COMPARATIVE EVALUATION OF ACTIVATED CARBON AND GRANULATED BLAST FURNACE SLAG IN TREATING GREYWATER

by

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A Thesis presented to the Faculty of the
American University of Sharjah
College of Engineering
In Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Civil Engineering

Sharjah, United Arab Emirates

May 2020

Declaration of Authorship

I declare that this thesis is my own work and, to the best of my knowledge and belief, it does not contain material published or written by a third party, except where permission has been obtained and/or appropriately cited through full and accurate referencing.

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Acknowledgement

Foremost, I want to offer this endeavour to Almighty ALLAH for the wisdom and ability HE bestowed upon me, the strength, peace of mind and good health in order to understand and finish this research.

I would like to acknowledge with deep sense of reverence, my gratitude towards my parents for the encouragement and financial support which helped me achieve every milestone to produce this work. Thank you to my beloved and supportive siblings, Naima, Sarim and Salman, who were always by my side and served as an inspiration to pursue this undertaking.

I am highly indebted to my thesis advisors, Dr. Kazi Fattah and Dr. Md. Mortula, for believing in me and imparting their knowledge and expertise in this study. Thank you for your continuous encouragement, support, indispensable advice and most importantly for your patience for all these years. Without your optimism concerning this work and unmeasurable guidance, this dissertation would have not been completed. Additionally, I would like to thank my committee members, Dr. Serter Atabay and Dr. Fatin Samara for making this journey joyful, memorable and knowledgeable. Thank you for providing your insightful and encouraging comments to produce the quality work. My experimental work would have not been possible without the help and support of John E.K., who formed the basis of this study by fabricating the experimental setup. In addition, I would also like to thank Ms. Syeda Maimoona and visiting research student Zied Kallel for introducing me to the pathogenic world. Your assistance, cooperation and experience were essential for the completion of this work along with my well-being during pathogenic experiments. Also, my deepest appreciation to the Department of Civil Engineering at the American University of Sharjah for providing me with all the support to complete this study.

This acknowledgement is not complete without mentioning my dearest friend, Al Ameer Basheer. Thank you for instilling in me the virtues of perseverance and commitment and relentlessly encouraging me to strive for excellence. Thank you for uplifting my confidence on the days I almost gave up. Thank you for helping me cross this bridge which I never thought I could.

Finally, I would convey my deep gratitude to all those who have been associated with this research study, but their names have not found their place in this recognition.

Dedication

To

My Mother

A strong and gentle woman without whom I would have never instigated this work. She has dedicated her life for our well-being and positive growth. She taught us to trust Allah, believe in hard work and that so much could be done with little. She prayed all along for us to smoothly cross every stepping stone.

My Father

For earning an honest living for us. For facing all the early mornings and hot sunny days for us. For compromising his needs to fulfill our desires. For giving us all his love and support. And finally, for putting his trust and belief in myself.

My Friend – Al Ameer Basheer

For his advice, his patience and his faith. Because he always understood.

Abstract

Recycling greywater (GW) for on-site, non-potable application can reduce the load to wastewater treatment plants and stress on potable water demand for domestic water supply. However, utilization of GW requires careful treatment to ensure reduction of all contaminants to acceptable level. The conventional methods for GW treatment are expensive and energy intensive. Consequently, the search for efficient and cost-effective treatment has been on a rise in recent decades. This study investigates the effectiveness of granulated blast furnace slag (GBFS) and activated carbon (AC) in the treatment of GW from a residential building in Sharjah, United Arab Emirates. GBFS is a by-product formed during the production of iron and steel-making. Since GBFS is commonly considered a waste, its utilization allows for waste reduction. Six configurations, each having a different combination of filter media, adsorbent, ultra-violet (UV) radiation and chlorine disinfection were setup at a pilot scale to assess (i) effectiveness of AC and GBFS in treating GW (ii) the impact of pre-treatment on treated water quality and (iii) the efficiency of UV and chlorine disinfection in microbial reduction. Results demonstrated that GBFS achieved higher or comparable removal efficiency for turbidity (90 – 92 %), BOD5 (76 – 86 %), COD (64.6 – 85.1 %), TSS (66.8 – 88.5 %) and TOC (80.6 – 92.7 %) in contrast to AC. GBFS displayed lower TDS removal (0 – 26 %) in contrast to AC (35.8 – 55.4 %). The addition of filter media prior to GBFS enhanced removal of TOC by 1- 3mg/l, TSS up to 99.1 % and turbidity up to 92.1 %. GBFS displayed higher reduction of TC (0.54 – 2.05 log removal) and FC (1.96 – 2.30 log removal) in contrast to AC. UV efficiency in FC and TC reduction varied in the range of 2.5 – 4.4 log removal and 0.4 – 2.7 log removal, respectively. Finally, human risk reduction performed on TC displayed GBFS combined with pre-treatment achieved lower hazard quotient (HQ) values, thereby producing reclaimed water of lower risk in comparison to AC. The study proved that it is possible to introduce GBFS as a sustainable alternative to conventional AC adsorbent for treatment of greywater at household level for non-potable use.

Keywords: ***Greywater recycling; granular blast furnace slag; activated carbon; adsorption; microbial reduction; human risk reduction.***

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Activated Carbon
APHA	American Public Health Association
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DPB	Disinfection by Products
FC	Fecal Coliform
GBFS	Granulated Blast Furnace Slag
GW	Greywater
GWR	Greywater Recycling
SEWA	Sharjah Electricity and Water Authority
TC	Total Coliform
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
TOC	Total Organic Carbon
MENA	Middle East and North Africa
UN	United Nations
UV	Ultra Violet
WBG	World Bank Group
WHO	World Health Organization

Chapter 1. Introduction

This chapter briefly addresses water scarcity and the necessity of water management through water reuse. It demonstrates the problems this study tries to address. The chapter also presents the objectives of this study and the research contribution. Finally, the general organization of thesis is presented.

1.1. Overview

Water scarcity is a significant issue in various parts of the world that impact quality of life, environmental sustainability, industries and economic development. Unprecedented pressures have been applied on the water resources due to population and economic growth. As prosperity spreads, water demands surges without the supply enhancement of freshwater resources [2]. According to recent report published by United Nations (UN) [3], there are over 2 billion people residing in countries with elevated water stress and more than 700 million individuals worldwide could potentially be displaced due to intensive water scarcity by the year 2030 [4]. It has also been predicted that, by the year 2030 the global water demand will increase by 50 %, aggravating the water shortage by 40 % [5].

The world's energy and availability of freshwater resources are inextricably interlinked. Water is a vital key for economic production, therefore lack of water availability and diminishing water supplies can cause poor economic growth. The overexploitation of freshwater resources threatens the economic activity across all sectors and regions of the global economy [6]. The continuous rise in demand for freshwater due to population growth, elevated agricultural activities and global climate change can result in water scarcity which can potentially threat the long terms viability energy dependant projects and impede development [7]. The depleted resource will induce a domino effect on the communities, including decline in local commerce and trade. According to World Bank Group (WBG) [8], by the year 2050 some water scarce regions such as Middle East and Africa will encounter 6 percent reduction of their Gross Domestic Production (GDP), sending them into sustained negative economic growth as a consequence of diminishing freshwater supply due to its over utilization in the field of agriculture, health, income and prosperity. In addition, reduction in freshwater availability can induce competition between regions by encouraging migration from

water stressed zones to water rich zone which increases social tensions and ignites civil conflicts [8]. One of the notable cases to support this conclusion is of Syria, where prolonged water scarcity and poor water management strategies, exacerbated social, economic and political unrest which eventually led to civil conflict and mass migration crisis in 2011, in which over 4.9 million Syrians fled the country in March 2017 [9]. Alternatively, water scarcity has an aggressive impact on agricultural production, food security, and commodity values. These factors can negatively impact human livelihoods and thus amplifying cycles of poverty, especially for 78 % of the world's poor that intensively rely on agriculture, livestock, or aquaculture for their survival [10]. If the water management is not done prudently, the crises will potentially elevate and become the catastrophes of tomorrow.

One of many strategies for water management includes recycling of greywater (GW) for non-potable purpose. GW treatment and reuse can be a potential solution to help mitigate water shortage issue and may well hold the key to reduce stress on freshwater resources by meeting the non-potable demands. However, the key concern associated with GW reuse includes reclaimed water quality, human health perceptions, and economic consideration [11]. The treatment system should be sustainable, and the reclaimed water quality should meet the standard reuse guideline to ensure public health safety in the long run. Amongst numerous techniques available around the globe for contaminant removal from wastewater (WW), adsorption using solid materials, is considered to be the most feasible, simple, useful and effective process [12]. Activated carbon (AC) is the most extensively used and widely adapted adsorbent material at the industrial scale for treatment of WW and drinking water [12]. Although AC is a preferred adsorbent, its widespread application is restricted due to several disadvantages. AC adsorbent is quite expensive [12]. In addition, the cost of regenerating saturated carbon is also an expensive and complicated energy intensive procedure which results in loss of the adsorbent material [13]. Also, the utilization of carbons based on relatively costly starting materials does not justify for most pollution control applications [14]. In the past decades, numerous studies have been conducted for the development of effective sustainable adsorbent which is both cost effective and eliminates pollutants at trace levels.

Hence, this study targets to evaluate and compare the impact of ground blast furnace slag (GBFS) and activated carbon (AC) on the reclaimed water quality. GBFS is an unavoidable by-product from steel and iron production industries. The usage of GBFS in grounded form, commonly known as ground granulated blast furnace slag (GGBFS), have recently gained extensive attention in construction industries mainly for enhancing concrete strength by replacing the usage of traditional cement, thereby, leading to a production of sustainable concrete [15]. Whilst some level of research has been conducted in utilization of GBFS for the extraction of heavy metals from aqueous solution and WW [16]-[17], however, no study has evaluated the use of GBFS in the treatment of reused WW. Therefore, to narrow the gap in the literature, this study targets to evaluate and compare the effect of GBFS and AC on treatment of domestic GW generated from bath and shower of a residential building located in Sharjah, United Arab Emirates (UAE).

1.2. Thesis Objectives

The primary goal of this study is to investigate different materials and disinfection processes for facilitating sustainable production of reclaimed water for non-potable applications. The specific objectives of this study are as follows:

- Assess and evaluate the effectiveness of activated carbon (AC) and granulated blast furnace slag (GBFS) in treating greywater (GW).
- Evaluate the impact of pre-treatment using sand filtration (SF) combined with AC and GBFS adsorbents on the reclaimed water quality.
- Assess the efficiency of UV and chlorination disinfection in microbial reduction.
- Conduct human risk reduction by assessing the reduction in TC contamination.

1.3. Research Contribution

The contributions of this research work can be summarized as follows:

- Narrow the gap in the academic literature by studying sustainable on-site greywater (GW) treatment in Sharjah city. Currently, there are no study established on evaluating current GW treatment systems or proposing alternate GW schemes for Sharjah. Assessing and evaluating existing and proposed GW

treatment configurations can potentially help providing wide range of technological choices in UAE. Furthermore, an understanding of the different treatment systems shall help reduce the dependency on limited water resources and desalination plants.

- Evaluation of the performance of low-cost adsorbent, granulated blast furnace slag (GBFS) in the treatment of GW. Both, economical and sustainable treatment methodology encourages stakeholders to invest and adapt long term sustainability and economical plan. Increase adaptation of greywater recycling (GWR) system with GBFS adsorbent has the potential to reduce the stress on deficient water resources and reduce the waste footprint of GBFS.
- Evaluation on the quality of reclaimed GW by substituting traditional chlorine disinfection with ultra violet (UV) irradiation. Chlorination can lead to potential production of disinfection by products (DBPs), hence replacement of this disinfection scheme with UV can mitigate the formation of DBPs, thereby increasing environmental sustainability and social well-being which can further encourage adaption of GW reuse.
- Bridge the gap in literature by documenting the treatment of GW using sustainable and low cost GBFS adsorbent. Although the utilization of GBFS is receiving widespread attention in construction industries, yet its application in GW treatment is yet to be investigated. Hence, this study adds to existing, narrow body of research and help to advance knowledge in performance of GBFS in treatment of GW for non-potable use.

1.4. Thesis Organization

The present thesis is divided into six organized parts. Following this introductory section (Chapter 1), Chapter 2 highlights the significance of addressing water scarcity and dependency on desalination as alternate water resource in the Middle East and North Africa (MENA) region. Furthermore, it reviews in depth the typical GW quantity, characteristics, reuse standards and GWR treatment technologies adapted around the globe and in Sharjah city. Finally, it provides information on production and leachate characteristics of GBFS. The study area, sampling locations, sampling procedure, laboratory experiments for assessing both physico-chemical characteristics and microbial contamination of the collected samples are presented in Chapter 3.

Subsequently, Chapter 4 presents detailed analysis and discussion of the results to cover all the objectives of this study. Chapter 5 presents the conclusion of this study. Finally, Chapter 6 highlights the limitation of this study and provides recommendations for future works.

Chapter 2. Background and Literature Review

This chapter highlights water scarcity in Middle East and North Africa (MENA) region. Furthermore, it describes typical greywater (GW) quantity, characteristics and reuse standards adapted around the globe and in Sharjah city. Additionally, it also focuses on the GW treatment technologies utilized and their associated efficiencies in treating GW generated from different source. It also briefly puts a light on the formation of disinfection by products (DBPs) during the treatment process and its toxicological impact on human health. Finally, it provides information on production and leachate characteristics of ground blast furnace slag (GBFS).

2.1. Water Scarcity in MENA Region

Water scarcity is a significant issue in various parts of the world that impact quality of life, environment, industries and economic development. Unprecedented pressures have been applied on the water resources due to population and economic growth. MENA regions are categorized as the most water scarce region around the globe [18]. Due to its relative scarcity, water is becoming a source of opportunities and risks in the MENA region [19]. The Gulf region specifically is a semi-arid region and is commonly known to be a home to the most water scare countries around the globe. It is classified to have hot desert climates (BWh) under the Koppen Climate Classification [20]. According to World Health Organization (WHO) [8], the Gulf region has already reached the water scarcity line of less than 1000 m^3 per annum per capita. Arab countries span approximately 10 percent of the global area, receive only 3 percent of the global average annual precipitation and comprises of only 0.3 percent of the global annual renewable water resources. This region accounts for having less than 370 m^3 of potable water resource, thereby endowing as the least potable water resource region around the world [21]. As also confirmed in the literature [22], there is scarcity of potable water resources in the Gulf Cooperation Council (GCC) countries due to the low average annual precipitation and high evaporation rate. Additionally, groundwater is generally non-renewable, and the deep aquifers have various potentialities. Considering the current population growth, it is projected that the available water resources will reduce to half the current capacity by the year 2030 when the population is expected to be approximately 56 million. By the year 2025, only Lebanon and Iraq

are anticipated to be above water scarcity levels, while the rest of the Arab countries shall be progressing towards water scarcity issues [22].

Large scale water management challenges have already started emerging in the region. Aquifers are over pumped, deterioration in water quality, and services including water supply and irrigation are usually rationed – with negative impacts on human wellbeing, agricultural efficiency and the nature [18]. It has also been reported that, over 60 percent of the MENA region's population resides in sectors confronting elevated surface water stress in comparison with global average of 35 percent. Similarly, 70 percent of the region's gross domestic production (GDP) is produced in sectors dealing with high water stress issues, compared to the global average of 22 percent [23]. For millennia, heavy investments have been made to employ innovative techniques to manage water resource across the region, however, exponential economic and population expansion coupled with ineffective governance have overwhelmed these efforts in various countries. The MENA region as whole encounters extreme water scarcity issues, however, each country has an alternate water resource endowment that supports to fulfil the broader water challenges. Some countries display high dependency on groundwater, while others heavily rely on large transboundary rivers to meet their daily requirements. GCC countries are mainly dependent on intensive over-drafting of groundwater resources, and by extensive installation of desalination plants for producing potable water, and finally by reusing a small percentage of wastewater (WW) [24].

The ongoing frequent use and over abstraction of groundwater in the absence of alternative sources may contribute in reaching the critical end where fossil aquifers are completely exhausted and renewable aquifers shall be drawn down to the limit where the cost of abstraction will no longer be economically feasible. The groundwater quality deteriorates and becomes unsuitable for human consumption as the aquifers nears depletion. Considering the presence of large uncertainties associated with the cumulative groundwater storage, it is extremely difficult to predict the time frame when the aquifers may become completely compromised [25]. The dependency on limited groundwater resources will not be able nurture the increasing population of GCC states and their growing water intensive lifestyles [19]. In some GCC countries, the aquifers have already been exhausted and drained [26].

2.2. Desalination

Desalination of seawater undoubtedly provides abundance of benefits to human health, economic development and environment by producing an indefinite supply of high-quality water without stressing the natural freshwater ecosystems. However, concerns have been raised considering the associated negative impacts of desalination plants [27]. The concerns are mainly related to the concentrate and chemical discharges that are liable for the destruction of the water quality, which subsequently has detrimental effect on the marine ecosystem, and emission of various air pollutant associated with the process of desalination as shown in Figure 2.1.

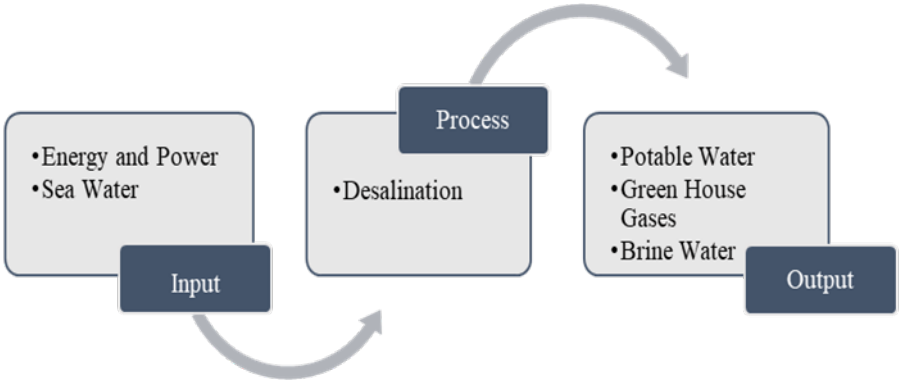


Figure 2.1: Typical desalination process.

There are several environmental impacts linked with the present desalination practices in the Gulf [28]. Sea water-oriented desalination plants commonly use sea water as receiving source. During the uptake of sea water, losses of aquatic life may occur when they interact and collide with the intake screens or are unwillingly drawn into the plant along with the feed water. Additionally, the construction of the intake infrastructure and pipe works interfere with the seabed, hence disturbing the natural ecosystem and resulting in the resuspension of sediments and nutrients. Proceeding the installation of the structure, the pipes act as an obstruction to the natural water exchange and sediment transport process.

Another issue associated with the desalination plant is the rejection of concentrated brine solution in the natural water bodies. By definition, reject brine is a by-product of desalination plant and is highly concentrated saline water, produced in the last stage of the desalination process. Various chemicals are used during

desalination process for both pre and post treatment operations. Apart from being highly saline and having high temperature, brine may contain various chemicals and corroded heavy metals at different concentration levels depending on the process of desalination and influent quality. It is reported that, the global brine production is approximately 141.5 million m^3/day, summing up to 51.7 m^3/year [29]. MENA region is leading the brine production, by generating roughly 100 million m^3/day of brine, which accounts to be 70.3 % of the total global brine production [29]. The usual practice is to discharge these brine water back into the water bodies, where, in the long run it has detrimental impacts on the marine ecosystem as well as the quality of sea water. The ambient seawater salinity in the Gulf region is approximately 45 ppm and the injection of brine in the water body increases this level in the range of 5 to 10 ppm above the normal condition at the point of discharge [27]. The discharge of reject brine in the water body can have direct detrimental impact on the marine ecosystem and the organisms dwelling in the area of discharge.

Additionally, the general process of desalination involves heating the sea water above the boiling point to separate the formation of vapor which are further treated to freshwater. However, the remaining hot sea water (brine) is discharged into the water bodies, thereby increasing the ambient temperature of discharging water body [27]. Minor deviation in the water temperature and salinity levels is generally adaptable by most of the marine organisms, and some may even endure the extreme conditions temporarily, however, they will not survive in continuous contact with unfavourable conditions. Therefore, the incessant discharge of high saline and high temperature water in the marine ecosystem can be fatal for aquatic life and can result in a permanent alteration in the species type. Also, increased temperature can affect water quality processes and result in lower dissolved oxygen concentrations, thereby reducing the availability of oxygen for marine life consumption.

Operating a desalination plant, especially in the GCC countries is an energy intensive exercise with the utilization of non-renewable fossil fuels [26]. Another key concern is the detrimental impact of the desalination process on the climate condition. The employment of fossil fuels to run these plants results in the depletion of natural resources and simultaneously contributes to the production of greenhouse gases which impacts human health, environment and results in the global climate change. Due to the

high energy consumption for the operation of these plants, the desalination industry is responsible for exacerbating nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions, thereby becoming the leading cause for air pollution [26] .

Furthermore, as a part of typical treatment process, chlorine is added in the intake water to reduce the effect of biofouling, which concurrently leads to the production of hypochlorite and hypobromite in the seawater. Chlorine concentration in the discharge water depends on the initial added chlorine concentration. Increasing the residual chlorine concentration significantly impacts the quality of ambient water and places the marine ecosystem under risk.

Due to continuous increase in the water stress and visioning the long-term impacts of the desalination process on the marine ecosystem and the environment, many governments have been prompted to reach out for alternate, innovative technologies to develop efficient uses of water resources. Extended reuse of reclaimed WW is observed to have higher potentials and help aid to reduce the stress on potable water resources and thereby reducing water scarcity, especially when designed as an integrated water resources management strategy [21].

2.3. Greywater (GW)

Greywater is generally defined as urban wastewater that excludes any contribution from toilets, which implies that it corresponds to wastewater (WW) generated in baths, showers, hand bowls, laundry, dishwashers and kitchen sinks, allocated in households, office buildings, schools and any other residing units [30]. Some literature excludes the contribution of kitchen WW from other GW streams, however, this research will account kitchen WW as a part of GW [31]-[32]. Approximately, 50 to 80 percent of the WW is categorized as GW. The quality of the GW varies depending on the source, geographical location, level of occupancy and demographics [31]. As also affirmed in literature [30], the elements present in the GW vary highly from source to source, and significantly depends on the lifestyles, traditions, installations and the usage of chemical household products. The concentration of compounds in the GW differ in terms of both time and location due to the variation in the consumption of water in relevance to the discharged amount of substances. Additionally, during storage and transportation of GW, biological and chemical degradation could occur which can further alter the quality of the GW.

2.3.1. Greywater quantity. Most of the published literatures have reported that the typical volume of GW ranges within 90 to 120 liter per capita per day (lpcd) based on the lifestyle, customs and habits, number of individuals dwelling in the source location and standard of living [33]. However, the volume of GW generated in low income countries which encounters water scarcity and sources of simple water supply can be as low as 20 – 30 lpcd [33]. Table 2.1 displays the generation rate of GW around the globe.

Table 2.1: Quantification of greywater across the globe.

Region/Country	Source	Generation rate (l/p/d)	Reference
Africa and the Middle East	Residential units	14 – 161	[34]
Asia	Residential units	72 – 225	[35]
Europe	Residential units	35 – 150	[36]
USA	Residential units	200	
North America	Residential units	196	[37]
England and Whales	Residential units	96	
South Africa	Residential units	80	
Senegal	Residential units	60	
Yemen	Residential units	35	
India	School	79	
Jordan	Residential units	59	[38]
Kuwait	School	2.9 – 16	[39]

A study projects that [40], there will be an increase in MENA water demand from 270 km^3 2000 to 460 km^3 in 2050, which can also increase the demand-supply gap from 50 km^3 to 150 km^3, from 2000 to 2050, respectively. This escalating trend is predicted to be same in the Arab region in future [41]. With the increased consumption rate, the cumulative volume of WW produced by both domestic and industrial uses in the Arab countries is approximately 10.85 km^3/annum; of which only 6.49 km^3 undergoes the process of treatment. The yearly discharge volume of the untreated WW in the Arab region is 4.36 km^3, which accounts to be nearly 40 % of the total WW generated in the entire region [41].

Sharjah city in specific has a residential water consumption rate of 400 lpcd corresponding to an approximate population of 1.4 million [42]. Sharjah Electricity and Water Authority (SEWA) has projected the water use by appliances in the residential building as illustrated in Figure 2.2. It is evident that water utilized for cleaning purpose (including laundry, basins and showering) comprises of more than 50 % of the cumulative water consumption. In addition, toilet flushing represents one fourth of the overall water consumption, thereby, becoming an alarming activity.

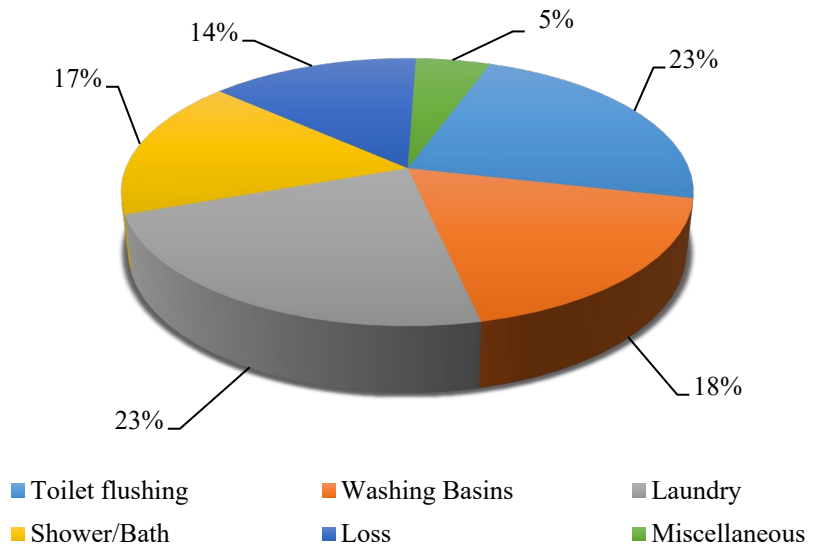


Figure 2.2: Water use by appliances in residential dwellings of Sharjah city [42].

2.3.2. Greywater characteristics. Greywater characteristics vary significantly based on the living habits of the individuals involved, the products they consume, culture and nature of installation [30]. Table A.1 in Appendix A confirms the variability in the GW quality coming from different domestic sources. The large differences in the values of the parameters show the difficulty in having a one fit all approach to treating and using GW. Biochemical oxygen demand (BOD) values can range from 5 to 536 mg/l, suspended solids (SS) ranging from 15 to 465 mg/l, turbidity ranging from 21 to 444 NTU and total coliforms (TC) ranging from 10^1 to 10^7 CFU/100ml.

Despite having variation in the water quality, the analysis of GW characteristics by various categories signifies that GW generated by kitchen and laundry tend to have

higher organics and physical pollutants in comparison with the toilet and mixed GW. This is due to the fact that the kitchen WW contains food wastes and laundry waters contains large volume of washing powder along with other materials such as sand and clay [42]. In contrast, the GW generated from the bathroom does not have high organic fraction since it mainly consists of washing products and hair which are diluted in larger volume of water. On an average, the carbon oxygen demand (COD) and biochemical oxygen demand (BOD) ratio (COD:BOD) for all the values mentioned from the literature is approximately 3.2. The typical COD:BOD ratio values corresponding to both domestic and final effluent is 2.2 and 3-10 respectively [43]. An increase in the COD:BOD ratio value for the GW indicates that there is a probability of the presence of non-biodegradable substances in the GW. Additionally, the concentration of both phosphorus and nitrogen are relatively low due to the exclusion of human excretions in the GW sample. It is reported that, 82 percent of nitrogen and 68 percent of phosphorus is originated from feces and urine in the cumulative domestic load [44].

All the sources mentioned in Table A.1 display variations in microbial contents that range from 10^1 to 10^7 CFU/100ml. The concentration of coliforms significantly depends on the demographic distribution of the individuals within the source of generation. A study concluded that, higher concentration of total and fecal coliforms were estimated in the GW generated from a household comprising of young children with values of 3.2×10^5 and 1.5×10^3 CFU/100 ml respectively, in comparison to 80 and 6 CFU/100ml for household without children [43]. Commonly, microbiological contaminations are measured using E. coli, total coliforms (TC) and fecal coliform (FC) indicators, however, in nature different types of bacteria exists including pathogenic viruses, protozoa and helminths to name a few. These bacteria are induced in the GW by performing activities such as washing hands after using latrine, washing of infants contaminated clothes including diapers and washing of food waste from the plates and utensils.

2.4. Greywater Reuse Standards and Criteria

Until present, no international set of standards have been established to regulate the quality of the treated effluent for reuse purpose. However, each region has individually published their own set of guidelines and standards based on their necessities. Since the significant issue associated with the utilization of recycled water

is potential risk to human health, the standards are generally more focused on microbial content. However, it has been indicated that, the aesthetical appearance of the recycled water also holds high priority due to the public perception [44]. Therefore, the standards established by each country comprise of a set of parameters, including the treatment of the organics and solids compounds such as biochemical oxygen demand, suspended solids and turbidity. Occasionally, a target to limit other parameters including ammonia, total phosphorus, total nitrogen and chlorine residual.

2.4.1. Typical greywater reuse standards. In general, reclaimed GW should achieve four criteria including hygienic safety, aesthetics, environmental tolerance and economic feasibility for reuse [45]. Reclaimed GW quality and specifications significantly depends and varies depending on the end use. Each application demands a different standard, quality and treatment of reclaimed GW. World Health Organization (WHO) published a GW reuse guideline in 2006, which underlined the restricted and non-restricted GW reuse for agricultural irrigation. This guideline only stressed on the contamination of reclaimed water with microbiological bacteria and no emphasis were made on the presence of other physical and chemical parameters [46]. Typical standards of non-potable GW reuse along with their corresponding applications have been extracted from the literature and presented under Table A.2 under Appendix A.

2.5. Greywater Reuse in Sharjah City

Sharjah city, like most of the urban cities in UAE, mainly utilizes desalination of sea water and brackish ground water to meet the demand. The Sharjah Electricity and Water Supply (SEWA) is a government entity responsible for providing and managing water and electricity supply in Sharjah. On the other hand, Sharjah Municipality (SM), a different government authority in charge of wastewater collection, treatment and reuse. Conserving freshwater resources and reducing the reliance on desalination plant by increasing water use efficiency, lessening loss of water, and developing innovative unconventional water sources is a strategic goal established by SEWA [41]. In fact, SEWA is targeting to crown Sharjah city as first City of Conservation in the region [51]. Amongst the seven emirates of the UAE, SEWA was the first amongst the region to introduce and implement GWR requirements in 2004 for large water consumers in Sharjah City [52].

According to the Executive Council of the Government of Sharjah [48], the grey water recycling (GWR) program to meet specific objectives including (i) reducing consumption of potable water for domestic activities; (ii) reduction of load on potable water distribution plants and sewage treatment plants within the city; (iii) reduction of stress on potable water and the corresponding need to construct new costly desalination treatment plants to meet the rising demand; (iv) achieve consumer satisfaction by reducing the monthly water consumption bill and (v) increasing environmental sustainability by reducing the dependency on desalination plants which utilizes energy intensive process and forms pollutants as by products (i.e greenhouse gases and reject brine solution). Additionally, the program also targeted to achieve public health and environmental protection by imposing restrictions on storage and usage of greywater. Under these restrictions, the greywater cannot (i) be attenuated for long duration in order to eliminate the growth of microorganisms provided the prevailing hot and humid weather of Sharjah City; (ii) used by domestic planters for irrigation purpose, (iii) be used in agricultural crops that are consumed raw in nature and (iv) have direct contact with humans.

2.5.1. Greywater reuse criteria, standards and guidelines. SEWA categorizes GW as WW generated from various domestic uses including washing, laundry and bathing, excluding any form of human waste. Initially, SEWA had developed a criterion for mandatory requirement in 2003 of GWR systems based on either consumer population, number of utilities, water consumption rate and area occupied by the facility as summarized in Table 2.2.

Although implementation of GWR systems was mandatory in 2003, for the criteria presented in Table 2.2, however, in 2014 SEWA have uplifted the mandatory requirement and replaced all the facilities to have optional GWR systems, excluding hotels/furnished apartments and residential/commercial buildings installed with cooling tower systems. The change in the criterion were due to the experience SEWA faced during the mandatory implementation of the GWR system. During the course of implementation and operation of on-site GWR systems, SEWA had encountered several issues [47] some of which are (i) poor workability of the retrofitted systems mainly due to faulty installations; (ii) use of poor quality and inefficient systems; (iii)

public rejection due to negative perception; and (iv) inadequate monitoring and maintenance of the implemented system.

Table 2.2: SEWA's criteria for mandatory requirement of GWR systems [42].

Facility	Criteria
Houses of Worship	Residential Areas: 1000+ prayers capacity Industrial/Commercial area: 500+ prayers capacity
Shopping Centers	If number of W/C is 25+ or water consumption rate is 85+ m^3/d
Schools	Number of classrooms 30+, including other facilities
Factories	Depends on activities and type of waste production. To be coordinated with municipality.
Government Facilities	Depends on the amount of water and type of project
Car Wash Facility	All
Hotels and Furnished Apartments	If area > 1000 m^2 and overall water consumption (excluding firefighting and cooling) > 95 m^3/d, or if number of apartment units > 120
Mixed use/Commercial use/Residential Buildings	If area > 1500 m^2 and overall water consumption (excluding firefighting and cooling) > 95 m^3/d, or if number of apartment units > 120 or if number of W/C > 50 for office building
Laborers camp	If area of laborers rooms > 1500 m^3

According to SEWA, several steps and actions have already been taken for the introduction of greywater systems in Sharjah City including addition of greywater requirements in standard drawings, schematic layout for basic greywater requirements, accreditation of contractors qualified for construction of greywater systems and introducing clauses related to greywater systems in the Water Violation Laws in the Directorate of Water. The typical schematic process layout for the minimal treatment of greywater set by SEWA is illustrated in Figure 2.3.

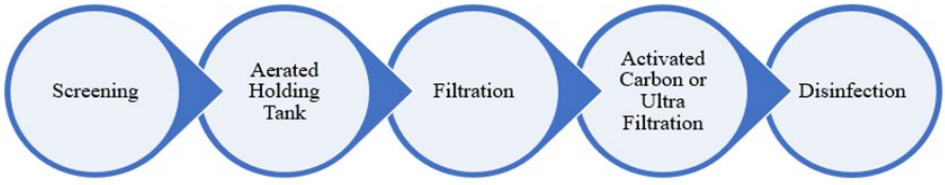


Figure 2.3: Typical schematic of greywater treatment process in Sharjah city (adapted from SEWA).

Prior to the process, the greywater shall be collected in closed tanks made of both non-corrodible and non-soluble materials. The quality of the greywater should be such that it can be feasible to be reused for toilet flushing, cooling system and irrigation of landscaped areas including parks and golf course. The minimum standard established by SEWA for different pollutant parameters for greywater reuse are summarized in Table 2.3.

Table 2.3: Minimum treated greywater requirement by SEWA [42], [48].

Parameters	**Minimum**
Turbidity (NTU)	≤ 2
pH	6-8
BOD_5 (mg/l)	≤ 10
COD (mg/l)	≤ 50
TSS (mg/l)	≤ 10
Total Coliform	≤ 100
Fecal Coliform	≤ 5
Free Chlorine (mg/l)	0.5 – 1

To ensure consumer safety, SEWA has identified key requirements that needs to be strictly followed regardless of voluntary or involuntary installation of GWR systems. These requirements are as follows [42]:

- All the implemented GW systems (including treatment, distribution and storage) is subject to approval from SEWA and other relevant authorities.
- The plumbing system for greywater collection should be separately installed and verified.
- Approval for only certified installed systems will be provided by relevant authorities, while uncertified systems will not be approved.
- The GWR systems implemented will only be approved for 5 years. After 5 years, the system needs to be re-inspected by the relevant authorities to obtain renewed approval for extended period.

- Only registered and certified vendors and service provides can assist with the supply and installation of the system.
- Greywater is restricted to water generated from hand washing basins, showers, baths and clothes washing machines. Any other discharge should not be diverted for reuse.
- Installation of systems without proper approvals will result in law violation and fine to the stakeholder.

2.5.2. Status of greywater treatment systems. To monitor the success of GWR system, SEWA carried out an assessment in 2011 in Sharjah City. It was concluded that many installations were not adequately functioning and some of them were abandoned. Table 2.4 displays the comparison between the number of installations in 2011 and 2017. There has not been a significant difference in the cumulative number of GWR system installed in year 2011 and 2017. However, sector wise, both commercial and mosques have significantly declined their adaptation to GWR systems, whereas commercial and schools have displayed positive response by increasing their implementation to GWR systems.

Following the execution of greywater systems in these sectors, economic feasibility analysis was conducted to ensure that the application of these systems is cost effective in the long term. As per the analysis reports generated, it had been concluded that the introduction of reclaimed greywater systems led to cost savings of approximately $ 3,500 in commercial building, $ 6200 in labor camps, $ 3005 in hotels and $ 620 in schools. By the application of greywater recycling systems, the stress on potable water resources can be significantly reduced by 25 – 40 percent.

Table 2.4: Status of installed GWR systems in Sharjah in 2011 and 2017 [42].

Sector	2011	2017
Industrial	115	91
Commercial	45	62
Mosques	18	7
Schools	22	29
Government Agencies	4	5
Hotels	---	7
Total	**204**	**201**

2.6. Treatment Technologies and Treatment Efficiencies

Technologies examined for the treatment of greywater are classified based on treatment principle including physical, chemical, biological [44] or combination of these [44]. Most of these technologies follow a similar sequence of operation during the pretreatment and post treatment. The pretreatment generally involves the solid-liquid separation phase which is carried out with the employment of various treatment technologies including septic tank, filter bags, screen and filters. In case the process of pretreatment fails to perform efficiently, the number of particles, oil and grease bypass to the downstream treatment process, thereby clogging the subsequent treatment. The post treatment involves the process of disinfection to meet the desired microbiological requirements. The greywater treatment system may comprise of different treatment phases which extensively depends on the desired quality of effluent.

