiency of water treatment and reuse, addressing the growing demand for sustainable water solutions in urban and rural areas. These systems leverage the natural metabolic processes of microorganisms to degrade organic contaminants, providing an environmentally friendly and sustainable approach to water purification. Among the microbiological constituents methods, membrane-based filtration has emerged as a particularly effective technology for greywater treatment. As detailed in the "Greywater Treatment Technologies" section, membrane-based systems demonstrate significant efficacy in eliminating a wide range of contaminants, including suspended solids, organic matter, and pathogens. The versatility and efficiency of membrane filtration make it a promising solution for the comprehensive treatment of greywater.

This section compiles and analyzes data to evaluate the effectiveness of membrane-based systems in greywater treatment. The analysis includes various configurations and operational parameters of membrane filtration technologies, providing a thorough understanding of their performance and potential applications. Table 3.3 presents a detailed overview of different membrane-based treatment technologies, highlighting their specific capabilities, advantages, and limitations in the context of greywater treatment. The compiled data underscores the potential of membrane-based systems to achieve high-quality effluent suitable for various non-potable uses, thereby contributing to water conservation efforts and sustainable resource management.

Researchers have extensively tested several biological treatment methods for greywater, including Rotating Biological Contactors (RBCs), Sequencing Batch Reactors (SBRs), and Upflow Anaerobic Sludge Blankets (UASBs). Each of these methods offers unique advantages and operates on distinct principles:

1. Rotating Biological Contactors (RBCs): RBCs involve a series of closely spaced, rotating disks that are partially submerged in greywater. As the disks rotate, they alternately expose their surfaces to air and water. This cyclic exposure fosters the growth of microbial biofilms on the disks, which degrade organic pollutants when submerged. The rotation enhances oxygen transfer and improves the efficiency of biological degradation (Eriksson et al., 2010).

2. Sequencing Batch Reactors (SBRs): SBRs are fill-and-draw activated sludge systems for treating greywater. The process occurs in a single reactor with five stages: fill, react, settle, draw, and idle. This method allows for flexible operation and control over the treatment process, making it effective in managing varying greywater loads. SBRs have demonstrated high removal efficiencies for organic matter and nutrients (Hernández-Leal et al., 2011).

3. Upflow Anaerobic Sludge Blankets (UASBs): UASBs treat greywater by promoting anaerobic digestion. Greywater flows upward through a dense blanket of granular sludge, where anaerobic microorganisms degrade organic pollutants. The process produces biogas, which can be collected and utilized as an energy source. UASBs are particularly effective for high-strength greywater with substantial organic content (Eriksson et al., 2010).

Before employing these biological treatments, pre-treatment methods are crucial to enhance the overall efficiency of the system. Common pre-treatment methods include:

- *Sedimentation:* This process involves settling out suspended solids from the greywater, reducing the load on subsequent treatment stages.
- *Septic Tanks:* These tanks provide initial treatment by separating solids from the liquid fraction and promoting anaerobic digestion of settled solids.
- *Screening:* Screening removes large debris and particles, preventing clogging and protecting downstream biological processes (Friedler et al., 2006).

In addition, Membrane biological reactors (MBRs) and various biological processes often incorporate sand filtration and disinfection techniques to achieve the standards required for non-potable water reuse. These integrated systems effectively treat greywater by removing organic matter, suspended solids, and pathogens, making the treated water suitable for applications such as irrigation, toilet flushing, and other nondrinking purposes. Sand filtration provides an additional physical barrier to remove residual suspended solids and microorganisms. Disinfection, typically through chlorination or ozonation, ensures the elimination of pathogenic microorganisms, rendering the treated greywater safe for non-potable applications such as irrigation and toilet flushing. These combined biological and physical treatment methods underscore the potential for greywater reuse, promoting sustainable water management and conservation.

In Rotating Biological Contactors (RBCs), a series of disks are mounted on a horizontal shaft, which rotates slowly, ensuring that the disks are alternately exposed to air and submerged in the greywater. This cyclical immersion promotes the growth of microorganisms on the surface of the disks, leading to the formation of a biofilm. The biofilm comprises a diverse community of bacteria, protozoa, and fungi, which thrive in the oxygen-rich environment provided during the aeration phase of the rotation.

As the disks rotate, the biofilm-covered surfaces come into contact with the greywater, allowing the microorganisms to metabolize and break down organic contaminants. The continuous rotation ensures that the biofilm remains active and well-oxygenated, which enhances the microbial degradation of organic matter. The efficiency of this process is further supported by the physical agitation caused by the rotating disks, which prevents clogging and ensures uniform exposure of the biofilm to the greywater.

The design of RBCs allows for a high surface area for microbial attachment while maintaining low energy requirements due to the slow rotation of the disks. This makes RBCs a cost-effective and efficient method for biological greywater treatment, capable of achieving significant reductions in biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Consequently, RBCs represent a viable and scalable option for the sustainable treatment of greywater in various residential and industrial applications.

The effectiveness of integrating microbiological constituents with membrane technologies highlights their robust potential for greywater treatment applications. By synergistically combining these methods, the treatment system achieves enhanced removal efficiencies across a spectrum of contaminants, including organic matter, pathogens, and suspended solids. This comprehensive approach not only elevates water quality standards but also aligns with sustainable water management principles by facilitating the safe reuse of treated greywater in non-potable applications. By mitigating the demand for freshwater resources, these integrated systems contribute significantly to water conservation efforts, addressing critical environmental and societal challenges associated with water scarcity and wastewater disposal in urban settings.

Table 3.5: Comparative Analysis of microbiological constituents technologies for greywater for Various Parameters

Process Name	Experiment Duration	Sampling Location	Sample Number	Parameters	Feed (mg/L)	Permeate (mg/L)	References
Aerobic MBR (pilot-scale)	90 days	Public bathing water	NR	COD, BOD5, TN	99–200, 40–60, 22–4, 21–4	15–20, 3–4, <15, 0.3–0.5	(Jifeng et al., 2008)
Aerobic MBR (pilot-scale)	3 months	Ecological settlement	NR	pH, Turbidity, TOC	7.5±0.5, 140±12, 1115±110	7.2±0.2, 0.5±0.3, 1200±120	(Li et al., 2008)
Aerobic MBR (pilot-scale) Stage-1	25 months	Bathroom	12–84 days	BOD5, COD, TSS	20±11, 87±38, 29±32	1±1, 47±13, ND	(Winward et al., 2008)
Aerobic MBR (pilot-scale) Stage-2	25 months	Bathroom	12–84 days	BOD5, COD, TSS	164±39, 495±192, 93±66	19±2, 53±24, ND	(Winward et al., 2008)

Anaerobic+Anoxic +Aerobic MBR	Over a month	Greywater from building	30 samples	BOD5, TSS, Turbidity	23.5–392.4, 72.5–4250, 152–4400	1.2–7.8, 0–4.3, 0–6	(Kim et al., 2009a)
Aerobic membrane sequencing batch reactor (pilot-scale)	Over 400 days	Synthetic greywater	NR	pH, TDS, Turbidity	7.91±1.02, 286±111, 96.6±87.8	7.89±0.18, 297±90, 5.0±3.1	(Scheumann & Kraume, 2009)
Aerobic MBR (pilot-scale)	10 months	Greywater from building	8–61 samples	Total COD, Dissolved COD, Total BOD5	148±49, 86±27, 95±29	42±32, 1.1±1.7, 4.5–7.8	(Friedler & Gilboa, 2010)
Aerobic MBR (lab-scale)	14 days	Greywater from household	NR	Total COD, Suspended COD, Soluble COD, TSS, TN, TP, Anionic surfactants	598–1014, 158–481, 203–289, 46–254, 12.9–32.3, 5.1–9.1, 40–57	NA	(Leal et al., 2010)

Aerobic MBR (lab-scale)	14 days	Synthetic greywater	4–17 samples	COD, TN, Ammonia, Nitrate, TP, Phosphate	675, 25.31, 0.16±0.39, 9.85±4.30, 0.45±0.00, 0.78±0.55	26.28±5.43, 12.06±2.57, 9.85±4.30, 0, 0.45±0.00, 0.78±0.55	(Huelgas & Funamizu, 2010)

Most greywater from laundry sources is alkaline, with pH values typically ranging from 8 to 10. This is largely influenced by the pH and alkalinity of the water supply. However, the elevated pH observed in laundry greywater also indicates that the use of chemical products plays a significant role. One approach to selecting relevant compounds for monitoring in greywater is to assess data from the characterization of standard household wastewater, as the sources of xenobiotic organic compounds (XOCs) are similar in both types of wastewater. A review of the published literature reveals that approximately 500 different organic and inorganic compounds have been analyzed in domestic wastewater (Paxeus, Robinson, & Balmer, 1992; Paxeus, 1996; Wilkie, Hatzimihalis, Koutoufides, & Connor, 1996 Therefore, it can be concluded that data on greywater characterization is crucial, particularly for assessing its potential for reuse and infiltration. This information is also essential for selecting the most appropriate treatment strategies for recycling raw greywater. However, current studies on the chemical, physical, and biological parameters of greywater are limited due to the scarcity of data and the lack of real-world implementation of these technologies. Much of the research has been focused on the removal of BOD and COD from wastewater, rather than on promoting greywater reuse. The physical and chemical characteristics of greywater from different countries are shown in Figure 3.5.

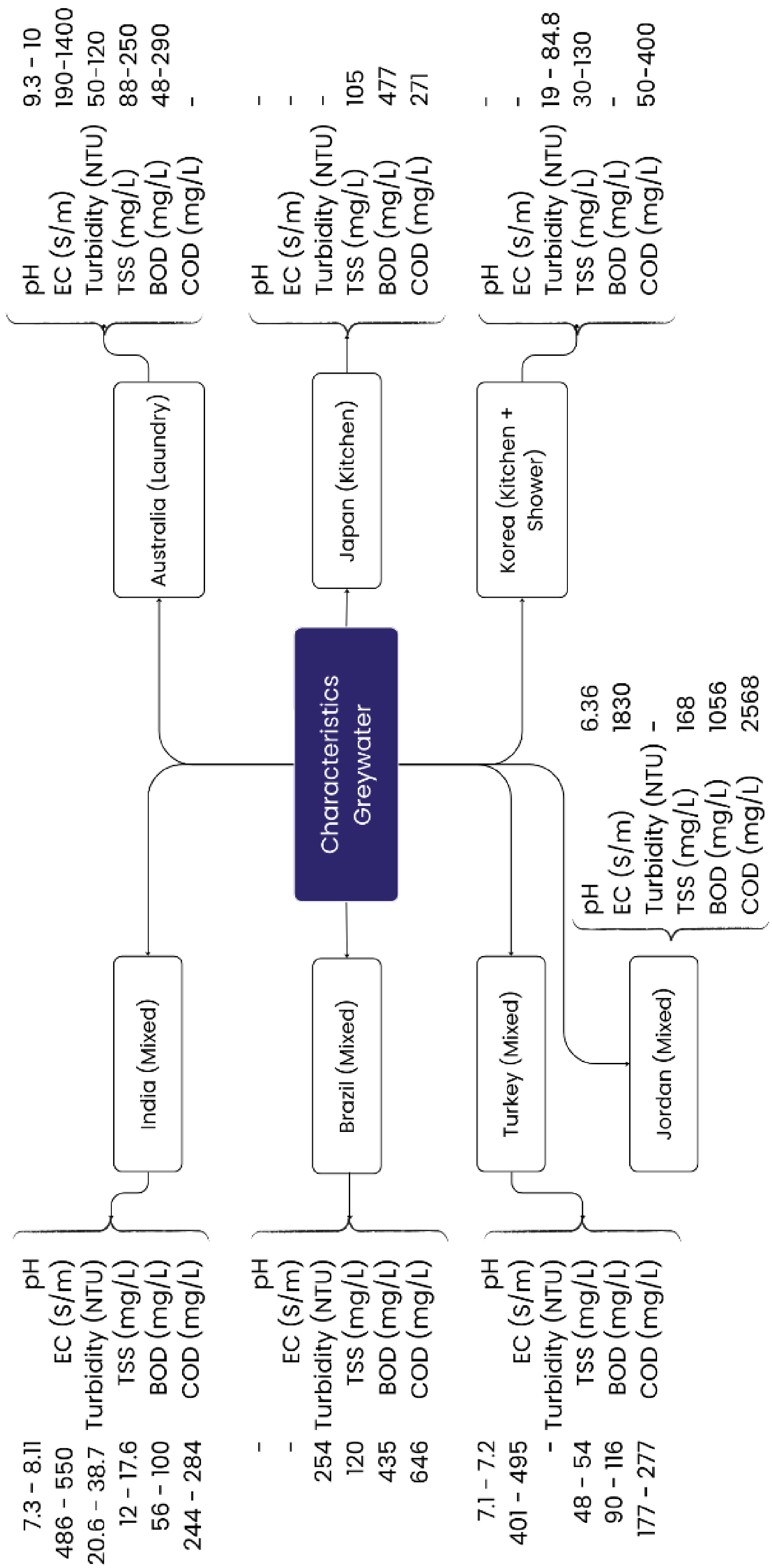


Figure 3.5: The characteristics of dark greywater from specific countries with their greywater resources

Untreated greywater requires proper treatment before storage and reuse. It must meet the highest possible standards of treatment, as it poses significant health risks to both humans and the environment. Whether used directly or indirectly—for cleaning houses, buildings, or for irrigation—greywater should always be given high priority in terms of treatment to ensure it meets stringent parameters (Winward et al., 2008; Li et al., 2009; Ghunmi et al., 2011) (Figure 3.6).

Table 3.6: Status of current techniques in monitoring greywater quality and their limitations

Parameter	**Technique**	**Limitations**
BOD	Non-specific sensor array (electronic nose)	The relationship is source/site-specific and time-dependent further development needed
BOD, COD	Oxidation by hydrogen peroxide with UV light	Range and correlation are dependent on the source, and the measurement intervals are lengthy (~55 min).
OD, COD, TOC, TSS, nitrates and anionic surfactants	UV spectral measurements and multivariate calibration	Sample handling presents challenges; for samples with varied origins, calibration and the acquisition of reference spectra are required.
BOD, nitrates, (TOC and COD)	Optical scattering (fluorescence)	Research is still necessary, temperature and pH have an impact on fluorescence, and the relationship with BOD is sensitive to planting conditions.
BOD	UV adsorption (280 nm)	Poor sensitivity, uses only one wavelength, interferences from particles and toxic metals

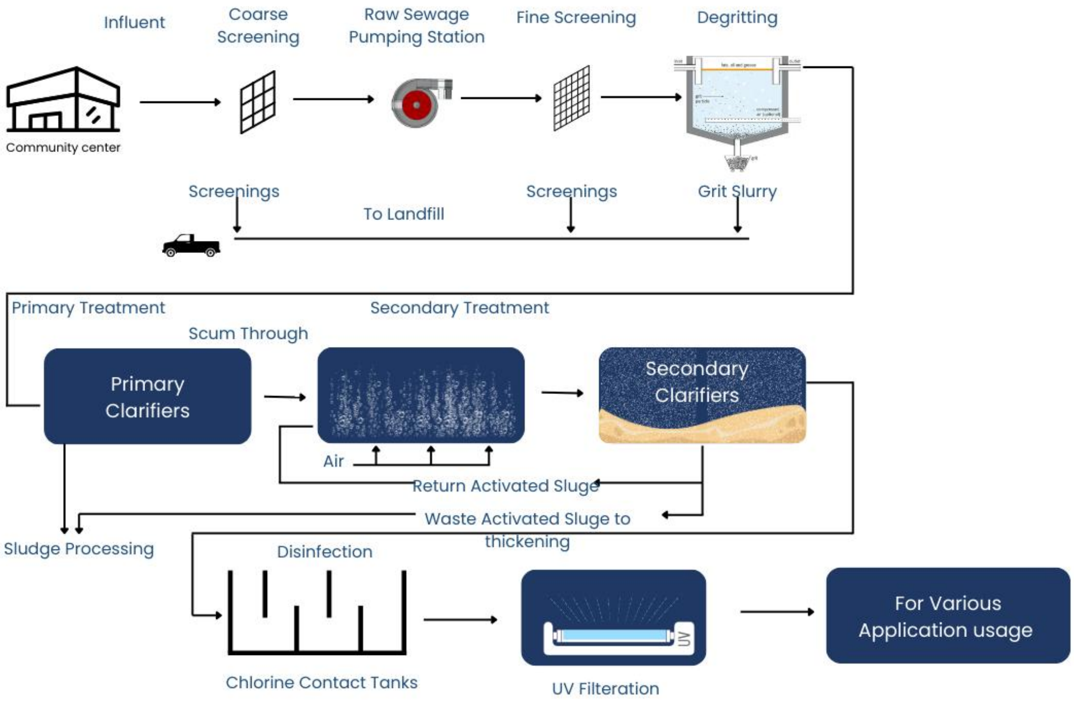


Figure: 3.6: A complete GW treatment plant with process setup

The primary goal of greywater treatment is to address health, aesthetic, and technical issues caused by pathogens, organic matter, and solids in raw greywater, and to ensure it meets reuse standards (Ghunmi et al., 2011). Figure 2.2 (Li et al., 2009) shows the number of research and scientific articles on the treatment, reusability, and application of greywater, highlighting a variety of technologies with differing complexity, performance, and efficiency. Over the past 17 years, there has been a continuous increase in research publications on this topic, with greywater treatment representing nearly 69% of all research in the field, according to data from the Web of Science database (Table 3.6). Despite the growing interest from the scientific community, there are still very few technologies available to evaluate the performance of these systems (Li et al., 2009), and cost-effective treatment methods remain underdeveloped with no new technologies emerging so far (Jabornig and Podmirseg, 2015).

Summary

This chapter delves into the comprehensive characterization of untreated greywater, focusing on its physical, chemical, and microbiological constituents. Understanding the baseline properties of untreated greywater is crucial for designing effective treatment solutions and assessing the potential for reuse.

The physical characterization involves analyzing parameters such as turbidity, colour, temperature, and total suspended solids (TSS). Turbidity, a measure of water clarity, indicates the presence of suspended particles and colloidal matter. The colour of greywater can vary depending on its source, and it provides insights into the presence of organic and inorganic materials. Temperature influences microbial activity and chemical reactions, making it a critical factor in treatment processes. TSS quantification helps in understanding the load of particulate matter that needs to be removed during treatment.

Chemical analysis of greywater includes the assessment of parameters like pH, total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD), and concentrations of nutrients and metals. The pH value affects the solubility and reactivity of various constituents. TDS indicates the concentration of dissolved substances, which can affect the efficacy of treatment processes. COD and BOD measurements provide insights into the organic load and biodegradability of greywater, respectively. Nutrient analysis, including nitrogen and phosphorus compounds, is essential for evaluating the potential for eutrophication if greywater is discharged into natural water bodies. Metal concentrations are monitored to assess the presence of potentially toxic elements that could impact human health and the environment.

The process of finding and measuring the harmful and non-pathogenic microorganisms in greywater is known as microbiological characterisation. Escherichia coli (E. coli), total coliforms, faecal coliforms, and other pathogenic bacteria, viruses, and protozoa are important indications. The presence and concentration of these microorganisms are critical for assessing the health risks associated with greywater reuse. Microbial load also influences the selection and design of appropriate disinfection methods in the treatment process.

CHAPTER 4

DESIGN AND PILOT-SCALE EVALUATION OF HYBRID GREYWATER TREATMENT SYSTEM

CHAPTER 4

Water scarcity is an escalating issue in urban areas globally, demanding innovative strategies for water conservation and reuse. Greywater, which is a substantial portion of residential wastewater, offers significant potential for recycling and reuse. This chapter explores the development of a portable greywater treatment solution that leverages hybrid technology, specifically designed for straightforward implementation in residential societies.

The primary focus of this chapter is the conceptualization, design, and pilot-scale evaluation of a hybrid greywater treatment system. This system integrates vertical and horizontal pipe-based mechanisms (as presented in Figure 4.1) to enhance the efficiency of the treatment process. The vertical configuration is intended to facilitate initial sedimentation and primary filtration, while the horizontal configuration focuses on secondary filtration and disinfection stages. By combining these mechanisms, the hybrid system aims to optimize contaminant removal, thereby significantly improving water quality. The design process involved thoroughly analysing various materials and configurations to ensure compatibility with existing residential infrastructure while maintaining ease of implementation. Initially, metal-based pipes were considered, but they presented challenges such as corrosion and complexity in installation. Consequently, the system design transitioned to using PVC pipes, which offered advantages in ease of handling, cost-effectiveness, and compatibility with common residential plumbing systems.

A pilot-scale evaluation was conducted to assess the performance of the hybrid system under realistic conditions. This involved initial implementation in a controlled laboratory environment, followed by testing in a residential setting to simulate actual greywater generation and usage patterns. Key performance indicators, such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), and microbial counts, were monitored to evaluate the system's efficacy.

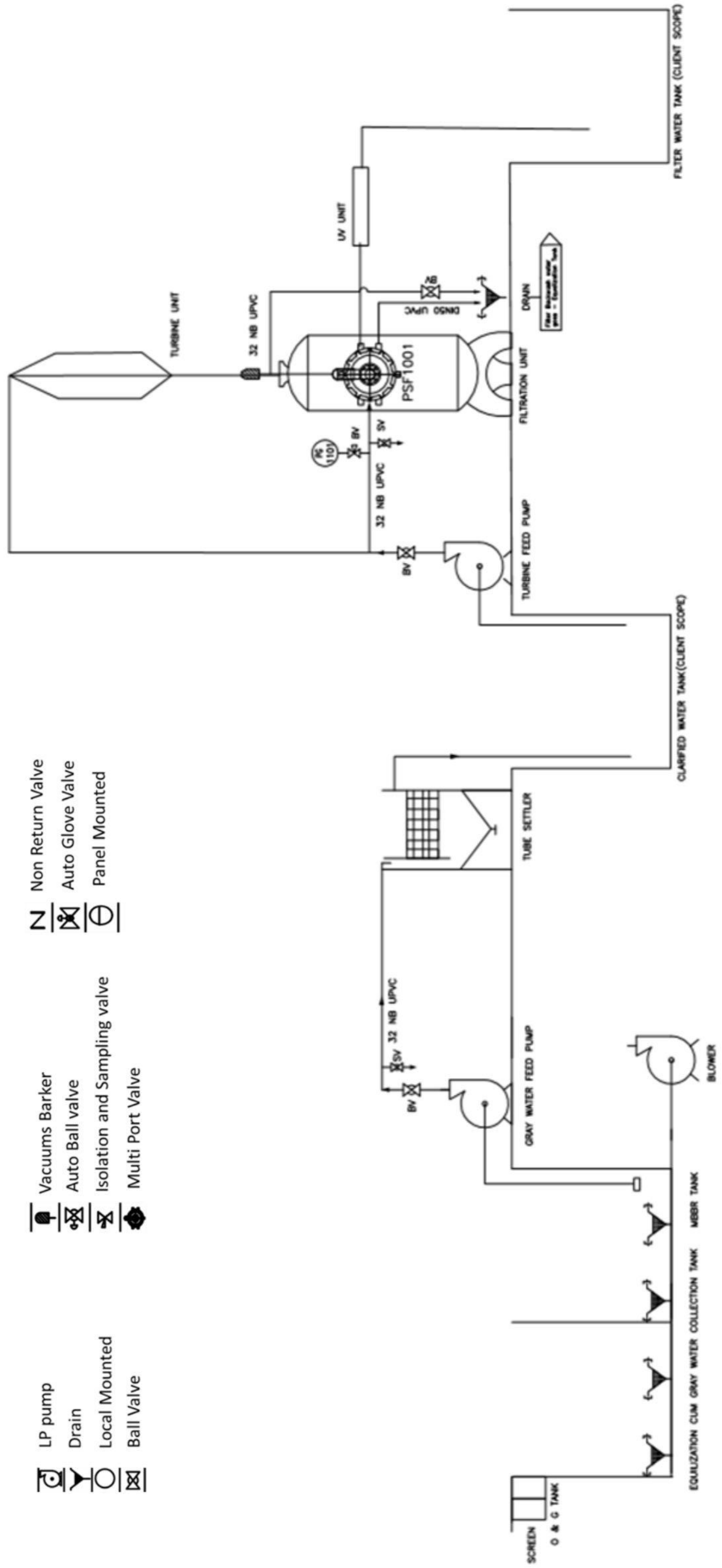


Figure 4.1: System design for Greywater system

The hybrid greywater treatment system not only improves the quality of treated greywater but also promotes sustainable water reuse practices in urban residential areas. This integrated approach addresses the critical issue of water scarcity by providing an efficient, practical, and sustainable solution for greywater treatment and reuse. Through detailed conceptualization, design refinement, and comprehensive pilot-scale testing, this chapter highlights the potential of hybrid technology in advancing greywater recycling efforts in urban environments.

4.1 Design and Development

The design and development of the hybrid greywater treatment system began with the conceptualization of a robust and efficient solution tailored for residential societies. Recognizing the pressing need for water conservation in urban areas, the initial focus was on creating a system that could be easily implemented and maintained within the existing infrastructure of residential buildings. The design aimed to leverage hybrid technology, combining both vertical and horizontal treatment mechanisms to enhance overall treatment efficiency.

4.1.1 Hybrid Structure Design

(Figure 4.1) mechanisms were meticulously developed to maximize treatment efficiency and elevate water quality standards while ensuring seamless integration into residential environments. This innovative approach aimed to exploit the benefits of gravity-driven vertical stages for initial sedimentation and primary filtration of greywater. The use of PVC pipes in this design transition was pivotal, driven by their lightweight nature, corrosion resistance, and compatibility with existing residential plumbing systems. These pipes facilitated easier handling, installation, and maintenance, thereby enhancing the system's practicality and long-term durability. Moreover, the integration of horizontal pipes for secondary filtration and disinfection stages allowed for extended contact time with filtration media, such as activated carbon, optimizing the removal of organic contaminants and pathogens. This comprehensive design not only addressed the technical challenges of greywater treatment but also positioned the system as a sustainable solution for urban water management, supporting the reuse of treated greywater for non-potable applications like irrigation and toilet flushing.

4.1.2 Initial Conceptualization

Figure 4.2: First Attempt, Iron-based Prototype developed in UPES

Figure 4.3: Different stages of lab testing to check for filtration unit and mechanism

The design process initiated with the conceptualization of a hybrid structure strategically incorporating both vertical and horizontal treatment stages. This hybrid approach was fundamentally driven by the objective of optimizing contact time between greywater and treatment media, thereby augmenting the efficiency of removing diverse contaminants. The integration of vertical treatment stages, employing gravity-driven mechanisms, was intended to facilitate initial sedimentation and filtration processes. These stages enabled the settling of heavier particles and the initial removal of suspended solids, thereby priming the greywater for further treatment.

Figure 4.4: Fabrication of the Prototype at Workshop

Concurrently, the inclusion of horizontal configurations was aimed at leveraging extended surface areas and optimized flow characteristics. This design element was crucial in enhancing secondary filtration capabilities, particularly through the use of media such as activated carbon and fine filters. The combination of vertical and horizontal treatments was meticulously engineered to synergistically improve overall water quality by effectively reducing levels of organic matter, chemicals, and microbial pathogens.

The resultant treated greywater from this hybrid system was intended to meet stringent quality standards suitable for various non-potable reuse applications within residential environments. This holistic approach underscores the system's capability to address the complex challenges of greywater treatment in urban settings, offering a sustainable solution that balances operational efficiency with practical implementation in existing infrastructure.

4.1.3 Material Selection

Phase 1: Metal-Based Pipes

During the initial phase of the project, (Figure 4.2, 4.4, 4.5) metal-based pipes were chosen for their anticipated durability and presumed efficacy in handling greywater treatment. The decision was based on the perception that metal pipes would offer robust structural integrity and long-term stability, essential qualities for managing wastewater effectively. However, as the implementation progressed, a series of substantial challenges surfaced that necessitated a reevaluation of this approach. These challenges included issues such as corrosion susceptibility when exposed to diverse chemical compositions present in greywater. Furthermore, the considerable weight of metal pipes posed logistical difficulties during the transportation, handling, and installation phases, especially within the confined spaces typical of residential settings. Moreover, integrating metal pipes into existing plumbing systems proved intricate and labour-intensive, requiring extensive modifications that increased both time and costs.

Figure 4.5: First Attempt: Iron-based prototype (12 Feet)

These challenges underscored the need for a more practical and sustainable alternative, leading to a subsequent transition in the design towards utilizing PVC pipes for their lighter weight, corrosion resistance, ease of handling, and compatibility with residential infrastructure. These included:

- *Corrosion:* Metal pipes used in greywater treatment systems exhibit susceptibility to corrosion, primarily influenced by the chemical composition of the greywater they handle. When exposed to greywater, which often contains dissolved salts, organic matter, and detergents, metal pipes are prone to chemical reactions that lead to corrosion. The presence of chloride ions, for instance, accelerates corrosion processes by promoting the formation of aggressive species like hypochlorite and chloramines. Additionally, the pH level of greywater can impact corrosion rates; acidic conditions tend to exacerbate metal degradation by enhancing the solubility of metal ions in water. Over time, corrosion compromises the structural integrity of metal pipes, potentially leading to leaks, reduced operational lifespan, and increased maintenance costs. Therefore, understanding the chemical interactions between greywater constituents and metal materials is crucial in mitigating corrosion risks and ensuring the long-term reliability of greywater treatment infrastructure.

- *Weight:* The significant weight of metal pipes presented substantial logistical challenges during the installation and handling processes, particularly within the confined spatial constraints typical of residential buildings. This issue primarily affected the feasibility and efficiency of implementing greywater treatment systems in urban settings. The weight of metal pipes necessitated specialized equipment and increased manpower to manoeuvre and position them correctly within designated spaces. Moreover, the logistical constraints imposed by their weight often led to extended installation times and heightened labour costs, thereby impacting the overall economic feasibility of greywater treatment system installations. These challenges underscored the impracticality of using metal pipes in residential environments where ease of handling and efficient installation are critical factors for successful implementation of water treatment technologies
- *Implementation Complexity:* The implementation complexity associated with integrating metal pipes into existing residential infrastructure stemmed from several technical and logistical challenges. Metal pipes, while initially chosen for their perceived durability and structural integrity, posed significant difficulties during installation. The process involved intricate planning to ensure compatibility with the existing plumbing systems within residential buildings. The heavyweight nature of metal pipes necessitated specialized equipment and handling procedures, contributing to increased labour intensity and installation time. Moreover, the need for precise fittings and connectors added complexity, requiring meticulous adjustments to align with the specific layout and dimensions of the building's plumbing network. These factors collectively resulted in elevated installation costs, as skilled labour and resources were essential to overcome the challenges posed by the integration of metal pipes into residential settings.

Phase 2: Transition to PVC Pipes

Figure 4.6: Second Attempt: PVC/UPVC based prototype

Figure 4.7: Prototype with the Turbine for Testing

In response to the challenges observed with metal pipes during the initial stages of design implementation, the decision was made to adopt PVC (polyvinyl chloride) pipes as a replacement material (Figure 4.6, 4.7). This transition was driven by a thorough evaluation of material properties and performance requirements essential for effective greywater treatment systems. PVC pipes were chosen primarily for their superior corrosion resistance compared to metal counterparts, which is crucial in environments where greywater may contain corrosive elements that could degrade metal over time. Additionally, PVC pipes offer advantages such as lightweight construction, facilitating easier handling and installation. Their inherent durability and longevity contribute to reduced maintenance needs and operational costs over the system's lifecycle. Moreover, PVC's compatibility with existing residential plumbing infrastructure streamlined the integration process, minimizing disruption during installation and ensuring seamless operation within urban residential environments. This strategic shift to PVC pipes underscores a commitment to optimizing system reliability, efficiency, and sustainability in greywater treatment applications. PVC pipes were selected based on their numerous advantages, including:

- *Lightweight Nature:* (Figure 4.6 and 4.7) PVC pipes offer distinct advantages over metal pipes due to their physical properties, particularly their low density and lightweight nature. This characteristic of PVC pipes significantly reduces the overall weight of the piping system compared to metal counterparts, facilitating easier transportation and installation processes. The lightweight nature of PVC pipes minimizes the need for heavy lifting equipment during handling and installation, which can be particularly advantageous in residential and urban settings where space constraints and accessibility challenges may exist. Moreover, the reduced weight contributes to lower transportation costs and logistical requirements, making PVC pipes a practical choice for various applications in plumbing and wastewater management systems. Additionally, the lightweight properties of PVC pipes ensure ease of manoeuvrability during installation procedures, enhancing efficiency and reducing labour costs associated with handling and positioning within complex plumbing networks. Thus, the lightweight characteristic of PVC pipes not only enhances practicality and ease of use but also supports cost-effective and efficient implementation across diverse infrastructure projects.
- *Ease of Handling:* The advantageous characteristics of PVC pipes extend beyond their material composition to include practical aspects critical to their application in greywater treatment systems. PVC pipes are selected for their inherent flexibility and dimensions that facilitate ease of handling, ensuring they can be manoeuvred efficiently during installation and maintenance phases. Their manageable size allows for precise customization to fit diverse residential plumbing configurations, optimizing spatial efficiency within constrained environments typical of urban housing layouts. This feature enhances the adaptability of PVC pipes to different system designs, supporting seamless integration into existing infrastructure without necessitating extensive modifications.
- *Compatibility with Existing Infrastructure:* The compatibility of PVC pipes with existing infrastructure is a crucial aspect of their selection in the design of greywater treatment systems for residential settings. PVC (polyvinyl chloride) pipes offer several advantages that contribute to their

seamless integration into residential plumbing networks. Firstly, their standardized dimensions and fittings ensure compatibility with commonly used plumbing components, minimizing the need for extensive modifications or custom adaptations during installation. This standardization not only simplifies the implementation process but also reduces labour costs associated with retrofitting or upgrading existing plumbing systems. Additionally, PVC pipes can be easily cut, joined, and manoeuvred to navigate around obstacles or fit into tight spaces within buildings. This flexibility enhances the versatility of installation approaches, accommodating various layouts and configurations typical of residential environments. Moreover, the lightweight nature of PVC pipes facilitates handling and transportation, reducing logistical challenges and operational delays during construction. Overall, these characteristics underscore PVC's suitability for effectively integrating greywater treatment systems into existing residential infrastructure, supporting cost-effective and efficient deployment strategies in urban settings focused on water conservation and reuse.

Figure 4.8: Turbine testing at two different positions (analysed with condition 1 and condition 2)

Figure 4.9: Testing of turbine for energy utilisation and generation

Figure 4.10: Final Bench Type Prototype (Working model)

4.1.4 Structural Configuration

The ultimate structural configuration of the hybrid greywater treatment system was meticulously planned to optimize treatment efficiency through a carefully orchestrated arrangement of both vertical and horizontal PVC pipes (as presented in Figure 4.10). This design was intricately crafted to ensure each stage of the treatment process seamlessly transitions from initial sedimentation to final disinfection. Vertically positioned PVC pipes were strategically employed at the outset to leverage gravity for effective sedimentation and primary filtration. This initial phase allowed heavier particles and sediments within the greywater to settle, thereby easing the subsequent filtration processes. Following this, horizontally aligned PVC pipes were strategically integrated to extend the contact time of the greywater with secondary filtration media, such as activated carbon and fine filters. These components were meticulously selected to enhance the system's capability to remove organic contaminants and residual chemicals effectively. Ultimately, this structural arrangement was designed not only to maximize treatment efficiency but also to ensure the system's practical implementation and operational reliability within residential environments, fostering sustainable greywater reuse practices effectively. This configuration was designed as follows:

- Vertical Pipes for Initial Sedimentation and Filtration:
    - In the system design, vertical PVC pipes were strategically positioned at the initial stage to capitalize on gravitational forces for sedimentation purposes based on calculative dimension after doing initial simulation and testing (Table 4.1). This configuration facilitated the separation of heavier particles and sediments present in the greywater. As the greywater flowed through these vertical columns, the particles settled at the bottom due to their higher density compared to the water. This process of sedimentation enabled primary filtration by effectively removing larger particulate matter and solids from the greywater stream. By utilizing gravity in this manner, the system optimized the initial phase of treatment, laying the foundation for subsequent filtration stages aimed at further refining water quality before eventual reuse or discharge.

- In subsequent vertical stages of the greywater treatment system, specific layers of filtration media were strategically implemented to address different aspects of water quality. These stages were designed to optimize the removal of suspended solids and reduce turbidity, which is crucial for enhancing the overall effectiveness of greywater treatment. The layering of filtration media began with coarse materials like gravel, which effectively trapped larger particles and sediment as the greywater flowed through. This initial stage served to physically separate heavier solids from the water, thereby reducing turbidity and preparing the greywater for further purification processes. Following the gravel layer, finer filtration media such as sand were employed to refine the treatment process. Sand beds are highly effective in capturing smaller suspended particles that may still be present after initial filtration. The interstitial spaces within the sand bed act as a natural filter, facilitating the retention of fine particulate matter and improving water clarity.

  Together, these layers of filtration media in the vertical stages of the system played a critical role in enhancing the overall water quality by significantly reducing suspended solids and turbidity levels. This sequential approach ensured that the greywater underwent thorough purification before progressing to subsequent treatment stages, contributing to the system's efficiency in producing treated water suitable for various non-potable reuse applications in residential settings.

- Horizontal Pipes for Further Filtration and Disinfection:
  - Following the primary treatment in the vertical PVC pipes, the greywater transitioned into horizontally configured stages within the treatment system. These horizontal stages were meticulously designed to optimize the treatment process by maximizing the contact time between the greywater and secondary filtration media. Specifically, the horizontal configuration facilitated prolonged exposure of the greywater to specialized media, such as activated carbon. This media was strategically selected for its high adsorption capacity, effectively targeting organic contaminants and residual chemicals present in the

greywater stream. By extending the residence time and enhancing the surface area available for interaction, the horizontal pipes ensured thorough filtration and removal of contaminants that may have persisted after the initial treatment stages. This sequential approach in the treatment system aimed to achieve comprehensive purification of greywater, aligning with standards for safe and sustainable reuse in residential and urban environments.

- In the ultimate phase of the horizontal configuration, the system integrated advanced disinfection units aimed at achieving comprehensive pathogenic microorganism removal. These units were meticulously chosen based on their efficacy in treating greywater to meet the requisite standards for non-potable reuse applications. The disinfection process primarily involved the use of ultraviolet (UV) lamps or chlorination chambers. UV disinfection, a chemical-free method, employed ultraviolet radiation to disrupt the genetic material of microorganisms, rendering them unable to replicate. On the other hand, chlorination involves the controlled application of chlorine compounds to eliminate microorganisms through oxidation. Both methods were meticulously calibrated to ensure maximum efficiency in eliminating pathogens from the greywater stream. This final treatment stage ensured that the treated greywater met stringent safety criteria, making it suitable for various non-potable reuse purposes, including irrigation, toilet flushing, and other residential applications aimed at conserving potable water resources.

Table 4.1: Dimensions of Prototype 1 (PVC / UPVC: Pipe based Model)

S.No	Connection Details	Length (in Inch)	Diameter (in Inch)
1.	Water Tank to L1 (from Motor of 0.5 HP)	10	¾
2.	L1 – L2	08	¾
3.	L2 – L3	102	¾
4.	L3 – L4	7.5	¾
5.	L4 – J1	10	¾
6.	J1 – J2	37	2.5
7.	J2 – J3	19	2.5

8.	J3 – J4	5.5	2.5
9.	J4 – J5	04	4.0
10.	J5 – J6	19	6.0
11.	J6 – J7	04	4.0
12.	J7 – J8	10	2.5
13.	J8 – L5	09	¾
14.	L5 – Out Let	12	¾

Important parameter:

- ❖ L1, L2, L3 L4, and L5 are the L shape joints; J1, J2, J3, J4, J5, J6, J7, and J8 are the reducer joints for reducing the size from ¾ inch to 2.5 inches, 2.5 inches to 4 inches, 4 inches to 6 inches used to reduce the size of the pipe as well as to join the connection.
- ❖ A motor of 0.5 HP and 30 Liter of the tank is used to collect the water sample
- ❖ XCLUMA 12V 10W DC MICRO HYDRO GENERATOR Tap Water Flow Hydraulic Hydropower Water Turbine Generator is used for the initial testing phase.

- ❖ ***Technical Specification of the Turbine:***
    - o A microhydro generator is a mechanical device that converts the potential energy of flowing water into electrical energy. It can be directly used for charging small batteries, powering mobile phones, 12V radios, LED lights, and other low-power devices, making it an effective solution for off-grid energy needs in small-scale applications.
    - o Maximum output voltage :12 V The output voltage:12V - between the wire resistance: 10.5 ± 0.5 R - Insulation resistance:10M (DC100 megger)

Maximum pressure: 0.6Mpa outlet closed - the outlet opening maximum pressure :1.2Mpa - Start pressure :0.05Mpa

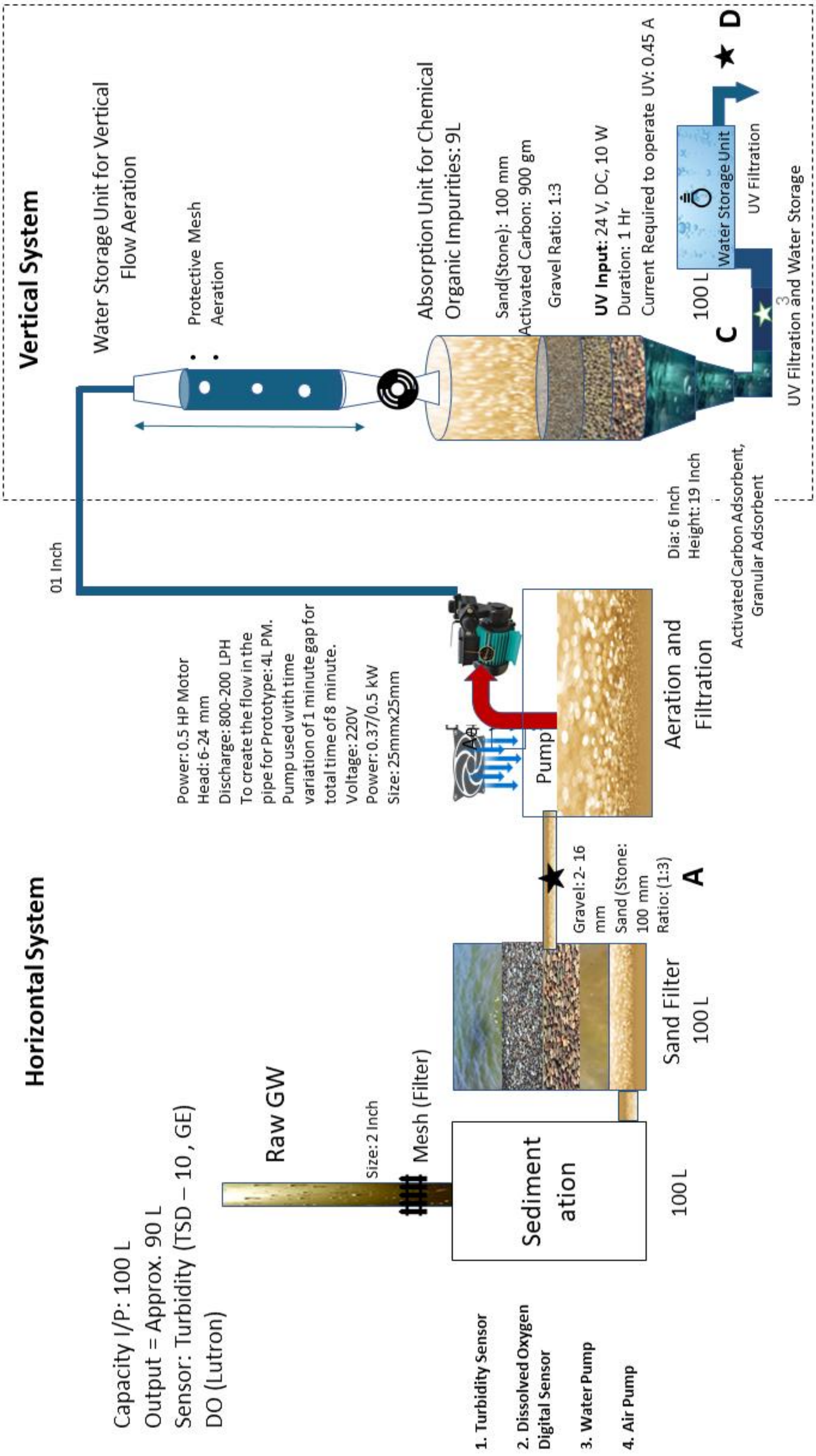


Figure 4.11: Hybrid Greywater Treatment System: Methodology

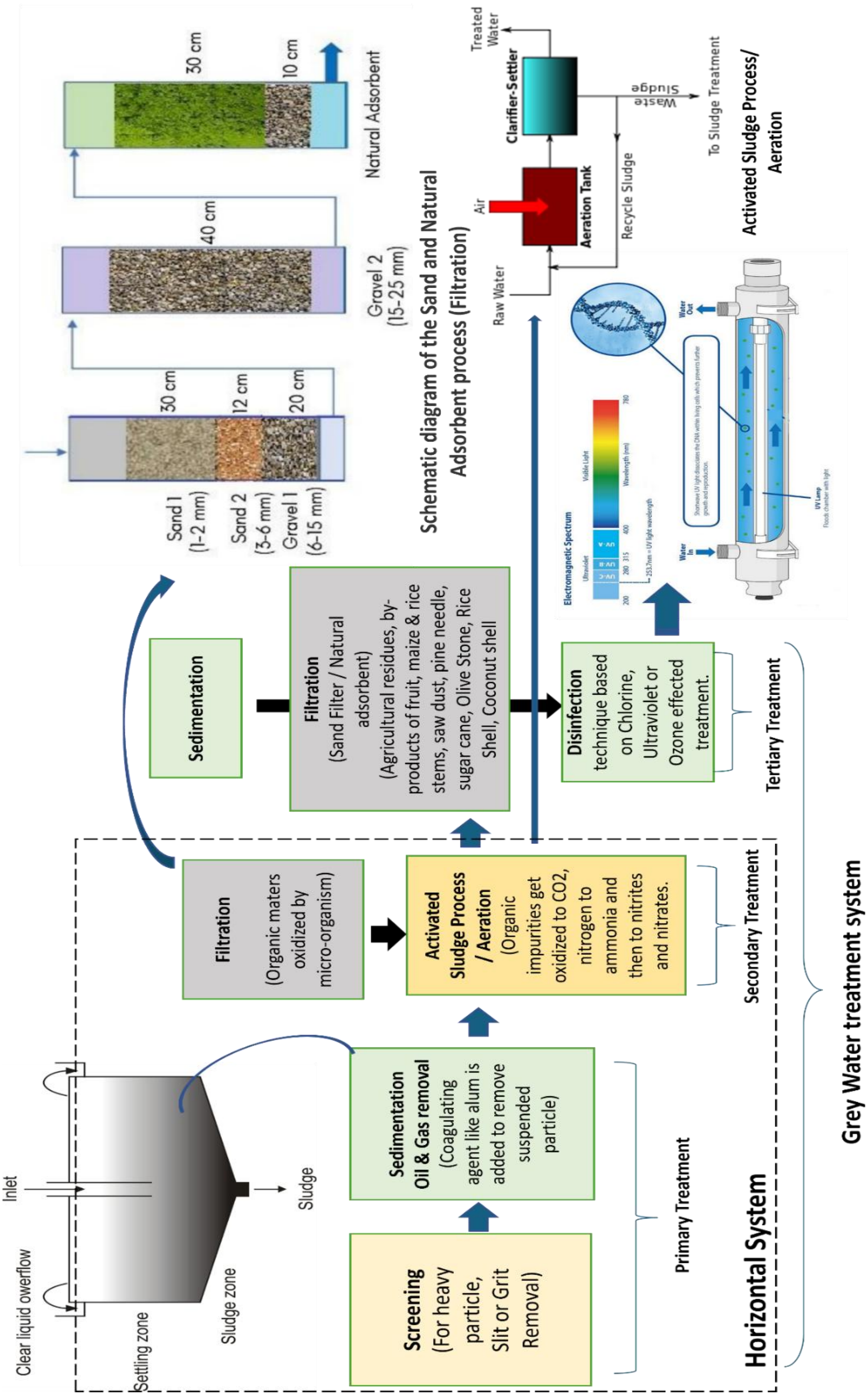


Figure 4.12: Hybrid Greywater Treatment System: Design Process

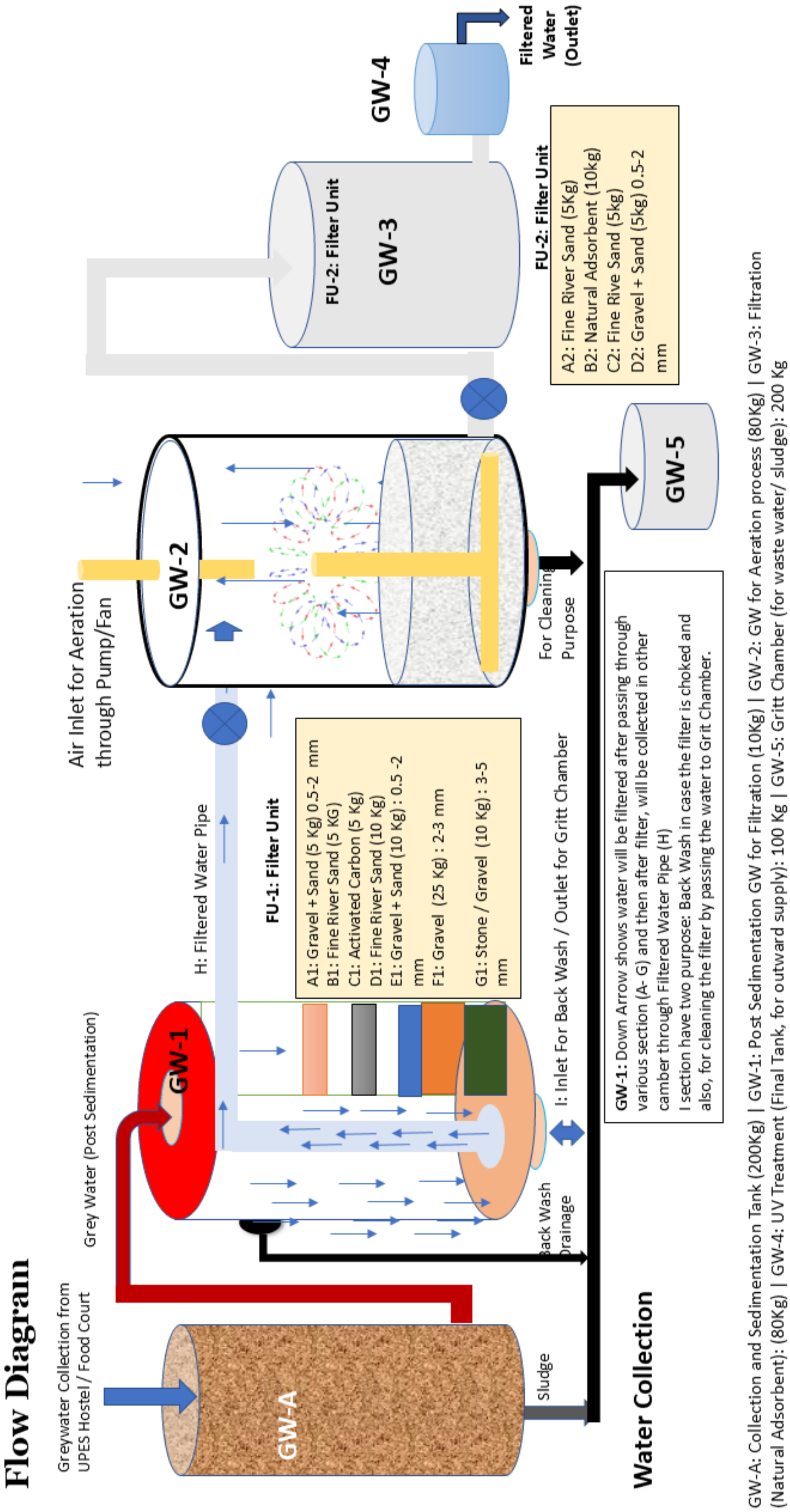


Figure 4.13: Flow diagram of the treatment system

4.2 System Design

In the realm of greywater treatment systems, the integration and functionality of various components play a pivotal role in ensuring efficient purification and safe reuse of wastewater within residential and commercial settings. Each component within the system is carefully designed and implemented to address specific stages of the treatment process, from initial particle removal to final disinfection. The systematic arrangement of these components not only enhances water quality but also supports sustainable water management practices aimed at mitigating freshwater scarcity challenges in urban environments.

Greywater treatment systems typically consist of several key components, each serving a distinct purpose in the purification process. These components include screening units for initial debris removal, sedimentation tanks for settling heavier particles, filtration units employing diverse media for fine particulate removal, and advanced disinfection technologies to eliminate pathogens. The selection and integration of these components are guided by principles of efficiency, reliability, and compliance with regulatory standards governing water quality.

As such, understanding the function and interaction of these system components is essential for designing and implementing effective greywater treatment solutions. This comprehensive approach not only ensures the removal of contaminants but also promotes the safe reuse of treated greywater for non-potable applications, contributing to sustainable water conservation efforts and environmental stewardship. The following sections delve into the detailed design and operational aspects of these system components, highlighting their critical roles in achieving high-quality greywater treatment and facilitating its beneficial reuse in diverse urban contexts.