Treatment technologies can be defined under five different categories as shown in Table 2.5. These categorizations were evaluated based on extensive review of twenty-six pilot or bench scale systems and thirty-eight full scale systems which were installed in the buildings. These categories were further reclassified by into physical, natural (which can be referred extensive system), biological, chemical and hybrid (which can be referred as simple system) [46].

Table 2.5: Greywater treatment technologies.

Category	Treatment Technology
Simple	Coarse filtration and disinfection
Physical	Sand filter, adsorption and membrane
Biological	Biological aerated filter, rotating biological contractor and membrane bioreactor
Extensive	Constructed wetlands
Chemical	Photocatalysis, electro-coagulation and coagulation

2.6.1. Coagulation and flocculation. This treatment process aids in the removal of colloidal particulates. In principle, the finely dispersed particles (colloids) that are present in WW have negative electric charge which induces repulsion force between the particles and causes dispersion effect [49]. However, the process of coagulation in support with rapid mixing helps neutralize the negative charges, because of which the colloidal particles come together and forms larger flocs instead of

dispersed particles. While, flocculation supports the formation of flocs resulting in producing larger and heavier particulates which are easier to settle [50].

An experimental study was carried out to assess the coagulation and flocculation impact on shower GW generated from a student hall of residence located in United Kingdom [51]. The coagulant utilized under this study was ferric sulphate and aluminium sulphate. The samples under test were flocculated for 30 minutes at 30 rpm and were allowed to settle for 30 minutes. It was reported that the turbidity was reduced by 90.82 % and 88.84 % corresponding to samples treated with ferric sulphate and aluminium sulphate coagulant, respectively. Moreover, BOD, COD, nitrate and total nitrogen removal efficiency was reported to be 88.28 %, 63.72 %, 14.93 % and 12.78 % using aluminium sulphate coagulant. On the contrary, the BOD, COD, nitrate and total nitrogen removal efficiency was found to be 85.37 %, 63.59 %, 8.96 % and 0.56 % using ferric sulphate coagulant. Both coagulants displayed comparable total coliform and E. coli removal efficiency from 56500 to less than 1 CFU/100ml and from 6460 to less than 1 CFU/100ml, respectively. However, in terms of dosing to achieve the desired results, it was observed that more ferric coagulant was required by mass in comparison to aluminium sulphate.

On a whole, flocculation and coagulation removal efficiency range between 85 – 89 % for BOD, up to 64 % for COD, up to 13 % for total nitrogen, greater than 99 % for total coliform and E. coli [49].

2.6.2. Filtration. This process involves removal of solid matter which is generally not removed by downstream processes. In the process of filtration, both physical and biological processes occur which helps remove the suspended solids [52]. Filtration media can comprise of any material including combination of sand, gravel, fine mesh and any other material which can aid in removing particulate from GW. Several studies have been conducted to assess the efficiency of filtration by using different filter media. One of the studies targeted to evaluate the recycled vertical flow bioreactor (RVFB) by treating synthetic GW [53]. The synthetic GW was prepared by combining laundry soap, shampoo, cooking oil, kitchen effluent, ground egg and tomato to reflect similar characteristics of GW generated from laundry, bath and kitchen. RVBF consisted of dual plastic containers (20 cm x 35 cm x 50 cm). Water drained by gravity from upper to the lower reservoir container. The drain holes were

designed to have two cm thick layer of pebbles comprising of crushed limestone and dolomite (2.5 cm diameter). The preceding layer consisted of 12 cm plastic filter media that had larger surface area of 800 m and large void volume. Finally, each of the treatment container was topped with 4 cm thick layer of peat. The experimental results demonstrated that the treatment system had displayed removal efficiency of 93.48 % for anionic surfactant, 93.48 % of TSS, 16,67 % of ammonia, 96.92 % of nitrite, 48.57 % of nitrate and 73.68 % of total phosphorus. Also, E. coli removal was observed to reduce from 501188 to 1.25 CFU/dL.

Another study was conducted to assess the filtration efficiency of various media including pine bark, activated charcoal, polyurethane foam and sad on synthetic greywater [54]. Findings concluded that the release of organic acids from the bark reduced the influent GW pH from 7.8 to 6.1, whilst no changes had been observed in the pH during the application of other media. BOD reductions were observed to be in 98 % for effluent treated using bark and 97 % for effluent treated using charcoal filter.

Overall, the removal efficiency of filtration treatment systems vary in the range of 53 – 93 % for TSS, 89 – 98 % for BOD, 37 – 94 % for COD, 17 – 73 % for ammonia, 5 – 98 % for total nitrogen, 0 – 100 % for total phosphorus and 100 % for E.coli [49].

2.6.3. Constructed wetland treatment (CWT). This is an artificial wetland that is designed to replicate natural wetland through utilization of ecological technologies including adaptation of special flora, fauna, soil and microorganisms for removal of target pollutants [52]. CW are known for removing contaminants including BOD, suspended solids, metals and toxic organics from WW [37]. Removal of these contaminants are supported by physical, chemical and biological processes. However, the removal efficiency of the contaminants is highly sensitive to surface loading rate [55].

A study was conducted to assess the removal efficiency of recycled vertical flow constructed wetland (RVFCW) with bed depth of 0.5 m and recycling rate of 390 liters/hour [56]. The study was conducted in Israel and influent GW was taken from a residential household comprising of five family members. It was reported that the system successfully achieved a removal efficiency of 98.1 %, 99.85 %, 81.29 %, 33.33 %, 68.51 % and 71.05 % for TSS, BOD, COD, nitrite, total nitrogen and total

phosphorus, respectively. No removal was observed for nitrate. Similar study was conducted to assess the performance of RCFVW in treating artificial GW that was produced to reflect characteristics of laundry and kitchen GW [57]. The wetland comprised of two different filter media including organic soil and limestone pebbles. The removal efficiency was reported to be 89.76 % for TSS, 99.22 % for BOD, 82.16 % for COD, 82.14 % for total nitrogen and 95.54 % for oil and grease. However, no removal was observed for total phosphorus. Whilst reduction of total coliform was found to be from 5×10^7 to 2×10^5 CFU/100ml.

As a whole, CW systems generally display removal efficiency in the range of 90 – 98 % for TSS, more than 99 % for BOD, 81 – 82 % for COD, 95 % for oil and grease and 26 – 82 % for total nitrogen [49].

2.6.4. Rotating biological contactor (RBC). They are fixed bed reactors that comprise of rotating disks which is mounted on horizontal shaft. This arrangement is partially submerged and continuously rotates as WW flows through it. The microorganisms responsible for the WW treatment are exposed to both atmosphere and WW, thereby allowing both aeration and assimilation of dissolved organic pollutants and nutrients for the purpose of degradation [52].

A study was performed to identify the removal efficiency of a single stage RBC on GW in Pakistan [58]. The GW was treated under three different hydraulic retention time (HRT) of 30 minutes, 60 minutes and 90 minutes. The removal efficiency of TSS was found to be nearly same (8.98 %, 11.56 % and 11.08 %) corresponding to 30 minutes, 60 minutes and 90 minutes HRT, respectively. Alternatively, the BOD removal efficiency was found to be 27.3 %, 41.4 % and 52.42 % for 30 minutes, 60 minutes and 90 minutes HRT, respectively. Likewise, COD removal percentage was also reported to be 21.48 % for 30 minutes HRT, 49.93 % for 60 minutes HRT and 60.36 % for 90 minutes HRT. Overall, the effluent quality generated after RBC treatment using 90 minutes HRT was desirable and met the standard requirement.

2.6.5. Membrane bio-reactor (MBR). Membrane bio-reactors (MBRs) is both a combination of biological treatment and microfiltration (MF) or ultrafiltration (UF) treatment system. The purpose of the membrane is to replace the clarifiers and segregate solids from the liquid [49]. The separation of solid from liquid using the

membrane is a significant process following biological treatment to ensure the prevention of any loss of biological solids in the effluent and thereby allowing the detention of higher concentration of biomass in the reactor itself [59]. Table 2.6 displays the removal efficiency achieved by MBR and is reported in the literature.

Table 2.6: Percentage removal efficiency of MBR for different pollutant parameter.

Source	Turbidity	TSS	BOD	COD	FC	TN[1]	TP[2]	Reference
Synthetic	98.0		93.37		100			[60]
Shower	98.28		93.22	86.24	99	62.50	18.75	[61]
Mixed	99.92	100	99.6	99.19				[62]

[1]Total Nitrogen, [2]Total Phosphorus

Overall, MBR systems achieve percentage removal in the range of 98 – 99.9 % for turbidity, up to 100 % for TSS, 93 – 97 % for BOD, 86 – 99 % for COD, 52 – 63 % for total nitrogen, 19 % for total phosphorus and 99.9 % for total coliforms [49].

2.7. Disinfection by-products (DBPs) and toxicological impacts

The main precursor of DPBs formation is natural organic matter (NOM) in wastewater which is frequently quantified as total organic carbon (TOC) [63]. Generally, 90 % of TOC is constituted with dissolved organic carbon (DOC) or dissolved organic matter (DOM), where DOM is categorized as the portion of TOC that travels through 0.45 μm [64]. When free chlorine comes in contact with DOM, it results in the formation of halogenated organic by-products such as Trihalomethanes (THMs). The major compounds under the class of THMs are reported to be Chloroform, Dibromochloromethane, Bromodichloromethane and Bromoform. Each of these compounds have regulated under guidelines including USEPA and WHO, as they all have been shown to have potential human health effect. United States National Institute of Cancer (NCI) has officially recognized THMs as carcinogenic in high dose and have displayed highest public health concerns [65]. Table 2.7 briefly summarizes the different THM compounds along with their toxicological effects on human health. It also records the associated guidelines and regulations established by WHO for drinking water [66].

Table 2.7: THMs compounds, toxicological effects and WHO guidelines for drinking water.

THMs Compound	Health Effects	Limit (µg/L)
Chloroform	• Damage liver, kidney and reproductive system • Carcinogenic	0.2
Bromodichloromethane		0.06
Bromoform		0.1
Dibromochloromethane	• Damage nervous system	0.1

To assess the formation of these DBPs and reveal the severity of potential toxicity levels, it is of high importance to know the concentration, reactivity and the composition of DOM which are all precursor to the production of DBPs. Any changes in these parameters have a direct impact on THMs production. Hence, in the case of reclaimed water, the concern becomes more complex due to the high variation in water quality [67], which have also been confirmed through the observed physico-chemical characteristics recorded under this study. Moreover, literature have confirmed that, an elevated TOC level (more than 2 mg/l) is an indicator for elevated capacity of DPB formation [64]. Also, the same study has revealed that, THM formation continues until either the chlorine or precursor is exhausted, hence higher values of TOC will generate higher levels of THMs. Therefore, it is significant to reduce the TOC levels from the WW prior to chlorination in order to lessen the potential risks of THMs formation.

To meet the requirements of THM concentration restricted by WHO, several approaches have been mentioned in the literature [64], [68]-[69] including (i) reduction of TOC levels in source water by pretreatment processes such as coagulation, flocculation and/or filtration (ii) removal of THMs after formation by methods including membrane technology, air stripping and GAC (iii) conducting disinfection at later stage of the treatment, thereby arriving at a stage with minimal levels of TOC (iv) reducing chlorine dosage by performing pre-disinfection treatment using alternate techniques like ozone oxide/UV rays or utilization of alternate disinfection techniques (other than chlorination).

Several studies have been conducted on assessing the performance efficiency of membrane technologies for removal of THMs and their precursors. According one of the study, RO results in efficient and simultaneous removal both organic and inorganic DPBs precursors [70], whereby achieving a removal efficiency of 89.7 % for microorganisms [71] and organic matter and 98 – 99.3 % for NOM [72]. However, with

regards to THMs removal, reverse osmosis (RO) efficiently removes THMs only when the concentration of contamination is not high. If the concentration of contaminants is high, RO will not efficiently remove THMs [73]. Supporting studies have recorded THMs removal efficiency to be 80 and 83.8 % using RO [74]. Another study concluded that the application of Nanofiltration (NF) is highly efficient in removing NOMs, small organic molecules and other DBPs precursors from the water simultaneously [70]. NF have been recorded to achieve a removal efficiency varying from 49 – 100 % for NOMs [75], > 90 % for DOM [76] and 96 – 99 % for THMs [77]. Likewise, studies have also been developed to explore ultrafiltration (UF) membranes and their impact of precursor and DBPs removal. The utilization of UF membranes is concluded to be a cost-effective treatment process in reducing turbidity, suspended solids and other particles, however, UF is not effective in segregating humic substances which are associated to have high THMs [69]. Finally, studies have also concluded that Microfiltration (MF) is another physical process that can be implemented both as a pretreatment to NF or RO or can work as a stand-alone system for treatment of water. MF like UF, is efficient in treating water with high turbidity. MF have pore sizes much larger that the NOMs particles thereby reducing their efficiency in removal of NOMs [69] .

From all the listed THM reduction methodology, the process of removing TOC (or DOM precisely) is expected to be the most effective approach towards reducing (or removing) the potential formation of THMs [78] in comparison to removing the DBPs. Although the reclaimed water produced under this study targets to meet the quality of reclaimed water for non-potable purpose, yet if GBFS is to be utilized for potable water production it is crucial to assess its efficiency in removal of precursors. Therefore, this study targets to evaluate and compare the performance of GBFS with and without pretreatment in reducing TOC. Since TOC is a precursor for potential THMs formation, the comparison in the effluent TOC values will enable to conclude the necessity of introducing pretreatment for reducing formation of potential heterogeneous structures (or DPBs) which are suspected to be carcinogens [69].

2.8. Granulated Blast Furnace Slag (GBFS)

Slag is a porous non-metallic by-product generated from iron and steel industries. During the production of steel, materials including iron ore, scrap metal and fluxing agents comprising of limes are fed into a furnace and heated at temperatures

beyond their melting points (1500°C - 1600°C) [79]. During this thermochemical process, the fed raw materials slowly start settling as the iron is melted from the ore and forms a molten pool at the bottom of the furnace. Slag, which comprises of lime, silicates and aluminates starts forming as the iron is reduced and coke is consumed as energy [80]. Slag having lower density and lighter in weight, floats on the top of the molten iron liquid which is then drained and separated from the molten iron. The slag is passed through a tough of high pressure and exposed to high volume of water sprays to form granulated blast furnace slag (GBFS) [15].

Since slag aggregates are by-product from steel industries, it is a known fact that the material will contain heavy metals which could be of potential concern as these heavy metals might be susceptible to leaching during treatment of WW. However, a study on metal leaching from blast furnace slag materials have been reported in the literature. The investigation concluded that although blast furnace slag do leach metals yet this occurs at a significantly low degree [81]. The leaching of steel slag was reported to be of similar degree and range as leaching from the natural gravel. Likewise, Landcare Research Institute from New Zealand and National Steel Slag Association in the United States, conducted a detailed study on leachate characteristics of eight steel slag material [82]-[83]. Both the studies concluded that the leaching from steel slag does not have any detrimental impact on the environment or human health.

On the other hand, blast furnace slag also constitutes of sulfuric compounds [84]. Under oxidizing conditions, these compounds can potentially leach and this phenomenon is also confirmed in a pilot scale experimental study [85]. In this study, when an on-site generated WW was fed to a blast furnace slag filter bed, sulfuric odor was detected, especially during the beginning of the experiment. Hence, the study concluded that the release of sulfuric compounds should be given significant consideration if the blast furnace slag is to be utilized as a WW treatment filter media. However, very few studies have been conducted in this area of research, thereby there is no conclusion if blast furnace slag is a suitable or un-suitable filter material in relevance to its sulfuric contents [84].

Chapter 3. Experimental Setup and Methodology

This chapter explains the materials and experimental methodology adopted in order to achieve the objectives of this study. The study area, experimental setup, sampling locations and procedure, analytical methods and mathematical equations applied for testing water quality parameters and evaluating human health risk reduction are discussed in this chapter.

3.1. Study Area

During the initial stage of the project, a close coordination was carried out with Al Kabeer Water Treatment LLC, a leading water and wastewater treatment company in the UAE. The key factor that dominated the selection of experimental location was to identify a residential facility that already had an inbuilt plumbing system to segregate the greywater (GW) from black water. For this study, a 30-floor residential tower (Al Jawad Building) located in Al Nahda area was chosen as shown in Figure 3.1.

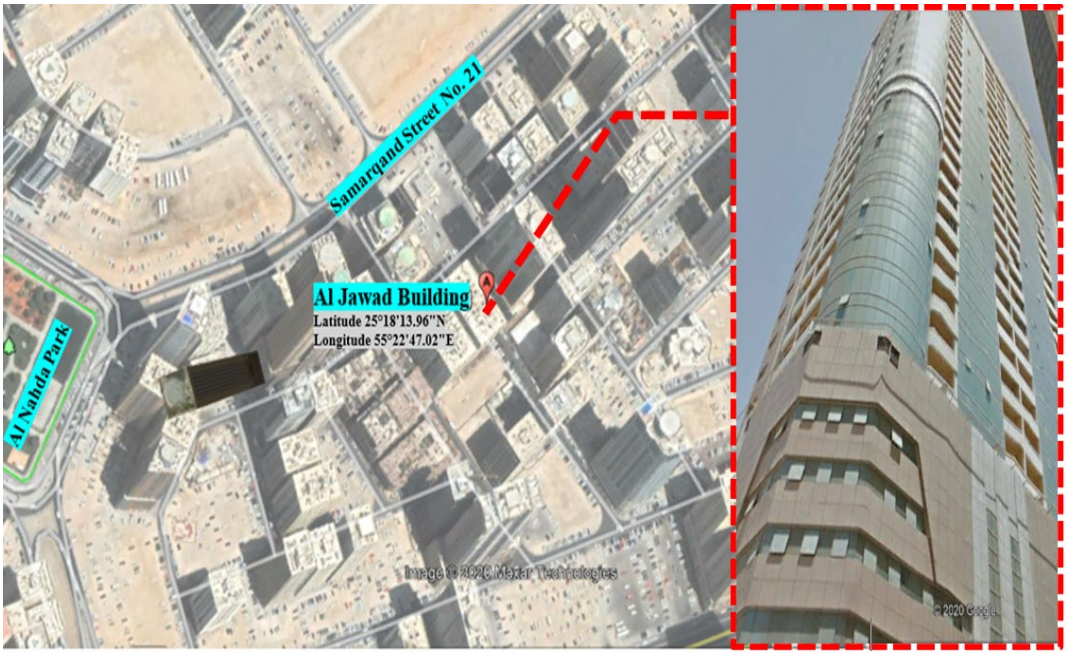


Figure 3.1: Study area location.

The study area was selected due to the following reasons (i) the building is already installed with a large-scale on-site GW treatment facility which is treating residential GW generated from bath and toilet sink, therefore, the proposed system under this study would only require a bypass pipe from the live setup to the proposed

treatment system under this study, aiding reduction of potential cost and workforce that would otherwise be needed to retrofit the segregated plumbing system (ii) the availability of space in the vicinity of the existing on-site GW treatment plant to install the configurations proposed under this study and (iii) the building owner had provided no objection certificate (NOC) to utilize the space and performing regular visits for configuration operation and sample collection.

3.2. Adsorbent and Filter Media

To conduct the experimental program and meet the objective of this study, three materials were required including AC, GBFS and filter media (sand filter). AC and sand filter media were provided by Al Khabeer water treatment company during the installation of the experimental setup. However, the core producers and suppliers for AC and sand filter were "Jacobi Carbons" and "National Factory for Processing and Treating Minerals," respectively. Table 3.1 shows the properties and particle size of AC media used under this study.

Table 3.1: Properties and particle size of AC adsorbent used in this study (adapted from Jacobi Carbons).

Properties	
Moisture content	5 %
Apparent density	450 kg/m^3
Total ash content	15 %
Wettability	99 %
Ball pan hardness	96 %
Surface area (BET)	900 m^2/g
Particle Size	
Effective size	0.4 mm
Oversize	< 5 %
Undersize	< 4 %
Mean particle diameter	0.6 mm
Uniformity co-efficient	1.5

In this study, GBFS was obtained from CEMEX UAE; industrial producers of concrete and cement products. Table 3.2 displays the physical and chemical properties of GBFS material directly imported from Japan (without grinding).

Table 3.2: Physical and chemical properties of GBFS used in this study (adapted from CEMEX).

Physical Properties	
Specific gravity	2.89 – 2.90 g/cc
Moisture	0.1 – 0.3 %
Bulk Density	1030 – 1098 kg/m^3
Chemical properties	
Sulphate content as SO_3	0.02- 0.08 %
Chloride content as Cl	0.01- 0.02 %
Magnesium Oxide /	5.0 – 7.0 %
Aluminum Oxide/Al_2O_3	11.0 – 14.0 %
Silicon Dioxide/SiO_2	32.0 – 34.0 %
Calcium Oxide/CaO	40.0 – 42.0 %

The filter media utilized to study the impact of pretreatment on supporting pollutant removal efficiency was silica sand. As mentioned in the literature, an effective sand filter to generate drinking quality water should have the following characteristics (i) effective size of particle to be 0.4 - 1.0 mm, (ii) uniformity coefficient of less than 1.6, and (iii) percentage of acid solubility less than 0.3 % [86]. Table 3.3 provides an overview of physical and chemical characteristic corresponding to the silica sand used under this study which is in line with the standard reported in the literature to achieve high quality effluent.

Table 3.3: Physical and chemical properties of silica used in this study (adapted from National Factory for Processing and Treating Minerals).

Physical Properties	
Particle Diameter	0.43 – 0.85 mm
Uniformity Coefficient	< 1.5
Bulk density, non-compact	> 1.5 kg/dm^3
Specific gravity	>2.6 g/cm^3
Hardness	7 Mohs scale
Water content	< 0.05 %
Chemical properties	
Silicon Dioxide	99.9 %
Acid Solubility	< 1 %

3.3. Existing Greywater Treatment System

Figure 3.2 illustrates the process configuration of the existing GW generation, treatment and reuse process.

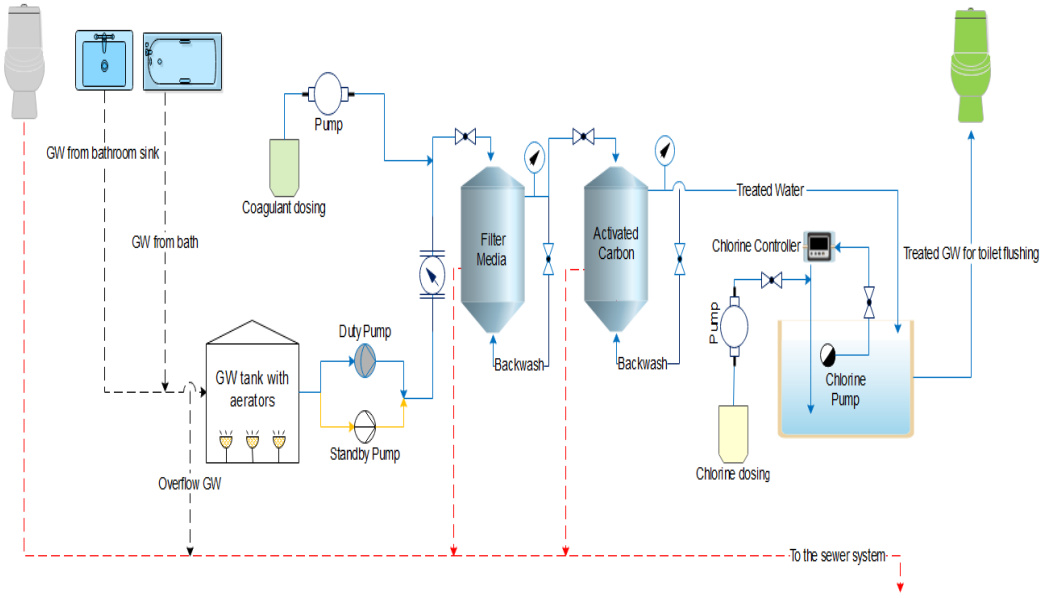


Figure 3.2: Existing greywater treatment system and reuse process.

While the commode flush water (black water) directly discharges into the sewer system, the water generated from bathroom sink and bath discharges into a separate plumping system installed only for the collection of GW from these two sources. During the days when volume of generated GW is higher than the treatment system's capacity, the excess GW overflows into the sewer system without treatment. The treatment process involves collection of GW in an aerated underground storage tank to enhance the dissolved oxygen level of GW that will subsequently support the microorganisms in decomposing organic matter. Two pumps (1 duty and 1 standby) are installed to lift the water from the tank into the filtration column filled with silica filter media. The standby pump is only utilized if the main pump breaks down or is powered off for regular maintenance. Before the GW discharges into the filter media, an automatic coagulant dosing pump injects aluminium sulphate ($Al_2(SO_4)_3$) into the GW stream to enhance clarification of GW by combining the suspended solids into larger flocs that can be filtered out easily by filter media. The effluent of filter media is then pumped into AC column. AC performs as an adsorbent and supports the removal of natural organic matter, color and odor. Both filter media and AC are installed to have

backwash facility with a backwash rate of 0.69 lps (or 2.5 m^3/s) to ensure regular cleaning of media. During the treatment process, when the filter medium is saturated with the contaminants, backwash is automatically initiated via control valve. During the backwash process, the clean water passes backward through the filter medium at a rapid rate and then exits from the top via control valve. Backwash water is polluted as it contains the pollutants clogging the filter media, hence the backwash water is discharged into the sewer system directly without treatment. The final stage of treatment involves discharging the treated water into a clean water storage tank. This tank is installed to have sensor and automatic disinfection dosing pump. Sodium hypochlorite is used for disinfection and the dosing value is adjusted automatically to maintain residual chlorine level of 1 mg/l in the final effluent. The disinfected treated water is then pumped into the toilet flushing infrastructure of all the residential apartments in the building.

3.4. Modification of Existing Greywater Treatment System

A portion of the existing treatment infrastructure is modified and utilized to feed the partially treated GW into the proposed configurations under this study as shown in Figure 3.3. The bypass connection ensures that the proposed configurations receives and treats on-site greywater with influent parameters reflecting the true site condition. Hence, the results generated from each of the configurations represents the performance efficiency of the system under real life scenario, which will provide a better perspective on the workability of each configuration.

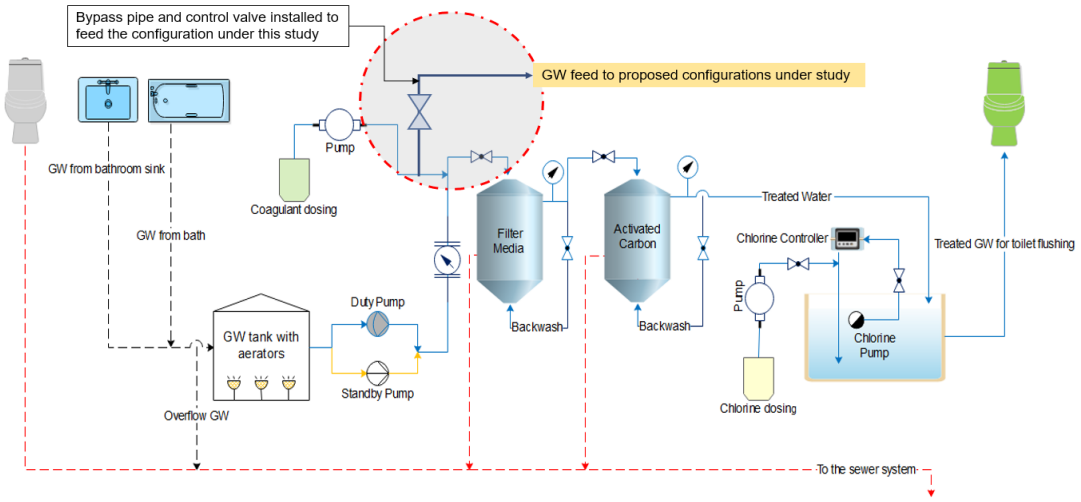


Figure 3.3: Modification of existing GW treatment system.

3.5. Proposed Greywater Treatment Configurations

Figure 3.4 shows the overall experimental setup installed at the ground floor of the residential building, in parallel to the existing GW infrastructure.

Figure 3.4: Experimental setup showing (1) Existing filter media vessel (2) Existing AC vessel (3) Bypass pipe (4) PVC flow valve (5) Pressure gauge and sampling point (6) Filter media vessel for this study (7) AC vessel for this study (8) GBFS vessel (9) Sodium hypochlorite storage tank (10) Dosing pump (11) Treated water storage container (12) Multi-purpose valve (13) UV unit.

A total of six different configurations are operated and samples from each of the configuration are collected and assessed in AUS laboratory, accordingly. Prior to the design of the proposed configurations, the space at the site location was assessed to ensure that the designed system can be accommodated in the available space. In line with restricted space criteria, the proposed configuration is designed to have column sizes of 137 mm in height and 33 mm in diameter. These columns sizes can treat a maximum flow of 1 m^3/hr at a pressure of 2.5 – 3.0 bar. The below points list down the items utilized to conduct the experimental program.

- Three polyglass pressure vessels for filter media, AC and GBFS adsorbent. Each vessel was 137.0 mm (or 54 inches) in length and 33.0 mm (or 13 inches) in diameter.
- Pipes and fittings made of polyvinyl chloride (PVC) material. The outer diameters and fittings of all the main carrier pipes and sampling location pipes are 50.8 mm (or 2 inches) and 25.4 mm (or 1.0 inches), respectively.
- Pressure gauges and flow meters at multiple locations.
- Chlorine (sodium hypochlorite) dosing tank of plastic material, having a storage capacity of 100 L.
- Treated water storage container of plastic material, having a storage capacity of 100 L.
- UV sterilizer with a treatment dose of 40 mJ/cm^2.

All the configurations were operated at a constant hydraulic loading rate (HLR) of 11.7 $m^3/m^2/hr$ (or 280.8 $m^3/m^2/day$). Based on this HLR it can be concluded that the filter media performed as rapid sand filtration (RSF). This is supported by a literature which reports that, rapid sand filters have effective particle diameters greater than 0.55 mm and uniformity coefficient less than 1.5. Additionally, the hydraulic loading rate classified for RSF is reported to be in the range of 4 - 21 m/hr [87].

Additionally, studies have also reported that most of the filter media are susceptible to blockage with suspended matters and flocs, resulting into clogging [88]. Clogging results in buildup of head loss (pressure drop) across the filter media, hence resulting into filter breakthrough, a condition in which the solids are no longer treated by the already overloaded filter [89]. Therefore, each of the configuration proposed under this study is designed to have a backwash facility, to ensure the pollutant removal efficiency is less impacted by clogging of the filter media. The filter media (silica), AC and GBFS, are backwashed every day for 10 minutes at a flow rate of 2.5 m^3/hr. The backwash was carried out using effluent from the media, however, outflow generated after the backwash was discharged into the sewer system due to high pollutant contamination.

3.5.1. Configuration 1. This configuration replicates the existing greywater treatment system which comprises of filter media (silica), AC and chlorination, in the same order. Figure 3.5 provides an overview of Configuration 1 along with sampling point locations identified as "SP." A total of three sampling locations has been selected where SP1 represents the samples of influent before entering the filter media, SP2 represents the samples of effluent after AC adsorption and SP3 represents the samples for the treated water after chlorine disinfection.

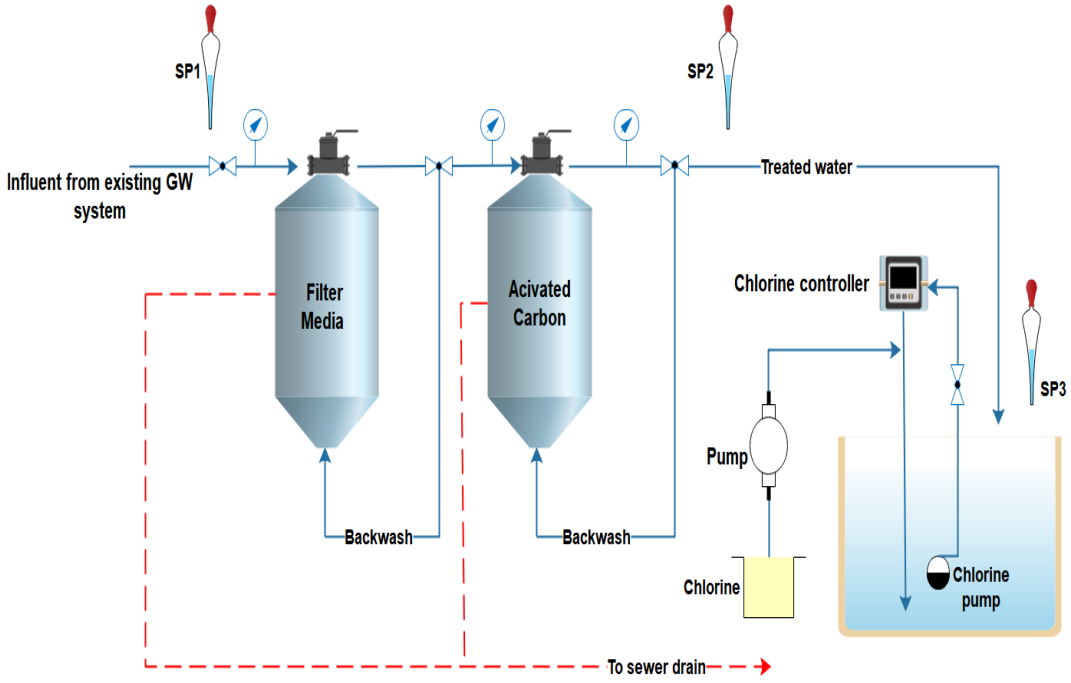


Figure 3.5: Configuration 1 and sampling points.

The three sampling points are selected based on the following considerations:

SP1 samples will provide with the influent pollutant parameter. The pollutant values recorded from this sample will serve as a datum to determine the treatment efficiency of the system. All the target pollutants including microbial contamination will be measured for SP1 samples.

SP2 samples will provide the targeted pollutant value after undergoing treatment using filter media (silica) and adsorbent process using AC. These values will determine the efficiency of pretreatment and AC in removal of pollutants. All the target pollutants including microbial contamination will be measured for SP2 samples.

SP3 samples will provide the water quality after disinfection process. Since the target of this study is to assess the efficiency of only filtration and adsorption process on pollutant removal from greywater, therefore, after the process of disinfection, the sample was only tested for microbial contamination, whilst no physico-chemical parameters were tested for samples collected at this location.

3.5.2. Configuration 2. This configuration is similar to Configuration 1 (Section 3.5.1.), however, it introduces UV disinfection prior to chlorination that is represented by sampling point location (SP3). Figure 3.6 provides the overall arrangement of Configuration 2.

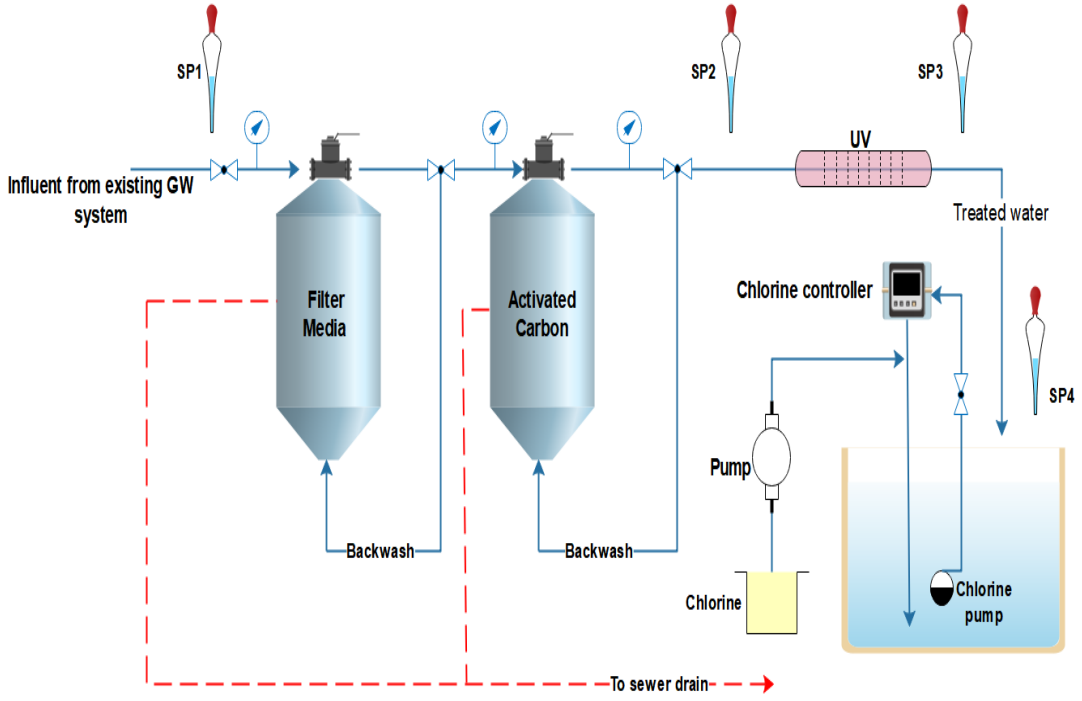


Figure 3.6: Configuration 2 and sampling points.

The key objective of this configuration is to assess the impact of UV disinfection on reduction of microbial contamination. Another motive of this configuration is to assess the microbial counts at the influent (SP1) and after filtration/adsorption treatment (SP2). These measured values will aid in assessing if AC is an effective medium in treating and reducing microbial contamination. The existing system is completely dependent on chemical disinfection using sodium hypochlorite (or chlorine disinfection). Chlorine is known to cause harmful DBPs therefore, this configuration

introduces physical disinfection (UV irradiation) before chlorine disinfection to reduce the microbial contamination, which will potentially reduce the complete dependency on chemical disinfection by limiting the chlorine dosage only to maintain standard residual chlorine requirement. The sampling points are same as defined under Section 3.5.1., however, there is an additional sampling point (SP3) due to the addition of UV unit. The sample taken from this point will only be assessed for targeted pathogens and compared to microbial values measured for SP2 and SP4. This comparison will help evaluate the microbial removal efficiency of UV disinfection.