4.2.1 Screening Unit

The greywater treatment system commences with a screening unit meticulously designed to effectively eliminate large particles and debris from the incoming greywater stream. This initial stage plays a pivotal role in safeguarding downstream components against potential clogging by preventing coarse solids such as hair, lint, and food particles from progressing further into the treatment process. Typically, the screening unit incorporates a mesh or perforated plate mechanism calibrated to allow water to permeate through while apprehending and detaining solid particles exceeding a specified size threshold. This preliminary filtration step not only enhances the overall operational efficiency of subsequent treatment stages but also contributes significantly to the reduction of suspended solids load within the greywater system. By effectively managing particulate matter at the outset, the screening unit ensures sustained performance and longevity of downstream treatment components, thereby optimizing the system's capacity for comprehensive greywater purification and reuse.

4.2.2 Sedimentation Tank

After undergoing initial screening to remove larger debris, the greywater enters a sedimentation tank constructed using vertical PVC pipes, which serves as a crucial primary treatment stage in the greywater treatment system. In this sedimentation tank, gravity plays a pivotal role in facilitating the separation process of heavier particles and sediments from the water. As the greywater flows through the vertical pipes, the velocity decreases, allowing suspended particles with higher specific gravity to settle downward and accumulate at the bottom of the tank. This sedimentation step is meticulously designed to enhance the overall treatment efficiency by removing finer particulate matter that might have escaped the initial screening process. By effectively reducing turbidity and the concentration of suspended solids, the sedimentation tank significantly improves the quality of the greywater, preparing it for subsequent stages of filtration and disinfection. The integration of vertical PVC pipes ensures a robust structural framework for the sedimentation process, enabling efficient operation and maintenance of the greywater treatment system in residential and urban settings.

4.2.3 Filtration Units

The treatment system is designed with a series of strategically positioned filtration stages, employing diverse media to achieve comprehensive purification of greywater. These filtration units are strategically placed in both vertical and horizontal orientations within the system. The vertical orientation facilitates the initial stages of sedimentation and primary filtration, allowing heavier particles to settle out and reducing the initial load of suspended solids. This setup ensures that the greywater undergoes a thorough initial treatment process, minimizing the particulate matter before entering subsequent filtration stages.

In the horizontal orientation, the filtration units are configured to provide extended contact time between the greywater and the filtration media. This configuration enhances the efficiency of secondary and tertiary filtration processes, where finer filtration media such as activated carbon are used to adsorb dissolved organic compounds and residual contaminants. By maximizing the surface area exposed to the filtration media and optimizing hydraulic residence times, the horizontal orientation significantly improves the overall removal of contaminants from the greywater. This systematic arrangement of filtration stages, combining vertical and horizontal orientations, plays a critical role in achieving high-quality treated greywater suitable for reuse in non-potable applications, thereby contributing to sustainable water management in residential and urban environments.

- *Horizontal Filtration Stages:* Within the hybrid greywater treatment system, the horizontal filtration stages play a critical role in refining the quality of treated greywater. Following initial treatment in the vertical sedimentation and filtration stages, the greywater progresses into the horizontal configuration where additional filtration units are strategically integrated. These stages are meticulously designed to maximize contact time between the greywater and the filtration media, thereby facilitating the thorough removal of residual impurities and contaminants.

  Horizontal filtration employs advanced filtration media or membranes that are selected based on their pore size and adsorptive properties. This allows for finer particulate removal and improves the clarity of the treated water. The extended contact time within the horizontal pipes ensures that the greywater undergoes thorough filtration, addressing remaining suspended solids, organic matter, and potentially harmful substances that may affect water quality.

  The design of the horizontal filtration stages considers factors such as hydraulic retention time, flow rate optimization, and media selection to achieve optimal performance. Filtration media such as activated carbon, ultrafiltration membranes, or other specialized materials are utilized to enhance the efficiency of contaminant removal. These stages are crucial in preparing the greywater for final disinfection, ensuring that the treated water meets quality standards suitable for non-potable reuse applications.

  The integration of horizontal filtration stages within the hybrid greywater treatment system reflects a comprehensive approach to water treatment. By combining effective sedimentation and preliminary filtration in vertical pipes with advanced horizontal filtration techniques, the system achieves high-quality treated greywater. This systematic approach not only enhances water clarity and purity but also contributes to sustainable water management practices in urban environments, supporting efforts towards water conservation and reuse.

- *Vertical Filtration Stages:* Within the vertical filtration stages of the greywater treatment system, a structured arrangement of filtration media optimizes the removal of contaminants. Sand, activated carbon, and gravel are sequentially layered within the vertical pipes to perform distinct purification functions.

- *Sand Filtration:* The initial layer of sand serves as a crucial component for removing suspended particles from the greywater. This process effectively clarifies the water by trapping and retaining finer particulate matter that may affect its clarity and quality. Sand filtration operates by allowing the greywater to percolate through the porous bed of sand, where particles larger than the interstices of the sand grains become trapped.
- *Activated Carbon Adsorption:* Following sand filtration, the greywater passes through a layer of activated carbon. Activated carbon is highly effective in adsorbing organic contaminants and residual chemicals present in the greywater. This includes substances that contribute to odour, colour, and potentially harmful compounds. The activated carbon's porous structure provides a large surface area for chemical bonding with contaminants, thereby significantly improving the aesthetic and health-related quality of the treated water.
- *Gravel Support Medium:* Throughout the vertical filtration stages, gravel acts as a vital support medium for the layers of sand and activated carbon. Gravel provides a stable bed that enhances the overall filtration efficiency by ensuring uniform flow distribution and preventing media compaction. It also facilitates proper drainage and allows for effective contact time between the greywater and the filtration media, optimizing the filtration process.

This structured approach within the vertical pipes of the greywater treatment system ensures thorough purification of the greywater by sequentially addressing different types of contaminants. By leveraging the specific characteristics of sand, activated carbon, and gravel, this filtration design achieves high removal efficiencies, making the treated greywater suitable for safe and sustainable reuse in residential and urban settings.

4.2.4 Disinfection Unit

At the culmination of the treatment process, a dedicated disinfection unit is integrated into the final stage of the horizontal pipe configuration. This unit plays a critical role in ensuring the elimination of pathogenic microorganisms from the treated greywater, rendering it safe and suitable for non-potable reuse applications. The disinfection options considered include UV (Ultraviolet) disinfection and chlorination:

- *UV Disinfection:* Utilizes UV lamps to emit ultraviolet light at specific wavelengths that penetrate the cell walls of microorganisms, disrupting their DNA and preventing reproduction. UV disinfection is effective against a broad spectrum of pathogens without introducing chemicals into the water.
- *Chlorination:* Involves the controlled application of chlorine compounds, such as chlorine gas or sodium hypochlorite, to the greywater. Chlorine acts as a powerful oxidizing agent, destroying microorganisms by attacking their cellular structure and metabolic processes. Chlorination offers residual disinfection benefits, ensuring continued microbial control beyond the treatment unit.

These disinfection methods are selected based on their proven efficacy in meeting regulatory standards for microbiological quality in treated greywater. By integrating advanced disinfection technology at the final stage, the system ensures that the treated greywater meets stringent safety criteria, making it suitable for environmentally sustainable reuse in applications such as landscape irrigation, toilet flushing, and other non-potable water demands in residential and commercial settings.

4.3 Pilot-Scale Evaluation

The pilot-scale evaluation of the hybrid greywater treatment system was conducted to bridge the gap between laboratory research and real-world application. This phase was crucial for validating the system's design, performance, and reliability under conditions that closely mimic actual residential greywater scenarios. By transitioning from controlled R&D environments to practical, real-life settings, we aimed to ensure that the system could consistently meet the demands of greywater treatment in urban residential societies. Implementation of the pilot scale consists following:

4.3.1 Initial R&D Implementation

The initial implementation phase was dedicated to the integration of the PVC-based hybrid structure within our R&D laboratory. This stage was essential for refining the overall design and addressing any operational challenges that arose during testing. Extensive trials were conducted in a controlled laboratory environment, allowing for precise monitoring and adjustment of the system. These trials provided critical insights into the structural configuration, enabling us to optimize each component for maximum efficiency and effectiveness. This thorough evaluation ensured the system's functionality and reliability, laying a solid foundation for subsequent large-scale testing phases.

Figure 4.14: Development phase of the Prototype at UPES lab

4.3.2 Pilot Testing

Upon achieving successful outcomes in the laboratory, the next phase involved pilot testing in an environment that closely simulated residential greywater conditions. This pilot setup was meticulously installed in a designated area within the R&D facility, designed to replicate real-world usage scenarios. Over an extended monitoring period, the system's performance was evaluated under these conditions, focusing on parameters such as turbidity reduction, dissolved oxygen levels, and contaminant removal efficiency. The pilot testing phase was essential for validating the system's operational reliability and effectiveness in treating greywater in a residential context.

Table 4.2: Sample data and site location at Hostel, UPES

Total Room: 32
Total Person: 73
Water Usage: 9.8 KLD
Sewage Generation: 7.8 KLD
Greywater: 6.2 KLD

Total Person: 482
Water Usage: 65.07 KLD
Sewage Generation: 52.05 KLD
Greywater: 41.64 KLD

Total Room: 65
Total Person: 109
Water Usage: 14.75 KLD
Sewage Generation: 11.72 KLD
Greywater: 9.46 KLD

Total Room: 75
Total Person: 170
Water Usage: 22.95 KLD
Sewage Generation: 18.36 KLD
Greywater: 14.68 KLD

Table 4.3: Characteristics of Greywater from Sources 1,2,3 and 4 (Near UPES Hostels)

Parameter	Sample 1	Sample 2	Sample 3	Average
Electrical conductivity (µS/cm)	2050	2230	1860.2	2046.73
TDS (mg/l)	1737	1890.21	1580	1735.73
pH	8.57	9.32	7.8	8.56
Turbidity (NTU)	40.83	44.41	35.56	40.26
Nitrate (mg/l)	8.9	9.74	7.80	8.81
Phosphorous (mg/l)	0.88	0.96	0.77	0.87
BOD (mg/l)	340	370	290	333.33
COD (mg/l)	916	990	783	896.33

Table 4.4: Greywater parameter at Difference Section during Pilot Stage

Parameter	Value at Input of A	Value at Output of B (Gravel Filtration)	Value at Output of C (Aeration)	Value at Output of E (Adsorbent, Activated Carbon Filter)	Performance of the System
BOD	290 (± 20)	194.3 (39%)	59.66 (69.5%)	34.33 (27%)	88%
COD	760 (± 20	554.8 (27%)	252.43 (54.5%)	157.77 (37.5%)	79%
pH	8.2	7.9	7.9	7.7	--
Turbidity	35 (± 4)	12.95 (63%)	9.90 (23%)	9.01 (09%)	74 %
Oil & Grease	50(± 8)			NIL (almost)	99%
TSS	<100 (± 5)	32 (68%)		<10-15	90-95%

Table 4.4: Greywater parameter before and after passing through prototype (Test 1)

S.N	Parameter	Inlet	Outlet	Change Percentage (%)
a.	pH	8.2 (± 0.4)	7.8 (± 0.4)	5%
b.	BOD (mg/l)	290 (± 20)	31 (± 5)	89%
c.	COD (mg/l)	760 (± 20)	160 (± 5)	79%
d.	Turbidity (NTU)	35 (± 4)	08 (± 4)	77%

e.	TDS (mg/l)	2700 (± 300)	2300 (± 300)	15%
f.	Nitrate (mg/l)	17 (± 2)	06 (± 2)	65%

Table 4.5: Greywater parameter before and after passing through prototype (Final Test)

S.N	Parameter	Inlet	Outlet	Efficiency
a.	pH	6.5-8.2 (± 0.4)	7.8 (± 0.4)	>95%
b.	BOD (mg/l)	210-320 (± 20)	31 (± 5)	> 89-93%
c.	COD (mg/l)	420 – 470 (± 20)	73 (± 5)	> 82 %
d.	Turbidity (NTU)	31-42 (± 4)	08 (± 4)	> 81%
e.	TSS (mg/l)	130 (± 50)	< 10	> 93%
f.	Oil and Grease	50(± 8)	NIL	>99%

Summary

This chapter details the design and development of a hybrid greywater treatment system tailored for efficient implementation in residential environments, aimed at addressing water scarcity through sustainable water reuse practices. Greywater, a significant component of residential wastewater, offers the potential for recycling and reducing freshwater demand in urban areas. The initial phase of system development involved conceptualizing a hybrid design integrating both vertical and horizontal treatment stages to optimize contaminant removal and enhance water quality.

Material selection played a crucial role in the system's evolution, beginning with metal-based pipes chosen for their durability but later transitioning to PVC pipes due to their lightweight nature, corrosion resistance, and compatibility with existing residential plumbing infrastructure. The structural configuration of the system included vertical pipes designed for initial sedimentation and primary filtration. These vertical stages utilized gravity to facilitate the settling of heavier particles and the removal of coarse contaminants, setting the foundation for subsequent treatment processes.

Horizontal filtration stages further refined the treated greywater, emphasizing longer contact times between the water and advanced filtration media or membranes. This phase aimed to achieve finer particulate removal and improve water clarity before final disinfection. The design parameters of the horizontal stages were meticulously planned to optimize hydraulic retention time, flow rates, and the selection of filtration media such as activated carbon and ultrafiltration membranes. These components played pivotal roles in effectively removing suspended solids, organic matter, and harmful substances from the greywater stream.

The hybrid greywater treatment system represents a significant advancement in sustainable water management practices for urban environments. By integrating innovative design concepts with practical implementation strategies, the system not only enhances water conservation efforts but also supports the safe and reliable reuse of greywater.

CHAPTER 5

DISCUSSION, ANALYSIS, AND IMPLICATIONS

CHAPTER 5

This chapter presents a comprehensive discussion, analysis, and exploration of the implications arising from the pilot-scale evaluation of the hybrid greywater treatment system. Following the successful implementation and pilot testing phases, it is crucial to delve into the detailed outcomes, assess the performance metrics, and understand the broader impact of the system on water management practices. The discussion section will provide an in-depth examination of the results obtained during the pilot-scale evaluation, highlighting the system's effectiveness in reducing turbidity, increasing dissolved oxygen levels, and removing contaminants. This analysis will draw comparisons between initial laboratory findings and pilot-scale observations to underscore the system's reliability and scalability.

Critical performance indicators like Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Microbial Counts will also be the focus of the analysis. By scrutinizing these metrics, we aim to elucidate the system's operational efficiency and potential areas for further optimization. The implications section will explore the broader impact of implementing this hybrid greywater treatment system within urban residential settings. This includes potential contributions to sustainable water management, cost savings, and environmental benefits. Additionally, the discussion will address the practical considerations and challenges associated with scaling up the system for widespread use.

5.1 Materials and Methods

5.1.1 Sample Collection and Water Quality Assessment

To comprehensively evaluate water quality and gain a thorough understanding of greywater characteristics within the state, a systematic sampling strategy was employed. Samples were carefully collected from various locations, including households and apartment complexes. In the initial phase of sampling, particular attention was given to the UPES-Dehradun campus. Over a period of four days each month, samples were collected from a food court and a hostel kitchen. Three grab samples were taken from each source on the same day at two-hour intervals. These individual grab samples were then combined to create a composite sample, with equal volumes from each grab to ensure the sample was representative of the source.

Key physico-chemical characteristics, such as pH, Total Dissolved Solids (TDS), and conductivity, were measured for each sample that was obtained through on-site evaluations. At the UPES Water Research Laboratory, more thorough evaluations of other factors such turbidity, nitrate, phosphorus, Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD) were carried out. This rigorous approach for collection and analysis made sure that the quality of greywater in different household contexts was accurately and completely characterized.

The greywater treatment process begins with sedimentation, sourced primarily from the UPES Food Court or Hostel Kitchen (as presented in Figure 4.3). The inlet flow rate is 100 litres per cycle, with an initial turbidity level (Ti) of 1000 NTU (Nephelometric Turbidity Units). Sedimentation occurs over a period of 12 to 24 hours, allowing suspended particles to settle out naturally. Turbidity levels are monitored during this phase to assess the effectiveness of sedimentation.

Following sedimentation, the greywater undergoes filtration through a gravity-driven sand filter. This filter utilizes a packed bed of fine sand, custom-designed for optimal filtration efficiency. The filtration process denoted as T2, is observed to ensure adequate removal of remaining particulates. Dissolved oxygen levels (D1) are also measured during this stage. If the turbidity level T2 is less than or equal to 50% of T1 (initial turbidity), the condition is categorized as C. Conversely, if T2 exceeds 50% of T1, it is categorized as B, indicating the need for further treatment.

Aeration follows the filtration stage, involving a motor-driven air pump to increase dissolved oxygen (DO) levels in the greywater. The RPM of the air pump is monitored to regulate aeration intensity. Higher dissolved oxygen levels correlate with lower temperatures, as indicated by observation (R). If the dissolved oxygen level (T3) surpasses 5% of T2, the aeration pump (P) and motor (M1) are deactivated. Conversely, if T3 remains below or equals 5% of T2, the pump (P) remains off while the motor (M1) continues operation. (Figure 5.1)

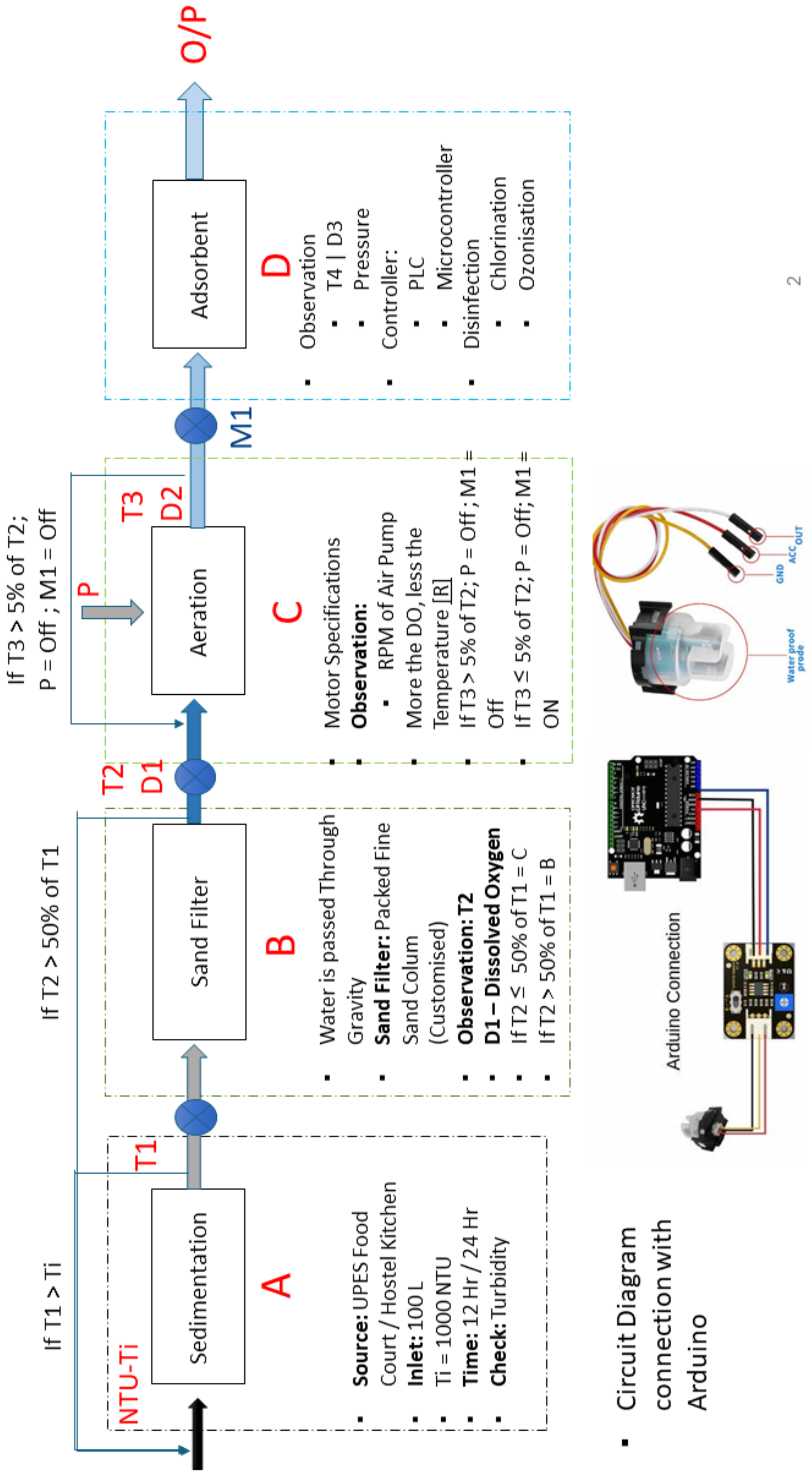


Figure 5.1: Hybrid Greywater Treatment System: Experimental Process Flow

The next treatment step involves adsorption using specialized adsorbents. Observations include monitoring T4 levels and measuring D3 pressure. The process is controlled through PLC (Programmable Logic Controller) or microcontroller systems, ensuring precise regulation and optimization of adsorption efficiency.

Final disinfection of the treated greywater is achieved through chlorination or ozonation processes, depending on specific requirements and regulatory standards. Disinfection ensures the elimination of pathogens and microorganisms, rendering the water safe for reuse.

The assessment of physico-chemical parameters involved the utilization of distinct methodologies. For instance, parameters such as pH and conductivity were promptly ascertained during sample collection using a multimeter, ensuring real-time data acquisition and precise measurements.

Table 5.1: Characteristics of Greywater Source-1

Parameters	**Grab sample 1**	**Grab sample 2**	**Grab sample 3**	**Composite sample**
Electrical Conductivity (µS/cm)	2075	2142	1985	2030
TDS (mg/l)	1725	1835	1590	1755
pH	8.3	9.6	7.4	8.5
Turbidity (NTU)	40	45	33	41
Nitrate (mg/l)	10	10.5	7.2	8.9
Phosphorous (mg/l)	0.9	1.1	0.8	0.76
BOD (mg/l)	179	192	167	183
COD (mg/l)	585	625	528	573

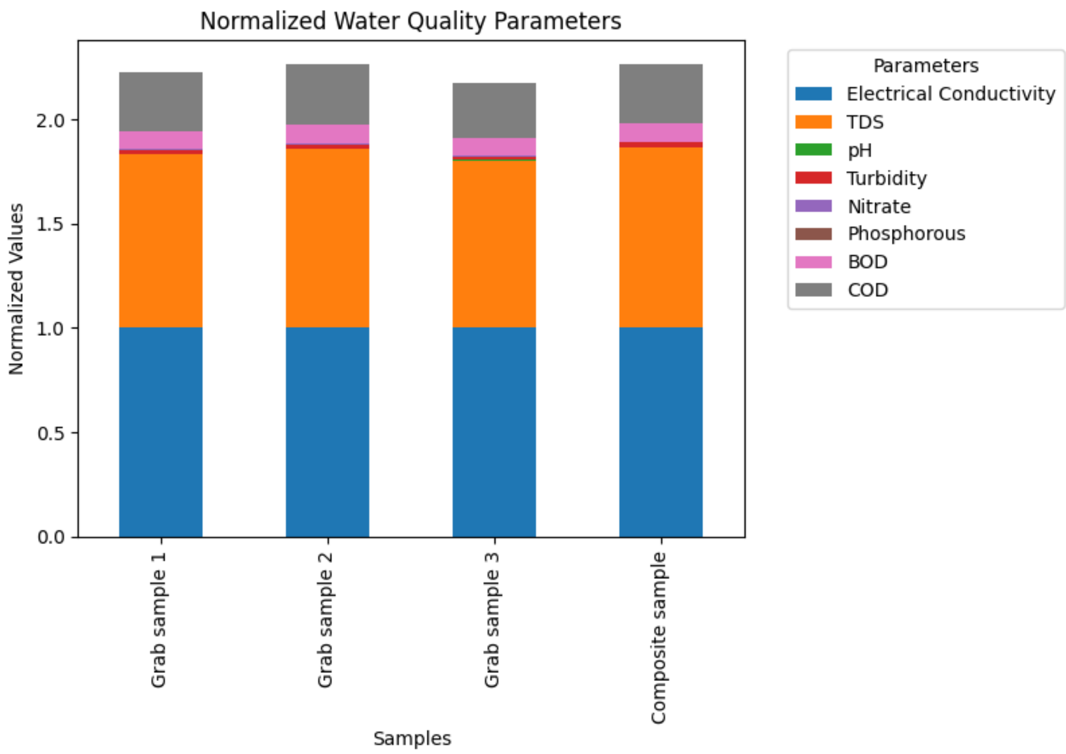


Figure 5.2: Comparative Analysis of Key Characteristics in Greywater Source-1 Samples

Table 5.1 and Figure 5.2 illustrates the characteristics of Greywater Source-1, based on multiple grab samples and a composite sample. The parameters under consideration encompass important water quality indicators. The electrical conductivity ranged from 1985 µS/cm to 2142 µS/cm across the grab samples, with the composite sample measuring at 2030 µS/cm. Total Dissolved Solids (TDS) exhibited values spanning from 1590 mg/l to 1835 mg/l for grab samples, and 1755 mg/l for the composite sample. Variations in pH levels were observed, with values between 7.4 and 9.6 for grab samples, and a composite sample pH of 8.5. Turbidity measurements indicated values ranging from 33 NTU to 45 NTU for grab samples, with the composite sample measuring at 41 NTU. Nitrate content varied from 7.2 mg/l to 10.5 mg/l among grab samples, with a composite sample nitrate content of 8.9 mg/l. Phosphorous concentrations ranged from 0.8 mg/l to 1.1 mg/l for grab samples and 0.76 mg/l for the composite sample. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) depicted variations, with BOD levels of 167 mg/l to 192 mg/l in grab samples and 183 mg/l for the composite sample, while COD ranged from 528 mg/l to 625 mg/l in grab samples and measured 573 mg/l in the composite sample. These results provide valuable insights into the quality of

Greywater Source-1, which can inform decisions regarding its potential treatment and reuse in various applications, considering the variations observed across grab samples.