3.5.3. Configuration 3. This configuration aims to assess the pollutant removal efficiency using the combination of filter media and GBFS adsorbent. Figure 3.7 illustrates Configuration 3 setup and treatment process along with sampling point location. Like Configuration 1 (Section 3.5.1.) the entire process treatment along with sampling point locations are identical, however, the only change is that the AC adsorbent is replaced with GBFS adsorbent.

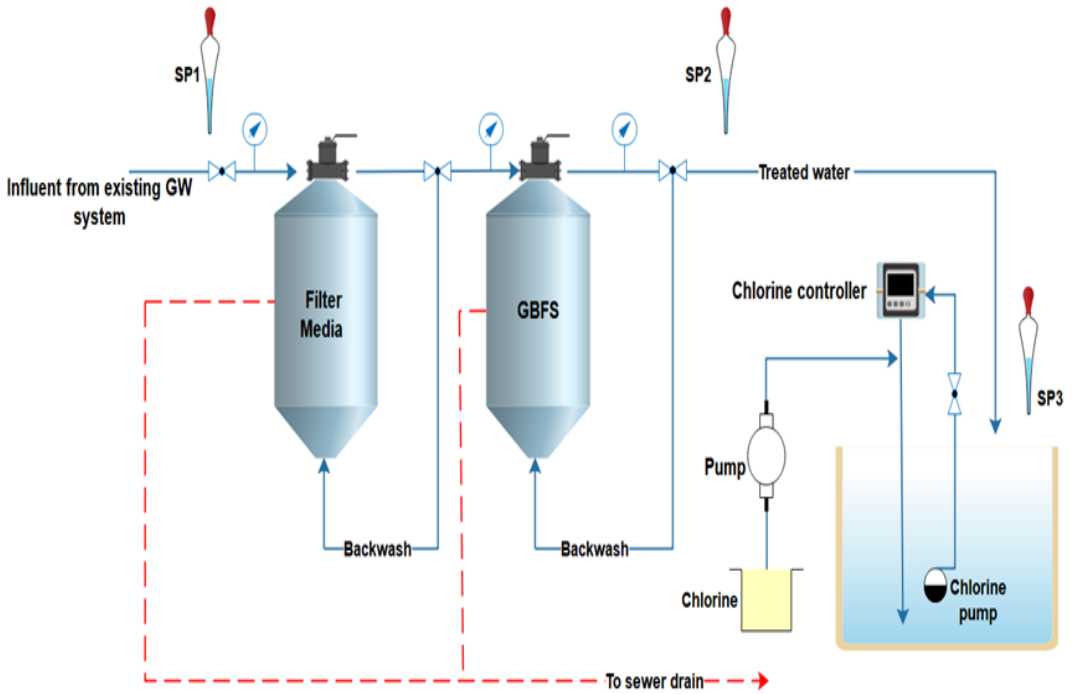


Figure 3.7: Configuration 3 and sampling points.

3.5.4. Configuration 4. This configuration is identical to Configuration 2 (Section 3.5.2.), however, AC is replaced with GBFS adsorbent. Similarly, the key significance of this configuration is to assess the impact of UV disinfection in the

reduction of microbial contamination. Figure 3.8 provides the overall arrangement of Configuration 4 along with sampling point locations.

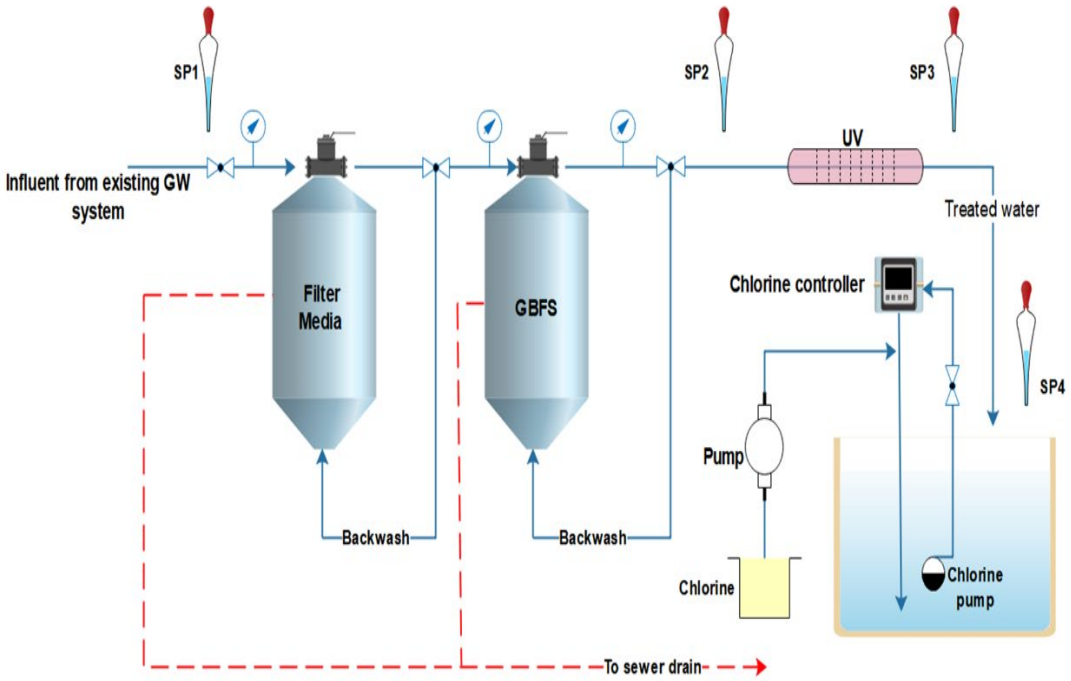


Figure 3.8: Configuration 4 and sampling points.

Similarly, the key objective of this configuration is to assess the impact of UV disinfection on reduction of microbial contamination. Another motive of this configuration is to assess the microbial counts at the influent (SP1) and after adsorption treatment (SP2). These measured values will aid in concluding if GBFS is an effective medium in treating and reducing microbial contamination.

3.5.5. Configuration 5. This configuration completely relies on AC adsorbent for the treatment of influent GW. This configuration solely targets to determine the pollutant removal efficiency of AC without any dependency on pre-treatment. Hence, the raw GW influent directly feeds into AC vessel, without any interaction with filter media (silica). Additionally, the configuration is installed to have a UV disinfection before chlorination process. Figure 3.9 illustrates the treatment process for Configuration 5.

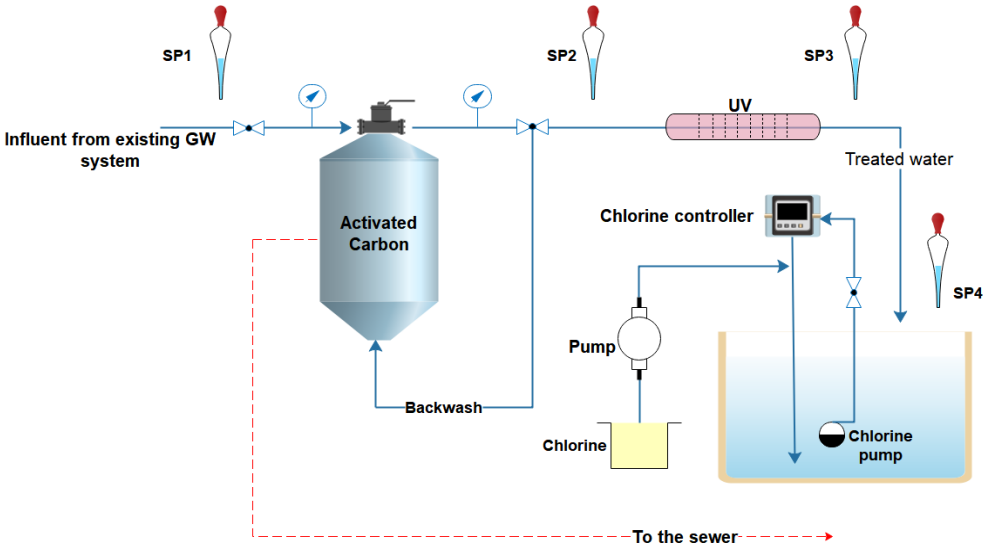


Figure 3.9: Configuration 5 and sampling points.

3.5.6. Configuration 6. This configuration is similar to Configuration 5 (Section 3.5.5.) including the location of sampling points, however, instead of AC, it completely relies on GBFS adsorbent for the treatment of influent GW. This configuration solely aims to determine the pollutant removal efficiency of GBFS without any dependency on pre-treatment. Hence, the raw GW influent directly feeds into GBFS vessel, without any interaction with filter media (silica). Additionally, the configuration is installed to have a UV disinfection before chlorination process. Figure 3.10 illustrates the treatment process for Configuration 6.

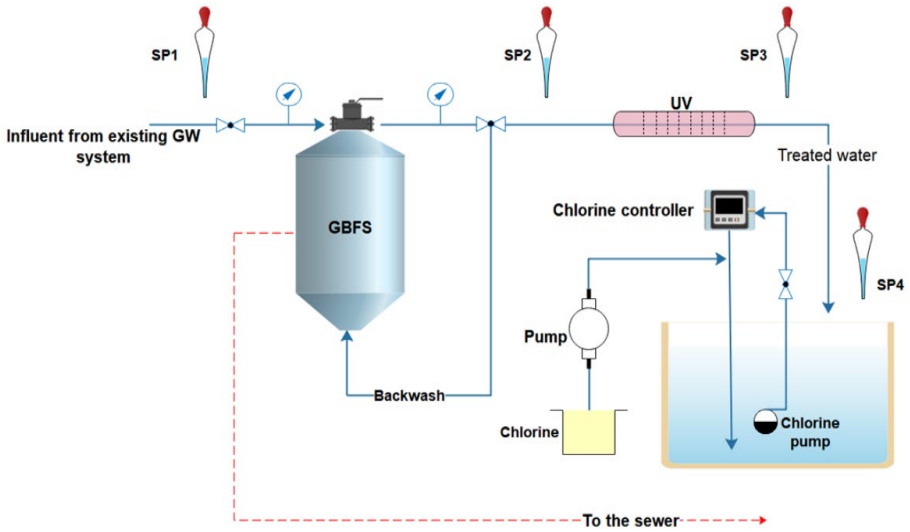


Figure 3.10: Configuration 6 and sampling points.

3.6. Target Pollutants

A total of eleven parameters are measured to determine the quality of GW and reclaimed water. Table 3.4 displays the pollutants measured under this study along with the reason of interest for their quantification.

Table 3.4: Target pollutant and reason of interest.

Pollutant parameter	Reason of interest	Reference
Biodegradable organics	GW with high concentration of biodegradable organic compounds if discharged into surface waters it can lead to oxygen depletion. Additionally, higher organic compounds can encourage microorganism growth.	[90]
pH	Optimum pH levels are needed for efficient removal of turbidity and support microorganism growth to reduce biodegradable organics.	[91]
Solids	High concentrations of solids can increase turbidity in water and can also cause clogging of the system.	[90]
Pathogens	Risk to human health	[66]
Temperature	Effects the microbial activity, directly impacting the removal of organic matter.	[92]
Turbidity	It indicates the presence of pathogens or particles in water. Also, measuring turbidity level after each treatment process can aid in identifying fault in the process treatment and if there is a need of maintenance.	[93]-[94]

3.7. Sampling Method

Grab sampling approach is followed in collecting the samples from all the identified sampling points. The run time for each configuration is seven days and the samples are collected every day at 6 pm (± 1 hr). Duplicate samples were collected from each sampling location to ensure the reliability and accuracy of the result. Although sample collection method is identical, however, the sampling bottles for testing physical and chemical characteristic of GW were different from the sampling bottles used for collecting microbial samples. Figure 3.11 illustrates the sampling bottles used for microbial and non-microbial sample collection.

Figure 3.11: Sampling bottle for (a) microbial samples (b) non-microbial samples.

500 ml regular plastic bottles were used to collect the samples to be tested for physical and chemical characteristic (non-microbial) of the GW and reclaimed water. However, as stated in the literature, for microbiological examination the collection bottles should be (i) sterile, to ensure there is no bacterial contamination which will introduce error in the result (ii) have sufficient sodium thiosulphate to neutralize the effect of any chlorine in the water to reflect the actual microorganism at the time of collection [95]-[96]. For this reason, 50 ml sterile bottles with sodium thiosulphate were used for collecting microbial samples. Additionally, prior to collecting bacterial samples, the sampling point was cleaned with 70 % ethanol to ensure minimal bacterial contamination of sample from out sources. Table 3.5 provides the summary of overall samples collected and tested for each configuration proposed under this study over a period of seven days.

Table 3.5: Number of samples collected over period of seven days.

Configuration	Physical and Chemical Analysis Sample	Bacterial Samples	Total Samples
1	28	42	70
2	28	56	84
3	28	42	70
4	28	56	84
5	28	56	84
6	28	56	84
Total number of samples collected			476

3.8. Sampling Preservation

All the samples to be assessed for physico-chemical parameters after collection are stored at 4˚C. Alternatively, all the samples for microbial analysis were tested on the day of collection.

3.9. Water Quality Analysis

The water quality analysis is divided into two parts (i) chemical and physical analysis and (ii) microbiological analysis.

3.9.1. Physical and chemical analysis. This analysis was carried out in the Environmental Engineering laboratory of the American University of Sharjah. All chemicals and reagents used during the laboratory test procedures complied with analytical grade and standard approval make. All the glass wares, containers and evaporating dishes used for analysis were rinsed with distilled water and oven dried. Standard solutions and reagents required for the testing procedure were prepared on regular basis to eliminate any induced error in the results. Wherever necessary, blank control tests were conducted to define the datum and background concentrations during analysis of the samples. Additionally, all the samples before pipetted out for analysis were vigorously shaken to achieve homogeneity which would aid in providing precise test results. Also, instrumental calibrations were performed on regular basis for all the equipment utilized for testing. Duplicate samples were tested to provide accuracy in the result. All the BOD5 samples were aerated for 5 minutes (± 1 minute) using potable aerator pump (as shown in Figure 3.12) to ensure there is sufficient dissolved oxygen in the sample for the microorganism to carry out the decomposition of organic matter. Alternatively, during the analysis process, the duplicate samples which yielded either completely different results or had significant differences were discarded and retested to eliminate any uncertainties in the results. Lastly, wherever necessary the samples were diluted to attain the analysis results within the measuring range of the test kit.

The samples are tested in accordance to the test methods identified under Standard Method for the Examination of Water and Wastewater (APHA 2012). All the experimental methods and procedures conducted for the analysis followed literature guidelines and are documented under Table 3.6.

Figure 3.12: Aeration of BOD_5 samples where (a) is BOD_5 bottle and (b) is portable aerator.

Table 3.6: Standard methods used for testing physical and chemical water quality parameters.

Parameter	Frequency of Testing	Method/Standard	Instrument
Temperature and pH	Every day	-	Oakton pH 11 hand held meter (measures pH, mV, °C)
BOD_5	3 times a week	5-Day BOD test	AQUALYTC AL606 BOD measuring system
COD	Every day	Standard ISO 6060-1989, DIN 38409-H41-H44 (HACH LCK 514)	HACH DRB200 and HACH Spectrophotometer DR5000
TOC	Every day	Standard EN 1484 & DIN 38409-H3 (HACH LCK 385)	HACH DRB200 and HACH Spectrophotometer DR5000
TSS	Every day	Standard Method for the Examination of Water and Wastewater, Method 2540D	-
TDS	Every day	Standard Method for the Examination of Water and Wastewater, Method 2540C	-
Turbidity	Every day	Standard Method for USEPA Approved HACH Method 1801	2100P Portable Turbidimeter

3.9.2. Microbial analysis. Three types of microorganisms are targeted to be assessed including total coliform (TC), fecal coliform (FC) and E. coli. The presence of TC and FC are detected using "most probable number", which involves passing a measured volume of through a fine filter (usually pore sizes less than or equal to 0.45 mm) that can retain the bacteria. The filter is then placed on culture medium and incubated. The assessment of bacteria using this technique is termed as membrane filter technique (MFT) [102]. The MFT method provides a direct count of TC and FC present

in the sample to be tested [103]. On the other hand, the presence of E. coli was detected using "spread plate method," where a small quantity of homogenized sample (0.5 ml) is spread on the medium with sterilized spreader and incubated. Several studies have adapted these detection and enumeration techniques due to several reasons including [102], [104]:

- Yields quantitative results and provides good precision subject to the number of colonies grown.
- Water soluble impurities that may interfere with the growth of target microorganisms are separated from the sample during the process of filtration.
- Results are obtained within 24 – 48 hours without the need of further cultivation, therefore making the technique less labor intensive, faster and low cost.

Table 3.7 shows the culture medium, culturing technique, standard and colony color used for assessing the target microorganism. Duplicate samples from each sampling location are collected 3 times a week and tested for the microbial contamination.

Table 3.7: Culture medium, culture technique, standard and colony assessment for bacterial count.

Bacteria	Culture Medium	Culturing Technique	Standard	Colony
Total Coliform	Triphenyl Tetrazolium Chloride (TTC) Tergitol-7 Agar	Membrane filtration on the medium; incubation at 36°C for 24 hrs. (± 1hr).	ISO 9308 -1	Brick red with yellow central halo
Fecal Coliform	Triphenyl Tetrazolium Chloride (TTC) Tergitol-7 Agar	Membrane filtration on the medium; incubation at 44°C for 24 hrs. (± 1hr)	ISO 9308 -1	Brick red with yellow central halo
E. coli	Tryptone bile X-glucuronide (TBX) Agar	Spread 0.5 ml sample on medium; incubation at 44°C for 24 hrs. (± 1hr)	ISO 16649-2	Blue-green

The later report describes the detailed procedure applied and material used for conducting the microbial test. It also highlights the calculation performed for the enumeration of TC, FC and E. coli coliform in accordance to standard method 9222B.5. (APHA 2012).

3.9.2.1. ***Preparation of culture medium and petri dishes.*** The first step for microbial requires preparation of petri dishes with culture medium. For TC and FC culture media, a total of 3 L of culture medium was prepared, under three separate batches upon the testing requirement. Each litre of culture medium was prepared by suspending 33.12 grams of TTC Tergitol-7 agar base in 1000 ml of distilled water. The solution was then heated until the boiling point to completely and homogenously dissolve the medium. The prepared agar solution was then transferred in to a sterilized glass bottle, which was further autoclaved at 15 lbs pressures (121°C). The mixture was then cooled to 45 - 50°C. The mixture was then poured into petri dishes until it reached sufficient thickness (15 ml) and covered the circumference of the dish. Alternatively, for E. coli analysis, petri dishes with TBX agar medium was prepared. A total of 2 L of culture medium was prepared under two separate batches. Each litre of culture medium was prepared by suspending 36.6 g of TBX agar in 1 litre of distilled water. The solution was then heated until the medium is completely dissolved and homogenized. The prepared culture medium was then poured into sterilized glass bottle, which was then autoclaved at the same temperature and pressure as before. The mixture was then cooled to 45 - 50°C. The mixture was then poured into petri dishes until it reached sufficient thickness (15 ml) and covered the circumference of the dish. Figure 3.13 displays the petri dishes prepared for TC, FC and E. coli under this study.

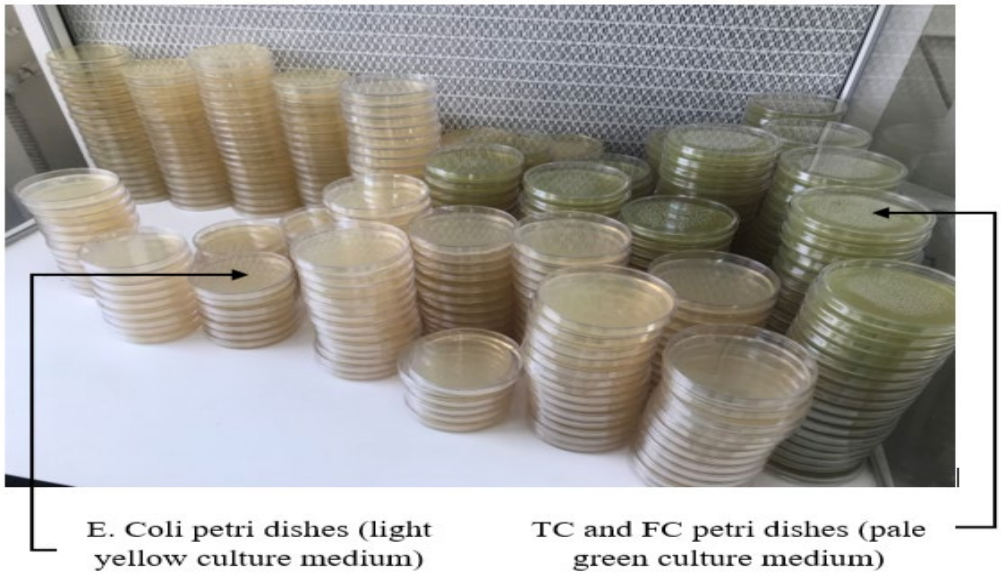


Figure 3.13: Petri dishes with culture medium.

3.9.2.2. ***Sample dilution.*** The GW samples, even of small quantities are highly contaminated with bacteria, hence it is necessary to dilute a portion of the sample in a sterile diluent to ensure that there is sufficient volume to filter across the surface of the membrane [97]. According to literature [98] and APHA standard [99] the recommended sample volume to be used for wastewater is 1 ml which needs to be added to a 9 ml sterile diluent to achieve a dilution factor of 10. The dilution glass tubes are required to be stirred well to ensure the tested sample is mixed properly and achieves homogeneity to yield precise results. Likewise, serial dilutions are performed to increase the dilution in cases where the number of bacteria is too many to count. Hence, to be in line with the literature, 1 ml of homogenous sample volume was mixed with 9 ml sterile diluent to conduct the tests for both TC and FC. An ideal result is achieved when the number of colonies lie within the range of 20 – 80 colonies per membrane [98] however the number of colonies should not be more than 200 [99]. Since the initial number of bacteria in the samples were unknown, hence to decide a dilution factor, couple of trial tests had been performed initially to ensure that the number of colonies on the membrane will be in optimum range for counting.

The dilution factor varied at different sampling point depending on the microbial contamination of the sample. It was noted that, highest dilution was required at SP1 (influent raw GW) and the dilution reduced for the downstream treatment, with no requirement of dilution for samples extracted from SP3 and SP4 locations. Additionally, since the spread plate technique involved for E. coli detection required small amount of sample to be tested (0.1 ml) therefore, no dilution was carried out for E. coli samples. Table 3.8 displays the summary of the dilution factors achieved using trial and error method for each sampling point to get the number of colonies to be less than or equal to 200.

Table 3.8: Dilution factor recorded to achieve optimum number of colonies.

Sampling Point	Total Coliform - Dilution	Fecal Coliform - Dilution
SP1	$1/10^{-10}$	$1/10^{-10}$
SP2	$1/10^{-6}$, $1/10^{-9}$, $1/10^{-10}$	ND, $1/10^{-3}$, $1/10^{-5}$
SP3	No dilution, $1/10^{-6}$	No dilution
SP4	No dilution	No dilution

Figure 3.14 displays a comparison of TC formation on grid marked, cellulose ester membrane before and after the process of dilution. As it can be seen from Figure 3.14 (left), without dilution the bacteria growth is extensive with the formation of huge clumped up colonies. Under this growth scenario, where the bacterial colonies are not segregated, the enumeration of coliforms cannot be carried out, thereby, leading to disposal of the tested sample. Whereas, Figure 3.14 (right) displays the result of sample after dilution ($1/10^{10}$). It is evident that the bacterial colonies are scattered, countable and lies within the optimum range of colonies as reported in the literature.

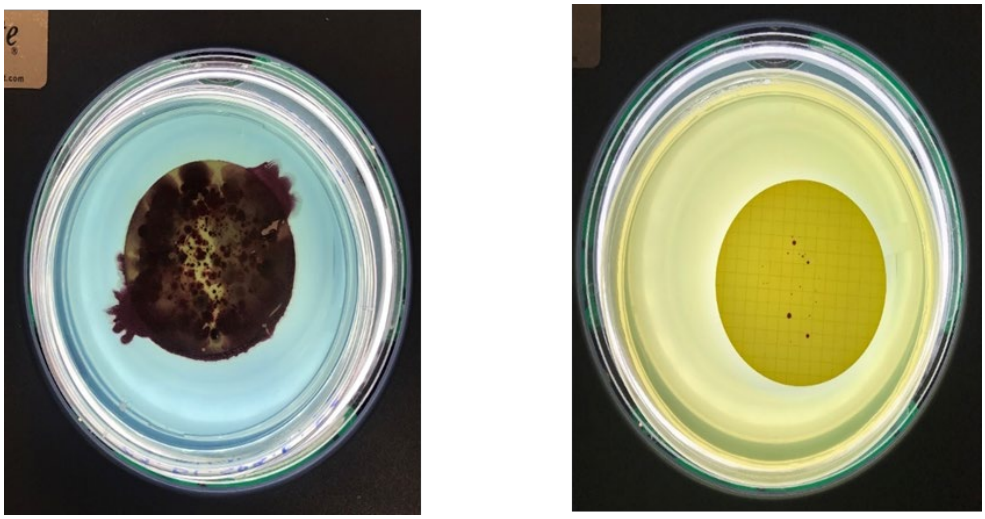


Figure 3.14: TC formation (left) before (right) after $1/10^{10}$ dilution.

3.9.2.3. Test Procedure. The experimental procedure for both TC and FC is identical. The samples to be tested are diluted (as per requirement) and filtered through a cellulose acetate grid marked membrane with uniform pore diameter of 0.45 µm. During the process of filtration, the bacteria are retained on the surface of the membrane. The bacteria retained membrane is then placed on the petri dishes with culture medium. The membrane is placed in a way to avoid the formation of any air pockets between the membrane and the culture medium. The lid of the petri dish is closed to avoid any bacterial contamination from the surrounding area which may impact the analysis of the results. Finally, the petri dishes with membrane are kept in the incubator at 36°C for 24 hrs (± 1hr) and 44°C for 24 hrs (± 1hr) for TC and FC growth, respectively. The respective colonies shall be formed and categorized by the

color code as mentioned under Table 3.7. Figure 3.15 illustrates the experimental setup established for enumeration of TC and FC.

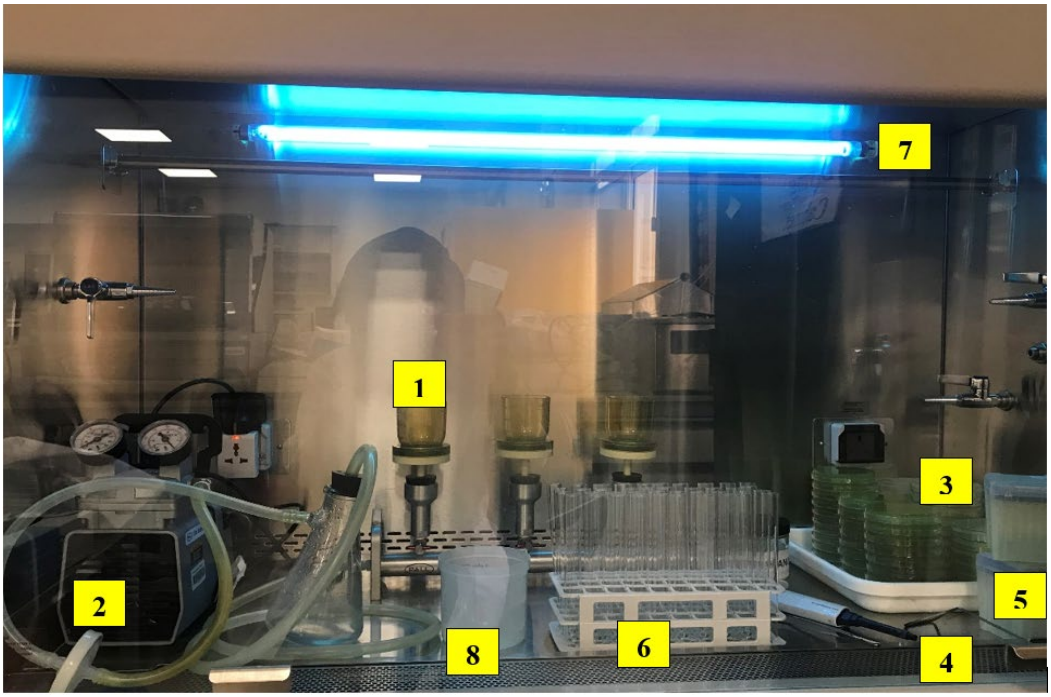


Figure 3.15: Biological safety cabinet and experimental apparatus including (1) filter unit (2) vacuum pump (3) petri dishes with culture medium (4) pipette (5) pipette tips (6) sterilized glass tubes (7) UV light (8) sample discard container.

All the tests are conducted inside the biological safety cabinet (BSC) to provide an aseptic environment and containment for cell culture. The BSC ensures to provide a controlled environment to obtain precise bacterial test results and increased health safety by reducing the potential for exposure of both the sample and the personnel to airborne biological agents by monitoring and controlling real-time airflow to maintain accurate laminar airflow and a dynamic air barrier. Also, BSC is installed to have UV light to get rid of any bypass bacteria or prevent potential growth of bacteria. All the required apparatus for the test was kept inside the BSC to ensure minimum contact with the outside environment to avoid contamination of sample and personnel. Throughout the process of test, it is highly essential to disinfect and sterilize all the apparatus between analysis of consecutive samples. Sterilizing of the samples are achieved by two methods including (i) immersion of components in boiling water for at least 1 minute and (ii) flaming the components with methanol.

The sterilized glass test tubes used once for the process of dilution or sampling cannot be reused without autoclaving or sterilizing. Additionally, during the process of incubation, the petri dishes with sampled membrane needs to be kept upside down in the incubator, to reduce the formation of droplets on the lid which may reduce the visibility and induce error during the enumeration process. Figure 3.16 illustrates a petri dish with condensation on the lid, thereby reducing visibility in counting the number colonies formed. Finally, to avoid personnel and sample contamination, simple practice needs to be followed including (i) not breathing heavily or talking while performing the experiment and (ii) washing hands before and after the experiment.

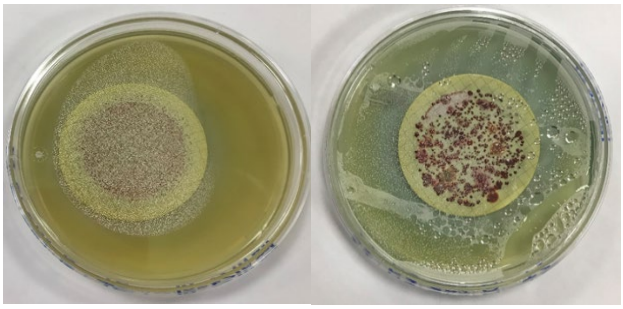


Figure 3.16: Condensation on petri dish lid inducing reduction in visibility.

Alternatively, for E. coli bacteria, spread plate technique is applied. Under this technique, 0.1 ml of sample (without any dilution) is pipetted on to the petri dish with TBX agar culture medium. A sterilized “delta- shaped” spreader was used to evenly spread the sample over the circumference of the petri dish with culture medium as shown in Figure 3.17. The petri dishes were sealed with lid and incubated at 44°C for 24 hrs. (± 1hr). The test was also conducted in BSC and the spreader was consistently sterilized with 70 % ethanol after spreading of each sample to avoid external bacterial contamination.

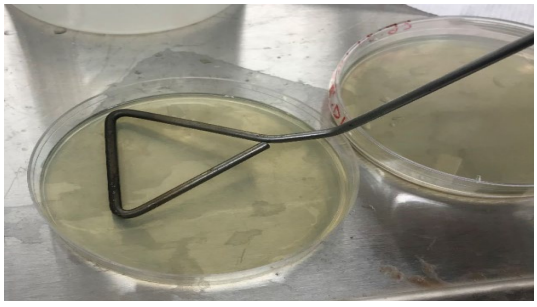


Figure 3.17: Delta shape spreader used for E. coli test.

3.9.2.4. Enumeration and quantification. After the complete process of incubation, the number of colonies formed on the medium are counted corresponding to each sample. Samples having more than 200 colonies are rejected and retested. Figure 3.18 (left) displays the test results which are acceptable as the colonies formed are within the optimum range reported in the standard and literature. On the contrary, Figure 3.18 (right) illustrates the test results which are rejected and requires retesting as the number of colonies are >200. The bacterial count is generally reported in terms of colony forming units (CFU), where CFU is a single cell or group of cells attached together and inseparable by shaking [99]. Therefore, the number of CFU in the sample being tested is achieved by multiplying by the dilution factor. After incubation the bacterial colonies were counted using colony counter (Figure 3.19). The petri dish was placed on the electronic pressure pad installed in the colony counter and each of the colony was traced using a marker. The touch during tracing process causes a count to be registered on the digital display and an audible tone confirms each count made to ensure there is no duplication or missed colony.

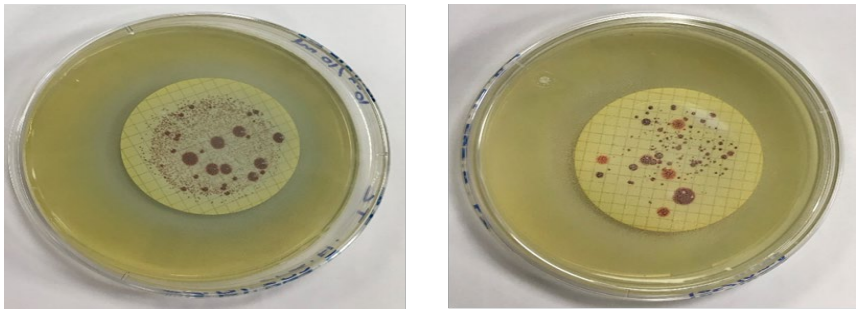


Figure 3.18: Sample (left) rejected as CFU >200 (right) accepted as CFU < 200.

The appearance of TC and FC bacterial colonies are identical, with colonies being brick red in color with yellow central halo. However, for E. coli most of the strains can be differentiated by the presence of glucuronidase enzyme [100]. The presence of chromogenic agent X-glucuronide in the culture medium aids in the detection of glucuronidase activity. Figure 3.20 displays the E. coli colony is one of the influent samples tested.

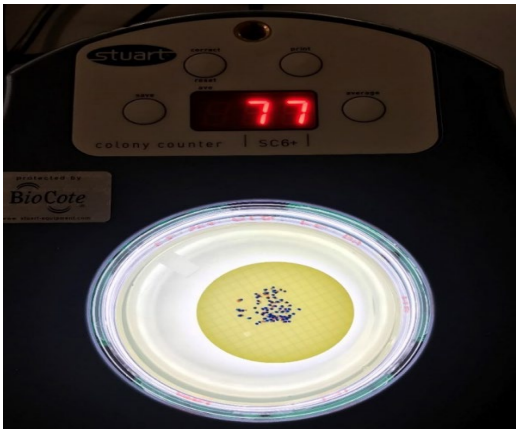


Figure 3.19: Colony counter.

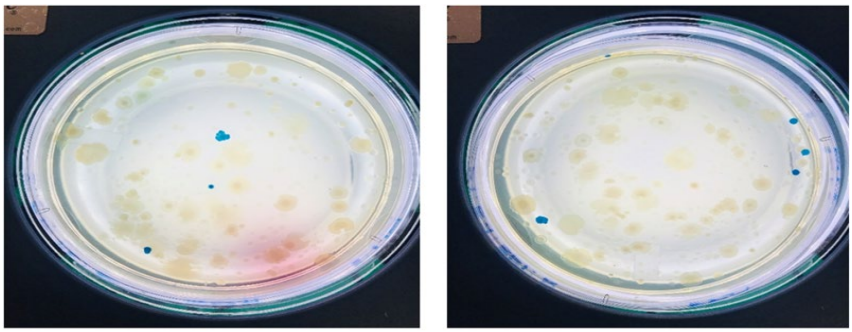


Figure 3.20: Formation of blue/green E. coli colonies.

As per standard method 9222.B (APHA 2012), Equation (1) is used for calculating number of TC/FC colonies per 100 ml whereas Equation (2) is used for calculating the number of E. coli colonies per 100 ml in the tested sample.

$$\boldsymbol{TC\ or\ FC\ (CFU)/100\ ml} = \left[\frac{Number\ of\ brick\ red\ colonies}{Volume\ of\ filtered\ sample}\right] x\ Diltuion\ factor x\ 100 \quad (1)$$

$$\boldsymbol{E.coli\ per\ \frac{CFU}{100}\ ml} = \left[\frac{Number\ of\ blue-green\ colonies}{Volume\ of\ filtered\ sample}\right] x\ 100 \quad (2)$$

3.9.2.5. Disposal. At the end of experiment, all petri dishes and pipette tips are to be wrapped in polypropylene bag (which is thermoresistant) and then autoclaved for 90 minutes at 121 °C to carry out biohazard sterilization. This process

ensures the destruction of all microbial life, which could be a potential health hazard if disposed without sterilization.

3.10. Microbial Reduction Efficacy

The microbial reduction efficacy is carried out for TC, FC and E. coli. Reduction in microbial counts before and after each treatment process is expressed as log reduction, a common approach for the evaluation and representation of microbial reduction [101]. For statistical analysis, the average of duplicate samples is taken for calculating the log reduction and percentage log removal achieved during each stage of treatment for all the six configurations. Log reduction and percentage log removal is calculated using Equation (3) and Equation (4), respectively. The log reduction calculated is plotted, evaluated and compared for all the configurations.

$$Log_{10}\ Reduction\ Factor\ (LR) = Log_{10}\ Prevalue - Log_{10}\ Postvalue \quad (3)$$

$$Percentage\ log_{10}\ removal = 100 - \frac{100}{10^{LR}} \quad (4)$$

3.11. Health Risk Reduction

Another objective of this study is to carry out the health risk reduction at every level of treatment for all the configurations. The risk under this study is evaluated for both adults and children and calculated in line with the Risk Assessment Guideline for non-carcinogens as detailed by EPA [102]. The pathway of exposure is considered to be inhalation, in line with a similar study conducted on human health risk reduction during toilet flushing [103]. To identify any risk, quantifying exposure concentration is one of the key elements. Any exposure assessment scenario depends on critical information including exposure of population to the pollutant, duration and level of exposure to the contaminant under assessment [104]. Under this study, both the adults and children are taken to be the exposed subjects to TC microbes by inhalation during toilet flushing. Firstly, the concentration of personal exposure expressed as mass of pollutant per unit body weight per day is calculated using Equation (5) for both adults (male and female) and children [105].

$$C = \frac{c_a\ x\ InhR}{BW} \quad (5)$$

Where; C is Concentration of microbes in air (personal exposure) (CFU/kg-day); Ca is Microbe concentration in sample (CFU/100 ml); InhR is Inhalation Rate (m3/hr) and BW is Body Weight (Kg).

Following the calculation for microbial concentration in air (C), the exposure concentration (EC) was quantified using Equation (6) [105].

$$EC = \frac{C\ x\ EF\ x\ ED}{AT} \tag{6}$$

Where; EC is exposure concentration (CFU/kg-day), C is concentration of microbes in air (personal exposure) (CFU/kg-day), EF is exposure frequency (days/year), ED is exposure duration (years) and AT is averaging time (days).

Since, microbial contamination under this study is categorized as non-cancerous, hence the risk is assessed based on presence or absence of adverse health effect due to exposure to TC. In order to assess the risk of reclaimed GW, the hazard quotient (HQ) is calculated for water samples at every stage of treatment in line with EPA guideline [105] and several other studies reported in the literature [104], [106]-[107]. The quantification of HQ significantly depends on either reference dose (RfD) or no observable adverse effect level (NOAEL). NOAEL represents the dose at which no adverse health effect is observed, thereby, a dose less than or equal to NOAL is considered safe. However, due to the introduction of uncertainty in this safe dose levels of non-carcinogens, a factor of safety or uncertainty factor (UF) is generally applied to the NOAEL to determine the RfD, hence RfD values are always lower than NOAEL. The factor of safety or uncertainty factor (UF) typically ranges from 10 – 1000 [102]. NOAEL values for TC could be found in the literature, therefore, the NOAEL values was considered same as the values reported in the international guideline criteria (EPA) for GW reuse. Equation (7) is used to calculate the RfD for all the target microbes, where NOAEL is No observable adverse health effect (CFU/kg-day) and UF is uncertainty factor.

$$RfD = \frac{NOAEL}{UF} \tag{7}$$

Following the above, HQ values for each sample were calculated using Equation (8) [105]; where HQ is hazard quotient (unitless) and RfD is reference dose is (CFU/kg-day).

$$HQ = \frac{Exposure\ Concentration\ (EC)}{Reference\ Dose\ (RfD)} \quad (8)$$

The values used in Equation (5) to (8) are presented in Table 3.9. These values are adapted from literature and international GW reuse guidelines.

Table 3.9: Risk assessment parameters and values used [102], [103], [107]-[108].

Parameter	Unit	Definition	Values Used		
			Male	Female	Children
InhR	m^3/day	Inhalation rate	0.6	0.6	0.6
EF	Day/year	Exposure frequency	350	350	350
ED	Years	Exposure duration	30	30	30
BW	Kg	Body Weight	70	50	10
AT	Day	Averaging time	EDx350	EDx350	EDx350
RfD (TC)	CFU/100ml	Reference dose	200	200	200
UF	Unitless	Uncertainty Factor	1000	1000	1000

Chapter 4. Results and Discussion

This chapter presents the results and analysis of the greywater samples collected during the study from residential tower in Sharjah city. This chapter evaluates the efficiency of different materials in removing the target pollutants and microbial contamination from the influent greywater and highlights the potential impact of pre-treatment process using sand filter media on pollutant removal. Furthermore, it assesses the impact of introducing UV disinfection by monitoring the reduction levels of microorganisms.

4.1. Influence of Adsorbent on Greywater Treatment

The influence of filter media on pollutant removal efficiency was investigated by comparing the influent and effluent physico-chemical characteristics between activated carbon (Configuration 5) and ground blast furnace slag (Configuration 6). The sub-sections here are arranged to compare the effects of both AC and GBFS on reclaimed water quality by assessing the removal efficiencies of the target pollutant for 7 days.

4.1.1. Aesthetic quality and turbidity. One of the key criteria to reuse reclaimed water is to maintain its aesthetic appearance [109]. The reclaimed water should be visually clean with no foul smell to ensure public health safety and support social acceptance for reuse purpose. Figure 4.1 and Figure 4.2 displays both the influent and effluent aesthetic water quality for Configuration 5 and Configuration 6, respectively.

Visual inspection indicates that the influent greywater is cloudy and has large volume of suspended solids for the samples representing both Configuration 5 and Configuration 6. On the other hand, treated greywater for both the configurations is transparent and did not exhibit the presence of any visible suspended solids thereby delivering an initial indication of reduced turbidity levels and effective removal of suspended solids. To affirm the visual conclusion, turbidity tests were performed to evaluate the performance and effectiveness of AC and GBFS in removing of suspended solids by monitoring reduction in turbidity levels.

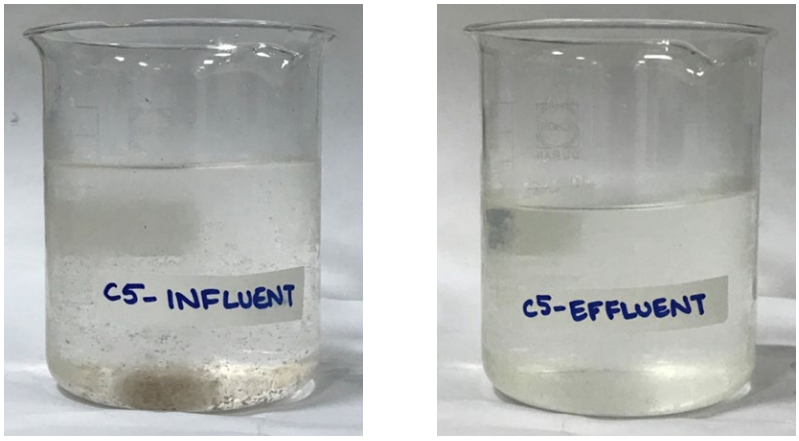


Figure 4.1: Day 1 – Sample for (left) influent greywater and (right) treated greywater from AC column (Configuration 5).

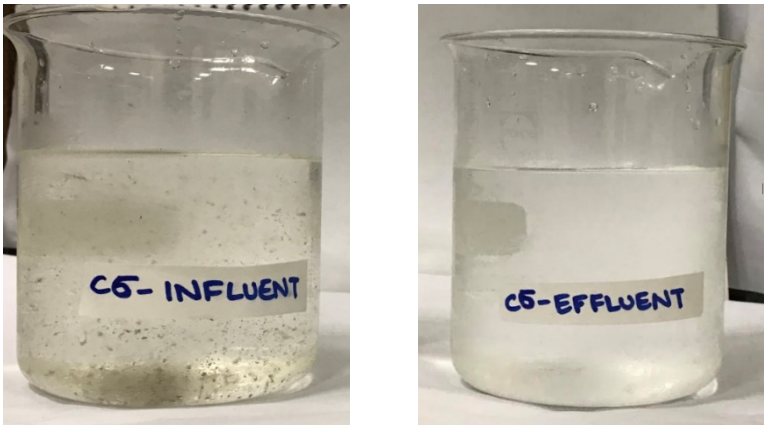
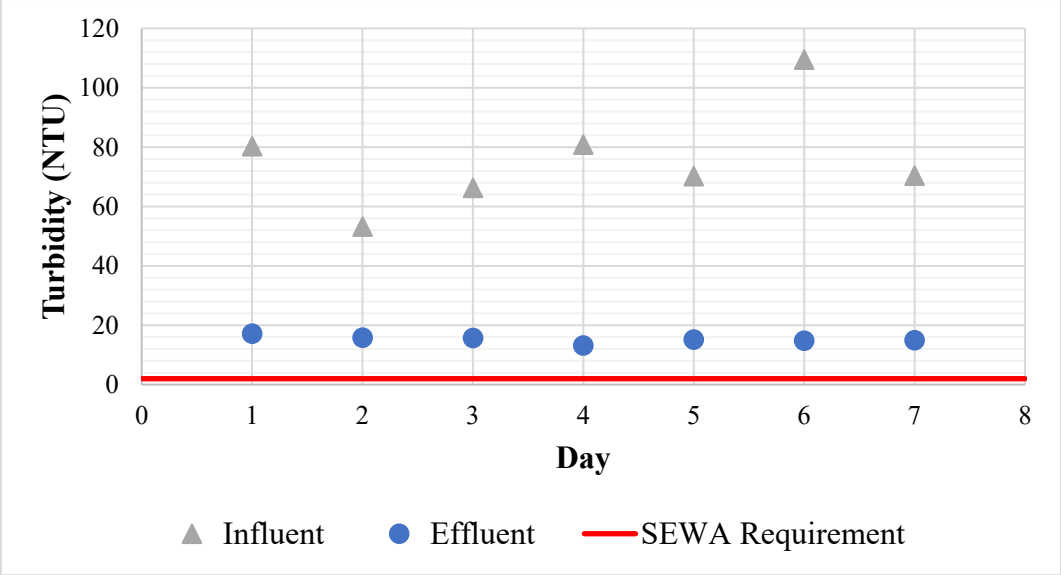
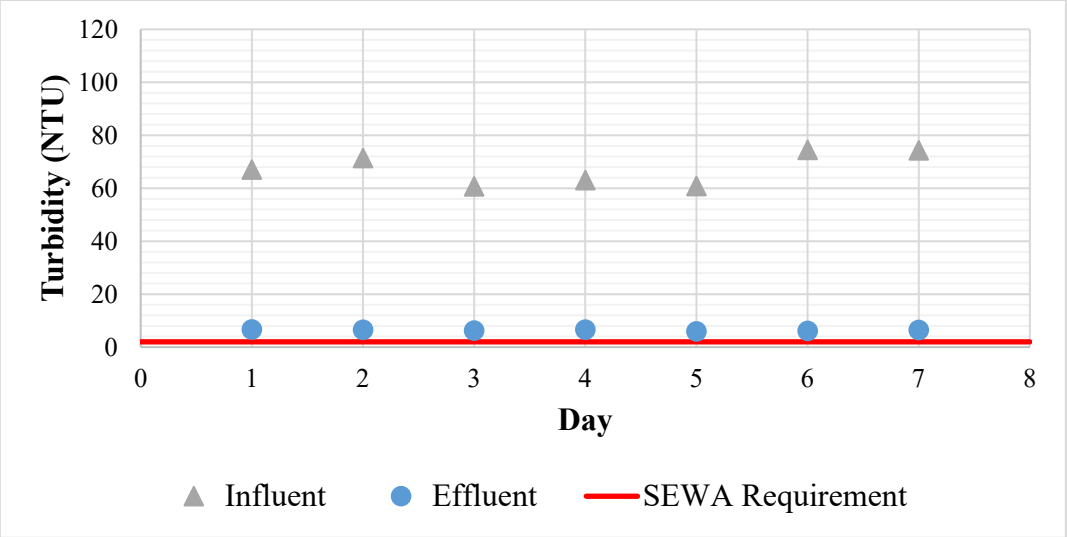


Figure 4.2: Day 1 – Sample for (left) influent greywater and (right) treated greywater from GBFS column (Configuration 6).

Figure 4.3 summarizes the reductions in turbidity levels with the application of AC and GBFS, respectively. The influent samples for AC displayed higher levels of turbidity (53.5 NTU – 109.5 NTU) with most values dwelling above 70 NTU. In addition, the turbidity is observed to be significantly fluctuating in all the samples for seven days. Whereas, the influent turbidity levels are observed to be on lower side for GBFS (60.7 NTU – 74.5 NTU) with most values oscillating below 65 NTU. In contrast to Configuration 5, the influent turbidity levels to Configuration 6 are predominantly uniform with slight variation. Despite the dissimilarity in the influent turbidity values obtained for 14 days, these values lie within the typical turbidity range mentioned in the literature focusing on typical greywater characteristics across the globe [49], [51], [110]-[111].



(a)



(b)

Figure 4.3: Influent and effluent turbidity levels for (a) AC (Configuration 5) and (b) GBFS (Configuration 6).

In addition to the above, the results populated in Figure 4.3 also exhibits the effluent turbidity levels obtained after the treatment utilizing AC and GBFS, respectively. It is evident that GBFS have displayed higher removal efficiency of suspended solids which sequentially reduced the turbidity levels of reclaimed water. The turbidity attained after bypassing the GW through GBFS is recorded to be in the range of 5.9 NTU – 6.6 NTU. Whereas, the residual turbidity levels post AC treatment are noted to be on the higher side varying between 13.1 NTU – 17.2 NTU. Furthermore,

it is also prominent that the effluent turbidity levels are almost invariable for all 7 days for GBFS in comparison to the effluent levels for AC which displayed higher variability. The irregularity in the effluent turbidity levels for treatment using AC could be introduced due the higher and inconsistent turbidity values of the influent. The permissible limit defined by SEWA requires turbidity levels in the reclaimed water to be less than or equal to 2 NTU. Although, this criterion is not achieved by utilizing either of the adsorbents, however, the reclaimed turbidity content following the GBFS adsorption process is closer to the required standard by SEWA. On the contrary, the reclaimed turbidity levels using AC adsorbent are recorded to be more than double of that recorded for GBFS. To provide a broader assessment and comparison on performance efficiency of AC and GBFS, Figure 4.4 illustrates the overall turbidity removal efficiency recorded for both the adsorbents for 7 consecutive days.

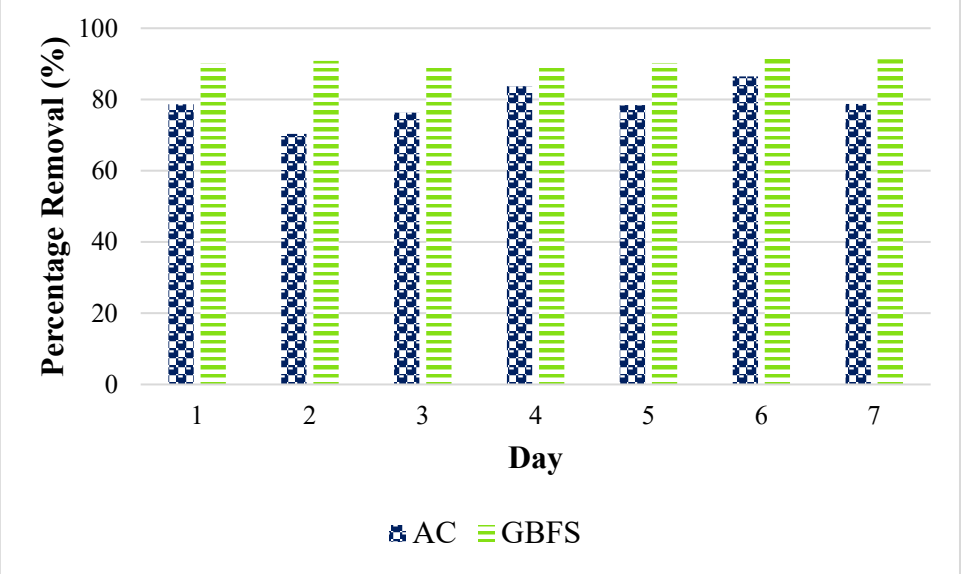


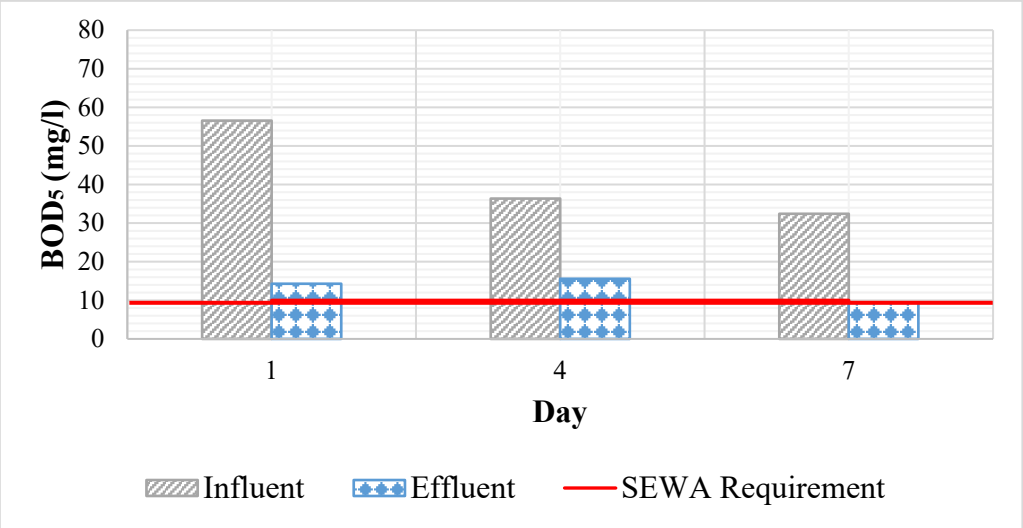
Figure 4.4: Percentage removal efficiency of turbidity using AC (Configuration 5) and GBFS (Configuration 6) adsorbent.

Overall, GBFS have displayed higher and consistent removal efficiency (90 – 92 %) in contrast to AC, which achieved lower and wider removal efficiency pattern (70 – 86 %). A number of studies have found that application of Membrane Bioreactor (MBR) system for greywater treatment achieved a removal efficiencies of 98 – 99 % [61]-[62], [112]-[113]. Another study reported to have achieved an overall turbidity removal of 98.7 % using alum coagulation process and reaching residual turbidity levels

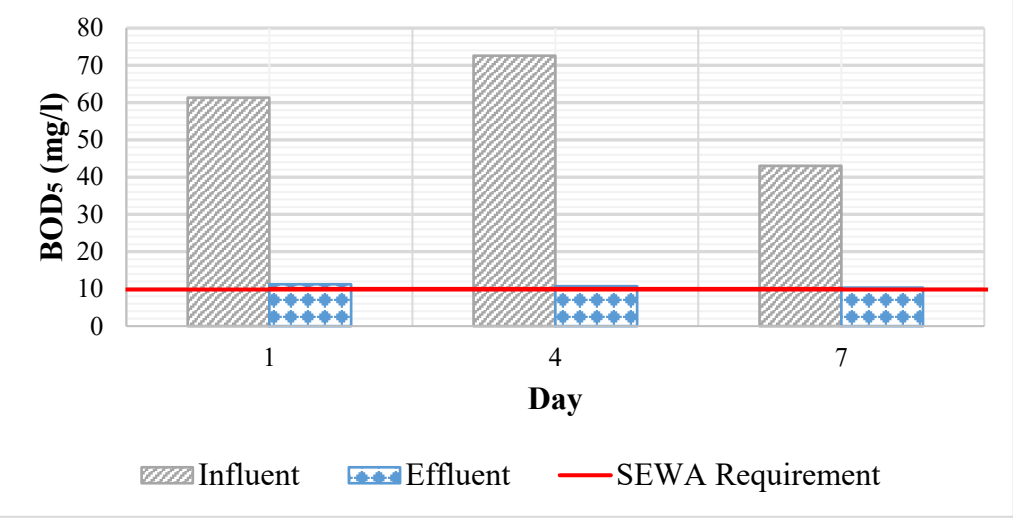
to less than 1 NTU when followed by AC adsorption [114]. A study evaluated the performance of low-cost natural adsorbent comprising of banana, orange and sapodilla peels for treatment of synthetic greywater. The fruit peels were washed, and oven dried to remove the moisture content following immersion in 30 % phosphoric acid for 24 hours. Finally, the peels were carbonized under 400°C, powdered well and activated at 800°C to generate final adsorbent. The study found that the removal percentage of turbidity achieved using 1g of banana, orange and sapodilla peel adsorbent are 90 %, 86 % and 83 %, respectively [115]. Moreover, studies have also been carried out using moringa oleifera as an adsorbent which reported to reduce turbidity levels by 85- 97 % [116]-[117]. A study [81] investigated the impact of multimedia filter comprising of readily available natural adsorbents including AC, sugarcane bagasse, risk husk and grass mulch on the physico-chemical content of domestic wastewater; experimental results showed significant removal efficiency of pollutants and a reduction of turbidity by 83.0 % [118]. Likewise, a batch adsorption study reported the initial turbidity removal efficiency using only sand filtration to be 60 %, which significantly increased to 94 % when supported with adsorption process using AC prepared from sawdust, sugarcane bagasse and pine needles [119]. Referring to the values reported in the literature for the turbidity removal achieved using various single and multi-media adsorbents, it can be concluded that GBFS have achieved removal levels higher than most of the natural adsorbent tested in the past, including the traditional AC that is widely adapted and implemented for greywater treatment.

4.1.2. Biochemical Oxygen Demand (BOD_5). BOD_5 values for the samples were monitored for Day 1, Day 4 and Day 7. Since the source of GW generation under this study is only from washroom showers and sink, hence large source of organic contamination is not anticipated, that would otherwise be in the case of GW generated from kitchen sink. The influent and effluent values for BOD_5 for AC (Configuration 5) and GBFS (Configuration 6) are presented in Figure 4.5, respectively. Results showed that the influent BOD_5 values for AC (Configuration 5) were ranging from 32.4 mg/l – 56.6 mg/l compared to the influent BOD_5 values for Configuration 6 which were in the range of 43.0 mg/l – 72.6 mg/l. The influent values for both the configuration are within the typical BOD_5 range reported in the literature for light greywater [52], [120]. Additionally, it is also found that although the influent BOD_5 values are higher during the application of GBFS (Configuration 6), yet the effluent BOD_5 values after GBFS

adsorption are observed to have low variability, ranging from 10.4 mg/l - 11.4 mg/l. On the contrary, although the influent values during GW treatment using AC (Configuration 5) were observed to be lower in comparison to GBFS, the effluent values are recorded to be unsteady and higher in the range of 9.4 mg/l - 15.6 mg/l.



(a)



(b)

Figure 4.5: Influent and effluent values of BOD_5 for (a) AC (Configuration 5) and (b) GBFS (Configuration 6).

According to SEWA reuse guidelines [48] the permissible limit for BOD_5 defined for reclaimed GW should not be more than 10 mg/l. This criterion is achieved only for day 7 during the employment of AC, when the influent BOD_5 was observed to

be the minimal (32.4 mg/l) amongst all the 14 days testing period for both AC and GBFS. The effluent BOD_5 values on day 1 and day 4 using AC are identified to be higher from the standard defined by SEWA, hence not achieving the minimum GW requirement. However, during the utilization of GBFS, although influent BOD_5 values are recorded to be higher and fluctuating throughout the testing period, yet the effluent BOD_5 values for all three days were considerably close to the defined SEWA standard. Although, GBFS also failed to achieve the standard criterion, yet the BOD_5 values achieved after the process of adsorption were significantly reduced (20 – 40 mg/l) and closer (≤ 1 mg/l) to the requirement. Overall, GBFS displayed higher potential to reduce BOD_5 of residential greywater in comparison to AC. Figure 4.6 displays the overall percentage removal of BOD_5 for day 1, day 4 and day 7 using AC and GBFS adsorbent. The results showed that the BOD_5 removal efficiency using GBFS adsorbent is higher compared to AC, with percentage removal efficiencies ranging from 76 % – 86 % and 57 % – 75 %, respectively.

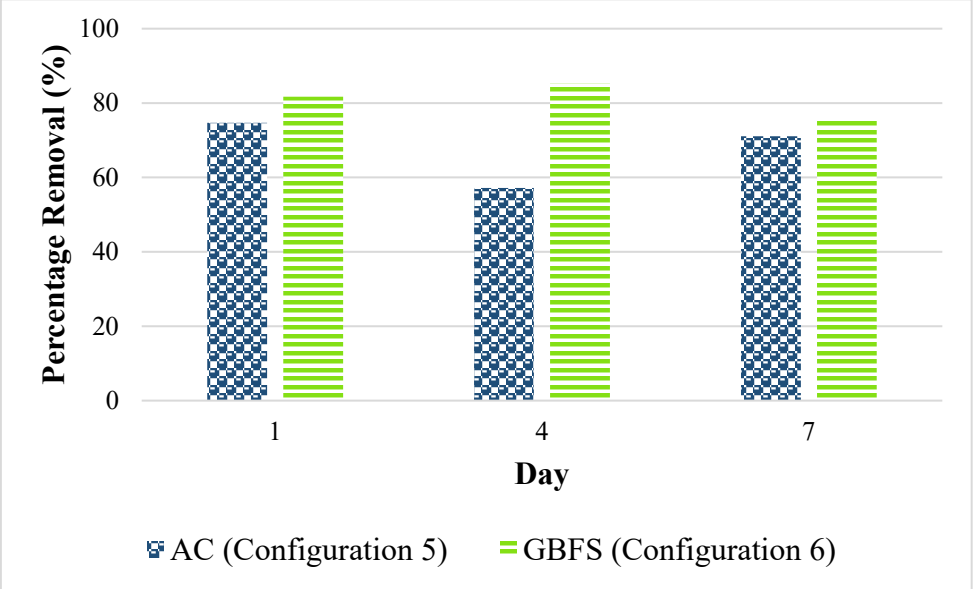


Figure 4.6: Percentage removal efficiency of BOD_5 using AC (Configuration 5) and GBFS (Configuration 6) adsorbent.

In addition to the above, since BOD_5 removal is dependent on microbial activity which is highly sensitive to temperature, hence the impact of temperature on BOD_5 removal is also evaluated and illustrated in Figure 4.7. The influent temperature corresponding to GW entering AC (Configuration 5) and GBFS (Configuration 6)

column ranges between 27.1 – 28.2 °C and 27.1 – 29.2 °C, respectively. The graphical pattern also indicates that with increasing temperature the effluent BOD_5 values have reduced for both the configurations. In addition to this, graphical pattern also demonstrates that the effluent BOD_5 was is measured to be the least (9.4 mg/l) for AC (Configuration 5) when the temperature was highest (28.2 °C). Similarly, the effluent BOD_5 was measured to be highest (15.6 mg/l) when the temperature was lowest (27.1 °C). The same pattern has been observed for GW treated using GBFS adsorbent. The effluent BOD_5 was measured to be the lowest (10.35 mg/l) when the temperature was highest (29.2 °C), whereas, the effluent BOD_5 was measured to be the highest (11.2 mg/l) when the temperature was lowest (27.1 °C).

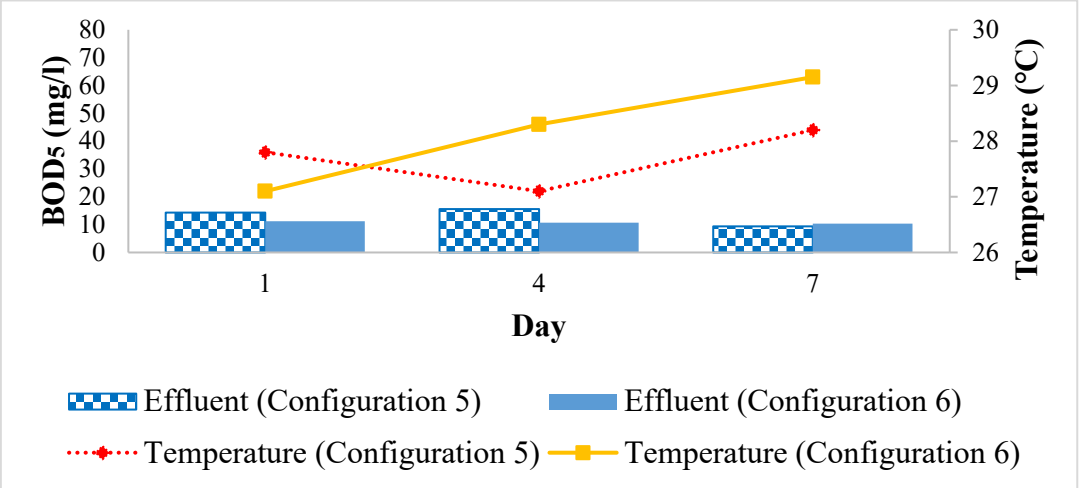
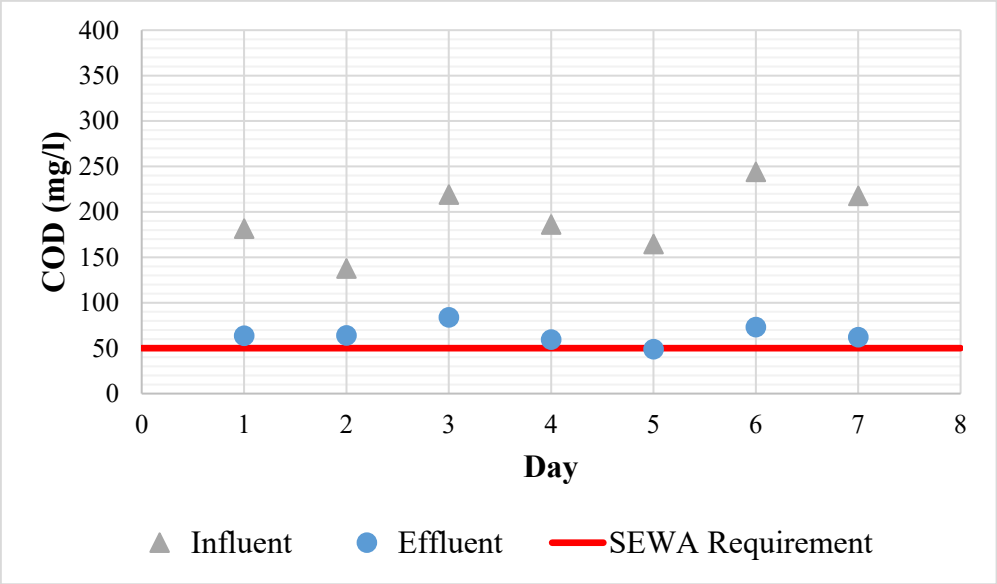


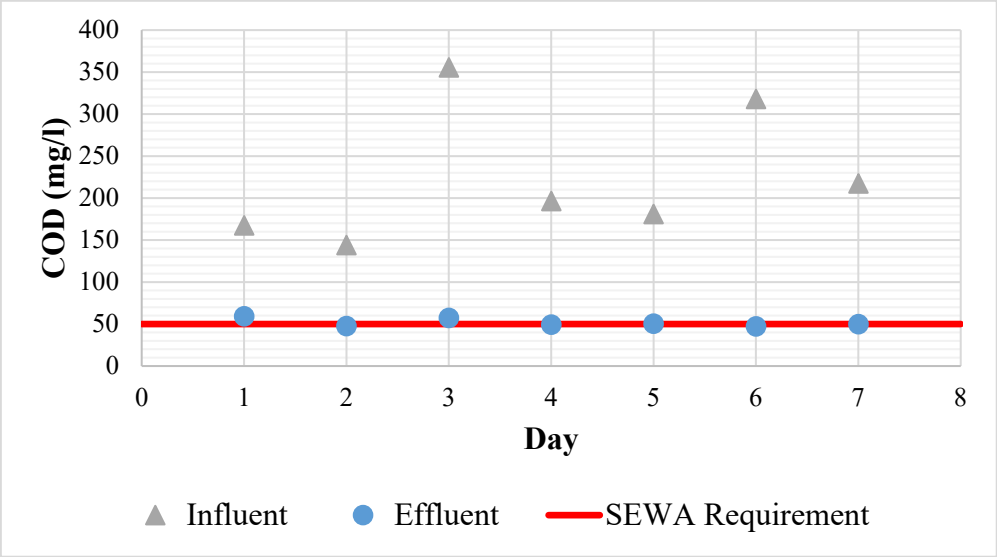
Figure 4.7: Effluent values of BOD_5 for AC adsorbent (Configuration 5) and GBFS adsorbent (Configuration 6) along with their associated temperature.

4.1.3. Chemical Oxygen Demand (COD). COD values of both influent and effluent were measured for both AC (Configuration 5) and GBFS (Configuration 6) and the results are summarized in Figure 4.8, respectively. The maximum COD value recorded (355.5 mg/l) represents the influent for GBFS (Configuration 6). Similarly, the minimum COD value recorded (137.5 mg/l) corresponds to the influent for AC (Configuration 5). It is evident that the influent values are inconsistent and varying every day. These fluctuations are unavoidable and expectable as the GW is directly generated from the residential units with no control measure on the target pollutant. The influent completely represents the physico-chemical characteristics associated with the activities carried out by the building users. Hence, on days when influent COD values

are measured to be higher, it can be hypothesized that the GW is contaminated with high levels of pollutants which could be the result of any human activity including but not limited to usage of household chemicals, detergents, bleaches, beauty products, surfactants and usage of pharmaceutical products [52].



(a)



(b)

Figure 4.8: Influent and effluent values of COD for (a) AC (Configuration 5) and (b) GBFS (Configuration 6).

Published GW strengths indicate that the organic load exerted by a GW can vary significantly depending from one usage to another but normally lies within the range of 77 – 645 mg/l and 386 – 587 mg/l for GW generated from shower and bathroom sink, respectively [37]. The COD values measured under this study is within the range reported in the literature for typical GW characteristic. The effectiveness of both the adsorbents (AC and GBFS) were evaluated by measuring and comparing the initial and residual COD values. Effluent COD values show that both the adsorbents significantly reduced contamination. The maximum COD removed during the application of AC (Configuration 5) and GBFS (Configuration 6) is from 217.5 mg/l to 61.9 mg/l (71.5 %) and 318.0 mg/l to 47.3 mg/l (83.1 %), respectively. Although AC displayed reasonably high removal efficiency, except on day 5 (48.7 mg/l) the residual COD values did not comply with the maximum permissible limit defined by SEWA (≤ 50.0 mg/l) [48]. On the contrary, GBFS successfully achieved the minimum standard requirement for most of the days, except day 1 (59.3 mg/l) and day 3 (57.4 mg/l). It is worth to highlight that, although GBFS could not achieve the permissible requirement for two days, yet the residual COD values are not drastically high (7.4 mg/l and 9.3 mg/l) in comparison to the required limit. It is worth to note that although on day 3 and day 6 the initial COD for GBFS (Configuration 6) is relatively higher than all the days, yet GBFS exhibited excellent removal efficiency with residual COD to be 52 ± 5 mg/l, thereby nearing the criterion. In contrast, AC (Configuration 5) is considerably above the permissible limit for most of the days.

As mentioned earlier, since the influent greywater is directly generated from the residential units with absence of any control on influent parameters, this live scenario substantially introduces variation in initial pollutants to depict on site greywater characteristics. Hence, to comparatively evaluate the performance of both the adsorbents, the overall percentage removal has been measured for 7 consecutive days and the results are summarized in Figure 4.9. Results demonstrated that while both adsorbents were very efficient in reducing the COD, GBFS showed relatively better performance than AC throughout the 7 days. The minimum and maximum percentage removal attained by AC and GBFS are 53.6 – 71.5 % and 64.6 – 85.1 %, respectively. The COD removal efficiency of GBFS is also compared against various other treatment systems and adsorbents reported also in the literature. Studies have reported the COD removal efficiency corresponding to RBC, Wetlands, SBR, MBR, filtration and UASB

treatment systems to be 21 – 61 % [58], 81 – 82 % [56], up to 98 % [52], 80 – 95 % [112], 37 – 94 % [52], 57.8 % [121], respectively. Furthermore, studies have revealed the COD removal efficiencies of various natural materials as mentioned in Table 4.1.

Based on the results achieved in this study, GBFS have displayed higher COD removal efficiency compared to RBC, UASB and some of the filtration treatment systems. In addition, GBFS have also achieved higher removal efficiency against natural materials including moringa oleifera and multimedia filter combining sugarcane bagasse, activated carbon and sand. Lastly, COD removal efficiency reported in the literature which is achieved through the application of pine bark is comparable to the efficiency recorded for GBFS under this study. Overall, GBFS have manifested remarkably well COD removal efficiency under the absence of any pre-treatment process.

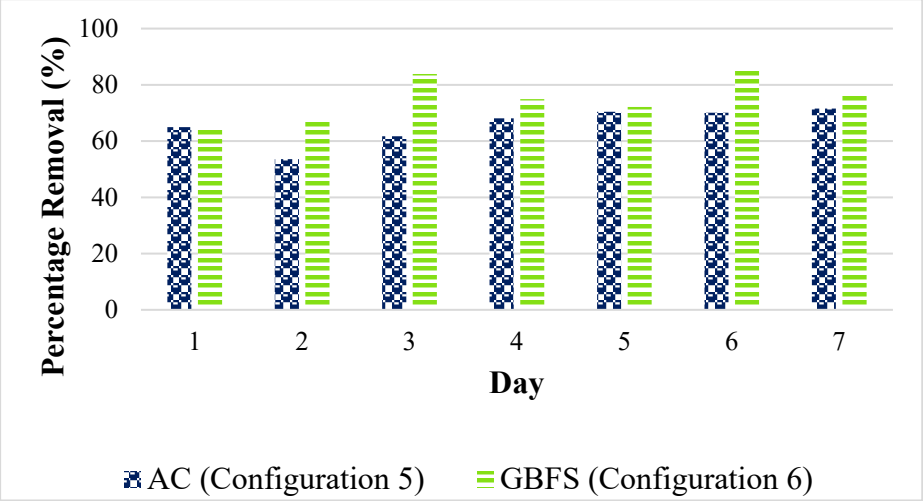


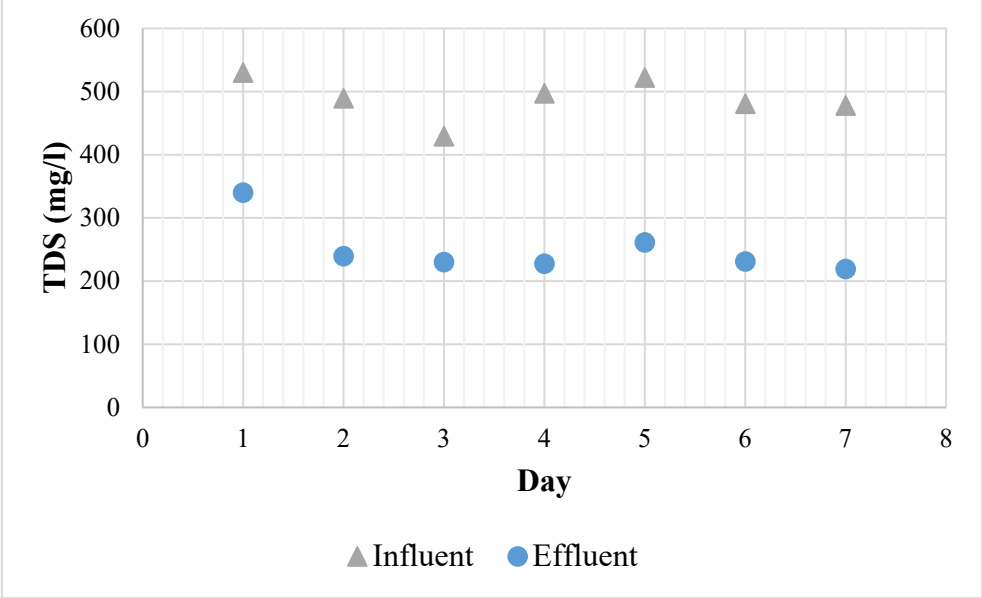
Figure 4.9: Percentage removal efficiency of COD using AC (Configuration 5) and GBFS (Configuration 6) adsorbent.