Table 5.2: Characteristics of Greywater Source-2

Parameters	Grab sample 1	Grab sample 2	Grab sample 3	Composite sample
Electrical Conductivity (µS/cm)	1685	1678	1789	1723
TDS (mg/l)	1457	1412	1530	1467
pH	7.2	6.88	7.48	7.38
Turbidity (NTU)	34.03	32.953	35.33	34.05
Nitrate (mg/l)	7.38	7.2	7.79	7.45
Phosphorous (mg/l)	0.7	0.7	0.77	0.79
BOD (mg/l)	148	144	155.1	149
COD (mg/l)	679	468	458	536

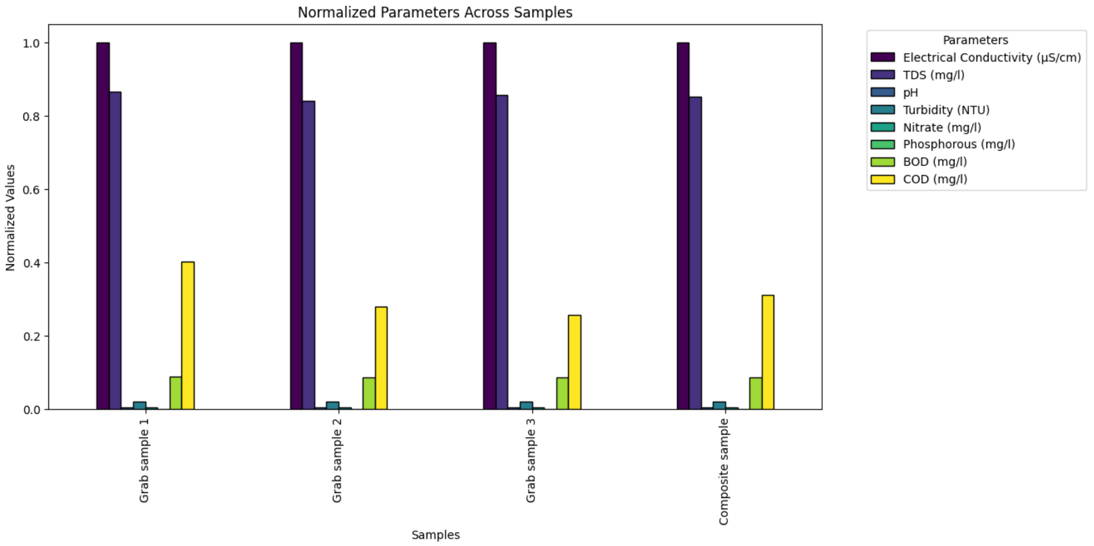


Figure 5.3: Comparative Analysis of Key Characteristics in Greywater Source-2 Samples

Table 5.2 and Figure 5.3 present the grab samples, the electrical conductivity ranged from 1678 µS/cm to 1789 µS/cm, with an average of 1685 µS/cm. TDS levels varied between 1412 mg/l and 1530 mg/l, averaging 1457 mg/l. pH values fluctuated between 6.88 and 7.48, with a mean of 7.2. Turbidity measurements fell within the range of 32.953 NTU to 35.33 NTU, averaging 34.03 NTU. Nitrate concentrations spanned from 7.2 mg/l to 7.79 mg/l, with an average of 7.38 mg/l. Phosphorous content remained relatively stable, ranging from 0.7 mg/l to 0.79 mg/l, with an average of 0.7 mg/l. BOD exhibited variations from 144 mg/l to 155.1 mg/l, averaging 148 mg/l. COD levels in grab samples ranged between 458 mg/l and 679 mg/l.

The composite sample provides an overall representation, with electrical conductivity at 1723 µS/cm, TDS at 1467 mg/l, pH at 7.38, turbidity at 34.05 NTU, nitrate concentration at 7.45 mg/l, phosphorous concentration at 0.79 mg/l, BOD at 149 mg/l, and COD at 536 mg/l. These measurements play a critical role in assessing the water quality, and the composite sample offers a consolidated view, aiding in the comprehensive evaluation of the environmental conditions and the potential impact on aquatic ecosystems and human health. Further analysis and interpretation of these results are essential for a more thorough understanding of the water quality in the examined area.

Table 5.3: Characteristics of Greywater Source-3

Parameters	**Grab sample 1**	**Grab sample 2**	**Grab sample 3**	**Composite sample**
Electrical Conductivity (µS/cm)	2315	2387	2242	2308
TDS (mg/l)	1927	1992	1863	1918
pH	9.4	9.7	9.1	8.9
Turbidity (NTU)	44.5	46.2	43.8	44.1
Nitrate (mg/l)	10.05	12.43	9.68	10.17
Phosphorous (mg/l)	1.02	1.24	0.93	1.01
BOD (mg/l)	231.8	238.5	250.2	237.3
COD (mg/l)	786.2	815.1	720.5	775.4

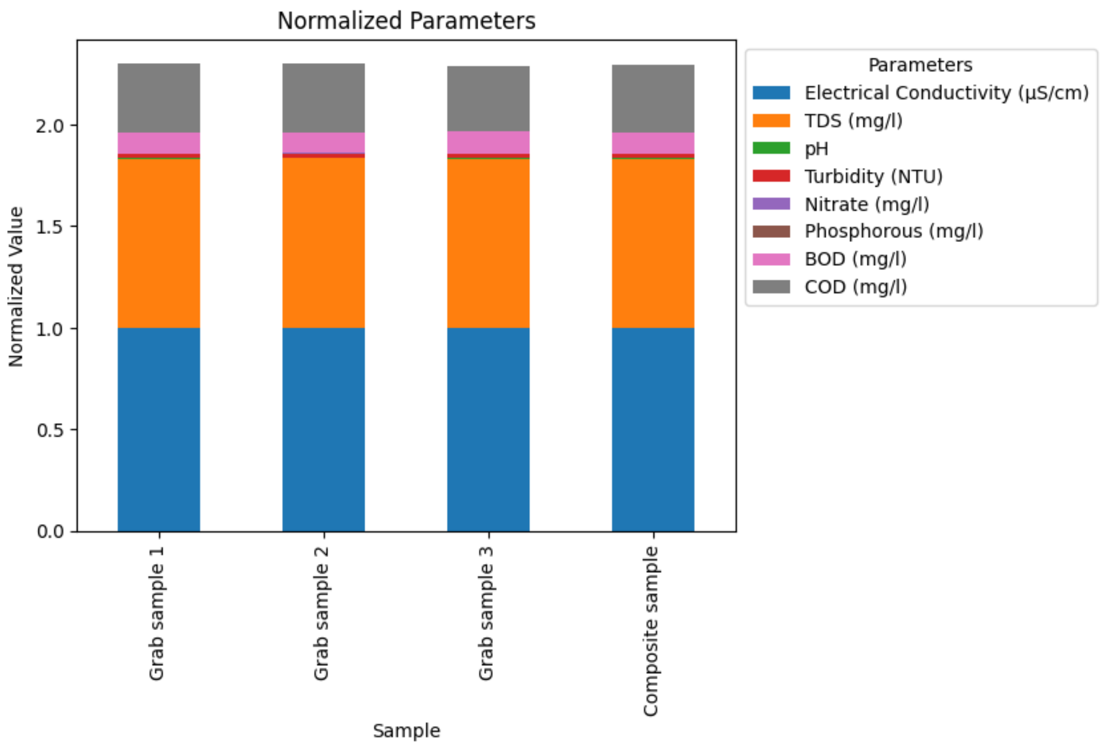


Figure 5.4: Comparative Analysis of Key Characteristics in Greywater Source-3 Samples

Table 5.3 and Figure 5.4 presents data for Greywater Source-3. Electrical conductivity values range from 2242 µS/cm to 2387 µS/cm, indicating some variability. TDS values vary between 1863 mg/l to 1992 mg/l, suggesting a moderate range of total dissolved solids. pH values range from 9.1 to 9.7, indicating relatively high alkalinity. Turbidity values show slight fluctuations, with a range from 43.8 NTU to 46.2 NTU. Nitrate levels exhibit a moderate variation from 9.68 mg/l to 12.43 mg/l. Phosphorous, BOD, and COD values demonstrate some variability but are generally in line with Greywater Source-1 and Source-2.

Table 5.4: Characteristics of Greywater Source-4

Parameters	**Grab sample 1**	**Grab sample 2**	**Grab sample 3**	**Composite sample**
Electrical Conductivity (µS/cm)	2070.3	2215.1	1857.8	2047.5
TDS (mg/l)	1721.6	1885.77	1595.2	1730.5
pH	8.61	9.29	7.82	8.48
Turbidity (NTU)	39.97	45.12	35.02	40.5
Nitrate (mg/l)	8.8	9.63	7.72	9.2
Phosphorous (mg/l)	0.87	0.95	0.76	0.88

BOD (mg/l)	256	271	279	265
COD (mg/l)	912	995	782	893

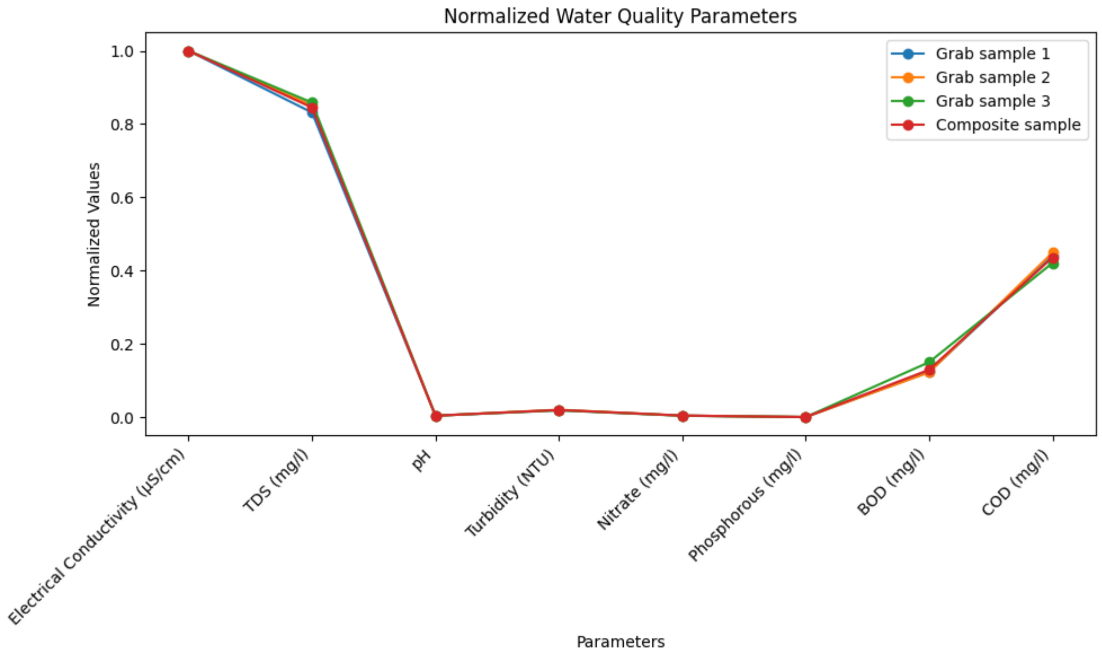


Figure 5.5: Comparative Analysis of Key Characteristics in Greywater Source-4 Samples

Table 5.4 and Figure 5.5 highlight the parameters of Greywater Source-4. Electrical conductivity values exhibit a moderate range from 1857.8 µS/cm to 2215.1 µS/cm. TDS values vary between 1595.2 mg/l to 1885.77 mg/l, showcasing a moderate range of total dissolved solids. pH values are relatively stable, ranging from 7.82 to 9.29. Turbidity values are consistent, with a range from 35.02 NTU to 45.12 NTU. Nitrate levels exhibit minimal fluctuation, varying from 7.2 mg/l to 9.63 mg/l. Phosphorous, BOD, and COD values are within a narrow range, similar to Greywater Source-2.

5.1.2Determination of Total Dissolved Solids (TDS)

The assessment of Total Dissolved Solids (TDS) was conducted employing the gravimetric method, a well-established technique in analytical chemistry. The procedure involved the following steps:

- Initial Weight Measurement: The measurement commenced with the determination of the weight of an empty beaker (designated as W1).
- Filtration and Evaporation: Subsequently, a 50 mL sample of water was carefully passed through a 0.2-micron filter and collected in the beaker. The beaker with the filtered water was then subjected to evaporation. The

evaporation process was carried out in an oven set to 180°C, persisting until the complete dryness of the beaker was achieved.

- Final Weight Measurement: Upon completion of the evaporation process, the beaker was extracted from the oven and allowed to equilibrate to room temperature within a desiccator. The final weight of the beaker, now containing the residual dissolved solids, was recorded as W2.

The calculation of the accurate TDS value was ascertained using the following mathematical formulation:

$$TDS\ (mg/L) = \frac{(W2 - W1) \times 1000}{50\ mL}$$

Where:

- **TDS (mg/L)** represents the concentration of Total Dissolved Solids in milligrams per litre.
- **W1** signifies the initial weight of the empty beaker (in grams).
- **W2** indicates the final weight of the beaker containing the dried dissolved solids (in grams).
- **50 mL** corresponds to the volume of the water sample subjected to analysis (in millilitres).
- The multiplication by 1000 is applied to convert grams to milligrams for consistency in the units of measurement.

This gravimetric method for TDS determination ensures a precise and reliable assessment of the concentration of dissolved solids within the analyzed water sample.

5.1.3Chemical Oxygen Demand (COD) Analysis

The determination of Chemical Oxygen Demand (COD) was conducted using the open reflux method. A 20 mL aliquot of the sample was placed in a COD flask, followed by the addition of a small quantity of mercuric sulfate. Subsequently, 10 mL of a 0.25 N potassium dichromate solution and 30 mL of concentrated sulfuric acid were introduced into the same COD flask. The sample was subjected to reflux for a duration of 2 hours, maintaining a temperature of 150°C. After cooling, the digested sample was titrated against a 0.1 N ferrous ammonium sulfate solution. The exact COD value (in milligrams per litre, mg/L) was determined employing the following formula:

$$COD\ (mg/L) = \frac{V \times N \times 8000}{20 \times 1.6}$$

Where:

- **V** represents the volume (in mL) of the ferrous ammonium sulfate solution consumed during titration.
- **N** signifies the normality of the ferrous ammonium sulfate solution (0.1 N).
- The factors 8000, 20, and 1.6 are constantly used for the COD calculation.

5.1.4 Turbidity Measurement

Turbidity (T) in the samples was quantified using a turbidity meter. The procedure began with the analysis of a standard solution on the meter, yielding a reference value denoted as $T_{standard}$. Subsequently, the turbidity T_{sample} of each sample was measured. This quantification was conducted by the following relationship:

$$T = \frac{T_{sample}}{T_{standard}}$$

where:

- T represents the turbidity of the sample.
- T_{emple} signifies the turbidity reading obtained for the sample.
- $_{A\ standard}$ denotes the turbidity of the standard solution, serving as the reference value for the meter calibration.

5.1.5Nitrate Analysis

Nitrate quantification was conducted employing the UV/Vis spectrophotometric method. Initially, a standard stock solution of nitrate was prepared by dissolving a precisely known quantity of sodium nitrate in 1000 mL of distilled water. Subsequently, five distinct standard solutions with varying concentrations were derived from this nitrate stock solution, each through dilution with distilled water. To these standard solutions, 1 mL of 1N hydrochloric acid was added within 50 mL of the respective standard solution. The absorbance was then measured using a UV/Vis spectrophotometer at two distinct wavelengths, namely 220 nm and 275 nm. A calibration curve was established by plotting the relationship between concentration and absorbance. The absorbance of the test sample was determined at the same wavelengths. To ascertain the nitrate concentration within the sample, the calibration curve was employed. This relationship is mathematically expressed as:

$$C_{sample} = \frac{A_{sample}}{S_{sample}}$$

Where:

- $_{The\ C\ sample}$ represents the concentration of nitrate in the sample.
- A_{sample} signifies the absorbance of the sample at the specified wavelengths.
- S_{ample} stands for the slope of the calibration curve obtained through a linear regression analysis.

5.1.6Phosphorus Analysis

Phosphorus content was quantified using the UV/Vis spectrophotometric method. To initiate this analysis, a standard stock solution of phosphorus was prepared by dissolving a precisely known quantity of sodium phosphate in 1000 mL of distilled water. From the prepared stock solution of phosphorus, a measured volume was extracted and placed in a 50 mL volumetric flask. Subsequently, 10 mL of VM reagent was introduced into the flask, and after a 10-minute incubation period, the absorbance of the solution was recorded using a UV/Vis spectrophotometer, with measurements conducted at a wavelength of 420 nm.

To establish a quantitative relationship between phosphorus concentration and the corresponding absorbance values, a calibration curve was constructed. The absorbance of the sample was assessed at the same wavelength (420 nm), allowing for a direct comparison with the calibration curve. Utilizing the calibration curve, the concentration of phosphorus within the sample was accurately determined, employing the principles of linear regression and the Beer-Lambert law:

$$A = \varepsilon \cdot b \cdot C$$

Where:

- A represents the absorbance of the sample.
- ε denotes the molar absorptivity of phosphorus at 420 nm.
- b is the path length (in this case, 1 cm).
- C signifies the concentration of phosphorus in the sample (in mol/L).

This enabled the precise calculation of the phosphorus concentration within the analyzed sample, contributing to the scientific rigour and accuracy of the assessment.

5.1.7 Biochemical Oxygen Demand (BOD) Analysis

Biochemical Oxygen Demand (BOD) was determined using the wrinkle method with a 5-day incubation period. The procedure involved several steps as follows:

- *Aeration:* Distilled water was aerated for 12 hours to ensure the removal of dissolved oxygen (DO).
- *Incubation:* The aerated water was then incubated for an additional 12 hours at 20°C to stabilize the temperature.
- *Chemical Additions:* Upon reaching room temperature, specific chemicals were added to the water, including calcium chloride, ferric chloride, magnesium sulfate, and phosphate buffer solution (1 mL per litre of distilled water). Thorough mixing was carried out to homogenize the solution.
- *Blank Preparation:* One BOD bottle was filled with this solution to serve as the blank.
- *Seed Inoculation:* A known volume (2 mL per litre) of seed material was introduced into the distilled water. Proper mixing was ensured, and another BOD bottle was filled to serve as the seed blank.
- *Sample Preparation:* The sample to be analyzed was taken in a volumetric flask and diluted with distilled water to obtain the desired concentration.
- *Sample Bottles:* Two BOD bottles were filled with the prepared sample: one for the initial day (zero-day) and one for the fifth day.
- *Zero-Day Analysis:* The sample in the zero-day bottle was immediately analyzed for DO. This was achieved by adding manganese sulfate, alkali azide, and sulfuric acid to the sample and subsequently titrating it against sodium thiosulfate. Starch was used as an indicator to detect the endpoint.
- *Fifth-Day Analysis:* The sample in the fifth-day bottle was placed in a BOD incubator for a 5-day incubation period at 20°C. After incubation, the fifth-day sample was also analyzed for DO.

Calculation of 5-Day BOD: The 5-day BOD was calculated using the following formula:

$$5 - Day\ BOD\ (mg/L) = \frac{DO_{zero-day} - DO_{fifth-day}}{}$$

Where:

- $DO_{zero-day}$ is the dissolved oxygen on the initial day.

- $DO_{fifth-day}$ is the dissolved oxygen after the 5-day incubation.
- f is the dilution factor.
- K is the BOD conversion factor (usually 1.5).

This method allows for the quantification of the organic pollution load in the analyzed sample based on the decrease in dissolved oxygen over the incubation period, providing valuable information for water quality assessment.

5.2 Result and Analysis

The output characteristics of treated greywater collected from various sources exhibit substantial variations that are contingent upon the specific treatment processes employed. Greywater, emanating from sources such as showers, hand basins, and kitchen sinks, initially possesses characteristics including relatively low levels of organic content and nutrients compared to freshwater. However, after undergoing primary, secondary, and tertiary treatment, the resulting treated greywater showcases significant improvements in various water quality parameters. These transformations are evident in reduced electrical conductivity, Total Dissolved Solids (TDS), turbidity, nitrate and phosphorous concentrations, as well as reduced Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) levels. The treated greywater's pH remains within a neutral range. Such improvements render treated greywater amenable to a variety of non-potable applications, including toilet flushing, garden irrigation, and car washing, demonstrating its potential as a sustainable alternative water source for specific purposes within the broader framework of water resource management and environmental preservation.

Table 5.5: Analysis of Treated Greywater from Source 1: Output Characteristics

Parameters	**The initial concentration of the composite sample**	**Concentration after primary treatment**		**Concentration after secondary treatment**		**Concentration after tertiary treatment**	
		Conc.	**% decrease**	**Conc.**	**% decrease**	**Conc.**	**% decrease**
Electrical Conductivity (µS/cm)	2048	1467	28.11	932	36.27	240	73.85
TDS (mg/l)	1755	1332	24.21	1087	19.21	391	64.47

pH	8.5	8.18	X	8.08	X	7.98	X
Turbidity (NTU)	41	16.2	60.39	12.5	26.83	10.8	9.76
Nitrate (mg/l)	8.2	6.45	20.12	3.62	45.12	2.94	19.51
Phosphorous (mg/l)	0.77	0.68	11.69	0.51	19.48	0.39	22.08
BOD (mg/l)	190	75.1	60.47	18.5	74.21	8.61	55.47
COD (mg/l)	580	260	55.17	76.5	69.83	35.2	53.1

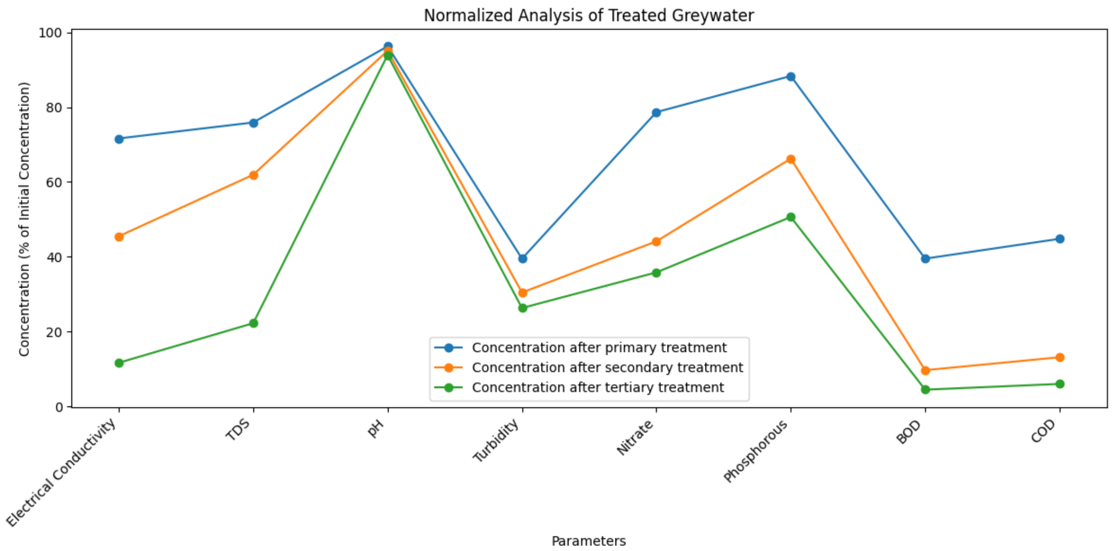


Figure 5.6: Transformation of Treated Greywater from Source 1: Evolution of Key Parameters

In Table 5.5 and Figure 5.6, an analysis of treated greywater from Source 1 is presented, detailing the evolution of various parameters through different treatment stages. The table starts with the initial concentrations of composite samples for each parameter, followed by concentrations after primary, secondary, and tertiary treatments. Notably, Electrical Conductivity exhibits a substantial decrease from its initial value of 2048 µS/cm to 1467 µS/cm after primary treatment, followed by further reductions to 932 µS/cm after secondary treatment and eventually reaching 240 µS/cm after tertiary treatment. Similarly, Total Dissolved Solids (TDS) concentrations decreased from 1755 mg/l to 1332 mg/l after primary treatment, 1087 mg/l after secondary treatment, and ultimately 391 mg/l after tertiary treatment. The pH levels exhibit a decreasing trend from 8.5 to 8.18 after primary treatment, 8.08 after secondary treatment, and 7.98 after tertiary treatment. Moreover, Turbidity levels significantly drop from the initial 41 NTU to 16.2 NTU after primary treatment, 12.5 NTU after secondary treatment, and 10.8 NTU after tertiary treatment. The analysis also reveals a substantial decrease in Nitrate concentrations, Phosphorous concentrations, Biochemical Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) across the various treatment stages, indicating the effectiveness of the treatment processes in improving the quality of the greywater from Source 1.

Table 5.6: Analysis of Treated Greywater from Source 2: Output Characteristics

Parameters	**The initial concentration of the composite sample**	**Concentration after primary treatment**		**Concentration after secondary treatment**		**Concentration after tertiary treatment**	
		Conc.	**% decrease**	**Conc.**	**% decrease**	**Conc.**	**% decrease**
Electrical Conductivity (µS/cm)	1720	1227	29.34	893	25.92	281	67.88
TDS (mg/l)	1455	1050	27.78	820	22.12	209	74.62
pH	7.3	7.45	X	7.27	X	7.19	X
Turbidity (NTU)	33	14.5	58.93	10.8	23.26	9.69	9.55
Nitrate (mg/l)	7.4	5.78	23.78	3.2	43.74	2.59	18.65
Phosphorous (mg/l)	0.79	0.72	8.22	0.59	18.51	0.46	24.61
BOD (mg/l)	148	64.4	56.61	17.5	72.8	6.75	61.51
COD (mg/l)	538	256	53.11	82.5	67.6	37.2	55.29

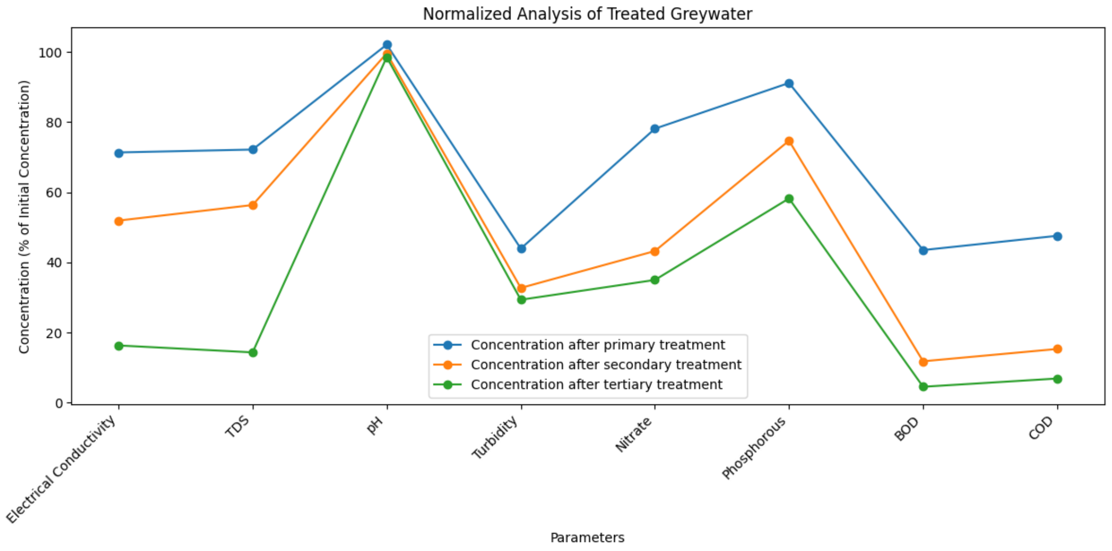


Figure 5.7: Transformation of Treated Greywater from Source 2: Evolution of Key Parameters

In Table 5.6 and Figure 5.7, an analysis of treated greywater from Source 2 is presented. The table provides insights into the changes in parameter concentrations at various treatment stages. Initially, the concentrations of each parameter are documented, and subsequent concentrations after primary, secondary, and tertiary treatments are recorded. Notably, the electrical conductivity decreases from an initial 1720 µS/cm to 1227 µS/cm after primary treatment, further diminishing to 893 µS/cm after secondary treatment, and ultimately reaching 281 µS/cm after tertiary treatment. Similarly, the concentrations of Total Dissolved Solids (TDS) decrease from 1455 mg/l to 1050 mg/l after primary treatment, followed by a reduction to 820 mg/l after secondary treatment, and a final concentration of 209 mg/l after tertiary treatment. pH levels exhibit fluctuations during the treatment process, moving from an initial value of 7.3 to 7.45 after primary treatment, 7.27 after secondary treatment, and finally stabilizing at 7.19 after tertiary treatment. Additionally, turbidity decreases significantly from an initial 33 NTU to 14.5 NTU after primary treatment, further lowering to 10.8 NTU after secondary treatment, and eventually to 9.69 NTU after tertiary treatment. Nitrate concentrations show a consistent decline from 7.4 mg/l to 5.78 mg/l after primary treatment, 3.2 mg/l after secondary treatment, and 2.59 mg/l after tertiary treatment. Phosphorous concentrations follow a similar trend, reducing from 0.79 mg/l to 0.72 mg/l after primary treatment, 0.59 mg/l after secondary treatment, and 0.46 mg/l after tertiary treatment. Moreover, the Biological Oxygen Demand (BOD) concentrations decrease from an initial 148 mg/l to 64.4 mg/l after primary treatment, 17.5 mg/l after secondary treatment, and 6.75 mg/l after tertiary treatment. Finally, Chemical Oxygen Demand (COD) concentrations exhibit a declining pattern from 538 mg/l to 256 mg/l after primary treatment, 82.5 mg/l after secondary treatment, and 37.2 mg/l after tertiary treatment. These results illustrate the efficacy of the treatment process in enhancing the quality of greywater from Source 2.