Table 4.1: COD percentage removal reported in literature and under this study.

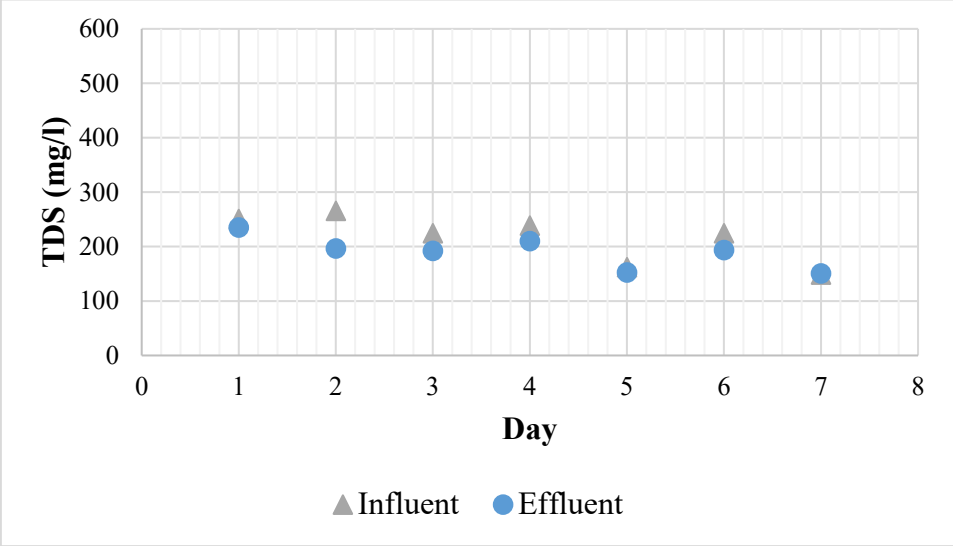
Material	Removal Efficiency	Reference
Banana, orange, sapodilla peel	84 %,87 %,84 %	[115]
Saw Dust	97.47 %	[119]
SB + AC + Sand	61.4 %	[118]
Pine bark	74 %	[54]
SB	91.77 %	[54]
Moringa oleifera	64 %	[122]
AC	53.6 -71.5 %	Under this study
GBFS	64.6 – 85.1 %	Under this study

4.1.4. Total Dissolved Solids (TDS) and Total Suspended Solids (TSS). The evaluation of two parameters including TSS and TDS were quantified and recorded separately for both influent and effluent samples collected for AC (Configuration 5) and GBFS (Configuration 6). Figure 4.10 provides an overall presentation of the measured data for TDS corresponding to AC and GBFS for 7 consecutive days. The results demonstrated that initial TDS values representing AC (Configuration 5) are significantly high, with minimum and maximum value measured to be 429.3 mg/l and 530.0 mg/l, respectively. On the contrary, the initial minimum and maximum value reported for GBFS (Configuration 6) are 148.6 mg/l and 265.7 mg/l, respectively. TDS values are reported in the literature corresponding to typical GW characteristic depending on the source, usage pattern and demographics. According to a study, the typical TDS value associated with GW generated from shower alone lies within a range of 279 – 565 mg/l [37]. In addition, it is also reported that TDS values are typically 565 – 2444 mg/l [123] in low income countries and 119 – 2385 mg/l [124] in high income countries. The initial TDS values measured for all the 14 samples lies within the mentioned typical range reported in the literature for domestic GW. In addition, the residual TDS values were measured to evaluate and compare the efficiency of both AC (Configuration 5) and GBFS (Configuration 6) in removal of TDS. It is evident that although initial TDS were on high side for AC (Configuration 5), the effluent generated post AC adsorption displayed lower TDS values in comparison to GBFS for all the 7 consecutive days. On the contrary, despite the initial TDS values being on lower side for GBFS (Configuration 6), the GBFS displayed poor removal efficiency in the treatment of TDS.

For almost all the days, the effluent TDS values were similar to the influent TDS values post GBFS adsorption. Unexpectedly, GBFS have also contributed in the increase of TDS pollutant by 2 mg/l on Day 7. Under SEWA water reuse guidelines, no restriction has been established for TDS pollutant. In fact, a detailed literature review was conducted in 2013 which explored 14 reuse standards of different countries and organizations, whereby none of them imposed any restricted values on residual TDS [34]. Also, under the USEPA water reuse guidelines, all the states except Florida and Washington D.C did not specify any restricted reuse requirement for TDS pollutant under non-potable application [125].



(a)



(b)

Figure 4.10: Influent and effluent values of TDS for (a) AC (Configuration 5) and (b) GBFS (Configuration 6).

The GW quality under this study reflects the true ground conditions and varies throughout the day as there is no control on the influent pollutant parameter, Figure 4.11 provides an overview of the percentage removal efficiency achieved by each of the adsorbents for 7 consecutive days. It is obvious that AC (Configuration 5) has achieved partial removal of TDS pollutant for all samples throughout the week, with removal efficiencies in the range of 35.8 – 54.2 %. For 5 out of 7 days, the removal efficiency of AC is calculated to be greater 50 %. On the contrary, GBFS

(Configuration 6) achieved very poor removal efficiencies ranging from 0 to 26.0 %. In fact, on Day 7 GBFS displayed negative removal efficiency and increased the effluent TDS slightly (1.3 %) compared to the influent value. Since majority of the reuse guidelines have not defined any restrictive TDS limits for non-potable reuse purpose, therefore, most of the study conducted have not focused on testing TDS pollutant parameter while assessing natural adsorbents or materials.

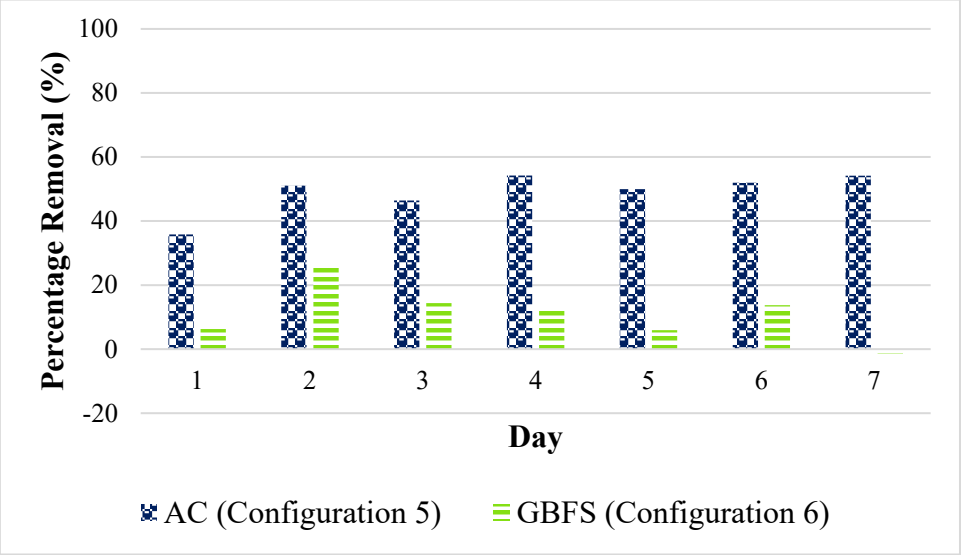
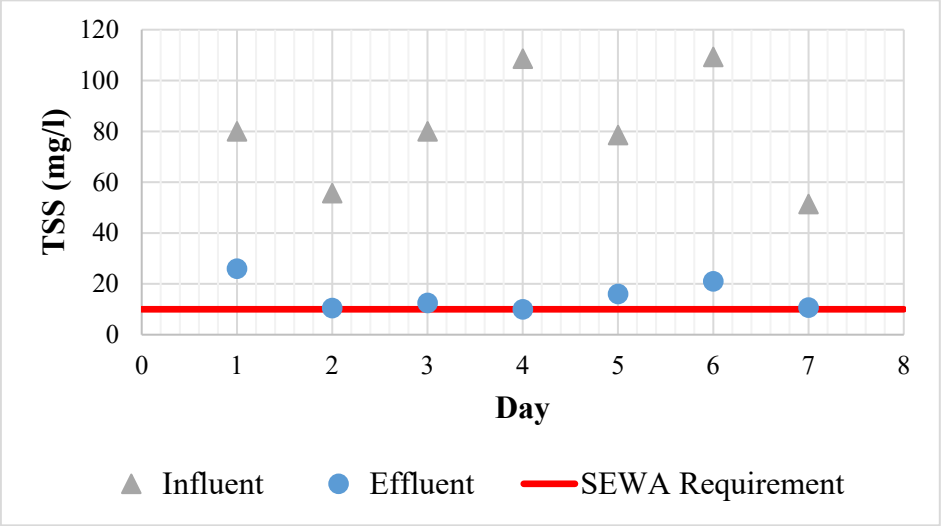


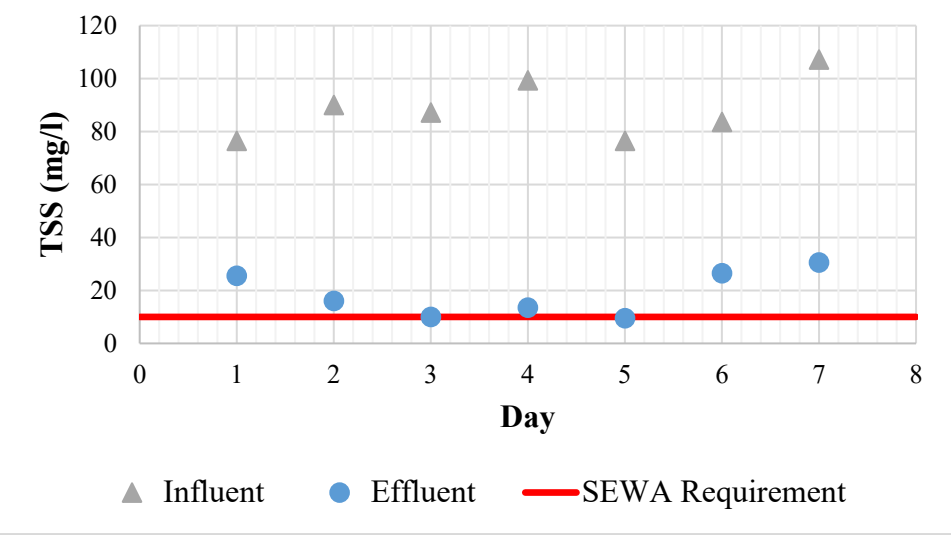
Figure 4.11: Percentage removal efficiency of TDS using AC (Configuration 5) and GBFS (Configuration 6) adsorbent.

Furthermore, Figure 4.12 demonstrates the initial and final TSS values recorded for AC (Configuration 5) and GBFS (Configuration 6). The influent TSS values for both the configurations were seen to be varying significantly every day and fluctuate in the range of 51.4 – 109.3 mg/l and 76.4 – 107.1 mg/l for AC (Configuration 5) and GBFS (Configuration 6), respectively. The maximum influent TSS pollutant level recorded for both the configurations are significantly close and comparable. The measured influent TSS range under this study align with the typical TSS range mentioned in the literature (40 – 120 mg/l) for GW generated from washroom/bath [126]. In order to assess the performance efficiency for AC (Configuration 5) and GBFS (Configuration 6), the post treatment TSS values were also recorded and plotted for 7 consecutive days. It is evident that both AC and GBFS have displayed excellent removal capacity, as significant reduction in TSS values are observed in the effluent. The TSS measured post AC and GBFS treatment vary in the range of 10 – 26 mg/l and

9.5 – 30.5 mg/l, respectively. With these recorded values, it can also be concluded that the performance efficiency of both the adsorbents in reducing TSS pollutant is significantly similar and comparable. As per SEWA reuse guidelines, the TSS values are required to be maintained at lower than 10 mg/l [48] for non-potable reuse purpose. Although this criterion has not been met for all the days, yet it is significant to highlight that, both AC and GBFS have met this criterion for two days and also generated TSS values closer to the standard requirement for most of the days without the implementation of any prefiltration treatment.



(a)



(b)

Figure 4.12: Influent and effluent values of TSS for (a) AC (Configuration 5) and (b) GBFS (Configuration 6).

In order to provide an enhanced overview and performance comparison between AC (Configuration 5) and GBFS (Configuration 6), Figure 4.13 is plotted to illustrate the TSS percentage removal efficiency achieved for 7 days by both the adsorbents under study. Both AC and GBFS has achieved comparable removal efficiencies, varying in the range of 67.7 – 90 % and 66.6 – 88.5 %, respectively. According to the literature, the TSS removal efficiency various depending on the treatment system or type of material exercised for the treatment of GW. Under the category of treatment systems, constructed wetlands reported to exhibit high TSS removal efficiencies (90 – 98 %) and are well recognized to produce effluent quality that meets TSS regulatory requirements [56]. On the contrary, RBC treatment systems demonstrate poor TSS removal efficiency (9 – 12 %), thereby demanding infusion of other techniques to enhance removal efficiency to generate effluent quality that meets the regulatory requirement [58]. Apart from the treatment systems, several other adsorbents and materials are studied to reveal their performance ability in removal of TSS including Moringa oleifera (88 %) [127], saw dust (83 %) [128], banana peel (90 %), orange peel (86 %), sapodilla peel (83 %) [115], and multimedia filter comprising of activated carbon, rice husk and sugarcane bagasse (58.4 %) [118]. The overall TSS removal efficiency identified over a period of 7 days for both AC and GBFS adsorbents and its comparison to the performance of other materials reported in the literature concludes that the adsorbents under this study are efficient in removal of TSS. This removal efficiency maybe further enhanced with the support of pre-treatment to meet the SEWA restriction requirement.

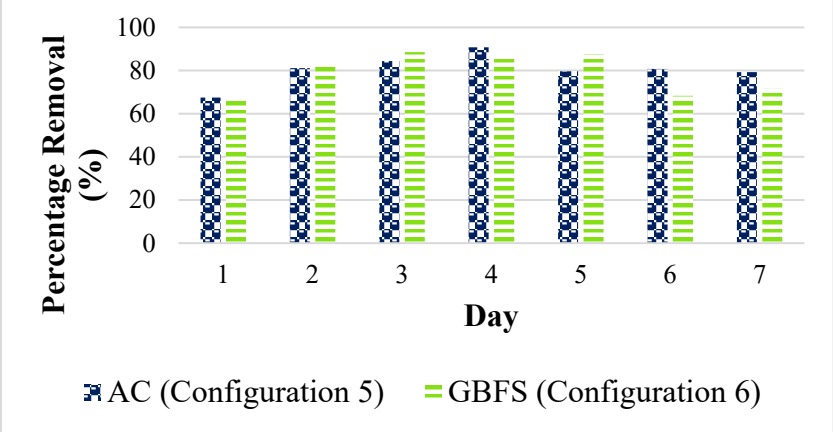
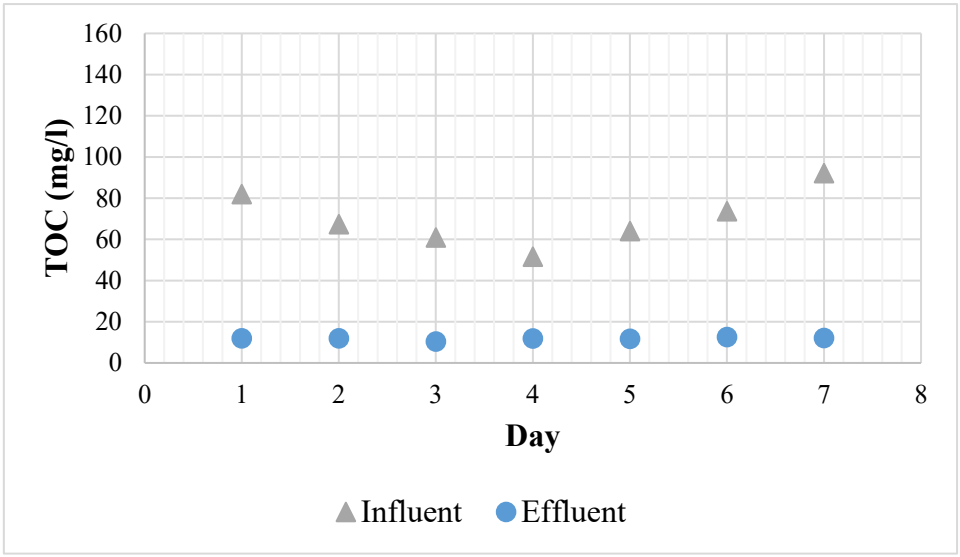


Figure 4.13: Percentage removal efficiency of TSS using AC (Configuration 5) and GBFS (Configuration 6) adsorbent.

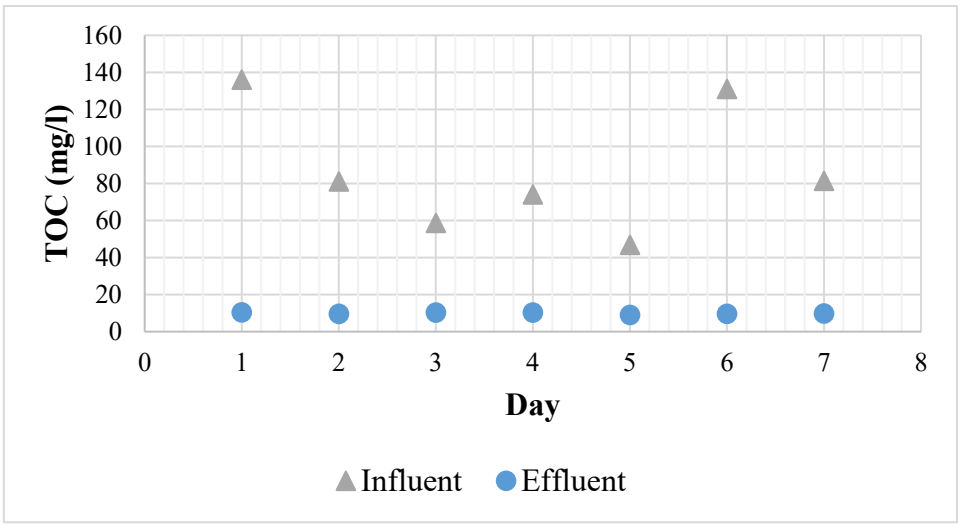
4.1.5. Total Organic Carbon (TOC). Another key pollutant evaluated under this study is TOC. Figure 4.14 displays the influent and effluent TOC values recorded for both AC (Configuration 5) and GBFS (Configuration 6). As the study is being carried out focusing on treating on site GW without any control on influent pollutant, this is evident from the significantly varying initial TOC values for both the configurations. The influent TOC values represent the true residential GW characteristic and usage pattern. The initial TOC values recorded for AC (Configuration 5) and GBFS (Configuration 6) fluctuate in the range of 51.6 – 92.1 mg/l and 46.8 – 136 mg/l, respectively. The influent TOC values exhibited variation for both the configurations, however, a higher invariability in the values have been identified for the influent received by GBFS (Configuration 6). The influent TOC values evaluated and mentioned in a study for GW generated from shower/bath and washbasin are 100 – 104 mg/l and 30 mg/l, respectively [30]. Another study identified and summarized the typical influent TOC range for low- and high-income countries to be 32.6 – 92.0 mg/l and 43 – 582 mg/l, respectively [37]. The initial TOC values identified under this study are in line with the TOC values recorded in the literature. Minor disparity in the measured range is expectable as the physico-chemical characteristics of the GW is extremely sensitive to many factors including user age, number of users, culture, demographics, season and time of day to label a few [37].

To evaluate the effectiveness of adsorbents under this study, the TOC effluent values post AC (Configuration 5) and GBFS (Configuration 6) treatment were also measured and charted for 7 consecutive days. Results demonstrated that both AC and GBFS performed efficiently in removing organic carbon from the GW by achieving low TOC values in the effluent. The final TOC values were measured to be varying between the range of 10.4 – 12.5 mg/l and 8.9 – 10.4 mg/l, for AC and GBFS, respectively. No restricted requirements have been underlined by SEWA authority regarding the effluent TOC concentration for reuse purpose. Likewise, a study conducted to explore global reuse guidelines also did not report any restricted TOC values [34]. Also, under the USEPA water reuse guidelines, none of the states specified any restricted reuse requirement for TOC pollutant under non-potable use [125]. Although there is no assigned limiting value or criterion for non-potable reuse purpose as it does not pose direct health concern, yet it can lead to formation of undesirable by products when in contact with chlorine during process of disinfection. Hence, targeting

reduced TOC pollutant in the reclaimed water is a key advantage to reduce the potential formation of disinfection by products (DBP's).



(a)



(b)

Figure 4.14: Influent and effluent values of TOC for (a) AC (Configuration 5) and (b) GBFS (Configuration 6).

In addition, to provide a holistic view and comparison on the performance of AC (Configuration 5) and GBFS (Configuration 6) the percentage removal for TOC pollutant has been measured for all 7 consecutives utilizing pre and post treatment pollutant values. Figure 4.15 illustrates the overall removal efficiency achieved by both the adsorbent from day 1 to day 7. It is evident that both AC and GBFS adsorbents

displayed excellent removal efficiencies by achieving percentage removal between 76.9 – 86.8 % and 80.6 – 92.7 %, respectively. It is crucial to underline that the percentage removal have wide limits for both the adsorbents mainly due to the variation in the influent TOC levels. The reclaimed water produced by both the adsorbents display decent and almost consistent values for TOC pollutant, thereby concluding that the removal is almost uniform throughout the period of 7 days. Nevertheless, GBFS have proven to treat TOC more effectively than AC on almost all days, however, the results are significantly close and highly comparable for both the adsorbents.

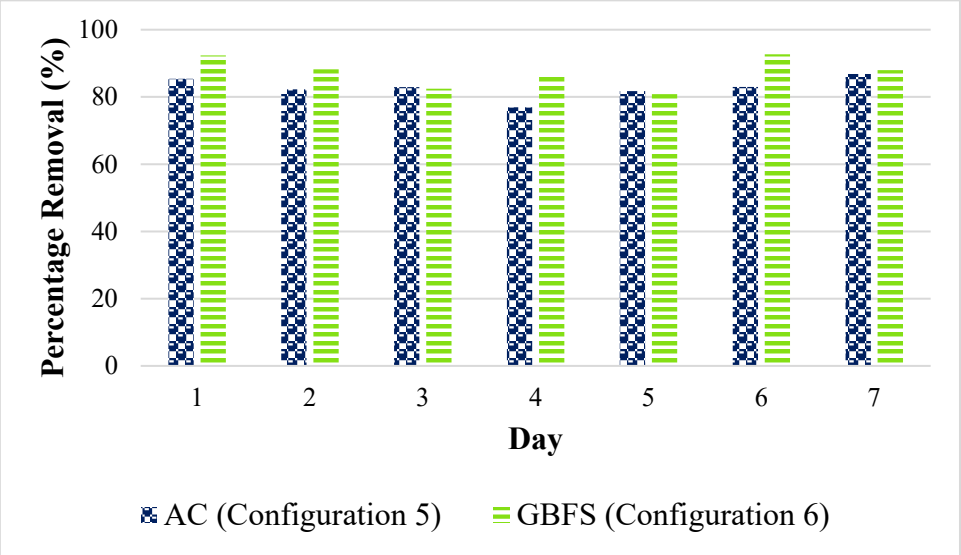


Figure 4.15: Percentage removal efficiency of TOC using AC (Configuration 5) and GBFS (Configuration 6) adsorbent.

4.2. Effect of sand filter (pre-treatment) combined with GBFS on reclaimed water quality

This section of the report evaluates the influence of pre-treatment (sand filtration) followed by adsorbent (GBFS) on residual pollutants values for turbidity, TSS, BOD and TOC. To assess the impact, the influent and residual target pollutant values recorded corresponding to Configuration 3 (sand filtration and GBFS adsorbent) and Configuration 6 (GBFS adsorbent alone without sand filtration) were compared. The comparison evaluation is detailed in the below sub-sections.

4.2.1. Aesthetic quality and turbidity. Figure 4.16 illustrates the day 1 aesthetic quality of both the influent and effluent corresponding to pre-treatment system combining sand filtration and GBFS adsorbent (Configuration 3) and GBFS adsorbent

alone without any pre-treatment (Configuration 6). From the initial aesthetic assessment, it can be concluded that the influent received by GBFS adsorbent alone without pre-treatment (Configuration 6) has high level of suspended solids and display more turbidity on day 1 in comparison to the influent received by the treatment system having sand filtration and GBFS (Configuration 3). On the other hand, the aesthetic effluent quality produced by both the configurations (with pre-treatment and without pre-treatment) are highly comparable. Under the naked eye, there were no visible signs of suspended solids in the reclaimed water for either of the configurations. Additionally, it is evident that both configurations have produced water quality that is translucent and see through without any noticeable suspension of solids. Solely based on visual analysis for day 1 sample, it can be projected that GBFS alone without pre-treatment (Configuration 6) have the potentials to efficiently remove suspended solids and turbidity equally in comparison to treatment systems that are installed to have sand filtration as pre-treatment along with GBFS adsorbent (Configuration 3).

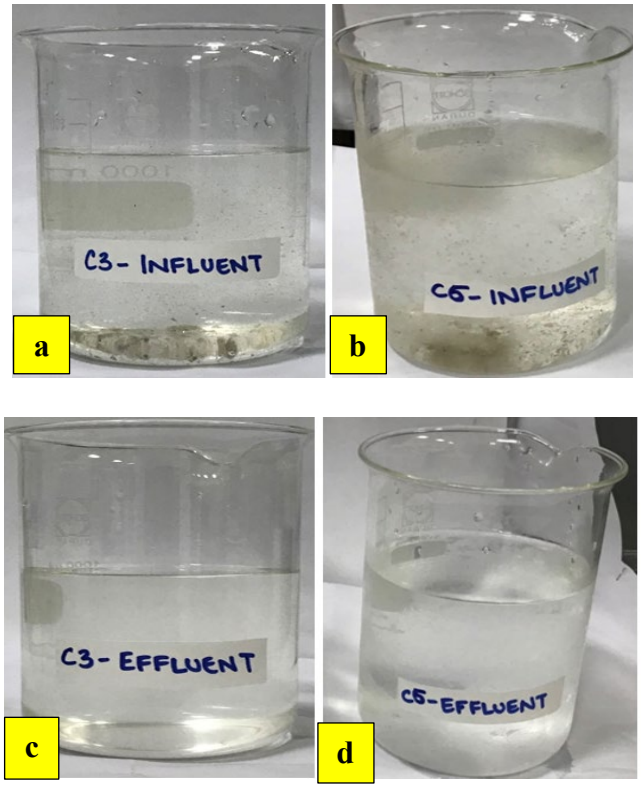


Figure 4.16: Day 1 sample representing (a) influent for pretreatment and GBFS (Configuration 3) (b) influent for GBFS without pretreatment (Configuration 6) (c) effluent for pretreatment and GBFS (Configuration 3) and (d) effluent for GBFS without pretreatment (Configuration 6).

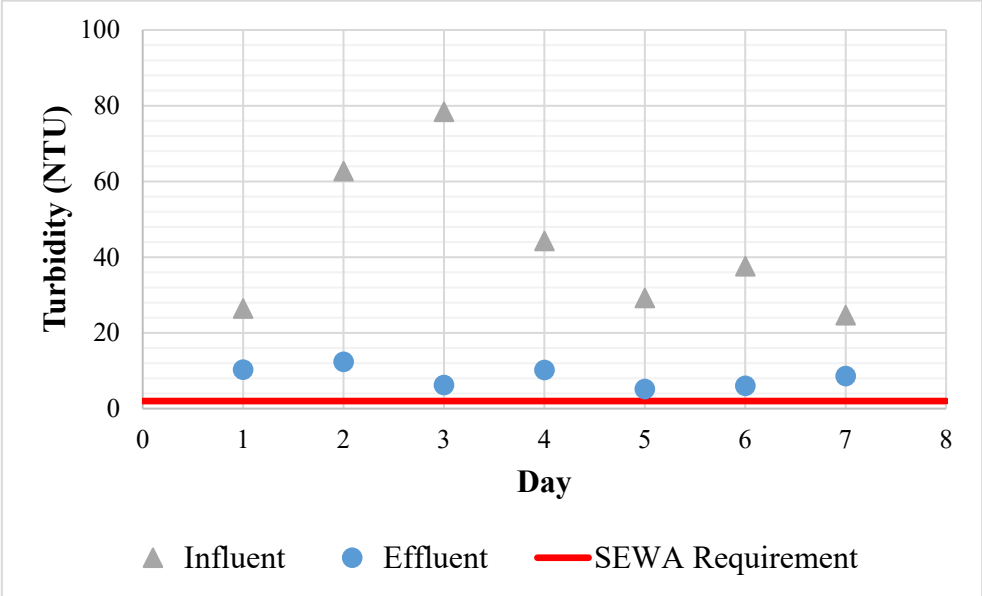
To validate the visual analysis, the initial and residual turbidity is measured for both the configurations for 7 consecutive days and plotted in Figure 4.17. Results for day 1 supported the visual analysis, as the influent turbidity is measured to be higher corresponding to the system installed with only GBFS adsorbent without pre-treatment (Configuration 6) compared to combined system of sand filtration and GBFS adsorbent (Configuration 3), with values measured to be 67.0 NTU and 10.3 NTU, respectively. Additionally, it is also evident that except day 3, for all the other days the turbidity is recorded to be significantly higher (70 ± 10 NTU) for influents conveyed to treatment system with GBFS adsorbent (Configuration 6) in contrast to influent received by system with pre-treatment facility (Configuration 3). However, the influent corresponding to system with pre-treatment (Configuration 3) displayed greater variations in initial turbidity levels with minima and maxima recorded to be 24.7 – 78.4 NTU, compared to system with no pre-treatment (Configuration 6) with values varying in a range of 60.7 – 74.5 NTU.

Results also demonstrated that, although influent turbidity values for GBFS adsorbent without prefiltration (Configuration 6) were high, yet the residual turbidity displayed more consistency with values in the range of 5.9 – 6.6 NTU. On the contrary, although the system installed with sand filtration and GBFS (Configuration 3) received lower initial turbidity (50 ± 20 NTU), yet the residual exhibited to have higher turbidity values fluctuating in the range of 12.4 – 5.2 NTU, with most values above 8 NTU. Figure 4.18 illustrates the comprehensive performance of both the configurations by displaying the percentage removal efficiency achieved by the configurations on each day for 7 consecutive days.

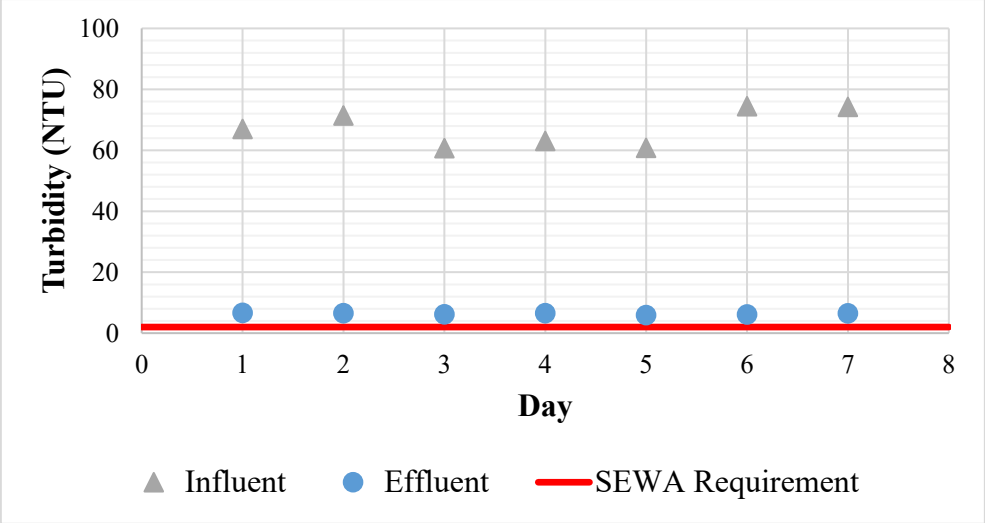
GBFS alone (Configuration 6) achieved higher and nearly consistent removal efficiency for almost all the days, except day 3. Even though the percentage removal for GBFS alone (Configuration 6) for day 3 is lower, yet the residual turbidity measured for effluent from GBFS alone displayed better results (6.1 NTU) compared to residual values measured for effluent treated using sand filtration and GBFS (6.3 NTU). The only reason percentage removal is measured to be more for pre-treatment system (Configuration 3) on day 3 is because on this day the influent sample was recorded to have the highest initial turbidity (78.4 NTU) in comparison to influent received by GBFS system without sand filtration (60.7 NTU). Overall, the percentage removal

displayed high span range for residual turbidity of reclaimed water treated using sand filtration and GBFS system (61 – 92.1 %), in comparison to the reclaimed water produced by GBFS alone (89.6 – 92 %). The results achieved under this study indicates that inclusion of pre-treatment using sand filtration did not improve the turbidity removal efficiency when combined with GBFS.

However, this conclusion does not align with common findings and understanding that pre-treatment does aid in suspended solids (SS) removal which subsequently should improve the turbidity. In addition to this, Section 4.2.2. studies the impact of pre-treatment on SS removal. It was found that reclaimed water produced from the system having sand filter and GBFS (Configuration 3) enhanced the SS removal in comparison to the GW produced using GBFS alone (Configuration 6). As mentioned earlier, turbidity is a direct indicator of SS, hence, reduction in SS should also reflect reduction in turbidity levels. However, this common relation between turbidity and SS was not established with the results quantified under this study. Hence, the effect of pre-treatment using sand filtration combined with GBFS in turbidity removal remains inconclusive. Further study is required to determine why the turbidity values were high when using the pre-treatment step.



(a)



(b)

Figure 4.17: Influent and effluent values of turbidity for (a) sand filtration and GBFS adsorbent (Configuration 3) (b) GBFS adsorbent alone (Configuration 6).

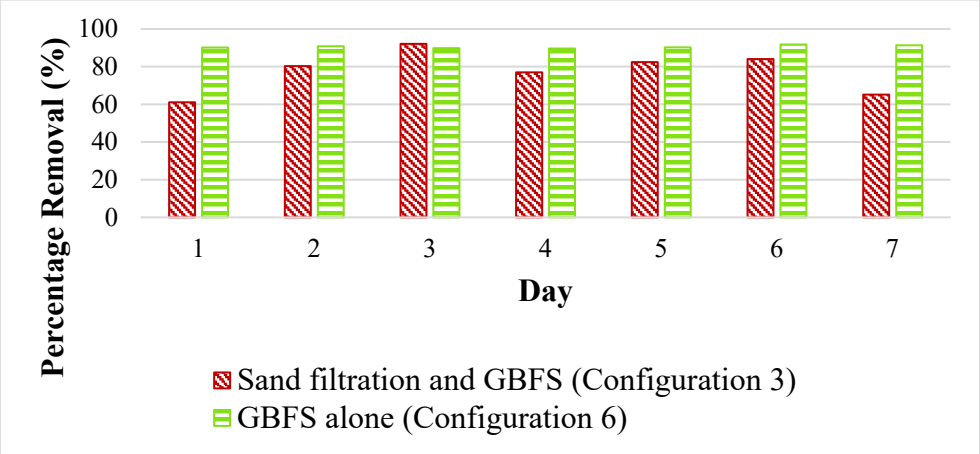
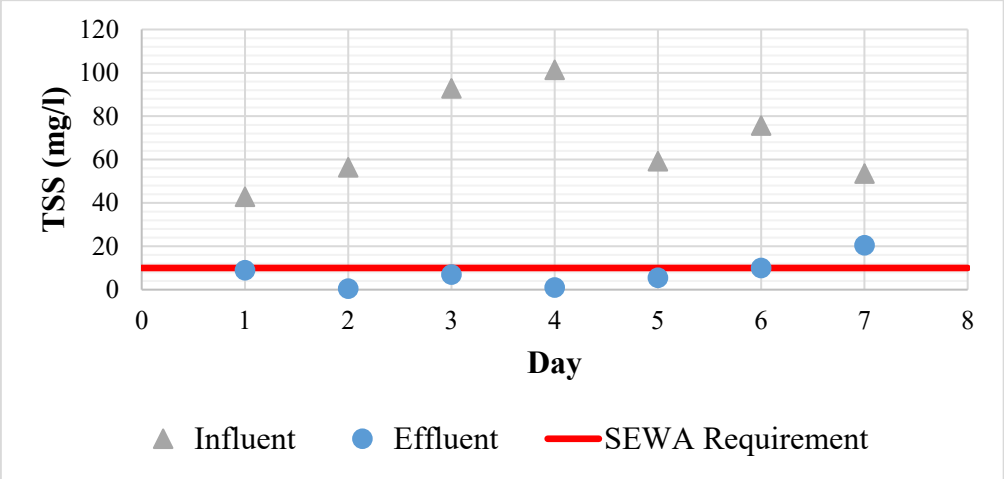


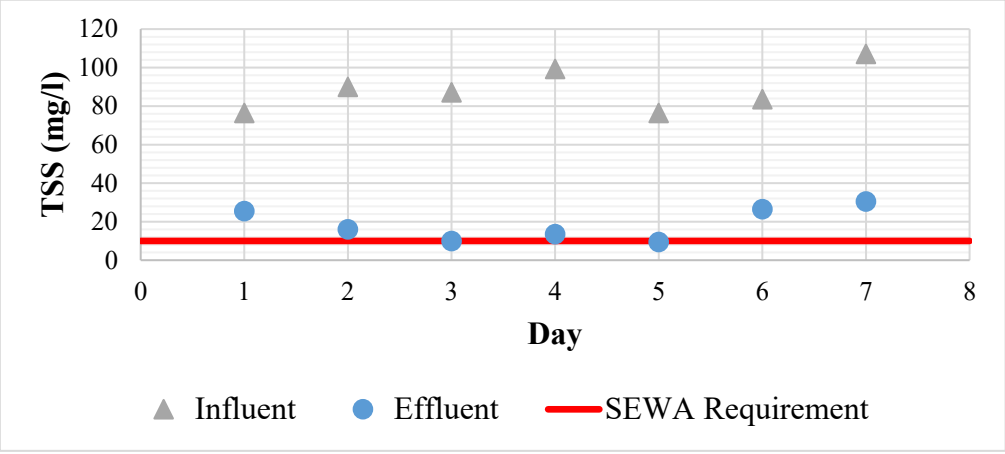
Figure 4.18: Percentage removal efficiency of turbidity using sand filtration and GFBS adsorbent (Configuration 3) and GBFS adsorbent alone (Configuration 6).

4.2.2. Total suspended solids (TSS). The influent and effluent values measured for both the configurations are represented in Figure 4.19. Results demonstrated that the influent TSS values varied for both the configurations, with values of 42.9 – 101.4 mg/l and 76.4 – 107.1 mg/l for system with and without pretreatment, respectively. Although there is a significant difference in the minima value (± 35 mg/l), however, the highest TSS recorded for both the configurations significantly comparable (± 6 mg/l). In addition to it, it is noticed that the initial TSS values corresponding to GBFS system (Configuration 6) were higher for most of the

days (> 80 mg/l) in contrast to TSS values (< 80 mg/l) recorded for sand filtration and GBFS system (Configuration 6). Since the treatment system is installed to receive onsite GW without any control on pollutant parameter, this variation in the TSS values are highly anticipated and predictable. Results also depicted that; the system installed with sand filtration as pretreatment along with GBFS adsorbent (Configuration 3) produced an effluent with TSS ranging from 0.5 – 20.5 mg/l. In addition, the residual TSS values measured for GBFS alone (Configuration 6) were recorded to be in the span of 9.5 – 30.5 mg/l. These effluent TSS values indicate that pretreatment using sand filtration has enhanced the effluent quality by increasing the removal of TSS by approximately 11.0 mg/l (or 8.2 %).



(a)



(b)

Figure 4.19: Influent and effluent values of TSS for (a) Sand filtration and GBFS adsorbent (Configuration 3) and (b) GBFS adsorbent alone (Configuration 6).

To provide a comprehensive evaluation on the overall performance efficiency of both the configurations, the percentage removal efficiency for TSS pollutant was calculated for 7 consecutive days and is illustrated in Figure 4.20. As anticipated from the influent and effluent values recorded for both the configurations, sand filtration combined with GBFS adsorbent (Configuration 3) displayed high removal efficiency for all the 7 days. The removal efficiency achieved by application of pretreatment and without pretreatment are calculated to be 61.7 – 99.1 % and 66.6 – 88.5 %, respectively. Although the span range for removal efficiency achieved for reclaimed water produced using sand filtration and GBFS adsorbent (Configuration 3) is large (± 30 %), yet it is evident that except for day 7, the removal efficiency achieved is ≥ 80.0 %. Both configurations achieved the minimum reduction in removal efficiency on day 7, which could be the result of exhaustion or clogging of the filter media due to its continuous operation for 7 consecutive days. Studies have reported that the removal efficiency of stand-alone sand filtration is not very effective in the removal of TSS, however, if coupled with other treatment media including membrane, the effluent produced by the system would be of high quality, as sand filtration is efficient in the removal of bigger and coarse particles [129]. Another study evaluated TSS removal efficiency utilizing sand filtration and reported to achieve reduction level of 70.7 % [130]. There is no single conclusion to the effectiveness of sand filtration because the treatment efficiency completely depends on the design and type of sand filter utilized [131]. Under this study, the addition of sand filtration prior to GBFS adsorbent, is concluded to be effective in reducing residual TSS.

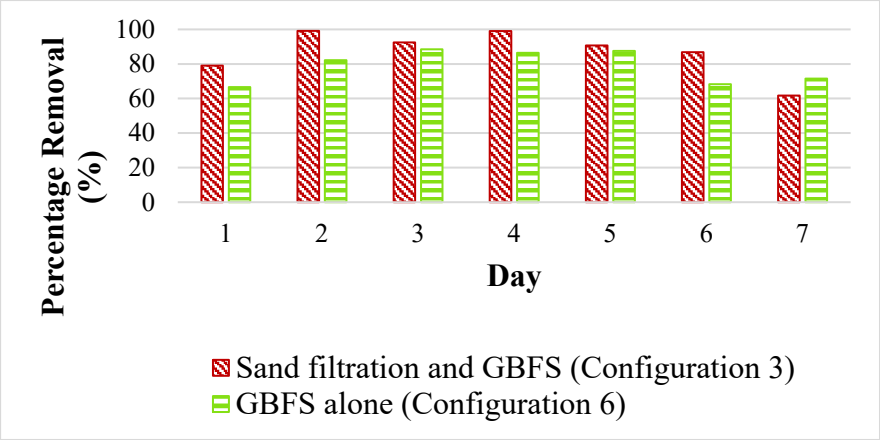
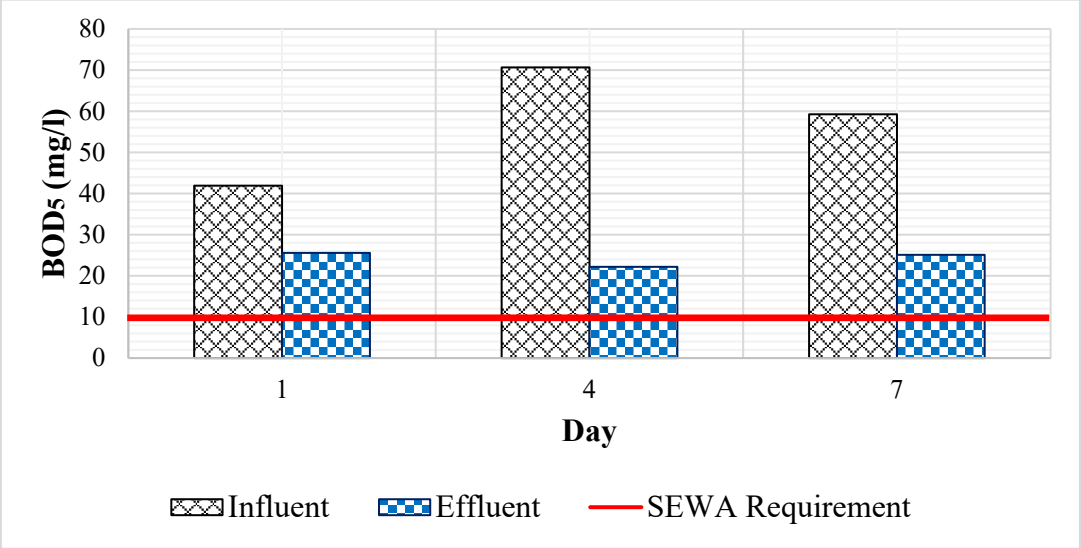
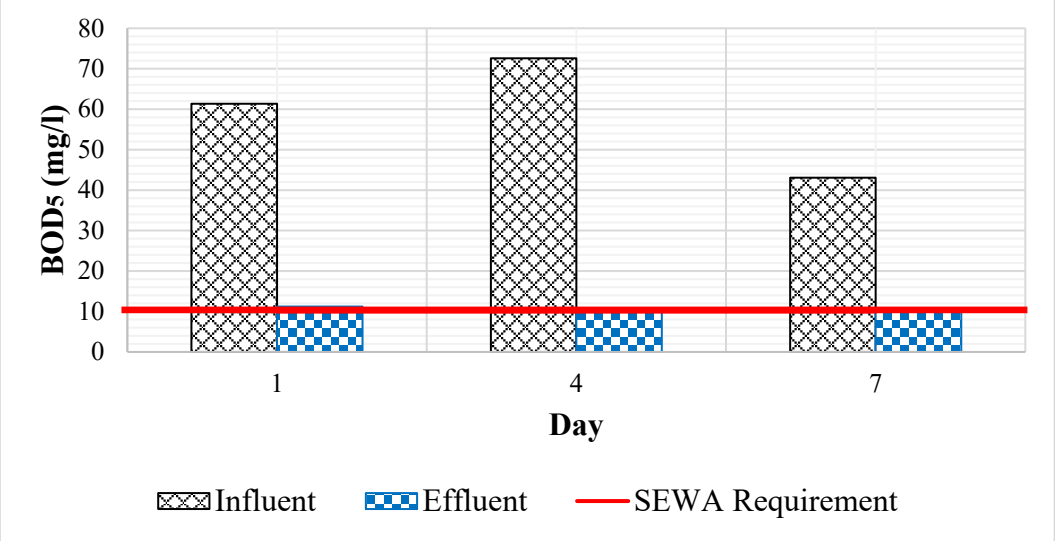


Figure 4.20: Percentage removal efficiency of TSS using sand filtration and GFBS adsorbent (Configuration 3) and GBFS adsorbent alone (Configuration 6).

4.2.3. Biochemical oxygen demand (BOD_5). The influent and effluent BOD_5 values measured for the configurations with pretreatment (Configuration 3) and without pretreatment (Configuration 6) are illustrated in Figure 4.21.



(a)



(b)

Figure 4.21: Influent and effluent values of BOD_5 for (a) Sand filtration and GBFS adsorbent (Configuration 3) and (b) GBFS adsorbent alone (Configuration 6).

The influent BOD_5 values quantified for both the configurations are highly similar and recorded to be in the range of 41.9 – 70.7 mg/l and 43.0 – 72.6 mg/l, for

sand filtration with GBFS adsorbent (Configuration 3) and GBFS adsorbent alone (Configuration 6), respectively. Despite the similarity in influent pollutant value, the effluent produced by both the configurations displayed significant difference (±15 mg/l) in residual BOD_5 value. It is evident from the results plotted that GBFS alone (Configuration 6) produced effluent with much lower and consistent BOD_5 with values ranging between 10.4 – 11.2 mg/l. Whereas, the residual BOD_5 measured for the reclaimed water produced utilizing sand filtration and GBFS adsorbent (Configuration 3) were more than double (22.2 – 25.6 mg/l) compared to GW treated using GBFS alone (Configuration 6). No literature has been found that reports the contribution of sand filtration in increasing the BOD_5 levels post treatment. Since BOD_5 mainly focuses on breakdown and removal of organic matter using aerobic biological organisms, hence the removal efficiency of BOD_5 is highly sensitive to temperature under which the microorganisms can thrive and work effectively [92]. Hence, to establish the relation between BOD_5 removal efficiency and temperature under this study, Figure 4.22 is plotted to display the effluent BOD_5 levels for both the configuration (with and without pretreatment) along with their corresponding temperature recorded on site at the time of sampling.

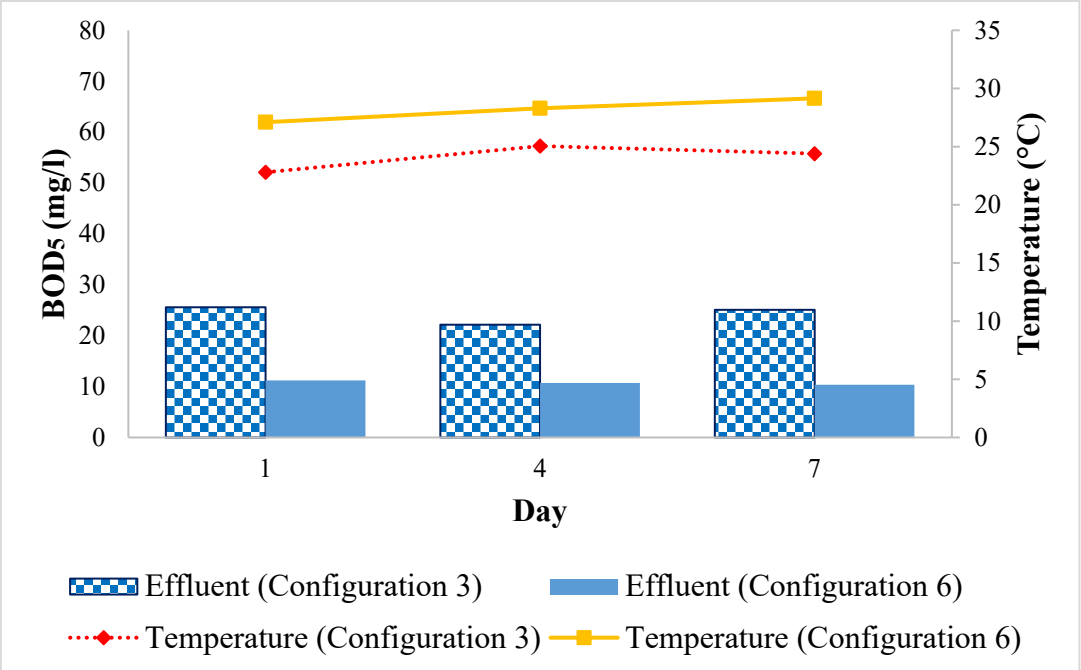


Figure 4.22: Influent and effluent values of BOD_5 for sand filtration and GBFS adsorbent (Configuration 3) and GBFS adsorbent alone (Configuration 6) along with their associated influent temperature.

Influent temperature values for GW corresponding to sand filtration and GBFS adsorbent were recorded to be lower (22.8 – 25.1 °C) compared to the influent received by GBFS alone (27.1 – 29.2 °C). In addition to this, the graphical pattern demonstrates that the BOD_5 removal efficiency increased along with increase in temperature and vice versa for both the configurations. For effluent undergone pretreatment (Configuration 3), the highest temperature recorded (25.1 °C) displayed the lowest residual BOD_5 (22.17 mg/l), while the lowest temperature recorded (22.8 °C) displayed highest residual BOD_5 of (25.6 mg/l). The same pattern was observed for GW that underwent GBFS treatment. However, since the overall influent temperature value for GBFS was higher (± 5°C), the residual BOD_5 was lower for the effluent produced by GBFS alone (Configuration 6). A study conducted to assess the impact of temperature on BOD_5 removal reported that the BOD_5 removal efficiency was significantly improved from 64 % to 78 %, with increasing influent temperature from 18°C and 32°C, respectively [132]. Another study has reported that, the optimum temperature which achieved highest removal BOD_5 efficiency (89.6 %) is recorded to be 30°C [133]. Hence, the relationship between BOD_5 removal efficiency obtained under this study is in line with the relationship reported in the literature.

4.3. Performance comparison of GBFS with pre-treatment (Configuration 3) and without pre-treatment (Configuration 6) and potential impact on THMs formation

One of the key objectives under this study is to comprehensively evaluate the performance efficiency of GBFS as an adsorbent. Based on the observations and evidences reported in the literature regarding necessitating the requirement of pretreatment to reduce potential THMs production, hence this section of the report targets to assess GBFS performance by comparing (i) the initial and residual TOC values generated with the implementation of pretreatment using sand filtration (SF) process following GBFS adsorption (Configuration 3) and (ii) the initial and residual TOC values generated using GBFS alone as an adsorbent without any pretreatment of the influent (Configuration 6). The pretreatment process involves filtration of the raw influent utilizing sand filtration column. A detailed TOC assessment using GBFS without pretreatment (Configuration 6) has already been evaluated and justified under Section 4.1.5. of this report. In addition, for ease of comparison Figure 4.23 represents the overall summary of initial and residual TOC levels measured for the GW samples

corresponding to Configuration 3 (SF and GBFS) and Configuration 6 (GBFS with no pretreatment).

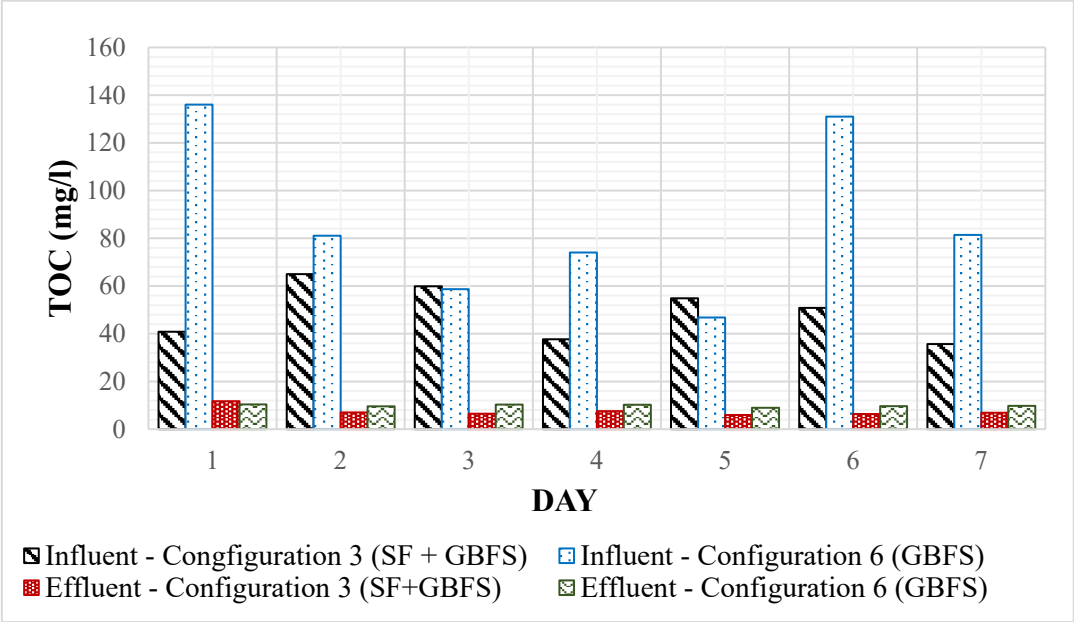


Figure 4.23: Influent and effluent TOC concentration for samples generated from (i) sand filtration (SF) and GBFS treatment (Configuration 3) and (ii) GBFS with no pretreatment (Configuration 6).

The results demonstrated that the influent TOC values measured for the samples corresponding to GBFS without pre-treatment (Configuration 6) varied significantly and generated a wide range from 46.8 – 136 mg/l. On the contrary, the influent TOC received by combined system of SF and GBFS (Configuration 3) also displayed fluctuations (51.6 – 91.2 mg/l) yet the range was not as significant as in samples for GBFS without pre-treatment (Configuration 6). Although, both the systems displayed inconsistent initial influent values and high variability in TOC range, the reclaimed water post treatment from both the configuration; with and without pre-treatment generated highly comparable and consistent results. Residual TOC values obtained by application of pre-treatment and no pre-treatment was measured to be 5.9 – 11.7 mg/l and 8.9 – 10.4 mg/l, respectively. Based on these effluent values, it can be concluded that the application of pre-treatment using sand filtration has improved the TOC removal efficiency (1 – 3 mg/l) compared to utilization of GBFS adsorbent alone. Simultaneously, the percentage removal efficiency for both the treatment systems are presented in Figure 4.24.

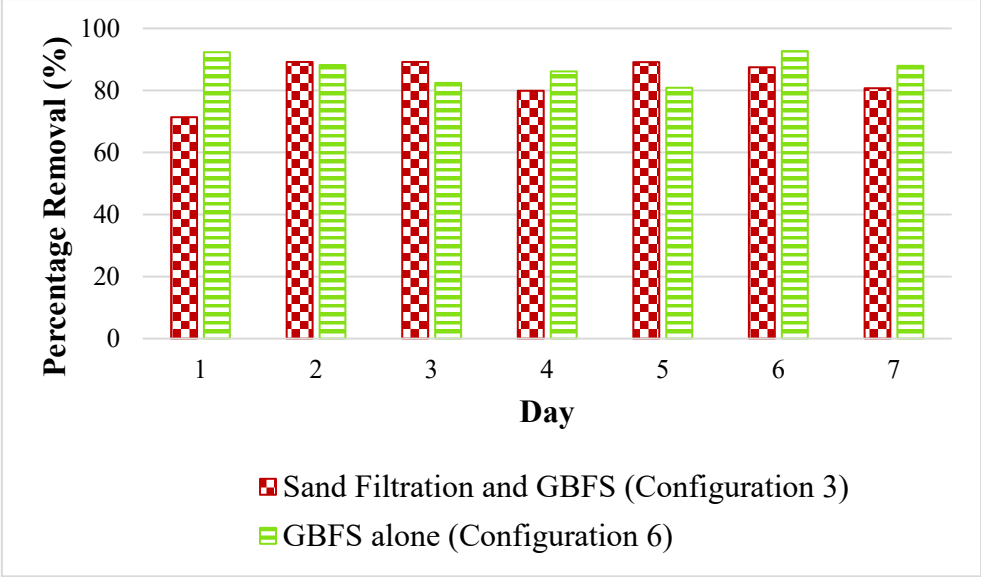


Figure 4.24: Percentage removal efficiency of TOC using pretreatment SF+GBFS (Configuration 3) and no pretreatment (Configuration 6).

The comparable and consistent pattern reflected in the reclaimed TOC values is also exhibited in the percentage removal efficiency. SF and GBFS system (Configuration 3) displayed a removal efficiency of 71.4 – 89.2 %, whereas, the removal efficiency for GBFS alone (Configuration 6) is measured to be 80.9 – 92.3 %. However, it is important to highlight that, the large percentage removal difference portrayed between pre-treatment (Configuration 3) and no pre-treatment (Configuration 6) systems on day 1, is introduced due to the elevated difference in the influent TOC values received by both the configurations. Hence, although the percentage difference may seem large and misinterpret the performance efficiency, yet the final effluent values serves as a datum to determine the effectiveness of the system with and without pre-treatment. The removal efficiency and effluent quality produced focusing on TOC levels alone using SF as pretreatment with GBFS versus GBFS alone is evidently similar and highly comparable. However, it also is critical to underline that GBFS alone (Configuration 6) have displayed consistent and high TOC removal efficiency despite the significant variations and high initial TOC values in contrast SF and GBFS system (Configuration 3). The TOC removal efficiency achieved by both the configurations are comparable to the removal efficiencies reported in the literature and identified under Section 2.7. of this report for RO and NF.

Overall, although the GW under this study reflected on site condition and measured to have varying TOC pollutant values for 7 consecutive days, yet the residual TOC values achieved by both the configurations displayed excellent reduction levels. Since TOC is a measurable indicator of NOM, which is a precursor of DBPs formation, therefore reductions in TOC levels can directly conclude potential reductions in DBPs formation, hence reducing the risk to public health. Since GBFS achieved to reduce precursor for DPBs, this could establish basis for carrying out further studies whereby utilizing GBFS adsorbent for treatment of DPBs itself. Also, impact of sand filtration (pre-treatment) was noticeable on TOC values, therefore this experimental analysis also concludes that addition of pre-treatment could further enhance in reduction of TOC values.

4.4. Microbial Reduction

The microbial reduction was calculated and evaluated in the form of log removal and percentage removal.

4.4.1. Total Coliform (TC). Table 4.2 displays mean influent TC for all the configurations. The TC enumerated is in the range $1.0 \times 10^{12} – 1.78 \times 10^{14}$ CFU/100ml. The values are higher than what was observed in previous studies in the range of $1.2 \times 10^{3} – 8.2 \times 10^{8}$ CFU/100 ml [134]-[138]. This is due to the fact that microbial organisms vary significantly based on various factors, including but not limited to; hand washing activity after toilet use, washing of babies or diapers of babies in the bath or sink, age distribution and number of household members, traces of urine, dead skin, sweating from body, usage pattern and season [139]-[140].

Table 4.2: Mean influent total coliform values for proposed configurations.

Configuration	Mean CFU/100 ml			Mean log CFU/100 ml		
	Day 1	Day 4	Day 7	Day 1	Day 4	Day 7
1	2.30×10^{13}	2.40×10^{13}	1.25×10^{13}	13.4	13.4	13.1
2	1.78×10^{14}	1.30×10^{13}	3.90×10^{13}	14.3	13.2	13.6
3	4.45×10^{13}	1.25×10^{13}	2.05×10^{13}	13.7	13.1	13.4
4	7.00×10^{12}	1.15×10^{13}	2.50×10^{12}	12.9	13.1	12.4
5	1.50×10^{12}	2.00×10^{12}	1.00×10^{12}	12.2	12.4	12.0
6	1.05×10^{14}	2.20×10^{13}	4.00×10^{12}	14.1	13.4	12.7

4.4.1.1. TC reduction efficacy of filter media (pre-treatment) combined with adsorbents. Figure 4.25 displays the overall log reduction achieved by both the configurations. The log reduction and corresponding percentage removal achieved by Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS) were in the range of 0.36 – 1.68 log CFU/100 ml (or 56.0 – 97.9 %) and 3.93 – 4.8 log CFU/100 ml (or 99.9 - 99.99 %), respectively. GBFS displayed higher TC removal efficiency to AC. It is also important to note that, although the influent received by Configuration 3 (SF+GBFS) had higher TC contamination in contrast to Configuration 1 (SF+AC), yet TC reduction had been much lower during the treatment of GW with Configuration 3 (SF+GBFS). In addition, the removal of TC following chlorination (SP3) for both the configurations were 100 %, with no detection of TC in all the samples.

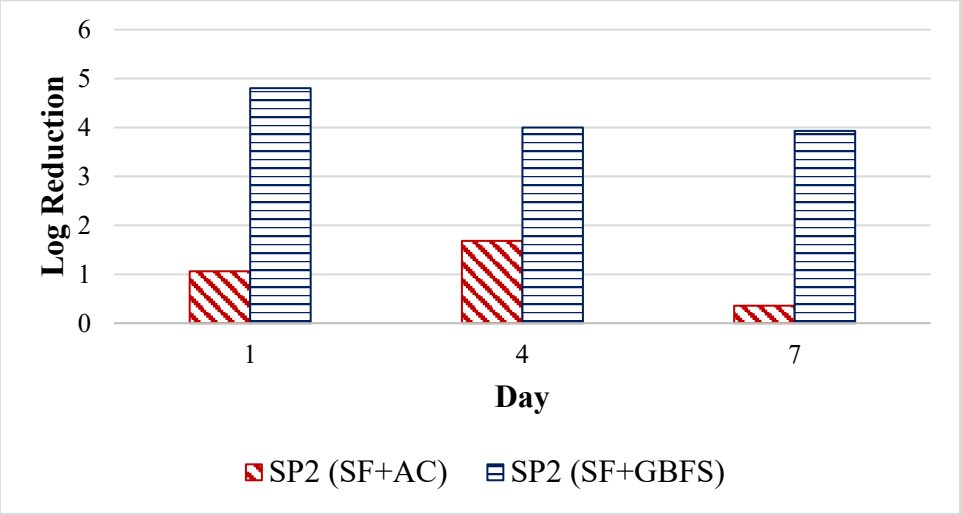


Figure 4.25: Mean TC log reduction for Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS).

4.4.1.2. TC reduction efficacy of adsorbent media. The performance efficiency in reduction of TC for both the filter media is shown in Figure 4.26. Results demonstrated that the GBFS (Configuration 6) achieved significantly higher log reductions for TC in comparison to AC (Configuration 5). GBFS successfully reduced TC in the range of 0.54 – 2.05 log CFU/100 ml, while the reduction efficiency of AC lied in the range of 0.22 – 0.48 log CFU/100 ml. In terms of percentage removal, GBFS displayed higher percentage removal efficiency of 97.8 %, 99.1 % and 71.3 % on day 1, day 2 and day 3, respectively. On the contrary, AC achieved limited percentage

reduction of 40.0 %, 40.0 % and 66.7 % on day 1, day 2 and day 3, respectively. Hence, based on this, it is evident that GBFS displayed higher TC removal efficiency in contrast to AC adsorbent. To further validate this statement, Section 4.4.1.2. also revealed similar results by displaying higher TC reduction efficiency for the system installed with GBFS filter media (Configuration 3) in comparison to the system installed with AC filter media (Configuration 1).

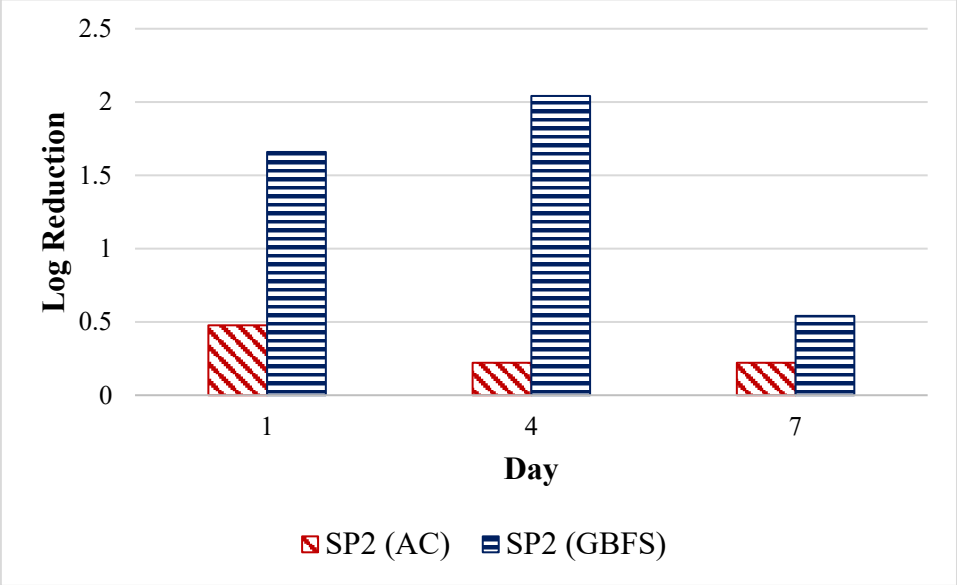
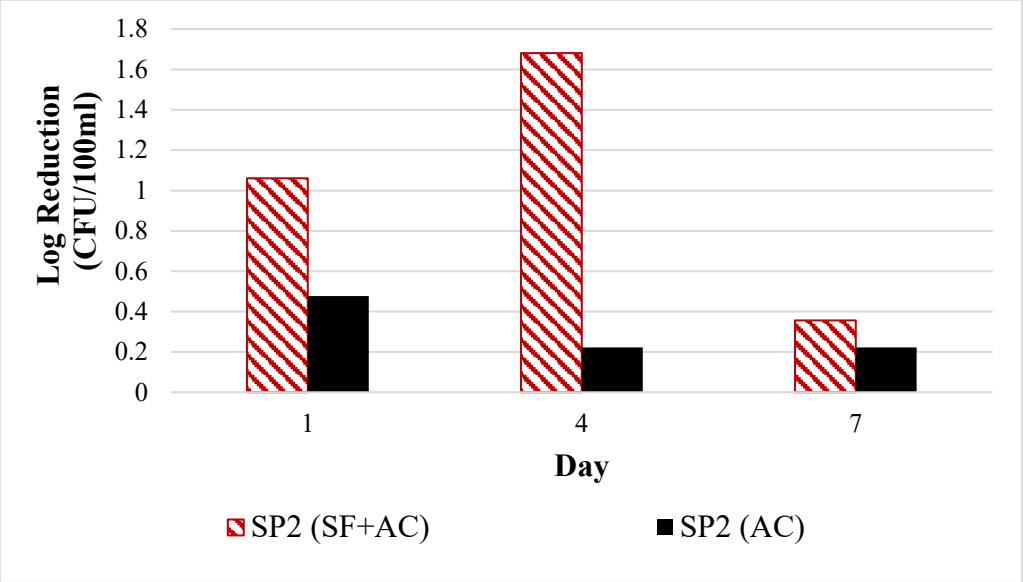


Figure 4.26: Mean TC log reduction for Configuration 5 (AC) and Configuration 6 (GBFS).

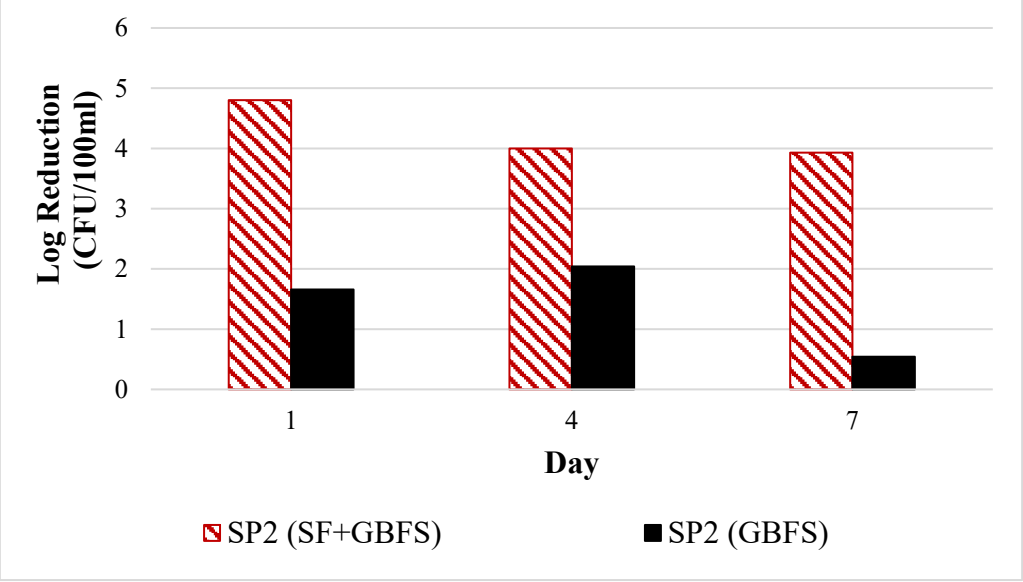
4.4.1.3. Effect of sand filter (pre-treatment) on TC reduction efficacy.

The key significance of this evaluation is to determine if inclusion of pre-treatment using sand filter media in the system is essential for supporting further TC reduction. Figure 4.27(a) compares the TC log reduction achieved by both SF+AC (Configuration 1) and AC alone (Configuration 5), whereas, Figure 4.27(b) exhibits the TC log reduction calculated for SF+GBFS (Configuration 3) and GBFS alone (Configuration 6). Results demonstrate that, the addition of pre-treatment significantly improved the TC removal efficiency of the system. While the reduction ranged between 0.22 – 0.48 log CFU/100 ml (or 40.0 – 66.7 %) during the application of AC as a standalone filter media (Configuration 5), this reduction range was improved to 0.36 – 1.68 log CFU/100 ml (or 56.0 – 97.9 %) during the inclusion of pre-treatment using sand filter with AC adsorbent (Configuration 1). Likewise, during the application of GBFS as a standalone

filter media (Configuration 6), the TC removal varied between 0.54 – 2.04 log CFU/100 ml (or 71.3 – 99.1 %), which was found to be improved and varied in the range of 3.93 – 4.80 log CFU/100 ml (or 99.9 – 99.99 %) for the system installed to have pre-treatment along with GBFS filter media (Configuration 3).



(a)



(b)

Figure 4.27: TC log reduction comparison between (a) SF+AC (Configuration 1) and AC alone (Configuration 5) and (b) SF+GBFS (Configuration 3) and GBFS alone (Configuration 6).

Various studies have provided different conclusions on total coliform removal efficiency of sand filtration as shown in Table 4.3. The removal efficiency has been found to be in ranges rather than individual values as bacterial reduction is sensitive to several parameters including the influent temperature, water quality, filtration rate, column depth, media size, biological maturity of the filter and maintenance practices [134].

Table 4.3: TC removal efficacy of sand filter reported in literature and under this study.

Removal	**Reference**
1 – 4 logs	[135]
0.6 – 1.5 logs	[136]
1 – 1.2 logs	[87]
0.13 – 3.39 logs	Under this study

TC reduction was enhanced by 0.13 – 1.46 log CFU/100 ml when pre-treatment was combined with AC (Configuration 1), while an increase in reduction by 1.96 – 3.39 log CFU/100 ml was achieved when sand filter was combined with GBFS (Configuration 3). As it is evident, TC log reduction corresponding to Configuration 3 was higher than Configuration 1. One possible reason for the decline in performance of sand filter during application with AC (Configuration 1) could be since Configuration 3 was operated before Configuration 1, hence, after 7 days of continuous operation, the sand filter efficiency could have been reduced. The reduction in filter efficiency is common phenomena, which occurs as the filter media becomes coated with flocs, which subsequently plugs the voids between the filter grains thereby reduction the straining and adsorption ability of the media [88]. In addition to this, during the operation of sand filter with GBFS (Configuration 3), the sand filter media was backwashed on a daily basis, which could potentially result in media lost [87]. Hence, during the operation of sand filter with AC, the media could possibly be reduced to some extent, thereby reducing the adsorption surface area and media depth, which would subsequently reduce the contact surface required for TC reduction.

4.4.1.4. Effect of UV on TC reduction efficacy. Table 4.4 is populated with the TC numbers enumerated before and after UV treatment and overall log reduction achieved by the application of UV irradiation.

Table 4.4: Mean TC values for Configuration 2, 4, 5 and 6 before and after UV treatment (rounded off to nearest decimal place).