Table 5.7: Analysis of Treated Greywater from Source 3: Output Characteristics

Parameters	**The initial concentration of the composite sample**	**Concentration after primary treatment**		**Concentration after secondary treatment**		**Concentration after tertiary treatment**	
		Conc.	% decrease	Conc.	% decrease	Conc.	% decrease
Electrical Conductivity (µS/cm)	2300	1600	30.32	1220	23.59	387	68.44
TDS (mg/l)	1935	1385	27.68	1120	19.23	286	74.35
pH	8.95	8.6	4.75	8.17	4.39	8.12	2.80
Turbidity (NTU)	45.5	17.8	61.89	12.4	24.63	10.9	14.59
Nitrate (mg/l)	10.5	8.38	23.48	5.03	39.49	3.77	25.34
Phosphorous (mg/l)	1.05	0.86	10.46	0.64	26.48	0.52	19.59
BOD (mg/l)	236.5	93.8	60.39	20.5	78.45	8.19	59.05
COD (mg/l)	772.5	249.5	67.43	86.8	65.29	45.5	48.62

Table 5.7 and Figure 5.8 presents a comprehensive analysis of treated greywater originating from Source 3. This table meticulously records the initial concentrations of composite samples and their subsequent evolution after primary, secondary, and tertiary treatment stages. Notable observations include a substantial reduction in Electrical Conductivity, shifting from 2300 µS/cm to 1600 µS/cm after primary treatment, followed by a further decrease to 1220 µS/cm post-secondary treatment, ultimately reaching 387 µS/cm after tertiary treatment.

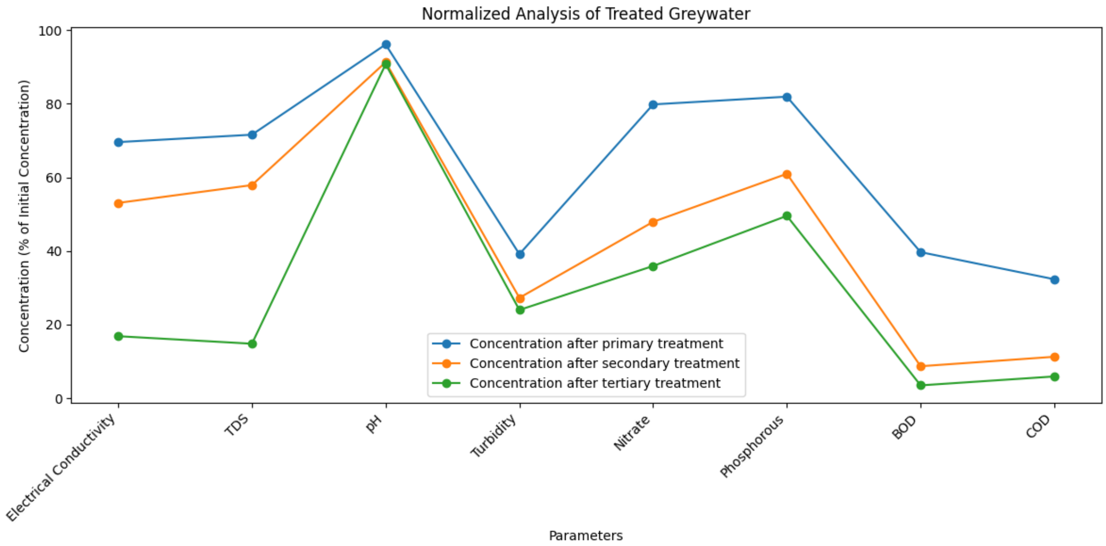


Figure 5.8: Transformation of Treated Greywater from Source 3: Evolution of Key Parameters

Similarly, Total Dissolved Solids (TDS) concentrations demonstrate a consistent decline, commencing at 1935 mg/l and progressively decreasing to 1385 mg/l after primary treatment, 1120 mg/l after secondary treatment, and ultimately bottoming out at 286 mg/l after tertiary treatment. The pH levels experience modest fluctuations, starting at 8.95 and settling at 8.6 after primary treatment, 8.17 after secondary treatment, and 8.12 after tertiary treatment. Moreover, the table reveals a marked reduction in turbidity, as evidenced by the initial 45.5 NTU diminishing to 17.8 NTU post-primary treatment, 12.4 NTU following secondary treatment, and 10.9 NTU after tertiary treatment. Furthermore, nitrate concentrations show a consistent decline, commencing at 10.5 mg/l and progressively decreasing to 8.38 mg/l after primary treatment, 5.03 mg/l after secondary treatment, and finally resting at 3.77 mg/l post-tertiary treatment. Phosphorous concentrations exhibit a similar trend, starting at 1.05 mg/l and progressively decreasing to 0.86 mg/l post-primary treatment, 0.64 mg/l following secondary treatment, and 0.52 mg/l after tertiary treatment. Additionally, Biochemical Oxygen Demand (BOD) concentrations undergo significant reduction, commencing at 236.5 mg/l and progressively decreasing to 93.8 mg/l after primary treatment, 20.5 mg/l after secondary treatment, and 8.19 mg/l following tertiary treatment. Lastly, Chemical Oxygen Demand (COD) concentrations also experience a notable reduction, with initial levels at 772.5 mg/l and successive declines to 249.5 mg/l after primary treatment, 86.8 mg/l after secondary treatment, and 45.5 mg/l after tertiary treatment. These findings underscore the efficacy of the treatment processes in improving the quality of greywater from Source 3, thereby highlighting the potential for greywater recycling in sustainable water resource management.

Table 5.8: Analysis of Treated Greywater from Source 4: Output Characteristics

Parameters	The initial concentration of the composite sample	Concentration after primary treatment		Concentration after secondary treatment		Concentration after tertiary treatment	
		Conc.	% decrease	Conc.	% decrease	Conc.	% decrease
Electrical Conductivity (µS/cm)	2035	1325	34.85%	1019	23.59%	330	67.39%
TDS (mg/l)	1727	1327	23.77%	1065	19.46%	277	73.77%
pH	8.45	8.55	X	8.27	X	8.08	X
Turbidity (NTU)	41.5	13.9	65.63%	10.5	28.74%	9.08	9.64%
Nitrate (mg/l)	8.9	6.49	27.60%	3.55	46.32%	2.78	19.42%
Phosphorous (mg/l)	0.88	0.81	8.18%	0.6	24.41%	0.46	24.50%
BOD (mg/l)	264	118	55.30%	23	80.46%	10.4	55.27%
COD (mg/l)	895	307	65.63%	80.2	73.89%	49	38.94%

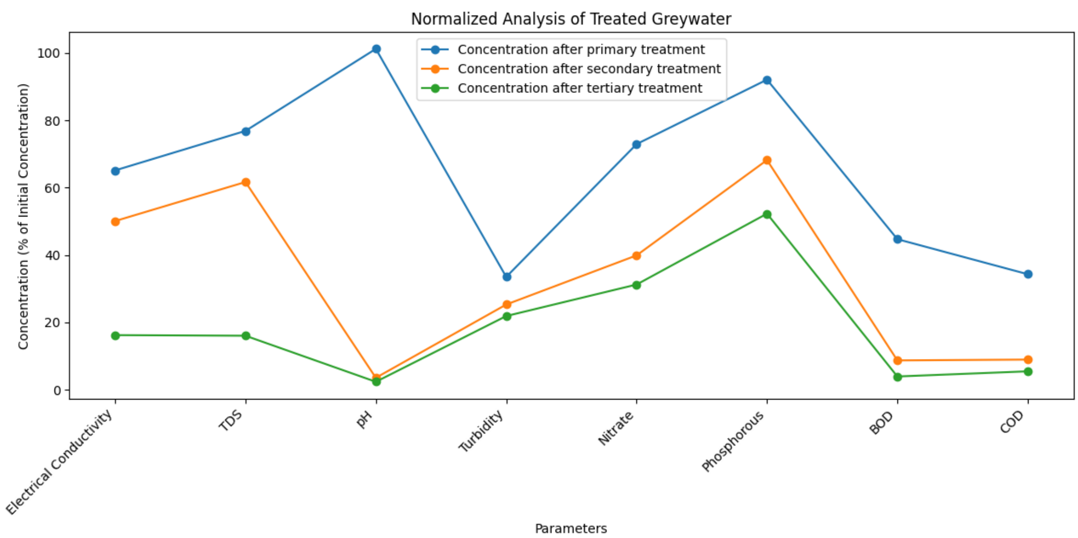


Figure 5.9: Transformation of Treated Greywater from Source 4: Evolution of Key Parameters

Table 5.8 and Figure 5.9 presents the analysis of treated greywater from Source 4. It provides insight into the changes in various parameters throughout the treatment process. The initial concentrations of each parameter are detailed, along with the concentrations after primary, secondary, and tertiary treatments. Electrical Conductivity experiences a significant reduction from the initial 2035 µS/cm to 1325 µS/cm after primary treatment. This reduction continues as it drops to 1019 µS/cm after secondary treatment and eventually reaches 330 µS/cm after tertiary treatment. Similarly, Total Dissolved Solids (TDS) concentrations also decrease notably. Starting at 1727 mg/l, they decrease to 1327 mg/l after primary treatment, then to 1065 mg/l after secondary treatment, and finally reach 277 mg/l after tertiary treatment. pH levels exhibit fluctuations through the treatment stages. The pH value, initially at 8.45, increases slightly to 8.55 after primary treatment, decreases to 8.27 after secondary treatment, and further decreases to 8.08 after tertiary treatment. Turbidity experiences a consistent decrease. Beginning at 41.5 NTU, it reduces to 13.9 NTU after primary treatment, 10.5 NTU after secondary treatment, and eventually reaches 9.08 NTU after tertiary treatment. The concentrations of Nitrate decline significantly during the treatment process. Starting at 8.9 mg/l, they reduce to 6.49 mg/l after primary treatment, further decreasing to 3.55 mg/l after secondary treatment, and reaching 2.78 mg/l after tertiary treatment. Phosphorous concentrations also exhibit notable reductions. Initially at 0.88 mg/l, they decrease to 0.81 mg/l after primary treatment, then to 0.6 mg/l after secondary treatment, and eventually reach 0.46 mg/l after tertiary treatment. Moreover, the Biochemical Oxygen Demand (BOD) concentrations decrease significantly. Starting at 264 mg/l, they reduce to 118 mg/l after primary treatment, further decreasing to 23 mg/l after secondary treatment, and reaching 10.4 mg/l after tertiary treatment. Finally, the Chemical Oxygen Demand (COD) concentrations also experience notable reductions. Beginning at 895 mg/l, they decrease to 307 mg/l after primary treatment, further reducing to 80.2 mg/l after secondary treatment, and finally reaching 49 mg/l after tertiary treatment.

The comparative performance evaluation of greywater sources, presented in Tables 4.5 to 4.8, demonstrates the significant impact of treatment processes on various water quality parameters. The percentage decrease in these parameters between the inlet and outlet concentrations reflects the efficacy of the treatment methodologies applied to each greywater source.

Table 5.9: Comprehensive Performance Evaluation of Greywater Source-1

Parameters	Inlet concentration	Outlet concentration	Percentage decrease
Electrical Conductivity (µS/cm)	2040	246	87.88
TDS (mg/l)	1745	396	77.62
pH	8.35	7.98	-
Turbidity (NTU)	41	11.5	73.17
Nitrate (mg/l)	7.9	2.88	64.37
Phosphorous (mg/l)	0.73	0.42	45.21
BOD (mg/l)	184	8.35	95.47
COD (mg/l)	572	35.5	93.78

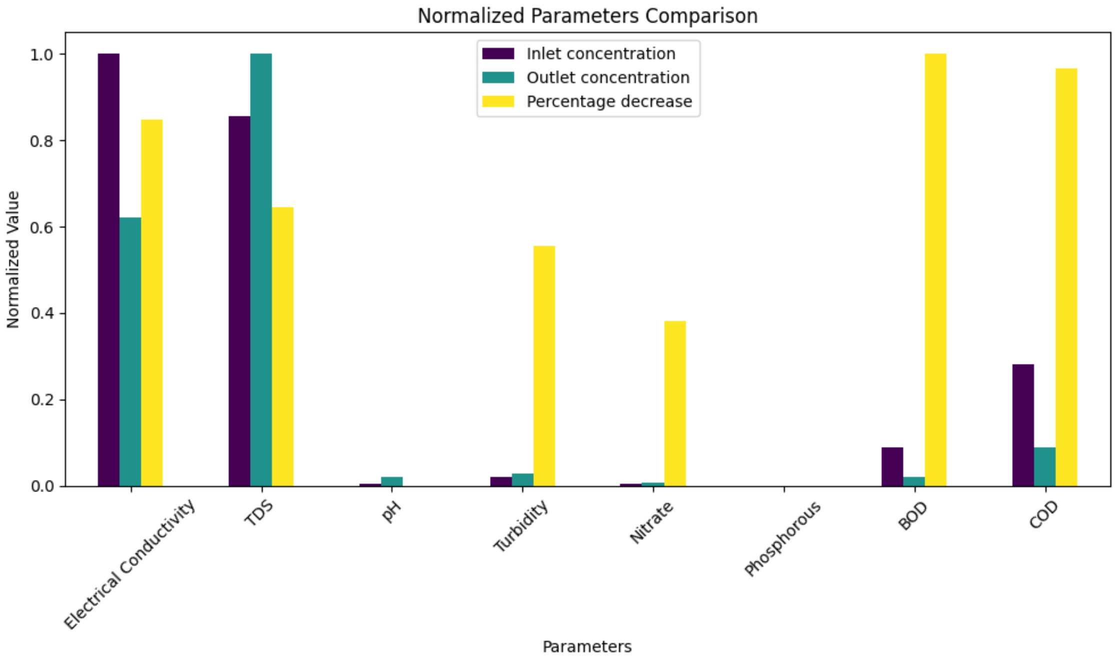


Figure 5.10: Performance Evaluation of Greywater Source-1: Reduction in Contaminant Levels

Table 5.9 and Figure 5.10 reveal a substantial improvement in the quality of greywater from Source 1. The electrical conductivity, TDS, turbidity, nitrate, phosphorous, BOD, and COD all exhibited remarkable reductions. Notably, BOD and COD experienced the most significant percentage decrease, at 95.47% and 93.78%, respectively. This indicates that the treatment processes for Source-1 are highly effective, resulting in a notable enhancement of water quality.

Table 5.10: Comprehensive Performance Evaluation of Greywater Source-2

Parameters	**Inlet concentration**	**Outlet concentration**	**Percentage decrease**
Electrical Conductivity (µS/cm)	1736	285	83.62
TDS (mg/l)	1465	215	85.36
pH	7.45	7.18	-
Turbidity (NTU)	36	9.87	71.27
Nitrate (mg/l)	7.3	2.58	64.47
Phosphorous (mg/l)	0.82	0.47	43.9
BOD (mg/l)	153	6.97	95.45
COD (mg/l)	536	37.4	93.03

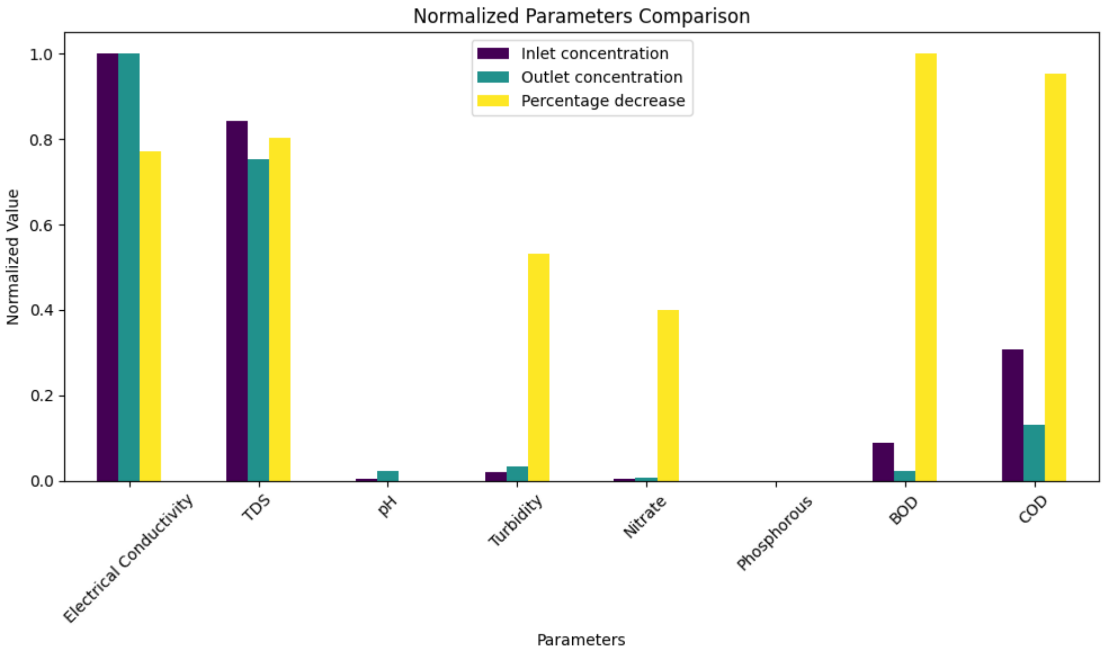


Figure 5.11: Performance Evaluation of Greywater Source-2: Reduction in Contaminant Levels

Table 5.10 and Figure 5.11 provide a similar trend for Source-2, where electrical conductivity, TDS, turbidity, nitrate, phosphorous, BOD, and COD exhibited considerable reductions. BOD and COD experienced a remarkable percentage decrease of 95.45% and 93.03%, respectively. The treatment processes for Source-2 showcase substantial efficiency in improving water quality.

Table 5.11: Comprehensive Performance Evaluation of Greywater Source-3

Parameters	**Inlet concentration**	**Outlet concentration**	**Percentage decrease**
Electrical Conductivity (µS/cm)	2307	390	83.17
TDS (mg/l)	1925	285	85.1
pH	8.95	8.13	-
Turbidity (NTU)	44.2	10.9	74.78
Nitrate (mg/l)	11.3	3.76	65.78
Phosphorous (mg/l)	1.05	0.51	47.62
BOD (mg/l)	235.5	8.32	96.47
COD (mg/l)	772.9	45.2	94.17

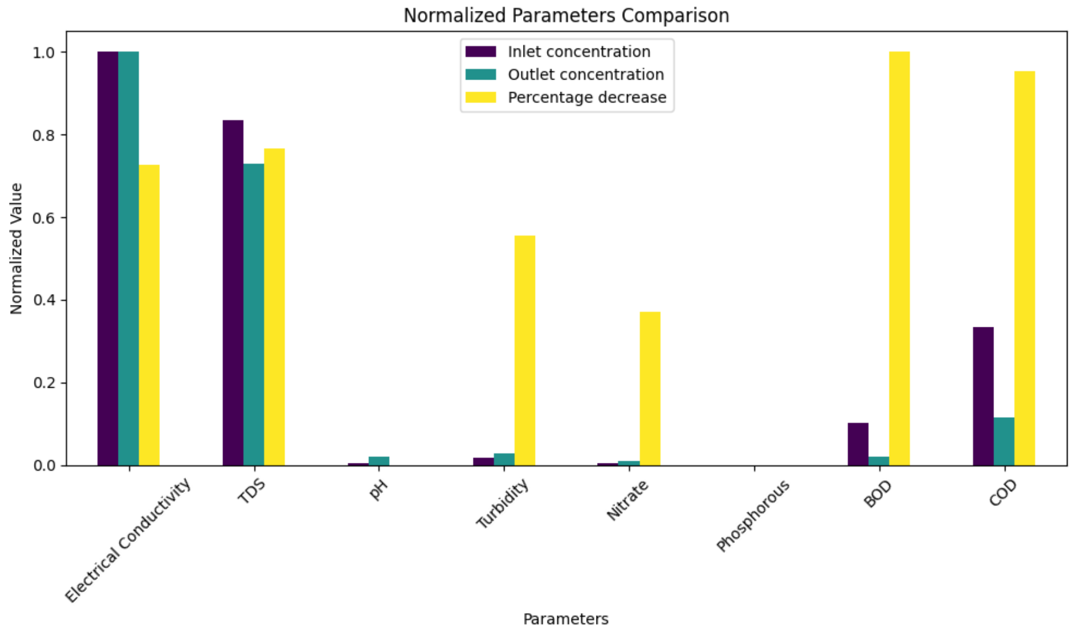


Figure 5.12: Performance Evaluation of Greywater Source-3: Reduction in Contaminant Levels

Table 5.11 and Figure 5.12 highlight the effectiveness of the treatment processes for Source 3. Significant reductions in electrical conductivity, TDS, turbidity, nitrate, phosphorous, BOD, and COD are observed. The percentage decrease is particularly noteworthy for BOD (96.47%) and COD (94.17%), emphasizing the remarkable enhancement in water quality.

Table 5.12: Comprehensive Performance Evaluation of Greywater Source-4

Parameters	Inlet concentration	Outlet concentration	Percentage decrease
Electrical Conductivity (µS/cm)	2038	334	83.57
TDS (mg/l)	1742	281	83.86
pH	8.48	8.15	-
Turbidity (NTU)	44	9.24	79.02
Nitrate (mg/l)	8.7	2.9	67.12
Phosphorous (mg/l)	0.87	0.45	48.28
BOD (mg/l)	268	10.7	96.02
COD (mg/l)	894	49.3	94.47

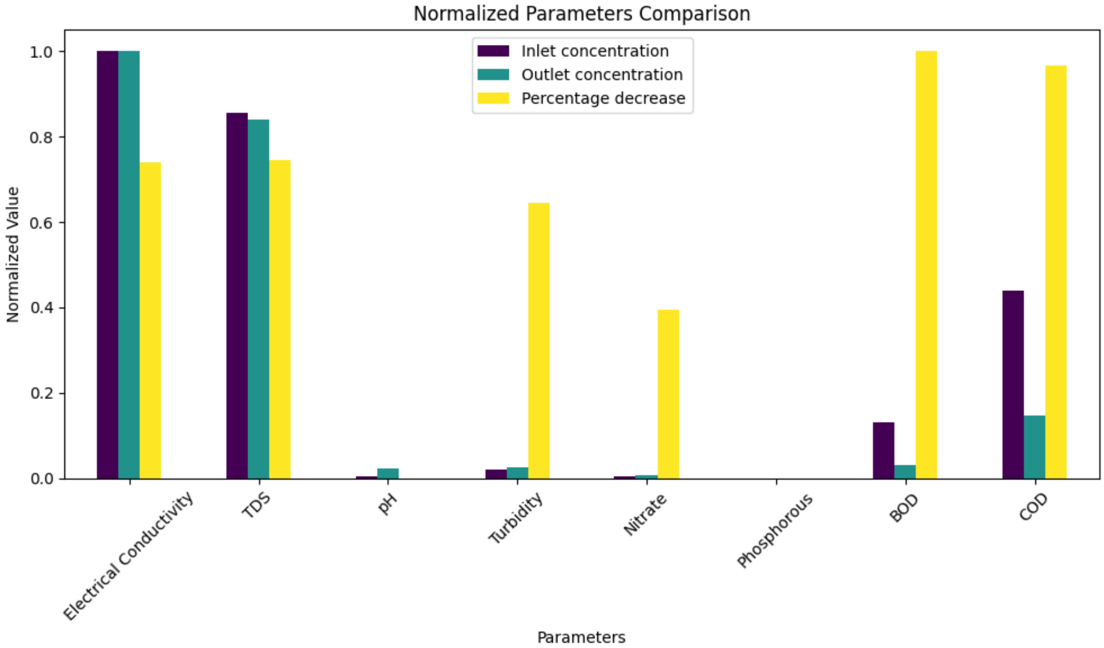


Figure 5.13: Performance Evaluation of Greywater Source-4: Reduction in Contaminant Levels

Table 5.12 and Figure 5.13 reflect the substantial improvement in water quality for Source 4. The treatment processes led to notable reductions in electrical conductivity, TDS, turbidity, nitrate, phosphorous, BOD, and COD. The percentage decrease is most pronounced for BOD (96.02%) and COD (94.47%), underscoring the effectiveness of the treatment methods applied to Source 4.

5.3 Decision Support Matrix for Greywater Treatment Optimization

5.3.1 Analysis Introduction to Decision Support Matrix

The presented Decision Support Matrix (Figure 5.14) is central to optimizing the treatment of greywater (GW) in this research. It provides a systematic framework that aids in the real-time evaluation and adjustment of two critical parameters in GW treatment: Turbidity and Dissolved Oxygen (DO). This section outlines the methodology used for integrating sensors and control systems into the GW treatment process, ultimately improving water quality.

The matrix leverages continuous monitoring of water samples using sensors and automates responses to deviations in DO and turbidity levels. The flow of decisions—from sensor readings to subsequent aeration or filtration steps—ensures that water quality standards are consistently met, optimizing the treatment process.

5.3.2Structure and Function of the Decision Matrix

The block diagram (Figure 5.14) provides a detailed process flow that starts from water sample collection and moves through key stages such as filtration, aeration, and disinfection. The following sections explain how the matrix handles real-time decision-making and treatment adjustments at each stage:

Initial Sensor Check (Turbidity): The first decision point involves measuring the turbidity of the water (T1). A turbidity sensor (NTU) continuously assesses whether the turbidity level is within acceptable limits (T1 < 11 NTU). If the turbidity is higher than acceptable, the water is directed toward further filtration processes, such as sand filtration, until it meets the required standard (T < 10 NTU).

Aeration Chamber & Dissolved Oxygen Monitoring: After passing through filtration, the water moves to the aeration chamber, where Dissolved Oxygen (DO) levels are measured using a DO sensor (D2 > 2 mg/L). This ensures that the oxygen levels in the water are within the optimal range for biological processes. If the DO level is below acceptable limits, the matrix triggers additional aeration via an air pump.

In cases where DO (D2) is insufficient, the water is cycled back for further aeration until the desired levels are met (D2 > 2 mg/L).

Final Quality Checks and Disinfection: As the water moves further along the matrix, a final turbidity check (T3) is performed, ensuring that the treated water meets the most stringent standards for clarity (T3 < 5% of T2). Once turbidity and DO are confirmed to be within safe levels, the water undergoes disinfection, typically through chlorination or UV treatment.

This multi-layered approach ensures that the treated greywater is safe for its intended uses, such as toilet flushing or irrigation.

5.3.3Key Impacts of the Decision Matrix

The integration of real-time monitoring through this matrix has several significant impacts on GW quality and the overall water treatment process:

Real-Time Response to Turbidity & DO Levels: The decision support matrix allows for immediate feedback and corrective actions based on the sensor readings. By integrating turbidity and DO sensors at critical junctures, the matrix ensures that each stage of the treatment process is optimized dynamically.

Reduction in Manual Oversight: The matrix reduces the need for constant human supervision, as the treatment steps are automatically adjusted based on sensor data. This not only improves operational efficiency but also ensures more consistent water quality over time.

Optimization of Aeration and Filtration: The aeration stages are key in maintaining DO levels, which are crucial for the biological processes that help break down contaminants in GW. By directing water to undergo further aeration only when needed, the matrix avoids overuse of energy, contributing to the sustainability of the system.

Enhanced Water Quality: The decision matrix has been shown to effectively maintain desired turbidity levels, ensuring the treated greywater is safe for use in applications like toilet flushing, irrigation, and vehicle washing. This is particularly important when greywater is being reused in urban or residential settings.

5.3.4Research Findings & Performance Evaluation

The application of this decision matrix in the research has yielded positive results, with consistent reductions in turbidity and optimal DO levels maintained throughout the treatment process. The system's ability to dynamically adjust based on sensor feedback has proven to be efficient in handling varying levels of GW contamination, particularly in complex water treatment scenarios.

For instance, turbidity levels were consistently reduced to below 10 NTU, while DO levels were maintained at or above 2 mg/L throughout the study. These results align with the research objective of improving GW quality through innovative decision support systems.

Turbidity Impact: The matrix successfully ensured that turbidity levels remained within regulatory limits, reducing particulate matter and enhancing water clarity. This has a direct impact on the performance of downstream disinfection processes, as lower turbidity allows for more effective disinfection.

DO Impact: By maintaining adequate DO levels, the matrix promotes aerobic biological activity, which is essential for breaking down organic matter in greywater. This has been particularly beneficial in residential settings where organic load can fluctuate.

The decision matrix serves as a robust tool for optimizing greywater treatment processes, particularly in maintaining optimal turbidity and DO levels. Through real-time monitoring and feedback loops, the system enhances water quality and improves the efficiency of the treatment process. Future work could focus on integrating additional sensors for other water quality parameters, such as pH and microbial content, to further improve the comprehensiveness of the decision support system.

These findings (Table 5.9 to 5.12 and Figure 5.10 to 5.13) indicate that the treatment of greywater from different sources resulted in a significant reduction in various water quality parameters. The high percentage decreases in BOD and COD across all sources highlight the efficacy of the treatment processes in improving water quality, rendering the treated greywater suitable for non-potable applications.

The presented decision matrix (Figure 5.14) exemplifies a robust decision support technique for evaluating and optimizing the dissolved oxygen (DO) levels and turbidity in water treatment processes. By systematically guiding the treatment of water samples from initial collection through various filtration and aeration stages, the matrix ensures precise monitoring and adjustment of critical parameters. The integration of sensors for real-time assessment and control facilitates the maintenance of desired water quality standards. Employing this technique in complex water treatment systems has significantly enhanced their performance, ensuring efficient and effective management of water quality.

For this research work, the application of this decision matrix has achieved high results, demonstrating its efficacy in optimizing water treatment processes. This accomplishment aligns with one of the key objectives of the PhD research work, showcasing the potential of decision support frameworks to drive substantial advancements in water treatment technologies.

The structured approach not only improves operational efficiency but also offers a scalable model for the development of advanced water treatment solutions, thereby contributing to the broader field of environmental engineering and public health. This decision support framework underscores the potential for significant advancements in water treatment technologies, promising improved outcomes in water purification and resource management.

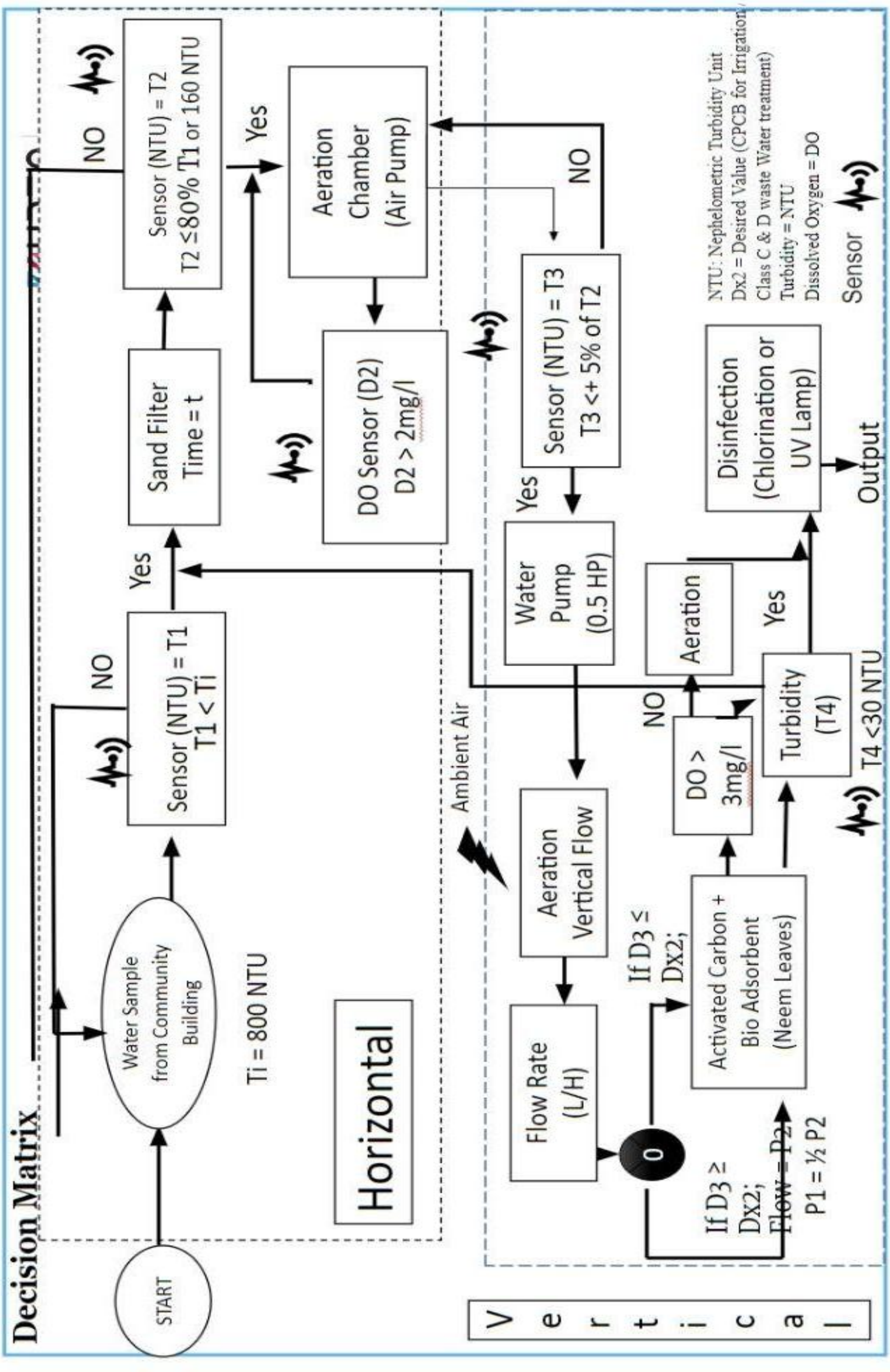


Figure 5.14: Decision support technique to evaluate the DO and Turbidity

Figure 5.15: Water Research Lab at UPES

Figure 5.16: Sample Collection, and Awareness for Greywater

Summary

This chapter presents a comprehensive discussion, analysis, and implications of the findings from the study on greywater treatment using hybrid technology. This chapter integrates the materials and methods employed, the procedures for sample collection, and the detailed water quality assessments conducted throughout the research.

The materials and methods section elaborates on the experimental setup and the specific technologies used, such as the combination of vertical and horizontal pipe-based mechanisms. It describes the rationale behind selecting these materials, particularly the transition to PVC pipes due to their ease of implementation and compatibility with residential infrastructure.

Sample collection and water quality assessment are crucial components of this study. Samples were systematically collected from various sources, including households and apartment complexes, with a special focus on the UPES-Dehradun food court and hostel kitchen. The sampling strategy ensured representativeness by aggregating grab samples collected at two-hour intervals into composite samples.

In the determination of Total Dissolved Solids (TDS), the research measures the concentration of dissolved substances in the greywater, providing an indicator of water quality and the effectiveness of the treatment process. The Chemical Oxygen Demand (COD) analysis evaluates the amount of oxygen required to oxidize organic and inorganic matter in the water. This parameter is crucial for assessing the level of pollutants and the efficiency of the greywater treatment system. Turbidity measurement involves assessing the clarity of the water by determining the presence of suspended particles. High turbidity levels indicate poor water quality, while significant reductions post-treatment highlight the system's effectiveness. Nitrate analysis focuses on the concentration of nitrates in the greywater, which is important for preventing algal blooms and ensuring the treated water is safe for reuse. Phosphorus analysis measures the levels of phosphorus compounds, which are key contributors to eutrophication in water bodies. The treatment's success in reducing phosphorus levels indicates its potential to mitigate environmental impacts. Biochemical Oxygen Demand (BOD) analysis assesses the amount of oxygen required by microorganisms to decompose organic matter in the water. Lower BOD levels post-treatment demonstrate the system's capability to reduce organic pollution.

The result and analysis section integrates the findings from these assessments, providing a detailed performance evaluation of the greywater treatment system. The chapter discusses significant improvements in water quality parameters, indicating the system's efficacy. It also explores the implications of these findings for sustainable water management practices, emphasizing the potential of greywater recycling for non-potable applications in urban areas.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

CHAPTER 6

In a world grappling with an escalating water crisis, the urgency for innovative and sustainable water management practices has never been more pronounced. This research, driven by the goal of enhancing greywater (GW) recycling and reuse, seeks to address this critical issue. The importance of GW recycling as an alternative water source is highlighted by its wide availability and relatively low organic content. This study focuses on a comprehensive performance evaluation of four distinct greywater sources, demonstrating the potential for GW recycling as an environmentally responsible and resource-efficient approach.

The detailed performance assessments presented in Tables 5.9, 5.10, 5.11, and 5.12 reveal significant improvements in key parameters following treatment, underscoring the efficacy of the employed methods. These improvements include substantial reductions in the analysis focused on several key parameters, including electrical conductivity, total dissolved solids (TDS), turbidity, nitrates, phosphorus, biological oxygen demand (BOD), and chemical oxygen demand (COD). These parameters provide a comprehensive understanding of water quality and its suitability for treatment or reuse.

The findings of Figure 6.1 indicate that GW recycling can be a valuable strategy for optimizing water resource management, particularly in non-potable applications such as toilet flushing, car washing, and garden irrigation. The research findings, as depicted in the provided chart, highlight a substantial improvement in various water quality parameters over a four-day treatment period. Electrical conductivity (µS/cm) exhibited a consistent decrease, starting at 87.99% on Day 1 and stabilizing at around 83.75% by Day 4. Total Dissolved Solids (TDS) followed a similar trend, with a significant reduction from 77.48% on Day 1 to 83.97% on Day 4. Turbidity (NTU) showed a notable decrease, improving from 73.82% on Day 1 to 77.79% by Day 4. The reduction in Nitrate (mg/l) levels was also significant, decreasing from 64.15% on Day 1 to 68.63% on Day 4. Phosphorous (mg/l) levels saw a gradual decline, reaching 47.66% by Day 4.

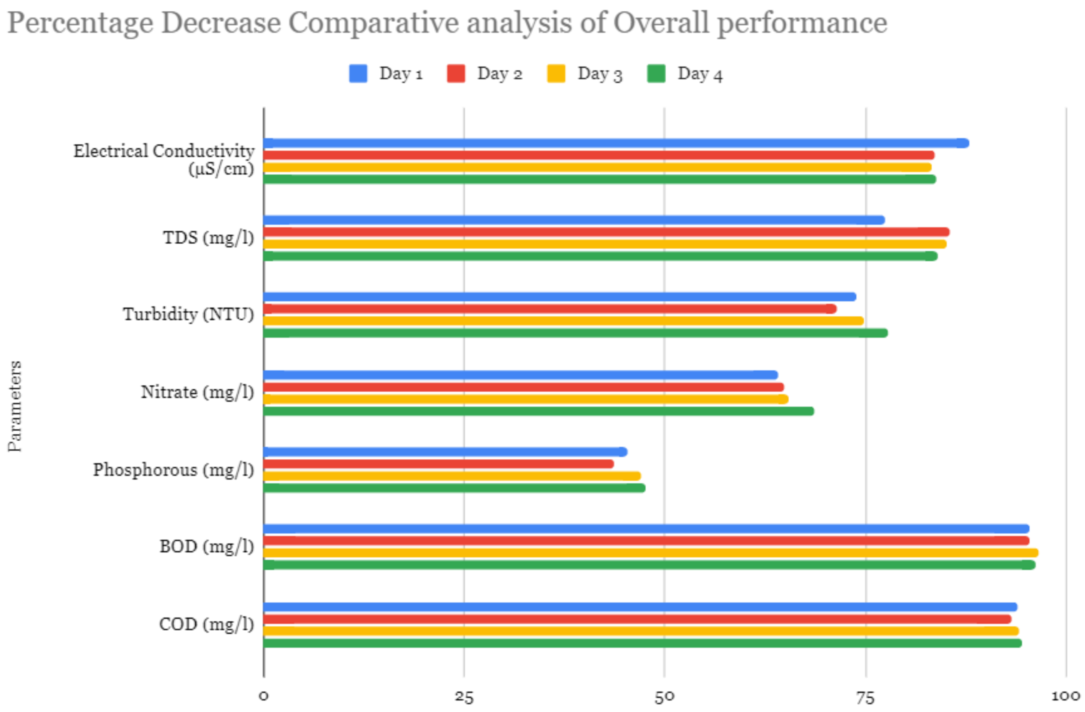


Figure 6.1: Comparative analysis of Overall performance

The Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) exhibited the most remarkable reductions, with BOD decreasing from 95.52% on Day 1 to 96.11% by Day 4 and COD from 93.92% to 94.52% over the same period. These results underscore the effectiveness of the water treatment process developed in this research. The consistent and substantial reductions across all parameters highlight the efficacy of the decision matrix and the treatment techniques employed.

Comparative analysis of the overall performance of this research, as part of the PhD work, demonstrates through the final executable design at the lab and hostel (Figure 6.2 & 6.3) as pilot work, that the objectives have been successfully met. The consistent improvements in water quality parameters indicate a high-performance system capable of significantly enhancing water purification processes. These findings validate the research approach and the application of decision support techniques in achieving optimal results in water treatment, contributing valuable insights to the field of environmental engineering and public health.

The final prototype was designed in the lab and also executed in the hostel/society as shown in Figures 6.2 & 6.3 and the result shows better progress as mentioned in Table 6.1.

Final 6.2: Final Lab based Prototype at UPES R&D Lab

Figure 6.3: Final executable design at Hostel

6.1 Key Findings

1. *Significant Reduction in Contaminants:* The study observed considerable decreases in contaminants and pollutants across all greywater sources post-treatment, indicating that treated greywater is suitable for a range of non-potable applications.

2. *Efficacy of Treatment Methods:* The substantial percentage decreases in critical parameters such as TDS, turbidity, nitrates, phosphorous, BOD, and COD validate the effectiveness of the treatment processes used in this study.
3. *Potential for Domestic and Outdoor Uses:* The quality of treated greywater suggests it can be effectively utilized for non-potable applications such as toilet flushing, car washing, and garden irrigation, thereby conserving freshwater resources.

Table 6.1: Comparison of characteristics of initial and final greywater pollutant

Parameter	Initial concentration	Concentration After the sand filter	Concentration After adsorption	% Removal after sand filter	% Removal after a combined process
EC (µS/cm)	2480	840	242	66.1	90.2
TDS (mg/l)	1612	514	138	68.1	91.4
COD (mg/l)	554	280	24	49.4	95.6
BOD (mg/l)	120	40	8	66.6	93.3
Phosphorous (mg/l)	8	3	0.5	62.5	93.7
Nitrate (mg/l)	14	8	1.5	42.8	89.2
Turbidity (NTU)	150	60	9	60	94

6.2 Implications for Sustainable Water Management

The findings from this study indicate that GW recycling can play a pivotal role in optimizing water resource management. By reducing reliance on conventional water sources for non-potable uses, treated greywater helps in preserving precious freshwater resources. This practice not only mitigates the environmental impact of wastewater disposal but also aligns with broader sustainable water resource management goals.

6.3 Future Directions

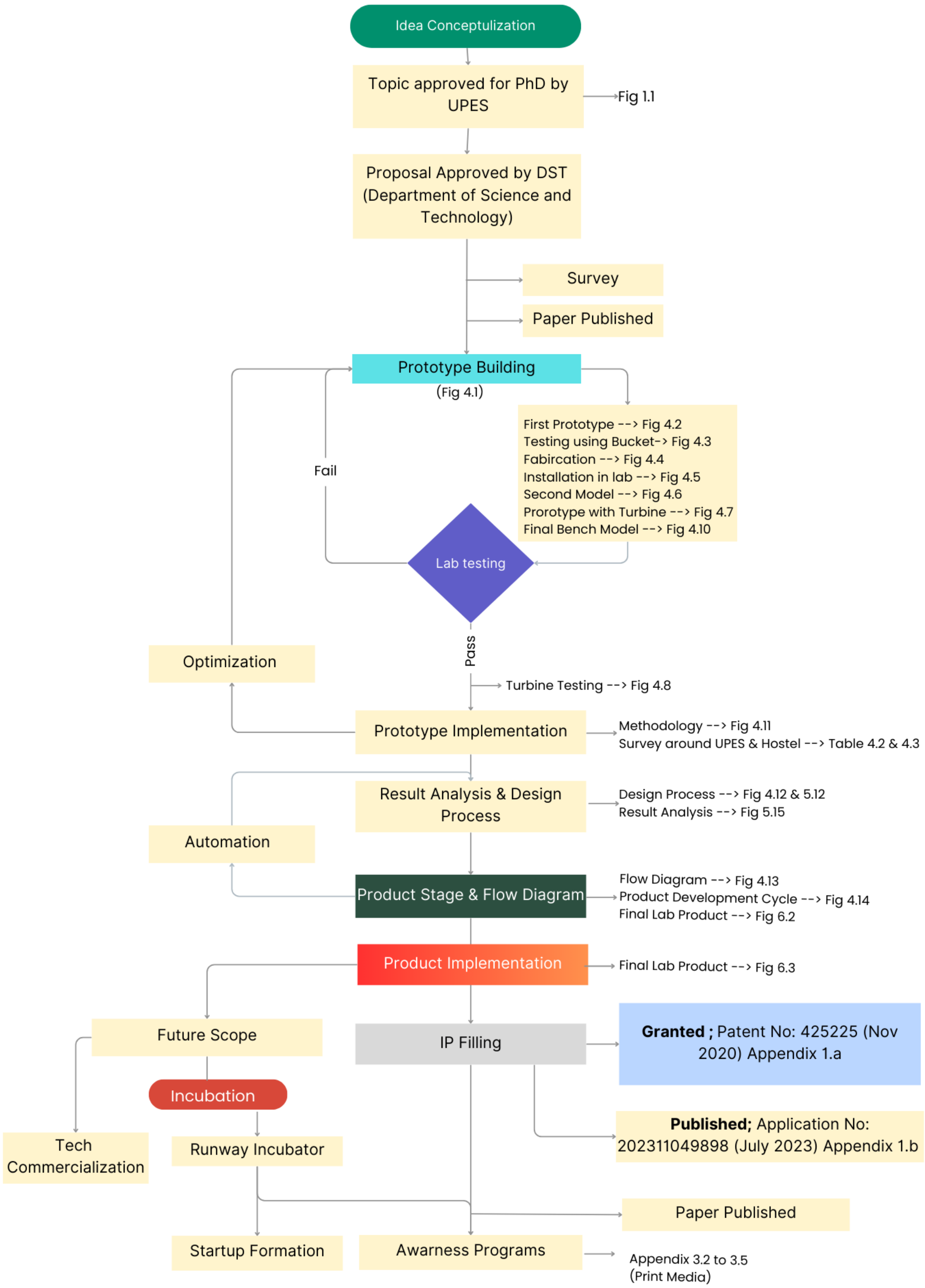
1. Long-term Performance and Scalability: Future research should explore the long-term performance and scalability of GW recycling systems across different residential settings. This will help in understanding the broader applicability and sustainability of these systems.

2. Technological Enhancements: Continued innovation in treatment technologies could further improve the efficiency and cost-effectiveness of GW recycling. Exploring advanced filtration, adsorption, and disinfection methods could enhance treatment outcomes.
3. Regulatory and Policy Support: For widespread adoption, supportive regulatory frameworks and policies are essential. Future studies should investigate the regulatory barriers and develop guidelines to facilitate the integration of GW recycling practices in urban planning.
4. Community Engagement and Education: Raising awareness and educating communities about the benefits and practices of GW recycling can foster greater acceptance and participation. Future efforts should include community-based projects and educational campaigns to promote sustainable water management practices.
5. Economic Feasibility: Conducting cost-benefit analyses to assess the economic viability of GW recycling systems will be crucial for encouraging investment and adoption. Understanding the financial implications can help in designing affordable and efficient systems for widespread use.

6.4 Conclusion

This research underscores the critical role of GW recycling in the pursuit of sustainable water management. The findings highlight the viability and resource efficiency of GW recycling, offering a promising solution to mitigate the global water crisis. By efficiently treating greywater, the burden on conventional water sources can be significantly reduced, contributing to the preservation of freshwater resources and reducing the environmental impact of wastewater disposal. We hope that these findings will inspire further exploration and adoption of GW recycling practices, fostering a more environmentally responsible and water-secure world for current and future generations. As part of the policy recommendation, awareness sessions were hosted with key stakeholders and media reports were published in various print media (as mentioned in Appendix 3)

6.5 Summary of the Research Work



REFERENCES

&

APPENDIX

Reference

Abdalla, H., Rahmat-Ullah, Z., Abdallah, M., Alsmadi, S., & Elashwah, N. (2021). Eco-efficiency analysis of integrated grey and black water management systems. *Resources, Conservation and Recycling*, 172, 105681.

Abdel-Shafy, H. I., El-Khateeb, M. A., Regelsberger, M., El-Sheikh, R., & Shehata, M. (2009). Integrated system for the treatment of blackwater and greywater via UASB and constructed wetland in Egypt. *Desalination and Water Treatment*, 8(1–3), 272–278.

Abdel-Shafy, H. I., El-Khateeb, M. A., & Shehata, M. (2014). Greywater treatment using different designs of sand filters. *Desalination and Water Treatment*, 52(28–30), 5237–5242.

Abed, S. N., Almuktar, S. A., & Scholz, M. (2017). Treatment of contaminated greywater using pelletised mine water sludge. *Journal of Environmental Management*, 197, 10–23.

Abu Ghunmi, L., Zeeman, G., Fayyad, M., & van Lier, J. B. (2011). Grey water biodegradability. *Biodegradation*, 22, 163–174.

Abusam, A. (2008). Reuse of greywater in Kuwait. *International Journal of Environmental Studies*, 65(1), 103–108.

Ahmadpari, H., Sedigh, M. M., & Hassanpour, F. (n.d.). Investigating the use of grey water to achieve sustainable water management and optimizing water consumption. *The 2nd International Conference on the New Horizons in the Agricultural Science Natural Resources and Environment*

Ahmed, M., Al Sidairi, S., Prathapar, S. A., & Al-Adawi, S. (2008). Evaluation of custom-made and commercial greywater treatment systems: a case study from Oman. *International Journal of Environmental Studies*, 65(1), 33–40.

Aizenchtadt, E., Ingman, D., & Friedler, E. (2009). Analysis of the long-term performance of an on-site greywater treatment plant using novel statistical approaches. *Urban Water Journal*, 6(5), 341–354.

Al-Jayyousi, O. R. (2003). Greywater reuse: towards sustainable water management. *Desalination*, 156(1–3), 181–192.

Al-Mashaqbeh, O. A., Ghrair, A. M., & Megdal, S. B. (2012). Grey water reuse for agricultural purposes in the Jordan Valley: Household survey results in Deir Alla. *Water,* 2012, 4(3), 580-596; doi:10.3390/w4030580

Alsulaili, A. D., & Hamoda, M. F. (2015). Quantification and characterization of greywater from schools. *Water Science and Technology*, 72(11), 1973–1980.

Altenbaher, B., & Turk, S. Š. (2009). Treatment of textile processing wastewaters with membrane filtrations. Tekstil: *Journal of Textile & Clothing Technology,* 58(8).

Alvisi, S., & Franchini, M. (2010). Pipe roughness calibration in water distribution systems using grey numbers. *Journal of Hydroinformatics*, 12(4), 424–445.