Configuration	TC before UV			TC after UV			TC Reduction		
	Log CFU/100ml			Log CFU/100ml			Log CFU/100ml		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
2	13.5	12.2	13.2	9.3	8.4	7.7	4.2	2.8	4.4
4	9.2	9.3	8.4	6.7	6.7	5.7	2.5	2.5	2.7
5	11.7	12.1	11.8	8.4	7.7	8.9	3.4	4.4	2.9
6	12.4	11.4	12.1	9.3	9.4	8.7	3.2	2.6	2.9

From the results obtained, the overall TC reduction achieved by UV disinfection varied between 2.5 – 4.4 log CFU/100ml. The results also displayed that, for 3 days UV disinfection was able to achieve good instant disinfection removal efficacy with percentage removal greater than 99.99 % (or 4 log removal), however, this efficiency is not consistently maintained, as for some days the removal efficiency decreases to 99.7 % (or 2.5 log removal). Studies have suggested the efficacy of UV disinfection is linked with the particle size of the greywater fractions [137]. The larger particle size (mean size ≥ 262 μm) tend to shield more coliforms from the UV light than smaller particles (mean size <119 μm) [138]. Since the GW influent and effluent quality was based on the actual site condition and the contaminant loading is varying throughout the experimental program, a potential possibility for the inconsistency in UV efficacy could be due to the continuous variation in the size and amount of suspended particle bypassed to the UV disinfection zone. In addition to it, the disinfection efficacy of UV depends on bacteria type, as some pathogens maybe more resistant to UV than others [139], which could also introduce fluctuations in the UV efficacy. Studies have reported that UV efficacy ranges between 70 – 99.99 % (0.5 – 4.0 log) [139]-[140] , depending on several factors including the intensity of the radiation applied, initial bacterial density, flow rate, contact time and bacterial characteristics [141]. Hence, since the water quality under this study was constantly varying as there was no control on the

influent pollutant parameter, these changes in water quality could have introduced variation in the UV efficiency.

Finally, although UV did reduce the TC counts however, it failed to achieve the minimum TC guideline recommended by SEWA (≤ 100 CFU/100 ml), which necessitated the need of either alternate disinfection technique.

4.4.2. Fecal Coliform (FC). Table 4.5 displays mean FC numbers for GW influent corresponding to all the configurations. Previous studies have reported typical FC values of GW depending on various influent sources ranging up to 6 log CFU/100ml [55], [142], [143]. However, the FC enumerated under this study vary in the range of 7.0 to 8.9 log CFU/100 ml (or 1.0 x 10^7 – 8.00 x 10^8 CFU/100 ml). Since the TC values as mentioned under Section 4.4.1. were also comparatively higher than the typical values mentioned in the literature, hence it was anticipated that the FC values will also be higher.

In addition to this, the residential building also has a nursery facility, therefore the fecal contamination could be higher due to washing of babies or diapers in the bath or sink [144]-[145]. Apart from this, during sample collection, it was observed that a large group of residents were pet owners. Another reason for potentially high FC values could be due to the washing of pets in the shower which may contribute to fecal discharge from the pets in the GW stream.

Table 4.5: Mean influent fecal coliform values for proposed configurations.

Configuration	Mean CFU/100 ml			Mean log CFU/100 ml		
	Day 1	Day 4	Day 7	Day 1	Day 4	Day 7
1	2.50 x10^7	8.0 x10^8	5.20 x10^8	7.4	8.9	8.7
2	9.50 x10^7	8.70 x10^8	2.50 x10^7	7.9	8.9	7.4
3	3.50 x10^7	1.20 x10^8	1.00 x10^7	7.5	8.1	7.0
4	1.50 x10^7	5.00 x10^7	3.00 x10^7	7.2	7.7	7.5
5	3.00 x10^7	9.00 x10^7	7.00 x10^7	7.5	7.9	7.8
6	2.00 x10^7	8.00 x10^7	1.40 x10^8	7.3	7.9	8.1

4.4.2.1. Effect of pre-treatment on FC reduction efficacy. Figure 4.28 is plotted to display the overall log reduction achieved by both the treatment configurations over the period of 3 days. The graphical pattern makes it evident that the GW water post filtration and adsorption treatment by Configuration 3 (SF+GBFS) showed higher performance efficiency by displaying lower FC counts (1.7 – 2.2 log or 50 – 150 CFU/100 ml) and higher removal efficacy (5.3 – 5.9 log CFU/100 ml or 99.9995 – 99.9998 %). On the contrary, Configuration 1 (SF+AC) displayed higher FC counts (4.1 – 4.3 log or 1.20 – 1.29 x 10^4 CFU/100 ml) and lower removal efficacy (99.95 – 99.99 %) post treatment. Whereas, no FC was detected after chlorine disinfection (SP3) for both the configuration.

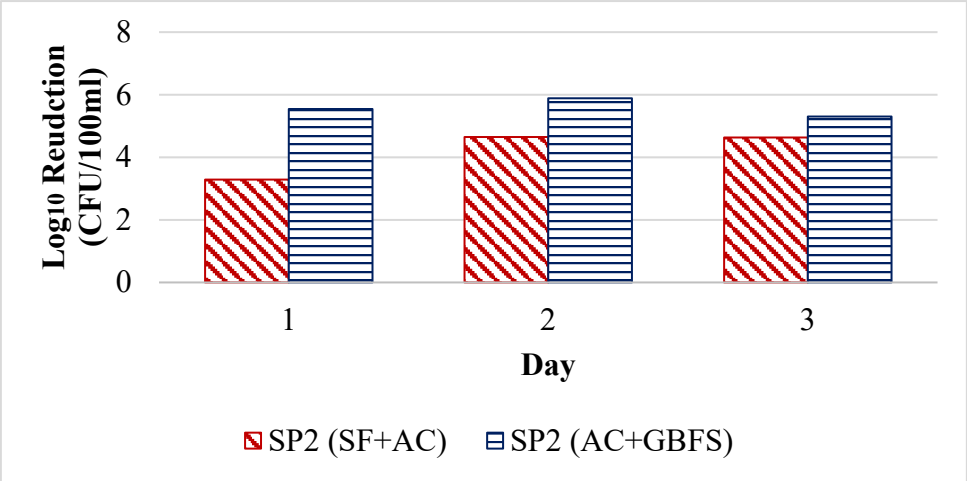


Figure 4.28: Mean FC log reduction for Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS).

Since the experimental approach including sampling method, filtration media (sand filter), sampling time, sampling location, HRT and backwash rate was identical for both the configurations, hence solely on the post treatment FC values (SP2) it can be determined that GBFS combined with sand filtration (Configuration 3) have higher TC reduction efficiency in comparison to AC and sand filtration (Configuration 1). Also, this finding coincides with the results achieved for TC detailed under Section 4.4.1.1. whereby Configuration 3 (SF+GBFS) displayed higher TC removal efficiency. Since TC is a representation of a group of bacteria including FC, thereby it is highly likely that the reduction of TC will support the reduction of FC as well.

To compare the performance efficiency of this system with other treatment systems, Table 4.6 tabulates the values extracted from the literature displaying FC removal efficiencies of other GW treatment systems prior to disinfection process and the efficiency of the treatment systems determined under this study. It is evident that both the configurations under this study displayed comparable higher FC removal efficiency compared to the configurations reported in the literature.

Table 4.6: FC removal efficacy reported in literature and under this study.

Treatment system	FC removal efficiency	Reference
RBC	88.5 – 99.5 %	[146]
MBR	Up to 99 %	[147]
Filtration	97.5 – 99.9999 %	[148]
Sand filtration and AC	99.95 – 99.99 %	Under this study
Sand filtration and GBFS	99.9995 – 99.9998 %	Under this study

4.4.2.2. FC reduction efficacy of filter media. In this section of the report, the efficacy of filter media AC (Configuration 5) and GBFS (Configuration 6) in reduction of FC is compared and evaluated. Since this section targets to specifically assess and compare the removal efficiency of AC and GBFS filter media alone, hence, the mean FC contamination values quantified at influent (SP1) and post adsorption (SP2) will be evaluated, while FC values post UV treatment (SP3) and chlorination (SP4) will not be included.

Figure 4.29 illustrate the FC removal efficacy achieved by both AC and GBFS. Results demonstrated that AC (Configuration 5) achieved a reduction of 2.17, 2.18 and 1.94 log CFU/100 ml (or percentage removal of 99.3, 99.4 and 98.9 %) for day 1, day 4 and day 5, respectively. Whereas, GBFS (Configuration 6) successfully removed 2.30, 2.20 and 1.96 log CFU/100 ml (or percentage reduction of 99.5, 99.4 and 98.9 %) on day 1, day 4 and day 7, respectively. A study conducted to assess the efficiency of GW treatment using aeration process followed by AC adsorption reported to achieve FC removal efficiency in the range of approximately 45 – 56.7 % [149].

However, the efficiency achieved under this study is comparatively higher and moderately invariable (98.9 – 99.3 %) in comparison to the reduction efficiency

reported in the literature. On the contrary, no studies have been performed on assessing the FC removal efficiency using GBFS, therefore, no comparison has been established for GBFS reduction efficacy.

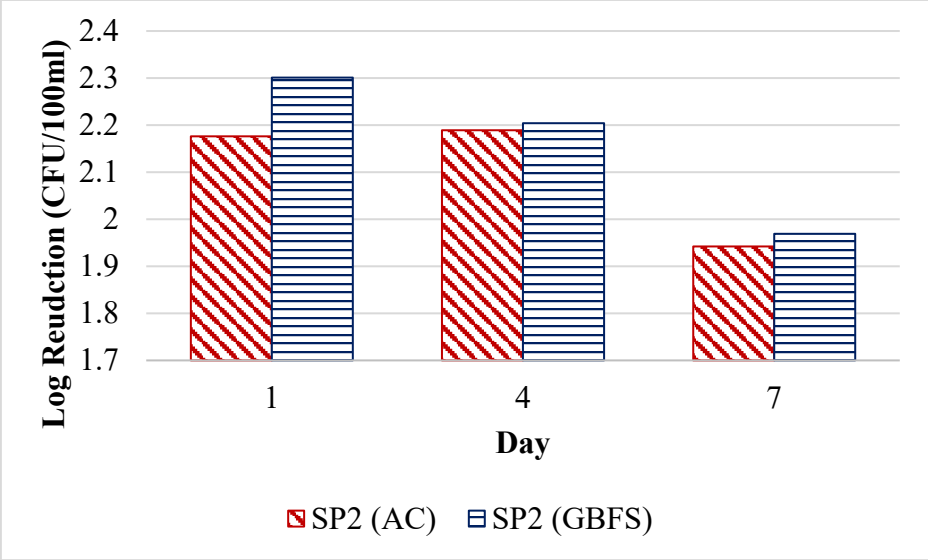
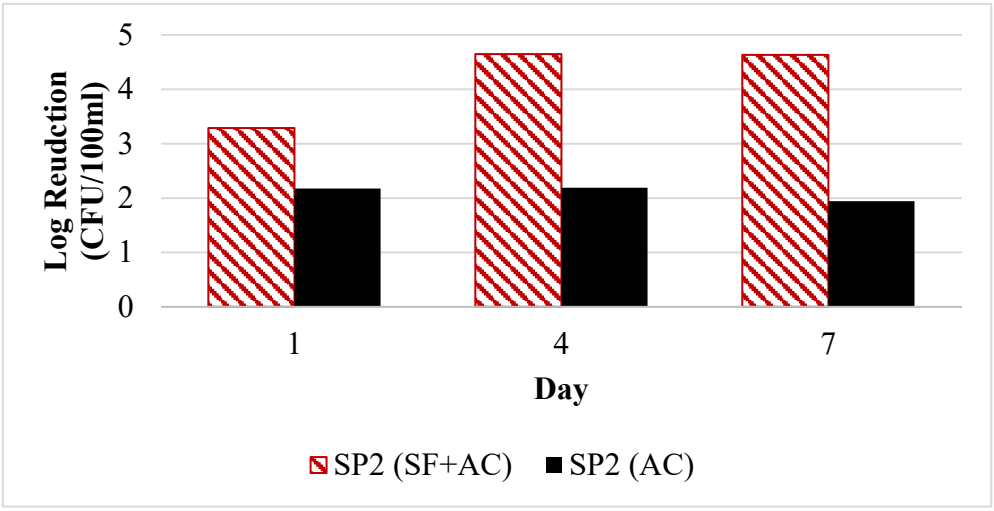


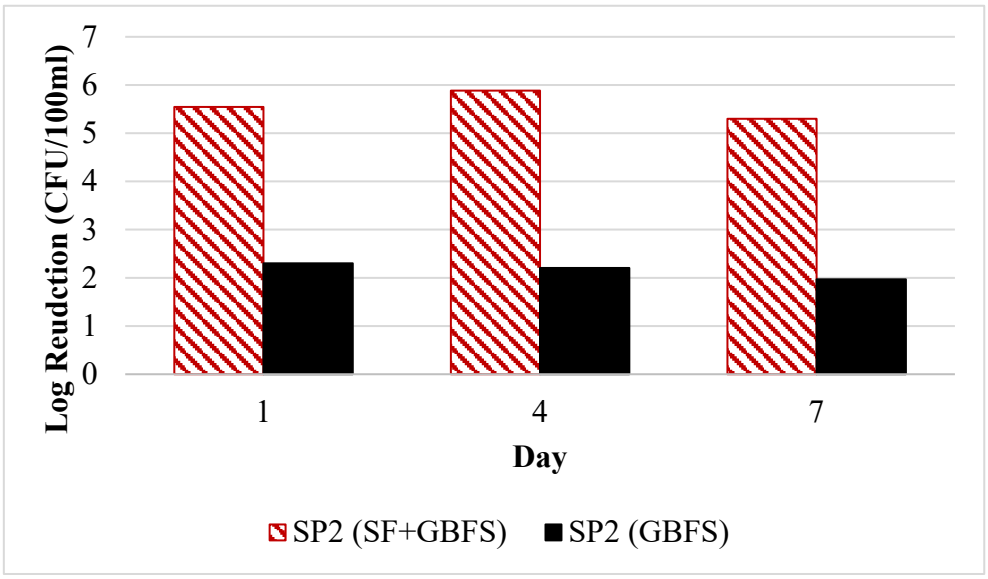
Figure 4.29: Mean FC log reduction for Configuration 5 (AC) and Configuration 6 (GBFS).

4.4.2.3. Effect of pre-treatment on FC reduction efficacy. The key significance of this evaluation is to determine if inclusion of pre-treatment in the system is essential for supporting further FC reduction. Figure 4.30a) compares the FC log reduction achieved by both SF+AC (Configuration 1) and AC alone (Configuration 5), whereas, Figure 4.30(b) exhibits the FC log reduction calculated for SF+GBFS (Configuration 3) and GBFS alone (Configuration 6). Results demonstrate that for the addition of pre-treatment significantly improved the FC removal efficiency of the system. While the reduction ranged between 1.94 – 2.19 log CFU/100 ml (or 98.86 – 99.35 %) during the application of AC as a standalone filter media (Configuration 5), this reduction range was improved to 3.28 – 4.64 log CFU/100 ml (or 99.94 – 99.99 %) during the addition of pre-treatment with AC filter media (Configuration 1). Likewise, during the application of GBFS as a standalone filter media (Configuration 6), the FC removal varied between 1.96 – 2.30 log CFU/100 ml (or 98.93 – 99.50 %), which was found to be improved and varied in the range of 5.30 – 5.88 log CFU/100 ml (or 99.9995 – 99.9998 %) for the system installed to have pre-treatment along with GBFS filter media (Configuration 3). Hence, the overall removal efficiency was increased by 1.34

– 2.45 log CFU/100 ml and 3.34 – 3.58 log CFU/100 ml when sand filtration was combined with AC and GBFS, respectively.



(a)



(b)

Figure 4.30: Mean FC log reduction comparison between (a) SF+AC (Configuration 1) and AC alone (Configuration 5) and (b) SF+GBFS (Configuration 3) and GBFS alone (Configuration 6).

Sand filtration displayed higher and more consistent removal for Configuration 3 (SF+GBFS) compared to Configuration 1 (SF+AC). As mentioned earlier in the report, a potential reason for this difference in removal efficacy could be introduced as Configuration 3 was operated before Configuration 1, thereby the performance of sand

filter could have been deteriorated due to partial clogging by pollutants. A similar reduction is FC removal efficiency has also been reported in several studies during the treatment of water using sand filtration [149]-[150], where the performance of sand filter deteriorates on daily basis due to the clustering of contaminants on the upper surface of the sand media which subsequently reduced the FC removal efficiency. Table 4.7 compares the FC removal efficiency of sand filter reported in the literature under different operational conditions and efficiency achieved under this study. In comparison to the sand filtration FC removal efficiency reported in the literature, the percentage removal achieved under this study displays to be within the range reported.

Table 4.7: FC removal efficacy of sand filter reported in literature and under this study.

Removal	Reference
*11.1 – **100 %	[150]
> 99 %	[134]
62.9 %	[149]
70.5 %, 96 %	[151]
95.5 – 99.97 %	Under this study

Column depth: *12.5 cm, **200 cm

4.4.2.4. Effect of UV on FC reduction efficacy. This section explores the impact of UV radiation on the reduction of FC numbers. As mentioned under Section 3.5., UV unit was installed in Configuration 2, Configuration 4, Configuration 5 and Configuration 6. Since the influent FC values represent the on-site condition which has varying influent contaminant loading, therefore, the mean FC values upstream and downstream of UV have been assessed for all the mentioned configurations to provide a representable result. Table 4.8 is populated with the FC numbers enumerated before and after UV treatment and overall log reduction achieved by the application of UV.

From the results obtained, the overall FC reduction achieved by UV disinfection varied between 0.4 – 2.7 log CFU/100 ml. UV removal efficiency highly depends on the contaminant concentrations and bacteria type, which can introduce variation in

removal efficiency. Particularly under this study, the influent contaminant concentration is varying throughout as there in no control on influent pollutant parameters, hence this subsequently generates an effluent quality with different residual contaminant concentration. This inconsistent contaminant concentration introduces further challenges in assessing the UV removal efficiency.

Table 4.8: Mean FC values for Configuration 2, 4, 5 and 6 before and after UV treatment (rounded off to nearest decimal place).

Configuration	FC before UV			FC after UV			FC Reduction		
	Log CFU/100ml			Log CFU/100ml			Log CFU/100ml		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
2	4.1	4.3	4.1	3.7	3.4	3.1	0.4	0.9	0.9
4	2.2	2.6	2.9	2.7	2.0	2.4	0.5	0.6	0.5
5	5.3	5.7	5.9	3.9	3.8	4.1	1.3	1.9	1.8
6	5.0	5.7	6.2	4.4	3.0	4.4	0.6	2.7	1.8

Similar study conducted to assess the effectiveness of UV treatment in removal of FC reports to achieve a reduction of 3.66 log with the application of same UV dose used under this study (40 mJ/cm^2) [140]. Another study reported to achieve UV removal efficacy in the range of 70 – 99.99 %, whereby attaining highest (99.99 %) removal percentage with maximum UV exposure time (15 minutes) [139].

Although the values in the literature can establish some grounds for comparison with the values achieved under this study, however, it is crucial to understand that UV efficiency is highly sensitive to many parameters some of which include contaminant levels, UV dose and contact time, hence there is no precise individual value or range for comparison which could determine the true effectiveness of UV treatment in this study.

Finally, although UV did reduce the FC counts however, it failed to achieve the minimum TC guideline recommended by SEWA (≤ 5 CFU/100 ml), which necessitated the need of either alternate disinfection technique.

4.4.3. Escherichia coli (E. coli). Table 4.9 displays mean E. coli numbers as CFU/100 ml quantified for GW influent corresponding to all the configurations. Studies

have reported typical E. coli values of GW depending on various influent sources ranges up to 6.5 x 10^6 CFU/100 ml [112], [152]-[153]. The E. coli enumerated under this study varied in the range of 3.7 to 4.2 log CFU/100 ml (or 4.0 x 10^3 – 1.60 x 10^4 CFU/100 ml) and were noted to be within the typical range reported in the literature.

Table 4.9: Mean influent E. coli values for proposed configurations.

Configuration	Mean CFU/100 ml			Mean log CFU/100 ml		
	Day 1	Day 4	Day 7	Day 1	Day 4	Day 7
1	5.50 x10^3	4.00 x 10^3	4.00 x10^3	3.8	3.7	3.7
2	5.00 x10^3	12.5 x 10^4	1.30 x 10^4	3.7	4.1	4.2
3	4.00 x 10^3	6.50 x10^3	1.20 x10^4	3.7	3.9	4.1
4	1.25 x 10^4	1.60 x 10^4	1.35 x 10^4	4.1	4.3	4.2
5	9.00 x10^3	1.60 x10^4	1.40 x10^4	4.0	4.3	4.2
6	2.00 x10^3	8.00 x10^3	1.35 x10^4	3.4	4.0	4.2

4.4.3.1. E. coli reduction efficacy of filter media and adsorbents. In this section of the report, the efficacy of pre-treatment (sand filtration) combined with filter media AC (Configuration 1) and GBFS (Configuration 3) in reduction of E. coli is compared and evaluated. Table 4.10 is populated with the mean E. coli values corresponding to Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS) for all the sampling locations, where SF represents sand filtration. No E. coli's were detected at sampling location SP3 (post chlorine disinfection).

Table 4.10: Mean E. coli values for Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS) at SP1 and SP2.

Configuration	Mean E. coli CFU/100 ml			Mean E. coli CFU/100 ml		
	Day 1	Day 4	Day 7	Day 1	Day 4	Day 7
Sampling Point		SP1			SP2	
1 (SF+ AC)	5.50 x10^3	4.00 x 10^3	4.00 x10^3	0	0	0
3 (SF +GBFS)	4.00 x 10^3	6.50 x10^3	1.20 x10^4	0	0	0

It is evident from the results that both the configurations were able to achieve 100 % E. coli removal efficacy as no E. coli were detected in any of the samples tested at SP2 location for both the configurations. Several studies have reported achieving 100 % E. coli removal efficacy by the application of filtration [49], [52], which is in line with the result achieved under this study. However, several literatures have stated otherwise that the E. coli removal efficiency of filtration system ranges between 90 – 99.9 % [134] and 95.0 – 98.5 % [151]. The variation in removal efficiency largely depends on several factors including temperature, filtration rate, media size, bed depth, and maintenance frequency [134].

4.4.3.2. E. coli reduction efficacy of filter media. In this section of the report, the efficacy of filter media AC (Configuration 5) and GBFS (Configuration 6) in reduction of E. coli is compared and evaluated. Since this section targets to specifically assess and compare the removal efficiency of AC and GBFS filter media alone, hence, the mean E. coli contamination values quantified at influent (SP1) and post adsorption (SP2) will be evaluated, while E. coli values post UV treatment (SP3) and chlorination (SP4) will not be included.

Table 4.11 illustrates is populated with mean E. coli values enumerated at SP1 and SP2 for Configuration 5 (AC) and Configuration 6 (GBFS). It is noticeable that despite minor variation in the influent E. coli numbers, both the configurations achieved 100 % E. coli removal efficiency. Also, it is significant to highlight that, although the E. coli values represent the true site condition with varying contaminant quality, yet both the adsorbents have displayed excellent E. coli removal efficiency even without the application of any pre-treatment.

Table 4.11: Mean E. coli values for Configuration 5 (AC) and Configuration 6 (GBFS) at SP1 and SP2.

Configuration	**Mean E. coli CFU/100 ml**			**Mean E. coli CFU/100 ml**		
	Day 1	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**
Sampling Point	SP1			SP2		
5 (AC)	9.00×10^3	1.60×10^4	1.40×10^4	0	0	0
6 (GBFS)	2.00×10^3	8.00×10^3	1.35×10^4	0	0	0

4.4.3.3. Effect of pre-treatment on E. coli reduction efficacy. This section of the report targeted to compare and assess the removal efficiency difference achieved with pre-treatment and without pre-treatment. However, since no E. coli were detected post filtration and/or adsorption process, hence this section of the report cannot be evaluated.

4.4.3.4. Effect of UV treatment on E. coli reduction efficacy. This section of the report mainly targets to evaluate samples post UV treatment (SP3). However, since all the E. coli's under all the configurations were removed post filtration and/or adsorption process, therefore the influent received by UV system had no E. coli. Since the UV already received an E. coli free influent, hence the UV efficiency cannot be assessed. Based on this, the efficiency of UV cannot be assessed. Therefore, this section of the report cannot be evaluated further.

4.4.4. Human Risk Reduction. Since no microbial contamination is found post chlorination treatment, hence microbial risk reduction is calculated for sampling points before chlorination. The risk reduction is evaluated only for total coliforms.

Risk reduction efficacy of pre-treatment and filter media. Table 4.12 is populated with the hazard quotient values calculated for the effluent collected at SP2 location for Configuration 1 (SF+ AC) and Configuration 3 (SF+ GBFS).

Table 4.12: Hazard quotient calculated using TC counts at SP2 corresponding to Configuration 1 and Configuration 3 (in 10^{12}).

Adult (Male)			**Adult (Female)**			**Children**		
Configuration 1 (SF+AC)								
Day 1	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**
0.86	0.21	2.36	1.20	0.30	3.30	6.00	1.50	16.50
Configuration 3 (SF+GBFS)								
Day 1	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**
0.00030	0.00054	0.00010	0.00042	0.00075	0.0014	0.0021	0.0038	0.0072

It is evident from the results that the effluent produced by Configuration 3 (SF+GBFS) have lower risk for all category (male, female and children) compared to the Configuration 1 (SF+AC). In general, HQ values less than 1 corresponds to no risk

while HQ values equal to or greater than 1 introduces human risk. For this study, all the values calculated are significantly higher than 1 due to higher concentration of total coliforms. The HQ values quantified for Configuration 1 (SF+AC) ranges between 2.36 – 0.86, 0.30 – 3.30, and 1.50 – 16.50 x 10^{12} for male, female and children, respectively. On the other hand, the HQ values ranged between 0.0001 – 0.00054, 0.0001 – 0.00075, and 0.0021 – 0.00038 for male, female and children, respectively.

Figure 4.31 displays the overall HQ percentage reduction achieved by both the configurations.

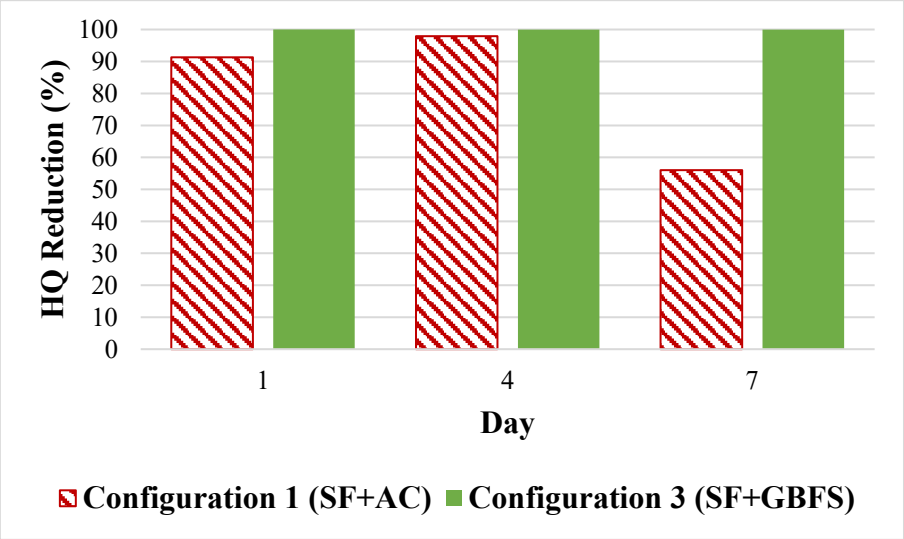


Figure 4.31: HQ percentage reduction achieved by Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS).

Results demonstrated that the HQ reduction was higher and consistent for GW treated using sand filter and GBFS (Configuration 3) whereby achieving a percentage removal between 99.98 – 99.99 %. In contrast, HQ percentage reduction is notably lower and inconsistent for GW treating using sand filter and AC (Configuration 1) which displayed a removal efficiency between 56.0 – 91.92 %. These results are also supported by the TC removal efficacy as explained under Section 4.4.1.1., where Configuration 3 (SF+GBFS) displayed higher TC removal efficacy which subsequently indicates lower health risk reduction in contrast to Configuration 1 (SF+AC). Although the effluent produced by Configuration 3 (SF+GBFS) did display reduced risk, yet the HQ values are indicating that the effluent quality is of high risk which can potentially cause health hazard to public. The results on the Configuration demonstrates that

although both the configurations did aid in reducing the TC counts, yet the introduction of disinfection is mandatory to ensure the effluent quality underlines under no risk category (i.e HQ < 1).

4.4.4.1. Risk reduction efficacy of filter media. Under this section of the report, the risk reduction achieved by Configuration 5 (AC) and Configuration 6 (GBFS) through exposure to total coliform is evaluated and compared. Table 4.13 is populated with the hazard quotient values calculated for the effluent collected at SP2 location for Configuration 5 (AC) and Configuration 6 (GBFS).

Table 4.13: Hazard quotient calculated using TC counts at SP2 corresponding to Configuration 5 and Configuration 6 (in 10^{11}).

Adult (Male)			**Adult (Female)**			**Children**		
Configuration 5 (AC)								
Day 1	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**
2.14	5.14	2.57	3.00	7.20	3.60	15.0	36.0	18.0
Configuration 6 (GBFS)								
Day 1	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**	**Day 1**	**Day 4**	**Day 7**
9.86	0.86	4.92	13.8	1.20	6.90	69.0	6.00	34.5

The HQ results demonstrated that AC alone (Configuration 5) had produced effluent quality with lower health risk in comparison to GBFS (Configuration 6). Although, GBFS did display higher TC log removal efficiency yet the effluent quality in terms of health risk is better corresponding to the effluent treated by AC. However, this could be due to the fact that the influent TC values corresponding to Configuration 6 (GBFS) were higher than the influent TC values for Configuration 5 (AC). Hence, to provide a holistic perspective, Figure 4.32 displays the overall percentage HQ reduced corresponding to both the configurations.

Results demonstrated that, GBFS (Configuration 6) achieved higher risk reduction efficacy in the range of 71.3 – 99.1 %. On the contrary, AC (Configuration 5) displayed lower risk reduction varying in the range of 40.0 – 66.67 %. However, although GW treated by Configuration 6 (GBFS) did display higher risk reduction

efficacy in comparison to GW treated by Configuration 5 (AC), yet the effluent quality is significantly above the requirement (HQ <1 or effluent to have TC count ≤ 200 CFU/ 100 ml). Hence, the effluent generated for either of the configuration cannot be reused for toilet flushing as it will impose serious health risk to the end users.

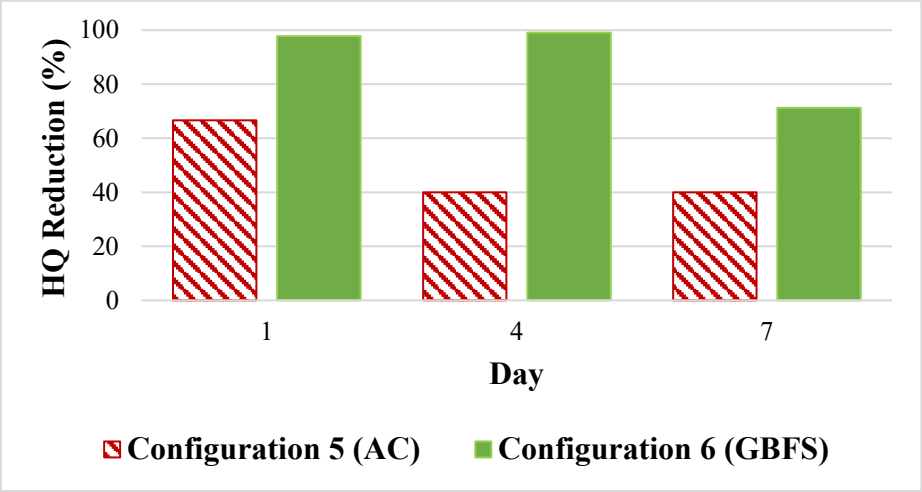


Figure 4.32: HQ percentage reduction achieved by Configuration 5 (AC) and Configuration 6 (GBFS).

4.4.4.2. Risk reduction efficacy of UV irradiation. Figure 4.33 displays the HQ reduction quantified for TC counts enumerated post UV treatment for Configuration 2, Configuration 4, Configuration 5 and Configuration 6.

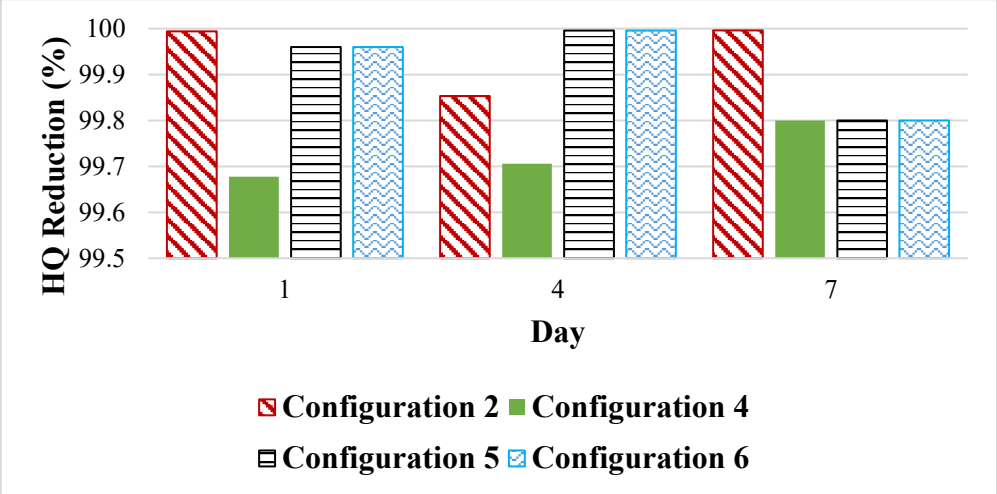


Figure 4.33: HQ percentage reduction using UV irradiation corresponding to Configuration 2, Configuration 4, Configuration 5 and Configuration 6.

It is evident that the UV efficacy in risk reduction is varying for all the configuration, achieving percentage reduction in the range of 99.60 – 99.99 %. As mentioned earlier under Section 4.4.1.4. , the UV removal efficiency highly depends on the contaminant concentrations and bacteria type, which can introduce variation in removal efficiency. Particularly under this study, the influent contaminant concentration is varying throughout as there in no control on influent pollutant parameters, hence this subsequently generates an effluent quality with different residual contaminant concentration. This inconsistent contaminant concentration introduces further challenges in assessing the UV removal efficiency which subsequently effects the health risk reduction achieved. Based on these findings, it is essential to have alternate disinfection technique to ensure the reclaimed water quality has HQ values less than one, to eliminate the introduction of health risk to the end users. Alternatively, the samples tested post chlorine disinfection (SP3) under this study did not have any strains of microbes, thereby indicating the necessity of chlorine disinfection to generate an effluent with no pathogens and risk free. Although, UV irradiation displayed excellent risk reduction efficacy, however, the HQ values are significantly higher, hence demanding alternate disinfection technique to reduce the human risk.

Chapter 5. Conclusion

This research work addresses a significant issue of water management. This study focuses on proposing an alternate by product from steel and iron industries; granulated blast furnace slag (GBFS) to be used as an adsorbent in the treatment of greywater.

In order to achieve the objectives of this study, six different configurations were retrofitted in a residential building which already had an existing on-site greywater reuse facility. The source of greywater was from shower and bath of the residential units in the building. The running time for each configuration under this study was 7 days, were dual samples at every sampling point were collected and analyzed for consecutive days, except samples for microbial contamination and BOD_5 were analyzed for 3 alternate days. The samples were tested for both physico-chemical parameters (pH, temperature, turbidity, COD, TOC, BOD_5, TSS, TDS) and microbial contamination (total coliform, fecal coliform and E. coli). In order to evaluate the true efficiency of the proposed treatment configurations, the feed water for all the configurations reflected the on-site condition, with no control on the influent parameters. The water quality for both the influent and effluent were recorded and analyzed.

The initial comparison was carried out assess and evaluate the performance efficiency of adsorbents alone (without any pre-treatment using filter media). Results demonstrated that GBFS (Configuration 5) displayed higher turbidity removal efficiency (90 – 92 %) in contract to AC (70 – 86 %). In addition, it is also found that after GBFS adsorption, the BOD_5 values were observed to have low variability, ranging from 10.4 mg/l - 11.4 mg/l compared to BOD_5 values corresponding to AC which were observed to be unsteady and higher in the range of 9.4 mg/l - 15.6 mg/l. The results showed that the BOD_5 removal efficiency using GBFS adsorbent is higher compared to AC, with percentage removal efficiencies ranging from 76 % – 86 % and 57 % – 75 %, respectively. Alternatively, the COD removal efficiency for both the adsorbents were highly comparable. The minimum and maximum COD percentage removal attained by AC and GBFS are 53.6 – 71.5 % and 64.6 – 85.1 %, respectively. Furthermore, GBFS displayed poor TDS removal efficiency in the range of (-1.3 – 26

%) whereas AC achieved removal efficiency in the range of 35.8 – 54.2 %. However, both AC and GBFS has achieved comparable TSS removal efficiencies, varying in the range of 67.7 – 90 % and 66.6 – 88.5 %, respectively. Also, both AC and GBFS adsorbents displayed excellent TOC removal efficiencies by achieving percentage removal between 76.9 – 86.8 % and 80.6 – 92.7 %, respectively. This study has found that GBFS achieved either improved or similar effluent quality in comparison to greywater treated with AC. Therefore, it is possible to introduce GBFS as sustainable alternative to conventional AC adsorbent, for the treatment of greywater at household level for non-potable use.

Another comparison was conducted to conclude the necessity of pre-treatment using sand filtration before GBFS adsorption. Results showed that the percentage removal displayed high span range for residual turbidity of reclaimed water treated with sand filtration and GBFS (61 – 92.1 %), in comparison to the reclaimed water produced by GBFS alone (89.6 – 92 %). However, the maximum TSS removal efficiency achieved by application of sand filter was higher (99.1 %) compared to maximum removal efficiency without sand filter (88.5 %). In addition, the effluent BOD_5 measured for the reclaimed water produced with sand filter were higher (22.2 – 25.6 mg/l) compared to BOD_5 values for reclaimed water treated without sand filter (10.4 – 11.2 mg/l). Finally, sand filtration and GBFS system displayed a lower TOC removal efficiency of 71.4 – 89.2 %, whereas, the removal efficiency for GBFS alone was measured to be 80.9 – 92.3 %. The study indicated that the inclusion of pre-treatment using sand filtration only improved TSS removal while the effluent quality for other physico-chemical parameters assessed were comparable to that achieved by AC. Hence, this concludes that inclusion of pre-treatment using sand filtration may not serve as an essential treatment process and alternate low cost TSS removal techniques could be employed during the utilization of GBFS adsorbent.