Atanasova, N., Dalmau, M., Comas, J., Poch, M., Rodriguez-Roda, I., & Buttiglieri, G. (2017). Optimized MBR for greywater reuse systems in hotel facilities. *Journal of Environmental Management*, 193, 503–511.

Badawy, M. I., Gohary, F. El, Ghaly, M. Y., & Ali, M. E. M. (2009). Enhancement of olive mill wastewater biodegradation by homogeneous and heterogeneous photocatalytic oxidation. *Journal of Hazardous Materials*, 169(1–3), 673–679.

Bani-Melhem, K., & Smith, E. (2012). Impact of Applying Electrocoagulation Pre-treatment Step on Grey Water Treatment by Submerged Membrane Bioreactor. *WEFTEC* 2012.

Barzegar, G., Wu, J., & Ghanbari, F. (2019). Enhanced treatment of greywater using electrocoagulation/ozonation: Investigation of process parameters. *Process Safety and Environmental Protection*, 121, 125–132.

Benami, M., Gillor, O., & Gross, A. (2015). The question of pathogen quantification in disinfected greywater. *Science of the Total Environment*, 506, 496–504.

Biswas, S. K., Rahman, M. M., Rahman, M. Y. A., & Rahman, M. M. (2012). Applicability of domestic grey water reuse for alleviation of water crisis in Dhaka City. *Journal of Water Reuse and Desalination*, 2(4), 239–246.

Boano, F., Caruso, A., Costamagna, E., Ridolfi, L., Fiore, S., Demichelis, F., Galvão, A., Pisoeiro, J., Rizzo, A., & Masi, F. (2020). A review of nature-based solutions for greywater treatment: Applications, hydraulic design, and environmental benefits. *Science of the Total Environment*, 711, 134731.

Boyjoo, Y., Pareek, V. K., & Ang, M. (2013). A review of greywater characteristics and treatment processes. *Water Science and Technology*, 67(7), 1403–1424.

Busgang, A., Friedler, E., Ovadia, O., & Gross, A. (2015). Epidemiological study for the assessment of health risks associated with greywater reuse for irrigation in arid regions. *Science of the Total Environment*, 538, 230–239.

Çalışkan, Y., Öztürk, H., Bektaş, N., & Yatmaz, H. C. (2021). UVA enhanced electrocoagulation comparing Al and Fe electrodes for reclamation of greywater. *Separation Science and Technology*, 56(9), 1622–1632.

Chong, M. N., Jin, B., Chow, C. W. K., & Saint, C. (2010). Recent developments in photocatalytic water treatment technology: a review. *Water Research*, 44(10), 2997–3027.

Chopra, A. K., & Sharma, A. K. (2013). Removal of turbidity, COD and BOD from secondarily treated sewage water by electrolytic treatment. *Applied Water Science*, 3, 125–132.

Chrispim, M. C., & Nolasco, M. A. (2017a). Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil. *Journal of Cleaner Production*, 142, 290–296.

Chrispim, M. C., & Nolasco, M. A. (2017b). Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil. *Journal of Cleaner Production*, 142, 290–296.

Chu, C., Ryberg, E. C., Loeb, S. K., Suh, M.-J., & Kim, J.-H. (2019). Water disinfection in rural areas demands unconventional solar technologies. *Accounts of Chemical Research*, 52(5), 1187–1195.

Ciabattia, I., Cesaro, F., Faralli, L., Fatarella, E., & Tognotti, F. (2009). Demonstration of a treatment system for purification and reuse of laundry wastewater. *Desalination*, 245(1–3), 451–459.

Collivignarelli, M. C., Abbà, A., Benigna, I., Sorlini, S., & Torretta, V. (2017). Overview of the main disinfection processes for wastewater and drinking water treatment plants. *Sustainability*, 10(1), 86.

Comino, E., Riggio, V., & Rosso, M. (2013). Grey water treated by an hybrid constructed wetland pilot plant under several stress conditions. *Ecological*

Engineering, 53, 120–125.

Coutinho Rosa, G., & Ghisi, E. (2020). A modelling evaluation of a system combining rainwater and greywater for potable water savings. *Urban Water Journal*, 17(4), 283–291.

Dakua, M., Mahmood, M., Bhowmik, S., & Khaled, F. (2016). Potential of Grey Water Recycling in Water Scarce Urban Areas in Bangladesh. *International Journal of Environmental Science and Development*, 7(8), 563.

De Girolamo, A. M., Miscioscia, P., Politi, T., & Barca, E. (2019). Improving grey water footprint assessment: *Accounting for uncertainty*. *Ecological Indicators*, 102, 822–833.

De Gisi, S., Casella, P., Notarnicola, M., & Farina, R. (2016). Grey water in buildings: a mini-review of guidelines, technologies and case studies. *Civil Engineering and Environmental Systems*, 33(1), 35–54.

Debnath, B., Raychaudhuri, A., & Mukhopadhyay, P. (2019). Grey Water Recycling for Domestic Usage. Waste Water Recycling and Management: 7th *IconSWM−ISWMAW* 2017, Volume 3, 85–96.

Do Couto, E. de A., Calijuri, M. L., Assemany, P. P., da Fonseca Santiago, A., & Lopes, L. S. (2015). Greywater treatment in airports using anaerobic filter followed by UV disinfection: an efficient and low-cost alternative. *Journal of Cleaner Production*, 106, 372–379.

Delhiraja, K., Philip, L. Characterization of segregated greywater from Indian households: part A—physicochemical and microbial parameters. *Environ Monit Assess* 192, 428 (2020).

Drewes, J. E., Khan, S., & Mujeriego, R. (2012). Water reuse: achievements and future challenges. *In Journal of Water Supply: Research and Technology*—AQUA (Vol. 61, Issue 8, pp. 461–462). IWA Publishing.

Dwumfour-Asare, B., Adantey, P., Nyarko, K. B., & Appiah-Effah, E. (2017). Greywater characterization and handling practices among urban households in Ghana: the case of three communities in Kumasi Metropolis. *Water Science and Technology*, 76(4), 813–822.

Edwin, G.A., Gopalsamy, P. & Muthu, N. Characterization of domestic grey water from a point source to determine the potential for urban residential reuse: a short review. *Appl Water Sci* 4, 39–49 (2014).

Elhegazy, H., & Eid, M. M. M. (2020). A state-of-the-art-review on grey water management: A survey from 2000 to 2020s. *Water Science and Technology*, 82(12), 2786–2797.

Eriksson, E., Auffarth, K., Henze, M., & Ledin, A. (2002). Characteristics of grey wastewater. *Urban Water*, 4(1), 85–104.

Eriksson, E., Srigirisetty, S., & Eilersen, A. M. (2010). Organic matter and heavy metals in grey-water sludge. *Water Sa*, 36(1).

Faruqui, N., & Al-Jayyousi, O. (2002). Greywater reuse in urban agriculture for poverty alleviation: a case study in Jordan. *Water International*, 27(3), 387–394.

Friedler, E., & Gilboa, Y. (2010). Performance of UV disinfection and the microbial quality of greywater effluent along a reuse system for toilet flushing. *Science of the Total Environment*, 408(9), 2109–2117.

Friedler, E., Kovalio, R., & Ben-Zvi, A. (2006). Comparative study of the microbial quality of greywater treated by three on-site treatment systems. *Environmental Technology*, 27(6), 653–663.

Gabarró, J., Batchellí, L., Balaguer, M. D., Puig, S., & Colprim, J. (2013). Grey water treatment at a sports centre for reuse in irrigation: A case study. *Environmental Technology*, 34(11), 1385–1392.

García, I., & Moreno, L. (2009). Use of GAC after enhanced coagulation for the removal of natural organic matter from water for purification. *Water Science and Technology: Water Supply*, 9(2), 173–180.

Ghaitidak, D. M., & Yadav, K. D. (2013). Characteristics and treatment of greywater—a review. *Environmental Science and Pollution Research*, 20, 2795–2809.

Gharbia, S. S., Aish, A., Abushbak, T., Qishawi, G., Al-Shawa, I., Gharbia, A., Zelenakova, M., Gill, L., & Pilla, F. (2016). Evaluation of wastewater post-treatment options for reuse purposes in the agricultural sector under rural development conditions. *Journal of Water Process Engineering*, 9, 111–122.

Ghisi, E., & Ferreira, D. F. (2007). Potential for potable water savings by using rainwater and greywater in a multi-storey residential building in southern Brazil. *Building and Environment*, 42(7), 2512–2522.

Ghunmi, L. A., Zeeman, G., Fayyad, M., & van Lier, J. B. (2011). Grey water treatment systems: A review. *Critical Reviews in Environmental Science and Technology*, 41(7), 657–698.

Gleick, P. H. (2003). Global freshwater resources: soft-path solutions for the 21st century. *Science*, 302(5650), 1524–1528.

Gual, M., Moià, A., & March, J. G. (2008). Monitoring of an indoor pilot plant for osmosis rejection and greywater reuse to flush toilets in a hotel. *Desalination*, 219(1–3), 81–88.

Halalsheh, M., Dalahmeh, S., Sayed, M., Suleiman, W., Shareef, M., Mansour, M., & Safi, M. (2008). Grey water characteristics and treatment options for rural areas in Jordan. *Bioresource Technology*, 99(14), 6635–6641.

Hashim, I. A., Hamma-adama, M., & Surendran, S. (2020). A strategic decision framework for sustainable wastewater treatment and management in the oil-producing region. *Civil and Environmental Research*, 12(8).

Henriques, J. J., & Louis, G. E. (2011). A decision model for selecting sustainable drinking water supply and greywater reuse systems for developing communities with a case study in Cimahi, Indonesia. *Journal of Environmental Management*, 92(1), 214–222.

Hernández-Leal, L., Temmink, H., Zeeman, G., & Buisman, C. J. N. (2011). Removal of micropollutants from aerobically treated grey water via ozone and activated carbon. *Water Research*, 45(9), 2887–2896.

Huelgas, A., & Funamizu, N. (2010). Flat-plate submerged membrane bioreactor for the treatment of higher-load greywater. *Desalination*, 250(1), 162–166.

Jamrah, A., Al-Omari, A., Al-Qasem, L., & Ghani, N. A. (2006). Assessment of availability and characteristics of greywater in Amman. *Water International*, 31(2), 210–220.

Janeiro, C. A. N., Arsénio, A. M., Brito, R., & Van Lier, J. B. (2020). Use of (partially) treated municipal wastewater in irrigated agriculture; potentials and constraints for sub-Saharan Africa. *Physics and Chemistry of the Earth, Parts A/B/C*, 118, 102906.

Jeong, H., Broesicke, O. A., Drew, B., & Crittenden, J. C. (2018). Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. *Journal of Cleaner Production*, 174, 333–342.

Jifeng, G. U. O., Siqing, X. I. A., Rongchang, W., & Jianfu, Z. (2008). Study on membrane fouling of submerged membrane bioreactor in treating bathing wastewater. *Journal of Environmental Sciences*, 20(10), 1158–1167.

Johnson, M. B., & Mehrvar, M. (2019). An assessment of the grey water footprint of winery wastewater in the Niagara Region of Ontario, Canada. *Journal of Cleaner Production*, 214, 623–632.

Kee, M., Soo, J., Lam, S., Sin, J., & Mohamed, A. R. (2018). Evaluation of photocatalytic fuel cell (PFC) for electricity production and simultaneous degradation of methyl green in synthetic and real greywater effluents. *Journal of Environmental Management*, 228, 383–392.

Keely, S. P., Brinkman, N. E., Zimmerman, B. D., Wendell, D., Ekeren, K. M., De Long, S. K., Sharvelle, S., & Garland, J. L. (2015). Characterization of the relative importance of human- and infrastructure-associated bacteria in grey water: a case study. *Journal of Applied Microbiology*, 119(1), 289–301.

Khalaphallah, R., & Andres, Y. (2012). The effect of various abiotic factors on the survival growth of Escherichia coli and Pseudomonas aeruginosa in bathroom greywater. *Journal of Water Reuse and Desalination*, 2(2), 92–101.

Khan, M. Z., Sim, Y. L., Lin, Y. J., & Lai, K. M. (2013). Testing biological effects of hand-washing grey water for reuse in irrigation on an urban farm: a case study. *Environmental Technology*, 34(4), 545–551.

Kim, J., Song, I., Oh, H., Jong, J., Park, J., & Choung, Y. (2009). A laboratory-scale greywater treatment system based on a membrane filtration and oxidation process—characteristics of greywater from a residential complex. *Desalination*, 238(1–3), 347–357.

Kobayashi, Y., Ashbolt, N. J., Davies, E. G. R., & Liu, Y. (2020). Life cycle assessment of decentralized greywater treatment systems with reuse at different scales in cold regions. *Environment International*, 134, 105215.

Lam, C.-M., Leng, L., Chen, P.-C., Lee, P.-H., & Hsu, S.-C. (2017). Eco-efficiency analysis of non-potable water systems in domestic buildings. *Applied Energy*, 202, 293–307.

Larsen*, T. A., Alder, A. C., Eggen, R. I. L., Maurer, M., & Lienert, J. (2009). Source separation: will we see a paradigm shift in wastewater handling? *ACS Publications*.

Leal, L. H., Temmink, H., Zeeman, G., & Buisman, C. J. N. (2010). Bioflocculation of grey water for improved energy recovery within decentralized sanitation concepts. *Bioresource Technology*, 101(23), 9065–9070.

Leong, J. Y. C., Balan, P., Chong, M. N., & Poh, P. E. (2019). Life-cycle assessment and life-cycle cost analysis of decentralised rainwater harvesting, greywater recycling and hybrid rainwater-greywater systems. *Journal of Cleaner Production*, 229, 1211–1224.

Leong, J. Y. C., Chong, M. N., & Poh, P. E. (2018). Assessment of greywater quality and performance of a pilot-scale decentralised hybrid rainwater-greywater system. *Journal of Cleaner Production*, 172, 81–91.

Leung, R. W. K., Li, D. C. H., Yu, W. K., Chui, H. K., Lee, T. O., Van Loosdrecht, M. C. M., & Chen, G. H. (2012). Integration of seawater and grey water reuse to maximize alternative water resource for coastal areas: the case of the Hong Kong International Airport. *Water Science and Technology*, 65(3), 410–417.

Li, Fangyue, Knut Wichmann, and Ralf Otterpohl. "Review of the technological approaches for grey water treatment and reuses." *Science of the total environment* 407.11 (2009): 3439-3449

Li, F., Behrendt, J., Wichmann, K., & Otterpohl, R. (2008). Resources and nutrients-oriented greywater treatment for non-potable reuses. *Water Science and Technology*, 57(12), 1901–1907.

Li, F., Wichmann, K., & Otterpohl, R. (2009). Review of the technological approaches for grey water treatment and reuse. *Science of the Total Environment*, 407(11), 3439–3449.

Liang, C., Jingchun, F., & Yuan, R. (2018). Risk evaluation of EPC supply chain based on SCOR and multi-level grey model: A case study of China's waste incineration plant project. *International Journal of Information Systems and Supply Chain Management (IJISSCM)*, 11(2), 54–76.

Liao, X., Chai, L., Xu, X., Lu, Q., & Ji, J. (2019). Grey water footprint and interprovincial virtual grey water transfers for China's final electricity demands. *Journal of Cleaner Production*, 227, 111–118.

Liu, W., Xie, Y., Ma, J., Luo, X., Nie, P., Zuo, Z., Lahrmann, U., Zhao, Q., Zheng, Y., & Zhao, Y. (2015). IBS: an illustrator for the presentation and visualization of biological sequences. *Bioinformatics*, 31(20), 3359–3361.

Malek, M. A., & Nor, M. A. M. (2013). Water security and its challenges for Malaysia. IOP Conference Series: *Earth and Environmental Science*, 16(1), 012123.

Mandal, D., Labhasetwar, P., Dhone, S., Dubey, A. S., Shinde, G., & Wate, S. (2011). Water conservation due to greywater treatment and reuse in urban settings with specific context to developing countries. *Resources, Conservation and Recycling*, 55(3), 356–361.

Manju, S., & Sagar, N. (2017). Renewable energy integrated desalination: A sustainable solution to overcome future fresh-water scarcity in India. *Renewable and Sustainable Energy Reviews,* 73, 594–609.

Marinoski, A. K., & Ghisi, E. (2019). Environmental performance of hybrid rainwater-greywater systems in residential buildings. *Resources*, *Conservation and Recycling*, 144, 100–114.

Marinoski, A. K., Rupp, R. F., & Ghisi, E. (2018). Environmental benefit analysis of strategies for potable water savings in residential buildings. *Journal of Environmental Management*, 206, 28–39.

Martínez-Alcalá, I., Pellicer-Martínez, F., & Fernández-López, C. (2018). Pharmaceutical grey water footprint: Accounting, influence of wastewater treatment plants and implications of the reuse. *Water Research*, 135, 278–287.

Masi, F., Rizzo, A., & Regelsberger, M. (2018). The role of constructed wetlands in a new circular economy, resource-oriented, and ecosystem services paradigm. *Journal of Environmental Management,* 216, 275–284.

Mergen, M. R. D., Jefferson, B., Parsons, S. A., & Jarvis, P. (2008). Magnetic ion-exchange resin treatment: Impact of water type and resin use. *Water Research*, 42(8–

9), 1977–1988.

Molinos-Senante, M., Hernández-Sancho, F., & Sala-Garrido, R. (2010). Economic feasibility study for wastewater treatment: A cost-benefit analysis. Science of the *Total Environment*, 408(20), 4396–4402.

Mourad, K. A., Berndtsson, J. C., & Berndtsson, R. (2011). Potential fresh water saving using greywater in toilet flushing in Syria. *Journal of Environmental Management*, 92(10), 2447–2453.

Nas, T. F. (2016). Cost-benefit analysis: Theory and application. Lexington Books.

Nnaji, C. C., Mama, C. N., Ekwueme, A., & Utsev, T. (2014). Feasibility of a filtration-adsorption grey water treatment system for developing countries.

Oh, K. S., Leong, J. Y. C., Poh, P. E., Chong, M. N., & Von Lau, E. (2018). A review of greywater recycling related issues: Challenges and prospects in Malaysia. *Journal of Cleaner Production*, 171, 17–29.

Oktor, K., & Çelik, D. (2019). Treatment of wash basin and bathroom greywater with Chlorella variabilis and reusability. *Journal of Water Process Engineering*, 31, 100857.

Oteng-Peprah, M., De Vries, N. K., & Acheampong, M. A. (2018). Greywater characterization and generation rates in a peri-urban municipality of a developing country. *Journal of Environmental Management*, 206, 498–506.

Otterpohl, R., Grottker, M., & Lange, J. (1997). Sustainable water and waste management in urban areas. *Water Science and Technology*, 35(9), 121–133.

Ozay, Y., Ünşar, E. K., Işık, Z., Yılmaz, F., Dizge, N., Perendeci, N. A., Mazmanci, M. A., & Yalvac, M. (2018). Optimization of electrocoagulation process and combination of anaerobic digestion for the treatment of pistachio processing wastewater. *Journal of Cleaner Production*, 196, 42–50.

Parjane, S. B., & Sane, M. G. (2011). Performance of grey water treatment plant by economical way for Indian rural development. *International Journal of ChemTech Research CODEN (USA)*, Vol 3, No 4, pp 1808-1815, Oct-Dec 2011

Penn, R., Hadari, M., & Friedler, E. (2012). Evaluation of the effects of greywater reuse on domestic wastewater quality and quantity. *Urban Water Journal*, 9(3), 137–

148.

Penn, R., Schütze, M., & Friedler, E. (2013). Modelling the effects of on-site greywater reuse and low flush toilets on municipal sewer systems. *Journal of Environmental Management*, 114, 72–83.

Pidou, M., Avery, L., Stephenson, T., Jeffrey, P., Parsons, S. A., Liu, S., Memon, F. A., & Jefferson, B. (2008). Chemical solutions for greywater recycling. *Chemosphere*, 71(1), 147–155.

Pidou, M., Memon, F. A., Stephenson, T., Jefferson, B., & Jeffrey, P. (2007). Greywater recycling: treatment options and applications. *Proceedings of the Institution of Civil Engineers-Engineering Sustainability*, 160(3), 119–131.

Pinto, U., Maheshwari, B. L., & Grewal, H. S. (2010). Effects of greywater irrigation on plant growth, water use and soil properties. *Resources, Conservation and Recycling*, 54(7), 429–435.

Prabhakar, D. K., Singh, A. K., Kumar, M., Kumar, A., Sarkar, S., & Alam, M. M. (2019). Characterization of grey water and its influence on some basic soil properties. *IJCS*, 7(3), 3644–3647.

Pradhan, S., Al-Ghamdi, S. G., & Mackey, H. R. (2019). Greywater treatment by ornamental plants and media for an integrated green wall system. *International Biodeterioration & Biodegradation*, 145, 104792.

Prajapati, B., Jensen, M. B., Jørgensen, N. O. G., & Petersen, N. B. (2019). Grey water treatment in stacked multi-layer reactors with passive aeration and particle trapping. *Water Research*, 161, 181–190.

Rajasulochana, P., & Preethy, V. (2016). Comparison on the efficiency of various techniques in the treatment of waste and sewage water–A comprehensive review. *Resource-Efficient Technologies*, 2(4), 175–184.

Rakesh, S., Ramesh, P. T., Murugaragavan, R., Avudainayagam, S., & Karthikeyan, S. (2020). Characterization and treatment of grey water: a review. *IJCS*, 8(1), 34–40.

Ramona, G., Green, M., Semiat, R., & Dosoretz, C. (2004). Low-strength greywater characterization and treatment by direct membrane filtration. *Desalination*, 170(3), 241–250.

Remy, C., & Jekel, M. (2008). Sustainable wastewater management: life cycle assessment of conventional and source-separating urban sanitation systems. *Water Science and Technology*, 58(8), 1555–1562.

Revitt, D. M., Eriksson, E., & Donner, E. (2011). The implications of household greywater treatment and reuse for municipal wastewater flows and micropollutant loads. *Water Research*, 45(4), 1549–1560.

Sanchez, M., Rivero, M. J., & Ortiz, I. (2010). Photocatalytic oxidation of grey water over titanium dioxide suspensions. *Desalination*, 262(1–3), 141–146.

Scheumann, R., & Kraume, M. (2009). Influence of hydraulic retention time on the operation of a submerged membrane sequencing batch reactor (SM-SBR) for the treatment of greywater. *Desalination*, 246(1–3), 444–451.

Seo, G. T., Moon, B. H., Park, Y. M., & Kim, S. H. (2007). Filtration characteristics of immersed coarse pore filters in an activated sludge system for domestic wastewater reclamation. *Water Science and Technology*, 55(1–2), 51–58.

Sharif, A., Baris-Tuzemen, O., Uzuner, G., Ozturk, I., & Sinha, A. (2020). Revisiting the role of renewable and non-renewable energy consumption on Turkey's ecological footprint: Evidence from Quantile ARDL approach. *Sustainable Cities and Society*, 57, 102138.

Shi, K.-W., Wang, C.-W., & Jiang, S. C. (2018). Quantitative microbial risk assessment of Greywater on-site reuse. *Science of the Total Environment*, 635, 1507–1519.

Shoults, D. C., & Ashbolt, N. J. (2017). UV disinfection of hand-rinse greywater and performance testing using indigenous Staphylococcus spp. *Water*, 9(12), 963.

Sushmitha, M. B., Chanakya, H. N., & Khuntia, H. K. (2019). Efficient grey water treatment and reuse options for India—A Review. *Waste Water Recycling and Management: 7th IconSWM–ISWMAW* 2017, Volume 3, 143–149.

Tiruneh, A. T. (2014). A greywater dam is designed for the treatment and reuse of greywater from single and multiple households. *Journal of Water Resource and Protection*, 6(14), 1259–1267.

Ushijima, K., Ito, K., Ito, R., & Funamizu, N. (2013). Greywater treatment by slanted soil system. *Ecological Engineering*, 50, 62–68.

Vakil, K. A., Sharma, M. K., Bhatia, A., Kazmi, A. A., & Sarkar, S. (2014). Characterization of greywater in an Indian middle-class household and investigation of physicochemical treatment using electrocoagulation. *Separation and Purification Technology*, 130, 160–166.

Vuppaladadiyam, A. K., Merayo, N., Prinsen, P., Luque, R., Blanco, A., & Zhao, M. (2019). A review on greywater reuse: quality, risks, barriers and global scenarios. *Reviews in Environmental Science and Bio/Technology*, 18, 77–99.

Vymazal, J. (2011). Constructed wetlands for wastewater treatment: five decades of experience. *Environmental Science & Technology*, 45(1), 61–69.

Wang, B., Liu, L., Huang, G. H., Li, W., & Xie, Y. L. (2016). Forecast-based analysis for regional water supply and demand relationship by hybrid Markov chain models: a case study of Urumqi, China. *Journal of Hydroinformatics*, 18(5), 905–918.

Winward, G. P., Avery, L. M., Frazer-Williams, R., Pidou, M., Jeffrey, P., Stephenson, T., & Jefferson, B. (2008). A study of the microbial quality of grey water and an evaluation of treatment technologies for reuse. *Ecological Engineering*, 32(2), 187–197.

Wu, L.-F., Liu, S.-F., Cui, W., Liu, D.-L., & Yao, T.-X. (2014). A non-homogenous discrete grey model with fractional-order accumulation. *Neural Computing and Applications*, 25, 1215–1221.

Zeng, S., Dong, X., Chen, J., & Li, P. (2013). Planning an urban wastewater system with centralised greywater reuse: a case in Beijing. *Civil Engineering and Environmental Systems*, 30(1), 40–55.

Zhang, D., Gersberg, R. M., Wilhelm, C., & Voigt, M. (2009). Decentralized water management: rainwater harvesting and greywater reuse in an urban area of Beijing, China. *Urban Water Journal*, 6(5), 375–385.

Zhou, P., Ang, B. W., & Poh, K. L. (2006). A trigonometric grey prediction approach to forecasting electricity demand. *Energy*, 31(14), 2839–2847.

Zipf, M. S., Pinheiro, I. G., & Conegero, M. G. (2016). Simplified greywater treatment systems: Slow filters of sand and slate waste followed by granular activated carbon. *Journal of Environmental Management*, 176, 119–127.

Appendix-1: List of Publications and Conferences

a) Patent (Granted)	01	A Water treatment system for greywater Patent No: 425225 Granted on 15 March 2023 Filed on 16 Nov 2020
b) **Patent** (Published and FER has been filed)	01	Apparatus for treatment of greywater and turbidity measurement and method Application No: 202311049898 Dated 24 July 2023
c) International Referred Indexed Journals	04	03 Scopus index (Published) 01 Communicated

d) Research Publication

1. International Journal on Recent and Innovation Trends in Computing and Communication, ISSN: 2321-8169 Volume: 11 Issue: 9; Article Received: 25 February 2023 Revised: 12 March 2023 Accepted: 30 March 2023 ***(Published)***
2. Harnessing automated analysis of turbidity and dissolved oxygen for sustainable water solutions; Eur. Chem. Bull. 2023, 12 (S3), 5704 – 5715; Received: 20.03.2023 Revised: 31.05.2023 Accepted: 11.07.2023 ***(Published)***
3. Recycling of Greywater (GW) through Natural Adsorbents; International Journal of Engineering &Technology, 7 (3.12) (2018) 1140 -1143 ***(Published)***
4. Innovative Greywater Management for Sustainable Water Resource Optimization: An Experimental Research Approach; Sustainable Environment Research ***(Communicated)***

Appendix 1.a) Patent Granted (01)

INTELLECTUAL PROPERTY **INDIA**
PATENTS | DESIGNS | TRADE MARKS
GEOGRAPHICAL INDICATIONS

सत्यमेव जयते

क्रमांक : 011158369
SL No :

भारत सरकार
GOVERNMENT OF INDIA
पेटेंट कार्यालय
THE PATENT OFFICE
पेटेंट प्रमाणपत्र
PATENT CERTIFICATE
(Rule 74 of The Patents Rules)

पेटेंट सं. / Patent No.	:	425225
आवेदन सं. / Application No.	:	202011049926
फाइल करने की तारीख / Date of Filing	:	16/11/2020
पेटेंटी / Patentee	:	University of Petroleum and Energy Studies

प्रमाणित किया जाता है कि पेटेंटी को, उपरोक्त आवेदन में यथाप्रकटित A WATER TREATMENT SYSTEM FOR GRAY WATER नामक आविष्कार के लिए, पेटेंट अधिनियम, 1970 के उपबंधों के अनुसार आज तारीख नवम्बर 2020 के सोलहवें दिन से बीस वर्ष की अवधि के लिए पेटेंट अनुदत्त किया गया है।

It is hereby certified that a patent has been granted to the patentee for an invention entitled A WATER TREATMENT SYSTEM FOR GRAY WATER as disclosed in the above mentioned application for the term of 20 years from the 16th day of November 2020 in accordance with the provisions of the Patents Act,1970.

INTELLECTUAL PROPERTY INDIA
PATENTS | DESIGNS | TRADE MARKS
GEOGRAPHICAL INDICATIONS

पेटेंट कार्यालय THE PATENT OFFICE GOVT.OF INDIA भारत सरकार

अनुदान की तारीख : 15/03/2023
Date of Grant :

पेटेंट नियंत्रक
Controller of Patent

टिप्पणी - इस पेटेंट के नवीकरण के लिए फीस, यदि इसे बनाए रखा जाना है, नवम्बर 2022 के सोलहवें दिन को और उसके पश्चात प्रत्येक वर्ष मे उसी दिन देय होगी।

Note. - The fees for renewal of this patent, if it is to be maintained will fall / has fallen due on 16th day of November 2022 and on the same day in every year thereafter.

Appendix 1.b) Patent FER Published (01)

Controller General of Patents, Designs & Trade Marks

सत्यमेव जयते

G.A.R.6
[See Rule 22(1)]
RECEIPT

INTELLECTUAL PROPERTY INDIA
PATENTS | DESIGNS | TRADE MARKS
GEOGRAPHICAL INDICATIONS

Docket No 84848

Date/Time 2023/07/24 22:46:14

To
VIKAS ASAWAT

UserId: vsasawat

3/183, Ganesh Takab, Basant Vihar, Kota

CBR Detail:

Sr. No.	App. Number	Ref. No./Application No.	Amount Paid	C.B.R. No.	Form Name	Remarks
1	202311049898	TEMP/E-1/57454/2023-DEL	1600	33282	FORM 1	APPARATUS FOR TREATMENT OF GREYWATER AND TURBIDITY MEASUREMENT AND METHOD THEREOF
2	E-106/9171/2023/DEL	202311049898	0	-----	FORM28	----

TransactionID	Payment Mode	Challan Identification Number	Amount Paid	Head of A/C No
N-0001187893	Online Bank Transfer	2407230053615	1600.00	1475001020000001

Appendix 2: External Review and Meetings

A) Review meeting on project & research work; Dr. Prasanjit Mondal (IIT Roorkee), Dr. Jitendra K. Pandey (PI and PhD Guide. UPES Dehradun)

B) Visit of hostel owner to discuss for implementation of prototype on premises

Appendix-3: Session and events organised for awareness of Greywater

3.1 Seminar and Brainstorming session on Greywater treatment technology, opportunity and challenges

Media Reports:

Annexure 3.2: Garhwal Post Media Coverage

Dehradun | Dehradun, 10 Jan, 2020 | www.garhwalpost.in | Garhwal Post | 9

Seminar on 'Greywater Treatment Technology' concludes at UPES

By OUR STAFF REPORTER

DEHRADUN, 9 Jan: A workshop on 'Greywater Treatment Technology: Opportunities & Challenges', organised by the Research & Development (R&D) Department at UPES, concluded successfully at the Bidholi campus of the University. The day-long event, sponsored by the 'Department of Science & Technology (DST)', Government of India, under its 'Water Technology Initiative (WTI)', was presided over by Dr Rajendra Dobhal, Director General, Uttarakhand State Council for Science & Technology (UCOST). Eminent Water Treatment & Management Professionals Dr Raman Sharma, Senior Scientist, CSIR-NEERI, Delhi, and Dr Brij Mohan Sharma, Secretary, Society of Pollution & Environmental Conservation Scientists (SPECS), were the Invited Experts.

Briefing the media on the event, Arun Dhand, Sr Director, Public Affairs, UPES, shared that the conservation and protection of water resources and environment had always been a prime concern for UPES. Delegates from reputed educational institutions such as Graphic Era University, Dehradun; SGRR University, Dehradun; Tula's Institute, Dehradun; Dev Sanskriti Vishwavidyalaya, Haridwar; SPECS, industry participant vian Engineering Private Limited, Delhi, also participated.

Welcoming Chief Guest Dr Dobhal and other experts, Dr SJ Chopra, Chancellor, UPES, Dr Deependra Jha, Vice Chancellor, Dr Kamal Bansal, Dean, Academic Development & Innovation, and all the delegates to the event, Dr Jitendra K Pandey, Associate Dean, Research, and 'Seminar Chair', shared that the event was specially customised to benefit students, educators, researchers, scientists, engineers and industrialists engaged in a wide range of water related research, applications and entrepreneurial activities. Dr Pandey hosted the proceedings of the seminar jointly with Dr SM Tauseef, Associate Professor & Assistant Dean (Research), School of Engineering. A brainstorming session on the treatment of Greywater from various sources witnessed eminent speakers from industries & reputed institutions addressing the key issues such as 'Greywater Technology - challenges & opportunities'; 'Greywater Treatment - reuse & its societal impact' and 'Entrepreneurial Opportunities in Water Domain'.

Dr Rajendra Dobhal spoke on the current water availability scenario focusing his discussions on its management. "The need of the hour is to regularly undertake steps for its proper management to avoid association of additional challenges with this already scarce resource," he said. Speaking on the current technology to treat the used water (greywater) for quality and making it reusable for various purposes other than the human consumption, the Chief Guest apprised the gathering about his personal experience on water conservation gained while visiting various foreign nations.

Amongst the Invited Experts, Dr Raman Sharma spoke about revival of waterbodies and lakes with NEERI & Delhi Jal Board's support and shared case studies of the projects. Dr Brijmohan Sharma, too, shared his field experiences and case studies on Water Treatment Units in Dehradun. In his talk on 'Wastewater Treatment using the novel SHEFROL Bioreactor Wastewater Treatment System', Dr SM Tauseef quoted his research experiences. A presentation by Mahendra Rana from State Intern College, Shilodi (Pauri Garhwal), on "Loss of Water in Mountains due to Lack of proper Water Management", and a talk by Sakshi Gupta, from Graphic Era University on "Rainwater Harvesting & Entrepreneurial Opportunities" were well received by all.

The event concluded with a 'Vote of Thanks' proposed by Dr Jitendra Pandey. The 'Organizing Team' consisted of Dr Tarun Dhingra, Dr SM Tauseef and Dr Kiran K Ruvulakollu as 'Conveners'; Mukesh Chandra Kestwal and Ravi Kumar Patel as 'Seminar Secretaries' and Rakhi Ruhal, Surajit Mondal, P Swami Sairam, Abhishek Sharma, Nikhil Raj, Anurag Barmola and Charu Chandra Pant as 'Steering Committee Members'.

Annexure 3.3: The pioneer Media Coverage

the pioneer

DEHRADUN | FRIDAY | JANUARY 10, 2020

Grey water treatment workshop concludes

PNS ■ DEHRADUN

A daylong workshop on opportunities and challenges in grey water treatment technology concluded at the UPES. The Uttarakhand State council for Science and Technology (UCOST) director general Rajendra Dobhal presided over the workshop sponsored by the Department of Science and Technology.

Addressing the gathering, Dobhal spoke on the current water availability scenario and its management.

"In view of the current water resource scarcity, its effective management has become even more important. The need of the hour is to regularly undertake requisite steps for its proper management to avoid association of additional challenges with this already scarce resource. Though 70 per cent of the earth's surface is covered by water, less than one per cent is available for human consumption, therefore it becomes even more essential that everyone should contribute for its conservation. Researchers and scientists need to develop technology for water solutions and collate its valuable data for the next generations," he added. Senior scientist from CSIR-NEERI, Delhi, Raman Sharma spoke about revival of water bodies and lakes carried out by NEERI with Delhi Jal Board's support. Brij Mohan Sharma from Society of Pollution and Environmental Conservation Scientists (SPECS) also shared his field experiences and case studies on water treatment units in Dehradun while addressing the audience. Associate professor and assistant dean (Research), School of Engineering, UPES, SM Tauseef spoke of his research experiences.

Water scarcity and its management pose a big challenge that should have been acted upon by yesterday instead of today or tomorrow. Despite the delay, it is still better to be late than never, he added.

Mahendra Rana from Government Inter College, Shilodi (Pauri) spoke on the loss of water in mountains due to lack of proper water management while Sakshi Gupta from Graphic Era University spoke on rainwater harvesting and entrepreneurial opportunities.

Annexure 3.4: Rashtriya Sahara Media Coverage

9 देहरादून

देहरादून। शुक्रवार • 10 जनवरी • 2020

राष्ट्रीय सहारा | www.rashtriyasahara.com |

मौजूदा हालात के मद्देनजर जल के प्रभावी प्रबंधन की जरूरतः डा. डोभाल

जल संसाधनों के संरक्षण पर जोर

■ सहारा न्यूज ब्यूरो

देहरादून।

यूनिवर्सिटी आफ पेट्रोलियम एण्ड एनर्जी स्टडीज (यूपीईएस) में 'ग्रेवाटर ट्रीटमेंट टेक्नोलाजी- अपर्चुनिटीज एण्ड चैलेंजेज' विषय पर कार्यशाला आयोजित की गई। कार्यशाला में मुख्य रूप से जल संसाधनों के संरक्षण व गुणवत्ता पर जोर दिया गया।

यूपीईएस के बिधोली परिसर में आयोजित कार्यशाला में बतौर मुख्य अतिथि यूकास्ट के महानिदेशक डा. राजेंद्र डोभाल ने जल उपलब्धता के मौजूदा परिदृश्य पर बात की। उन्होंने कहा कि मौजूदा परिवेश में जल संसाधनों की कमी के मद्देनजर जल का प्रभावी प्रबंधन जरूरी हो गया है। जल को लेकर भविष्य की चुनौतियों से निपटने के लिए अभी से ही कारगर कदम उठाने की जरूरत है। उन्होंने जल संरक्षण को लेकर अपने अनुभवों को भी साझा किया। साथ ही शोधकर्ताओं व वैज्ञानिकों से जल से जुड़ी समस्या के समाधान के लिए प्रौद्योगिकी विकसित करने पर जोर दिया।

विशेषज्ञ डा. रमन शर्मा ने दिल्ली की वाटरबाडी और झीलों के पुनरुद्धार से जुड़ी

यूपीईएस में जल की गुणवत्ता व प्रबंधन को लेकर कार्यशाला आयोजित

परियोजनाओं से जुड़ी जानकारी दी। डा. बृजमोहन शर्मा ने देहरादून में जल की गुणवत्ता को लेकर अपने अनुभवों व अध्ययनों को साझा किया। डा. एसएम तौसीफ ने पानी की कमी एवं प्रबंधन बड़ी चुनौती बताया।

राजकीय इंटर कालेज शिलोदी (पौड़ी) के महेन्द्र राणा ने 'उचित जल प्रबंधन की कमी के कारण पहाड़ों में पानी की कमी' पर प्रजेंटेशन दिया। विशेषज्ञों ने कहा कि जल प्रबंधन और पानी की कमी की चुनौतियों से निपटने के लिए ग्रेवाटर को तकनीक के जरिये उपचार महत्वपूर्ण साबित हो सकता है। ग्रेवाटर का ट्रीटमेंट कर उसका उपयोग सिंचाई, बागवानी, सड़क निर्माण में छिड़काव आदि के लिए किया जा सकता है।

यूपीईएस के सीनियर डायरेक्टर अरुण ढांड ने कहा कि कार्यशाला में अनुसंधान आधारित मुद्दों से लेकर प्रबंधन, नीति, सामाजिक जागरूकता पर चर्चा की गई जिसमें विशेषज्ञों के साथ विभिन्न विश्वविद्यालयों व संस्थानों के प्रतिनिधियों ने हिस्सा लिया। इससे पूर्व यूपीईएस के चांसलर डा. एसजे चोपड़ा, कुलपति डा. दीपेन्द्र झा, डीन डा. कमल बंसल ने विशेषज्ञों व प्रतिनिधियों का स्वागत किया। एसोसिएट प्रोफेसर डा. जितेन्द्र पांडे ने कार्यशाला को सफल बनाने के लिए सभी का आभार जताया। कार्यशाला के आयोजन में संयोजक डा. तरुण डींगरा, डा. किरन, मुकेश चन्द्र केस्टवाल, रवि कुमार पटेल, सुरजीत मंडल, अभिषेक शर्मा, निखिल राज आदि ने सहयोग दिया।

कार्यशाला में शामिल विशेषज्ञ।

Annexure 3.5: The Himachal Times Media Coverage

Dehradun & Shimla 71st year of Publication Founded by S.P Pandhi
DEHRADUN
The Himachal Times
UTTARAKHAND EDITION

Thursday – 9th January 2020
By Our Staff Reporter

"SEMINAR ON 'GREYWATER TREATMENT TECHNOLOGY' CONCLUDES SUCESSFULLY AT UPES"

Dehradun : A workshop on *'Greywater Treatment Technology: Opportunities & Challenges',* organized by the Research & Development (R&D) UPES, concluded successfully at the Bidholi campus of University. The daylong event, sponsored by the 'Department of Science & Technology (DST)', Govt. of India under its *'Water Technology Initiative (WTI)'*, was presided by Dr. Rajendra Dobhal - *Director General, Uttarakhand State Council for Science & Technology (UCOST)* as the *'Chief Guest'*. Eminent Water Treatment & Management Professionals - Dr. Raman Sharma - *Senior Scientist, CSIR-NEERI Delhi* and Dr. Brij Mohan Sharma, Secretary - Society of Pollution & Environmental Conservation Scientists (SPECS) graced the event as 'Invited Experts'.

Briefing the media on the event, Mr. Arun Dhand - Sr. Director, Public Affairs UPES shared that the conservation & protection of water resources and environment has always been a prime concern for UPES. *"This workshop has been sponsored by the Department of Science & Technology under its Water Technology Initiative for development of technology and to address the diversified water challenges ranging from various fundamental research based issues to management, policy & societal awareness"* Mr. Dhand shared. Delegates from reputed educational institutions viz. *Graphic Era University, Dehradun; SGRR University, Dehradun; Tulas Institute, Dehradun; Dev Sanskriti Vishwavidyalaya, Haridwar, SPECS,* industry participant *M/s Evian Engineering Private Limited, Delhi* along with the hosts *UPES* participated in the seminar.

Welcoming the *'Chief Guest'*, *'Invited Experts'*, Dr. S.J. Chopra - *Chancellor UPES*, Dr. Deependra Jha - *Vice Chancellor UPES*, Dr. Kamal Bansal - *Dean, Academic Development & Innovation UPES* and all the delegates to the event, Dr. Jitendra Kr. Pandey - *Associate Dean Research UPES* & *'Seminar Chair'* shared that the seminar was specially customized to benefit students, educators, researchers, scientists, engineers & industrialists engaged in a wide range of water related research, applications & entrepreneurial activities. *"The dissemination of knowledge from the invited lectures by experienced researchers, expert talk by the Hon'ble Chief Guest, presentations by the participants along with the brainstorming session & panel discussion will provide valuable learnings to the delegates"* he stated. Dr. Pandey hosted the proceedings of the seminar jointly with Dr. S.M. Tauseef - Associate Professor & Assistant Dean (Research), School of Engineering, UPES. A brainstorming session on the treatment of Greywater from various sources witnessed eminent speakers from industries & reputed institutions addressing the key issues in *'Greywater Technology - challenges & opportunities'; 'Greywater Treatment - reuse & its societal impact'* and *'Entrepreneurial Opportunities in Water Domain'*.

Delivering the *Chief Guest* lecture, Dr. Rajendra Dobhal spoke on the current water availability scenario focusing his discussions on its management. *"In view of the current water resource scarcity scenario, its effective management has become even more important. The need of the hour is to regularly undertake requisite steps for its proper management to avoid association of additional challenges with this already scarce resource"* he said. Speaking on the current technology to treat the used water (greywater) for quality & making it reusable for various purposes other than the human consumption, the Chief Guest apprised the gathering about his personal experience on water conservation gained while visiting various foreign nations. *"Water is a most precious resource. Even though 70% of the earth's surface is covered by water but less than 1% only is available for human use, therefore is becomes even more essential that everyone should contribute for its conservation for the coming generations. Researchers & scientists need to develop technology for water solutions and collate its valuable data for the next generations"* Dr. Dobhal added. Amongst the *Invited Experts*, Dr. Raman Sharma spoke about revival of waterbodies & lakes in with NEERI & Delhi Jal Board's support and shared case study of the projects completed by NEERI and referred to *'In-SITU' & 'Ex-SITU'* technologies for treatment of contaminated soil. Dr. Brijmohan Sharma too shared his field experiences & case studies on *Water Treatment Units* in Dehradun while addressing the audience. In his talk on *'Wastewater Treatment using the novel SHEFROL Bioreactor Wastewater Treatment System'*, Dr. S.M. Tauseef quoted his research experiences. *"Water scarcity & its management poses a big challenge that should have been acted upon by yesterday instead of today or tomorrow. We are already late but it is still better to be late than never"* Dr. Tauseef shared. A presentation by Mr. Mahendra Rana from *State Intern College, Shilodi (Pauri Garhwal)* on *"Loss of Water in Mountains due to Lack of proper Water Management"* and a talk by Ms. Sakshi Gupta, from *Graphic Era University* on "Rainwater Harvesting & Entrepreneurial Opportunities" were well received by all.

The event concluded with a *'Vote of Thanks'* by Dr. Jitendra Pandey who acknowledged WTI-DST Govt. of India for supporting the Greywater Treatment project. Thanking the *Chief Guest, Invited Experts* & the delegates, Dr. Pandey appreciated the organizing team for conducting the event successfully. *"Greywater could be a valuable asset to handle the water management, and water scarcity challenges. Generated in form of water ousted from households, office buildings & streams without the fecal contamination, the use of treated greywater will help save large amounts of freshwater. The treated water has its usage for Irrigation, Gardening, Cleaning, Mopping, Flushing, Road Making, Sprinkling, Railways, Private Sectors, Housekeeping services etc."* he informed. The *'Organizing Team'* constituted of Dr. Tarun Dhingra, Dr. SM Tauseef & Dr. Kiran K Ruvulakollu as *'Conveners'*; Mukesh Chandra Kestwal & Ravi Kumar Patel as 'Seminar *Secretary'* and Rakhi Ruhal, Surajit Mondal, P. Swami Sairam , Abhishek Sharma, Nikhil Raj, Anurag Barmola & Charu Chandra Pant as *'Steering Committee Members'*.

Annexure 4: Code for Decision Matrix

```
# Enable logging to capture the performance at each stage
logging.basicConfig(filename='greywater_treatment.log', level=logging.INFO,
format='%(asctime)s %(message)s')

# Adjustable parameters for simulation flexibility
class GreywaterTreatmentSystem:
  def __init__(self, initial_turbidity, acceptable_turbidity, acceptable_do):
    self.initial_turbidity = initial_turbidity
    self.acceptable_turbidity = acceptable_turbidity  # Target: 30 NTU for safe outcome
    self.acceptable_do = acceptable_do  # e.g., 2 mg/L minimum DO level as per system
requirement
    self.current_turbidity = initial_turbidity
    self.current_do = 0  # Initial DO set to 0

    logging.info(f"Initialized system with turbidity {self.initial_turbidity} NTU and acceptable
standards")

  def check_turbidity_initial(self):
    logging.info(f"Checking initial turbidity: {self.current_turbidity:.2f} NTU")
    return self.current_turbidity

  def sand_filtration(self):
    # Sand filtration process reducing NTU from 800 to around 100
    reduction = self.current_turbidity - 100  # Simulate fixed reduction to around 100 NTU
    self.current_turbidity = 100
    logging.info(f"Turbidity after sand filtration: {self.current_turbidity:.2f} NTU")
    return self.current_turbidity

  def check_do(self):
    # Checking DO sensor values based on system requirements from image
    self.current_do = 1.5  # Initially DO is less than the desired 2 mg/L
    logging.info(f"Dissolved Oxygen (DO) level: {self.current_do:.2f} mg/L")
    if self.current_do < self.acceptable_do:
      logging.info(f"DO is below threshold, initiating aeration")
      self.aeration()
    return self.current_do

  def aeration(self):
    # Aeration process to increase DO to desired level
    logging.info("Performing Aeration...")
    self.current_do = 3.0  # After aeration, DO is increased to 3.0 mg/L
    logging.info(f"DO after aeration: {self.current_do:.2f} mg/L")
    return self.current_do
```

```
    def final_turbidity_check(self):
        # Final turbidity check reducing NTU to around 30
        logging.info("Performing Final Turbidity Check...")
        final_improvement_factor = self.current_turbidity - 30  # Simulate reduction to around
30 NTU
        self.current_turbidity = 30
        logging.info(f"Final turbidity after filtration improvement: {self.current_turbidity:.2f}
NTU")
        return self.current_turbidity

    def disinfection(self):
        # Disinfection process that minimally reduces the NTU further
        logging.info("Performing Disinfection...")
        final_reduction_factor = self.current_turbidity * 0.95  # Minimal change post
disinfection
        logging.info(f"Turbidity after disinfection: {final_reduction_factor:.2f} NTU")
        return final_reduction_factor

    def decision_matrix(self):
        # Simulating the full process
        self.check_turbidity_initial()

        # If the initial turbidity is too high, filter it
        if self.current_turbidity >= 11:
            self.sand_filtration()

        # Check Dissolved Oxygen levels and aerate if necessary
        self.check_do()

        # Perform final turbidity check
        self.final_turbidity_check()

        # Disinfect the water
        final_turbidity = self.disinfection()

        # Evaluate final quality
        logging.info(f"Final Treated Water Quality: Turbidity {self.current_turbidity:.2f} NTU, DO
{self.current_do:.2f} mg/L")

        if self.current_turbidity <= self.acceptable_turbidity and self.current_do >=
self.acceptable_do:
            logging.info("Water quality meets the required standards for reuse.")
            print("Water quality meets the required standards for reuse.")
        else:
```

```
        logging.info("Water quality does not meet the required standards.")
        print("Water quality does not meet the required standards.")


# Run a simulation with fixed initial turbidity of 800 NTU, target turbidity of 30 NTU, and
minimum DO of 2 mg/L
greywater_system = GreywaterTreatmentSystem(initial_turbidity=800,
acceptable_turbidity=30, acceptable_do=2)
greywater_system.decision_matrix()
```

PLAGIARISM CERTIFICATE

1. We **Dr Jitendra Kumar Pandey** (Internal Guide), certify that the Thesis titled ***Development of Hybrid System for Grey Water Treatment*** submitted by Scholar Mr/ **Mukesh Chandra Kestwal** having SAP ID **500063535** has been run through a Plagiarism Check Software and the Plagiarism Percentage is reported to be **7 %.**

2. Plagiarism Report generated by the Plagiarism Software is attached .

Signature of the Internal Guide

Signature of the Scholar

Mukesh Kestwal 16 Dec 2024.pdf

ORIGINALITY REPORT

7%	6%	5%	%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	ijritcc.org Internet Source	3%
2	link.springer.com Internet Source	2%
3	A. Awasthi, K. Gandhi, S. Rayalu. "Greywater treatment technologies: a comprehensive review", International Journal of Environmental Science and Technology, 2023 Publication	2%
4	listens.online Internet Source	1%

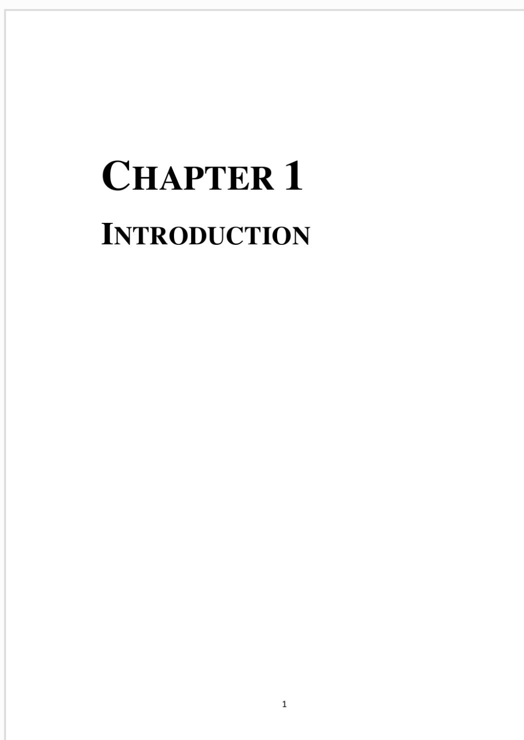
Exclude quotes	Off	Exclude matches	< 1%
Exclude bibliography	On		

Digital Receipt

This receipt acknowledges that Turnitin received your paper. Below you will find the receipt information regarding your submission.

The first page of your submissions is displayed below.

Submission author:	Mukesh Kestwal
Assignment title:	Mukesh Kestwal Final Thesis 16 Dec - Development of Hybri...
Submission title:	Mukesh Kestwal 16 Dec 2024.pdf
File name:	Mukesh_Kestwal_16_Dec_2024.pdf
File size:	7.62M
Page count:	185
Word count:	38,868
Character count:	227,202
Submission date:	17-Dec-2024 03:46PM (UTC+0530)
Submission ID:	2554504765


CHAPTER 1

INTRODUCTION

1