Also, the efficacy of pre-treatment (sand filtration) combined with AC (Configuration 1) and GBFS (Configuration 3) in reduction of TC and FC was evaluated. The log reduction and corresponding percentage removal achieved by Configuration 1 (SF+AC) and Configuration 3 (SF+GBFS) were in the range of 0.36 – 1.68 log CFU/100 ml (or 56.0 – 97.9 %) and 3.93 – 4.8 log CFU/100 ml (or 99.9 - 99.99 %), respectively. Likewise, Configuration 3 showed higher FC removal efficacy (5.3 –

5.9 log removal or 99.9995 – 99.9998 %) compared to Configuration 1 (4.1 – 4.3 log removal or 99.95 – 99.99 %). In addition, the efficacy of AC (Configuration 5) and GBFS (Configuration 6) in reduction of TC without any pre-treatment was evaluated. GBFS displayed higher percentage removal efficiency of 97.8 %, 99.1 % and 71.3 % on day 1, day 2 and day 3, respectively. On the contrary, AC achieved limited percentage reduction of 40.0 %, 40.0 % and 66.7 % on day 1, day 2 and day 3, respectively. Alternatively, AC achieved a reduction of FC by 2.17, 2.18 and 1.94 log CFU/100 ml (or percentage removal of 99.3, 99.4 and 98.9 %) for day 1, day 4 and day 5, respectively. Whereas, GBFS (Configuration 6) successfully removed 2.30, 2.20 and 1.96 log CFU/100 ml (or percentage reduction of 99.5, 99.4 and 98.9 %) on day 1, day 4 and day 7, respectively. Finally, the inclusion of ultra violet (UV) disinfection achieved TC reduction in the range 2.5 – 4.4 log CFU/100ml and FC reduction varied between 0.4 – 2.7 log CFU/100 ml. No E. coli strains were detected for any of the configurations after single treatment step. The study concludes that GBFS (with or without the inclusion of sand filter) achieved higher microbial removal than AC. Hence, the study recommends further exploring GBFS as a disinfection media for treatment of water.

Lastly, the risk reduction achieved by Configuration 5 (AC) and Configuration 6 (GBFS) through exposure to total coliform was evaluated and compared. The HQ results demonstrated that AC alone had produced effluent quality with lower health risk in comparison to GBFS. However, for both the configuration, the effluent quality is quantified to have significantly high HQ values, hence, the effluent generated for either of the configuration cannot be reused for toilet flushing as it will impose serious health risk to the end users. This concludes that, alternate and appropriate disinfection is required prior to reuse to ensure safety of end users.

Chapter 6. Study Limitation and Future Recommendation

Although the results achieved under this study indicates that GBFS could be a potential sustainable adsorbent for improving physico-chemical characteristics and aiding in microbial removal from greywater, however, further studies are required in light with the below considerations:

- To conduct effective comparison of adsorbent performance, AC and GBFS treatment system should operate parallelly, ensuring both the system receives influent having same contaminant levels. Hence, further study is required evaluating the performance efficiency of AC and GBFS under the same influent condition.
- This research evaluates the performance of adsorbents under a black box environment; however, no consideration was given on the reproducibility of the adsorption properties and the equilibrium data, which is known as adsorption isotherms. The design and efficient operation of adsorption process requires further study on equilibrium adsorption data for use in kinetic and mass transfer models. These models play a significant role in predictive modeling for the design, analysis and optimization of adsorption systems, hence additional work considering the adsorption isotherm and kinetics is needed.
- The applicability and efficiency of any given adsorbent for water treatment strongly depends on their origin, composition and the process followed for production. These parameters influence the adsorption properties and the characteristics of the particles can also introduce hydrodynamic limitations and column fouling, which limits the use of these materials for large scale columns. This study focuses on evaluating the reclaimed water quality utilizing GBFS from a single source. Hence, further study is required assessing the efficiency of GBFS with different characteristics, particle size, origin and composition.

References

[1] O. Olanrewaju and A. Illemobade, “Greywater Reuse Review and Framework for Assessing Greywater Treatment Technologies for Toilet Flushing,” *Advances in Research*, vol. 5, no. 4, pp. 1–25, 2015.

[2] R. Khalaphallah, “Greywater treatment for reuse by slow sand filtration: study of pathogenic microorganisms and phage survival,” M. S. thesis, Ecole des Mines de Nantes, France, 2012.

[3] United Nations, “Sustainable Development Goal 6 Synthesis Report on Water and Sanitation,” New York, 28 June 2018.

[4] E. Hameeteman, “Future Water (In) security : Facts , Figures , and Predictions,” Global Water Institute, Ohio, USA, 2013.

[5] K. Anderson and L. Guppy, “Global Water Crises: The Facts,” Water Crisis Report, United Nations University Institute of Water, Enviornment and Health, Hamilton, Canada, 7 Nov. 2017.

[6] T. Distefano and S. Kelly, “Are we in deep water ? Water scarcity and its limits to economic growth,” *Ecological Economics*, vol. 142, pp. 130–147, 2017.

[7] T. W. Hertel and J. Liu, “Implications of water scarcity for economic growth,” Organisation for Economic Co-operation and Development, Purdue University, USA, 8 Aug. 2016.

[8] World Bank Group, “High and Dry: Climate Change, Water and the Economy,”Water Global Practice, Washington DC, 3 May 2016.

[9] C. E. Werrel and F. Femia, “The Arab Spring and Climate Change: A Climate and Security Correlations Series,” Center for American Progress, Feb. 2013.

[10] C. Kenney, “Climate Change, Water Security, and U.S National Security,” Center for American Progress, 22 Mar. 2017.

[11] S. Vigneswaran and M. Sundaravadivel, “Recycle and reuse of domestic wastewater,” in *Wastewater Recycle, Reuse and Reclamation*, vol. 1, S. Vigneswaran, Ed. Australia: Encyclopedia of Life Support Systems, 2004, pp. 1-324.

[12] G. Crini, E. Lichtfouse, L. D. Wilson, and N. Morin-Crini, “Conventional and non-conventional adsorbents for wastewater treatment,” *Envrionmental Chemistry Letters.*, vol. 17, pp. 195–213, 2019.

[13] R. Paper, “Non-conventional low-cost adsorbents for dye removal: A review,” *Bioresource Technology*, vol. 97, pp. 1061–1085, 2006.

[14] M. Streat, J. . Patrick, and M. . Perez, “Sorption of phenol and para-chlorophenol from water using conventional and novel activated carbons,” *Water Resource*, vol. 29, pp. 467–472, 1995.

[15] A. N. Khan, F. A. Memon, S. H. Rizvi, Q. Bhanbhro, and N. Bheel, “Fresh and Hardened Properties of Ground Granulated Blast Furnace Slag Made Concrete,” I*nternational Journal of Modern Research in Engineering & Management*, vol. 1, no. 11, pp. 1–7, 2018.

[16] S. Lu, S. Bai, and H. Shan, “Mechanisms of phosphate removal from aqueous solution by blast furnace slag and steel furnace slag,” *Journal of Zhejiang University - Science A: Applied Physics & Engineering*, vol. 9, no. 1, pp. 125–132, 2007.

[17] K. Rout, M. K. Sahoo, and C. R. Sahoo, “Adsorption potential of Blast Furnace Granulated slag towards removal of aqueous cyanide,” *International Research Journal of Engineering and Technology*, vol. 5, no. 1, pp. 273–277, 2018.

[18] W. Immerzeel *et al.*, “Middle-East and Northern Africa Water Outlook,” Wageningen, Netherlands, Apr. 2011.

[19] World Bank, “Beyond Scarcity: Water Security in the Middle East and North Africa,” Washington DC, USA, 23 Aug. 2017.

[20] M. C. Peel, B. L. Finlayson, T. A. Mcmahon, M. C. Peel, B. L. Finlayson, and T. A. M. Updated, “Updated world map of the Köppen-Geiger climate classification,” *Hydrology and Earth Sciences Discussion, European Geosciences Union*, vol. 4, no. 2, pp. 439–473, 2007.

[21] “Water Reuse in the Arab World: From Principle to Practice,” in *Expert consultation wastewater management in the Arab World*, 2011, pp. 1–53.

[22] M. F. Al-Rashed and M. M. Sherif, “Water resources in the GCC countries: An overview,” *Water Resources Management*, vol. 14, no. 1, pp. 59–75, 2000.

[23] Veoli Water North America, “Sustaining Growth via Water Productivity : 2030 / 2050 Scenarios,” International Food Policy Institute, 5 Jan. 2011.

[24] L. Power, “Scarcity and Abundance: UAE Food and Water Security,” Future Directions International, 25 Nov. 2014.

[25] A. S. Richey, B. F. Thomas, M.-H. Lo, and J. S. Famiglietti, “Uncertainity in global groundwater storage estimates in a Total Groundwater Stress Framework,” *Water Resouces Research*, vol. 51, no. 7, pp. 5198–5216, 2015.

[26] R. Al Hashemi, S. Zarreen, A. Al Raisi, F. Al Marzooqi, and S. Hasan, “A Review of Desalination Trends in the Gulf Cooperation Council Countries,” *International Interdisciplinary Journal of Scientific Research*, vol. 1, no. 2, pp. 72–96, 2014.

[27] M. A. Dawoud, “The role of desalination in the augmentation of water supply in GCC countries,” *Desalination*, vol. 186, pp. 187–198, 2006.

[28] O. Saif, “The Future Outlook of Desalination in the Gulf,” M. S. thesis, McMaster University, Ontario, Canada, 2012.

[29] E. Jones, M. Qadir, M. T. H. Van Vliet, V. Smakhtin, and S. Kang, “The state of desalination and brine production: A global outlook,” *Science of the Total Environment*, vol. 657, pp. 1343–1356, 2019.

[30] E. Eriksson, K. Auffarth, M. Henze, and A. Ledin, “Characteristics of grey wastewater,” *Urban Water*, vol. 4, no. 1, pp. 85–104, 2002.

[31] O. Al-jayyousi, “Greywater reuse : knowledge management for sustainability,” *Desalination*, vol. 167, no. 1, pp. 27–37, 2004.

[32] D. Christova-Boal, R. E. Eden, and S. McFarlane, “An investigation into greywater reuse for urban residential properties,” *Desalination*, vol. 106, no. 1–3, pp. 391–397, 1996.

[33] A. Morel and S. Diener, *Greywater Management in Low and Middle-Income Countries: Review of Different Treatment Systems for households or neighbourhoods*. Dubendorf, Switzerland: Swiss Federal Institute for Environmental Science and Technology, 2006.

[34] Y. Boyjoo, V. K. Pareek, and M. Ang, “A review of greywater characteristics and treatment processes,” *Water Science & Technology*, vol. 67, no. 7, pp. 1403–1424, 2013.

[35] D. Mandal, P. Labhasetwar, S. Dhone, A. S. Dubey, G. Shinde, and S. Wate, “Water conservation due to greywater treatment and reuse in urban setting with specific context to developing countries,” *Resources Conservation & Recycling*, vol. 55, no. 3, pp. 356–361, 2011.

[36] World Health Organization. *Guidelines for the Safe use of Wastewater, Excreta and Greywater: Excreta and Greywater use in Agriculture*. Geneva, Switzerland: WHO, 2006.

[37] D. M. Ghaitidak and K. D. Yadav, “Characteristics and treatment of greywater-a review,” *Environmental Science and Pollution Research*, vol. 20, no. 5, pp. 2795–2809, 2013.

[38] A. Jamrah, A. Al Omari, L. Al-Qasem, and N. Abdel Ghani, “Assessment of Availability and Characteristics of Greywater in Amman,” *Water International*, vol. 31, no. 2, pp. 210–220, 2011.

[39] A. D. Alsulaili and M. F. Hamoda, “Quantification and characterization of greywater from schools,” *Water Science & Technology*, vol. 72, no. 11, pp. 1973–1980, 2015.

[40] P. Droogers *et al.*, “Water resources trends in Middle East and North Africa towards 2050,” *Hydrology and Earth System Sciences*, no. 16, pp. 3101–3114, 2012.

[41] A. K. Mohamed, “Environmental impact of desalination plants on the environment,” in *Thirteenth International Water Technology Conference*, 2009, pp. 951–863.

[42] A. Shanableh *et al.*, “Greywater reuse policies and practice in the city of Sharjah, United Arab Emirates,” in *10th International Conference on Water Sensitive Urban Design: Creating water sensitive communities (WSUD 2018 & Hydropolis 2018)*, 2018.

[43] J. B. Rose, G. Sun, and C. Gerba, “Microbial Quality and Persistence of Enteric Pathogens in Graywater from Various Household Sources,” *Water Resource*, vol. 25, no. November 2017, pp. 37–42, 1991.

[44] P. Jeffrey and B. Jefferson, “Public receptivity regarding ‘in-house’ water recycling: results from a UK survey,” *Water Science & Technology Water Supply*, vol. 3, no. 3, pp. 109–116, 2003.

[45] E. Nolde, “Grey Water Reuse Systems for Toilet Flushing in Multi-Storey Buildings – over Ten Years Experience in Berlin,” *Urban Water*, pp. 275–284, 2000.

[46] O. Olanrewaju and A. Ilemobade, “Greywater Reuse Review and Framework for Assessing Greywater Treatment Technologies for Toilet Flushing,” *Advances in Research*, vol. 5, no. 4, pp. 1–25, 2015.

[47] A. Shanableh, M. Imteaz, T. Merabtene, and A. Ahsan, “A framework for reducing water demand in multi-storey and detached dwellings in the United Arab Emirates,” in *WSUD 2012: Water sensitive urban design; Building the water sensiitve community; 7th international conference on water sensitive urban design*, 2012, p. 647.

[48] A. Shanableh, M. Ali, A. Mustafa, and M. Abdallah, “Greywater reuse experience in Sharjah, United Arab Emirates: feasibility, challenges and opportunities,” *Desalination Water Treatment*, pp. 1–12, 2020.

[49] D. Ghaitidak and K. Yadav, “Characteristics and treatment of greywater — A review,” *Environmental Science and Pollution Research*, vol. 20, no. 5, pp. 2795–2809, 2013.

[50] Metcalf and Eddy. *Wastewater engineering - treatment, disposal and reuse*. New York: McGraw-Hill, 1991.

[51] M. Pidou *et al.*, “Chemical solutions for greywater recycling,” *Chemosphere*, vol. 71, no. 1, pp. 147–155, 2008.

[52] M. Oteng-peprah and K. Nanne, “Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception — a Review,” *Water Air and Soil Pollution*, vol. 229, no. 8, pp. 2–16, 2018.

[53] A. Gross, K. D., and K. Baker, “Remocal of chemical and microbiological contaminant from domestic greywater using a recycled vertical flow bioreactor (RVFB),” *Ecological Engineering.*, vol. 31, pp. 107–114, 2007.

[54] S. S. Dalahmeh, M. Pell, and B. Vinnerås, “Efficiency of Bark, Activated Charcoal, Foam and Sand Filters in Reducing Pollutants from Greywater,” *Water Air and Soil Pollution*, vol. 223, pp. 3657–3671, 2012.

[55] M. Halalsheh, S. Dalahmeh, M. Sayed, W. Suleiman, M. Shareef, and M. Safi, “Grey water characteristics and treatment options for rural areas in Jordan,” *Bioresource Technology*, vol. 99, pp. 6635–6641, 2008.

[56] A. Gross, O. Shmueli, Z. Ronen, and E. Raveh, “Recycled vertical flow constructed wetland (RVFCW)—a novel method of recycling greywater for irrigation in small communities and household,” *Chemosphere*, vol. 66, pp. 916–923, 2007.

[57] M. Travis, A. Weil-Shafran, N. Weisbrod, E. Adar, and A. Gross, “Greywater reuse for irrigation: effect on soil properties,” *Sciene of the Total Environment*, vol. 408, pp. 2501–2508, 2010.

[58] A. A. Pathan, R. B. Mahar, and K. Ansari, “Preliminary Study of Greywater Treatment through Rotating Biological Contactor,” *Journal of Engineering &. Technology*, vol. 30, pp. 531–538, 2011.

[59] S. J. Arceivala and S. R. Asolekar. Wastewater Treatment for Pollution Control and Reuse. New York: McGraw-Hill, 2017.

[60] M. Hu *et al.*, “Treatment of greywater wuth shredded-tire biofilters and membrane bioreactors,” in *World Environmental and Water Resources Congress 2011: Bearing knowledge for sustainability*, 2011, pp. 1877–1887.

[61] C. Merz, R. Scheumann, B. El Hamouri, and M. Kraume, “Membrane bioreactor technology for the treatment of greywater from a sports and leisure club,” *Desalination*, vol. 215, no. 1–3, pp. 37–43, 2007.

[62] J. Jong *et al.*, “The study of pathogenic microbial communities in graywater using membrane bioreactor,” *Desalination*, vol. 250, no. 2, pp. 568–572, 2010.

[63] H. Chang and G. Wang, “Fractionation of nitrogen-enriched dissolved organic matter in water,” *Separation & Purification Technology*, vol. 117, pp. 89–97, 2013.

[64] D. Ghernaout, “Disinfection and DBPs Removal in Drinking Water Treatment: A Perspective for a Green Technology,” *International Journal of Advanced and Applied Sciences*, vol. 5, no. 2, pp. 108–117, 2018.

[65] N. Costet *et al.*, “Environmental and urinary markers of prenatal exposure to drinking water disinfection by-products, fetal growth, and duration of gestation in the PELAGIE birth cohort (Britanny, France, 2002-2006),” *Am J Epiemiol*, vol. 174, no. 4, pp. 263–275, 2012.

[66] World Health Organization, “Guidelines for Drinking-water Quality - Fourth Edition,” 2014.

[67] X. Tang, Q. Y. Wu, Y. Du, H. Huang, X. . Shi, and H. Y. Hu, “Anti-estrogenic activity formation potential assessment and precursor analysis in reclaimed water during chlorination.,” *Water Research*, vol. 48, pp. 490–497, 2014.

[68] U. Iriarte-Velasco, J. I. Alvarez-Uriarte, and J. R. Gonzalez-Velasco, “Enhanced coagulation under changing alkalinity-hardness conditions and its implications on trihalomethane precursors removal and relationship with UV absorbance,” *Separation & Purification Technology*, vol. 55, no. 5, pp. 368–380, 2007.

[69] M. A. Zazouli and L. R. Kalankesh, “Removal of precursors and disinfection by-products (DBPs) by membrane filtration from water; a review,” *Journal of Environmental Health Science and Engineering*, vol. 15, no. Artical 25, pp. 1–10, 2017.

[70] F. J. Benitez, J. L. Acero, F. J. Real, and C. Garcia, “Removal of phenyl-urea herbicides in ultrapure water by ultrafiltration and nanofiltration processes,” *Water Research*, vol. 43, no. 2, pp. 267–276, 2009.

[71] J. N. Hakizimana *et al.*, “Assessment of hardness, microorganism and organic matter removal from seawater by electrocoagulation as a pretreatment of desalination by reverse osmosis,” *Desalination*, vol. 393, pp. 90–101, 2016.

[72] M. Zazouli, S. Nasseri, A. Mahvi, M. Gholami, A. Mesdaghinia, and M. Younecian, “Studies on rejection and fouling of polyamide reverse osmosis membrane in the treatment of water solutions containing humic acids,” *World Applied Sciences Journal*, vol. 3, no. 3, pp. 434–440, 2008.

[73] A. Waniek, M. Bodzek, and K. Konieczny, “Trihalomethane Removal from Water Using Membrane Processes,” *Polish Journal of Environmental Studies*, vol. 11, no. 2, pp. 171–178, 2002.

[74] R. Rajamohan, V. P. Venugopalan, M. Debasis, and N. Usha, “Efficiency of reverse osmosis in removal of total organic carbon and trihalomethane from drinking water,” *Research Journal of Chemistry and Environment*, vol. 18, no. 1, 2014.

[75] A. Matilainen, R. Liikanen, M. Nystrom, N. Llndqvist, and T. Tuhkanen, “Enhancement of the natural organic matter removal from drinking water by nanofiltration,” *Envrionmental Technology*, vol. 25, no. 3, pp. 283–291, 2004.

[76] M. Siddiqui, G. Amy, J. Ryan, and W. Odem, “Membranes for the control of natural organic matter from surface waters,” *Water Resource*, vol. 34, no. 13, pp. 3355–3370, 2000.

[77] M. Samadi, S. Nasseri, A. Mesdaghinia, and M. Alizadefard, “A comparative study on THMS removal efficiencies from drinking water through nanofiltration and air stripping packed-column,” *Iranian Journal of Water and Wastewater*, vol. 57, pp. 14–21, 2006.

[78] Y. Du *et al.*, “Formation and control of disinfection byproducts and toxicity during reclaimed water chlorination: A review,” *Journal of Environmental Science*, vol. 58, pp. 51–63, 2017.

[79] C. Vohla, M. Kõiv, H. J. Bavor, F. Chazarenc, and Ü. Mander, “Filter materials for phosphorus removal from wastewater in treatment wetlands — A review,” *Ecological Engineering*, vol. 37, no. 1, pp. 70–89, 2011.

[80] Australasian Slag Association, “Blast Furnance Slag (BFS).” Internet: https://www.asa-inc.org.au/products/blast-furnace-slag, Oct. 6, 2019 [Feb. 3, 2020].

[81] M. Tossavainen and E. Forssberg, “The potential leachability from natural road construction materials,” *Science of Total Enviornment*, vol. 239, pp. 31–47, 1999.

[82] M. Taylor, “An Assessment of Iron and Steel Slag for Treatment of Stormwater Pollution. Landcare Research Contract Report: LC0506/064 prepared by Landcare Research for The Australasian (iron & steel) Slag Association Incorporation,” 2006.

[83] D. M. Proctor, E. C. Shay, K. A. Fehling, and B. L. Finely, “Assessment of Human Health and Ecological Risks Posed by the Uses of Steel-Industry Slags in the Environment,” *Human and Ecological Risk Assessment*, vol. 8, no. 4, pp. 681–711, 2002.

[84] L. J. Westholm, “The Use of Blast Furnace Slag for Removal of Phosphorus from Wastewater in Sweden—A Review,” *Water*, vol. 2, pp. 826–837, 2010.

[85] L. R. Amofah, “A Small Scale Wastewater Treatment System Adapted to Nutrient Recovery in Cold Climate,” M. S. thesis, Lulea University of Technology, Lulea, Sweden, 2007.

[86] R. M. Galvin, “Ripening of silica sand used for filtration,” *Water Resource,* vol. 26, no. 5, pp. 683–688, 1991.

[87] ITACA, “An Introduction To Slow Sand Filtration,” 1 Dec. 2005.

[88] Envrionemental Protection Agency, “Water treatment manuals: Filtration,” Ardcavan, Wexford, Ireland, 1995.

[89] H. S. Kandra, D. Mccarthy, T. D. Fletcher, and A. Deletic, “Assessment of clogging phenomena in granular filter media used for stormwater treatment,” *Journal of Hydrology*, vol. 512, pp. 518–527, 2014.

[90] O. C. Eklund and L. Tegelberg, “Small-scale Systems for Greywater Reuse and Disposal,” M. S. thesis. Swedish University of Agricultural Sciences, Sweden, 2010.

[91] O. T. G. Lunga, D. Moyakhe, F. B. Waanders, and C. De Klerk, “Effects of Pretreatment on the Removal of COD from Brewery Wastewater,” in *17th Johannesburg International Conference on Science, Engineering, Technology and Waste Management (SETWM-19)*, 2019, pp. 118–123.

[92] D. S. El Monayeri, N. N. Atta, S. El Mokadem, and A. M. Aboul-fotoh, “Effect of organic loading rate and temperature on the performance of horizontal biofilters,” in *Eleventh International Water Technology Conference, IWTC11*, 2007, pp. 671–681.

[93] S. Diamant, “The importance of monitoring turbidity in industrial water treatment,” *Water Technology - Industrial Water Management*, 1 Dec. 2013.

[94] S. S. Mohammed, “Effect of pH on the Turbidity Removal of Wastewater,” *Open Access Library Journal*, vol. 2, pp. 1–9, 2015.

[95] The Public Health Laboratory Service Water Sub-Committee, “The Effect of Sodium Thiosulphate on the Coliform and Bacterium coli Counts of Non-

Chlorinated Water Samples," *The Journal of Hygiene*, vol. 51, no. 4, pp. 572–577, 1953.

[96] A. L. Murray, E. Kumpel, R. Peletz, R. S. Khush, and D. S. Lantagne, "The effect of sodium thiosulfate dechlorination on fecal indicator bacteria enumeration: laboratory and field data," *Journal of Water and Health*, vol. 16, no. 1, pp. 70–77, 2018.

[97] Organisation for Economic Corportation and Development World Health Organisation, "Analytical methods for microbiolofical water quality testing," in *Assessing Microbial Safety of Drinking Water: Improving Approaches and Methods*, 2003, pp. 237–292.

[98] J. Bartram and R. Ballance, "Microbiological Analyses," in *Water Quality Monitoring - A Practicle Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes*, 1996, pp. 229 - 255.

[99] American Public Health Association (APHA), *Standard Methods For the Examination of Water and Wastewater*, 2012.

[100] Microbial Food Safety, "Enumeration of Escherichia coli in bivalve molluscan shellfish by the colony-count technique (based on ISO 16649-2)," 2014, pp.1-14.

[101] M. Singh, R. Sharma, P. K. Gupta, J. K. Rana, M. Sharma, and N. Taneja, "Comparative efficacy evaluation of disinfectants routinely used in hospital practice: India," *Indian Journal of Critical Care Medicine*, vol. 16, no. 3, pp. 123–129, 2012.

[102] J. R. Mihelcic and J. B. Zimmerman, *Environmental Engineering: Fundamental, Sustainability, Design*. New York: Wiley, 2010.

[103] K. Shi, C. Wang, and S. C. Jiang, "Quantitative microbial risk assessment of Greywater on-site reuse," *Sci. Total Environment*, vol. 635, pp. 1507–1519, 2018.

[104] S. Nayek and P. K. Padhy, "Personal exposure to VOCs (BTX) and women health risk assessment in rural kitchen from solid biofuel burning during cooking in West Bengal, India," *Chemosphere*, vol. 244, 2020.

[105] U.S.EPA, "Risk Assessment Guidance for Superfund (RAGS), Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Rosk Assessment): Final (EPA/540/-R-070/002)," Washington, DC., 2009.

[106] D. Lucas, D. Barcelo, and S. Rodriguez-Mozan, "Removal of pharmaceuticals from wastewater by fungal treatment and reduction of hazard quotients," *Sci. Total Environment*, vol. 571, pp. 909–915, 2016.

[107] V. M. Ngole-jeme and P. Fantke, "Ecological and human health risks associated with abandoned gold mine tailings contaminated soil," *PLoS One*, vol. 12, no. 2, pp. 1–24, 2017.

[108] A. Wiedenmann, P. Krüger, K. Dietz, J. M. López-pila, R. Szewzyk, and K. Botzenhart, "A Randomized Controlled Trial Assessing Infectious Disease Risks from Bathing in Fresh Recreational Waters in Relation to the Concentration of Escherichia coli, Intestinal Enterococci, Clostridium perfringens, and Somatic," *Environmental Health Perspective*, vol. 114, no. 2, pp. 228–236, 2006.

[109] E. Nolde, "Greywater reuse systems for toilet flushing in multi-storey buildings - over ten years experience in Berlin," *Urban Water*, vol. 2, no. 3, pp. 275–284, 2000.

[110] D. Christova-Boal, R. E. Eden, and S. McFarlane, "An investigation into greywater reuse for urban residential properties," *Desalination*, vol. 106, no. 1–3, pp. 391–397, 1996.

[111] R. Birks and S. Hills, "Characterisation of indicator organisms and pathogens in domestic greywater for recycling," *Enviornmental Monitoring Assessment*, vol. 129, no. 1–3, pp. 61–69, 2007.

[112] N. Atanasova, M. Dalmau, J. Coman, M. Poch, I. Rodriguez-Roda, and G. Buttiglieri, "Optimized MBR for greywater reuse systems in hotel facilities," *Journal of Environmental Management*, vol. 193, pp. 503–511, 2017.

[113] A. Huelgas and N. Funamizu, "Flat-plate submerged membrane bioreactor for the treatment of higher-load graywater," *Desalination*, vol. 250, no. 1, pp. 162–166, 2010.

[114] S. K. Alharbi, M. Shafiquzzaman, H. Haider, S. S. AlSaleem, and A. R. Ghumman, "Treatment of Ablution Greywater for Recycling by Alum Coagulation and Activated Carbon Adsorption," *Arabian Journal for Science and Engineering*, vol. 44, no. 8398–8399, 2019.

[115] M. Yousuf and J. Baloch, "Treatment of Synthetic Greywater by Using Banana, Orange and Sapodilla Peels as a Low Cost Activated Carbon," *Journal of Materials and Environmental Sciences*, vol. 10, no. 10, pp. 966–986, 2019.

[116] Hendrawati, I. R. Yuliastri, Nurhasni, E. Rohaeti, and E. Hefni, "The use of Moringa Oleifera Seed Powder as Coagulant to Improve the Quality of Wastewater and Ground Water," in *Earth and Environmental Science 31*, 2016.

[117] T. C. Shan, M. Al Matar, E. A. Makky, and E. N. Ali, "The use of Moringa oleifera seed as a natural coagulant for wastewater treatment and heavy metals removal," *Applied Water Science*, vol. 7, pp. 1369–1376, 2017.

[118] I. Imran, A. Nusrat, and A. Neha, "Domestic Wastewater Treatment by Low-Cost Natural Adsorbents," *Internation Journal for Scientific Research & Development*, vol. 4, no. 3, pp. 1768–1771, 2016.

[119] P. Patel, A. Muteen, and P. Mondal, "Treatment of greywater using waste biomass derived activated carbons and integrated sand column," *Science of the Total Environment*, vol. 711, p. 134586, 2020.

[120] A. Albalawneh and T. Chang, "Review of the greywater and proposed greywater recycling scheme for agricultural irrigation reuses," *International Journal of Research - Granthaalayah*, vol. 3, no. 12, pp. 16–35, 2015.

[121] H. Abdel-shafy, A. Makki, and M. S. M. Mansour, “Anaerobic/aerobic treatment of greywater via UASB and MBR for unrestricted reuse,” *Water Science & Technology*, vol. 71, pp. 630–637, 2015.

[122] H. Bhuptawat, G. K. Folkard, and S. Chaudhari, “Innovative physico-chemical treatment of wastewater incorporating Moringa oleifera seed coagulant,” *Journal of Hazardous Material*, vol. 142, no. 1–2, pp. 477–482, 2007.

[123] H. Al-hamaiedeh and M. Bino, “Effect of treated grey water reuse in irrigation on soil and plants,” *Desalination*, vol. 256, no. 1–3, pp. 115–119, 2010.

[124] S. A. Prathapar, A. Jamrah, M. Ahmed, and S. Adawi-Al, “Overcoming constraints in treated greywater reuse in Oman,” *Desalination*, vol. 186, pp. 177–186, 2005.

[125] United Stated Environmental Protection Agency, “Guidelines for Water Reuse,” Washington D.C., USA, 2004.

[126] G. Oron *et al.*, “Greywater use in Israel and worldwide: Standards and prospects,” *Water Research*, vol. 58, pp. 92–101, 2014.

[127] H. Effendi, R. D. Sari, and S. Hasibuan, “Moringa oleifera as coagulant for batik effluent treatment,” in *35th Annual Conference of the International Association for Impact Assessment*, 2015.

[128] S. Parjane and M. G. Sane, “Performance of grey water treatment plant by economical way for Indian rural development,” *International Journal of ChemTech Research*, vol. 3, no. 4, pp. 1808–1815, 2011.

[129] M. Pidou, “Greywater recycling : A review of treatment options and applications,” in *Engineering Sustainability*, 2007, vol. 160, pp. 119–131.

[130] C. C. Nnaji, C. N. Mama, A. Ekwueme, and T. Utsev, “Feasibility of a Filtration-Adsorption Grey Water Treatment System for Developing Countries,” *Hydrology: Current Research*, pp. 1–6, 2013.

[131] H. I. Abdel-Shafy, M. A. El-Kateeb, and M. Shehata, “Greywater treatment using different designs of sand filters,” *Desalination*, vol. 52, pp. 5237–5242, 2014.

[132] Z. N. Abudi, “THE EFFECT OF SAND FILTER CHARACTERISTICS ON REMOVAL EFFICIENCY OF ORGANIC MATTER FROM GREY WATER,” *Al - Qadisiya Journal of Engineering Science*, vol. 4, no. 2, pp. 143–155, 2011.

[133] R. A. Azeez, “A Study on The Effect Of Temperature on The Treatment of Industrial Wastewater Using Chlorella Vulgaris Alga,” *Journal of Engineering Technology*, vol. 2, no. 4, pp. 785–792, 2009.

[134] E. Guchi, “Review on Slow Sand Filtration in Removing Microbial Contamination and Particles from Drinking Water,” *Journal of Food and Nutrition*, vol. 3, no. 2, pp. 47–55, 2015.

[135] J. C. Van Dijk and J. H. C. Ooman, *Slow sand filtration for community water supply in developing countries: a design and construction manual*. The Hague, Netherlands: WHO International Reference Center for Community Water Supply, 1978.

[136] Y. Li, J. Yu, Z. Liu, and T. Ma, "Estimation and modeling of direct rapid sand filtration for total fecal coliform removal from secondary clarifier effluents," *Water Science & Technology*, vol. 65, no. 9, pp. 1615–1623, 2012.

[137] B. A. Madge and J. Jensen, "Ultraviolet Disinfection of Fecal Coliform in Municipal Wastewater: Effects of Particle Size," *Water Environment Research*, vol. 78, no. 3, pp. 294–304, 2006.

[138] G. P. Winward, L. M. Avery, T. Stephenson, and B. Jefferson, "ULTRAVIOLET (UV) DISINFECTION OF GREY WATER: PARTICLE SIZE EFFECTS," *Environmental Technology*, vol. 29, no. 2, pp. 235–244, 2008.

[139] H. Rizvi, N. Ahmad, A. Yasar, K. Bukhari, and H. Khan, "Disinfection of UASB-Treated Municipal Wastewater by H2O2, UV, Ozone, PAA, H2O2/Sunlight, and Advanced Oxidation Processes: Regrowth Potential of Pathogens," *Polish Journal of Environmental Studies*, vol. 22, no. 4, pp. 1153–1161, 2013.

[140] M. Antonelli, V. Mezzanotte, and C. Nurizzo, "Wastewater Disinfection by UV Irradiation: Short and Long-Term Efficiency," *Envrionmental Engineering Science*, vol. 25, no. 3, pp. 363–373, 2008.

[141] EPA, "Wastewater Technology Fact Sheet Ultravoilet Disinfection," Washington, D.C., Sept. 1999.

[142] D. Mandal, P. Labhasetwar, S. Dhone, A. S. Dubey, G. Shinde, and S. Wate, "Water conservation due to greywater treatment and reuse in urban setting with specific context to developing countries," *Resource, Conservation & Recycling*, vol. 55, pp. 356–361, 2011.

[143] F. Masi, B. El Hamouri, H. Abdel Shafi, A. Baban, A. Ghrabi, and M. Regelsberger, "Treatment of segregated black/grey domestic wastewater using constructed wetlands in the Mediterranean basin: the zer0-m experience," *Journal of AOAC International*, vol. 61, pp. 97–105, 2010.

[144] M. Blanky, S. . Martinez, M. Halpern, and E. Friedlier, "Legionella pneumophila: from potable water to treated greywater; quantification and removal during treatment," *Sciene of the Total Environment*, vol. 533, pp. 557–565, 2015.

[145] M. H. Al-mughalles, R. A. Rahman, F. B. Suja, M. Mahmud, and N. A. Jalil, "Household Greywater Quantity and Quality in Sana ' a , Yemen," *European Journal of Government and Economics*, vol. 17, p. 2012, 2015.

[146] E. Friedler, A. Yardeni, Y. Gilboa, and Y. Alfiya, "Disinfection of greywater effluent and regrowth potential of selected bacteria," *Water Science & Technology*, vol. 63, no. 5, pp. 931–940, 2011.

[147] J. Jong, J. Lee, J. Kim, and K. H. Hyun, “The study of pathogenic microbial communities in graywater using membrane bioreactor,” *Desalination*, vol. 250, no. 2, pp. 568–572, 2010.

[148] G. Ausland, T. K. Stevik, J. F. Hanssen, J. C. K, and P. D. Jenssen, “Intermittent filtration of wastewater — removal of fecal coliforms and fecal streptococci,” *Water Research*, vol. 36, pp. 3507–3516, 2002.

[149] A. A. Radhi and M. Borghei, “Effect of aeration then granular activated carbon on removal efficiency of TOC, COD and Coliform, Fecal coliform for “Sorkheh Hesar Canal" water,” *International Journal of Computation and Applied Sciences*, vol. 3, no. 2, pp. 201–206, 2017.

[150] A. M. Nassar and K. Hajjaj, “Purification of Stormwater Using Sand Filter,” *Journal of Water Resource Protocol.*, vol. 5, no. 11, pp. 1007–1012, 2013.

[151] D. Sharath, B. T. A, and K. Sushma, “Design of sand filter unit for surface water treatment in Gubre City, SNNPR, and Ethopia,” *Journal of Industial Pollution Control*, vol. 33, no. 2, pp. 1120–1127, 2017.

[152] E. Friedler, R. Kovalio, and A. Ben-Zvi, “Comparative Study of the Microbial Quality of Greywater treated by Three On-Site Treatment Systems,” *Environmental Technology*, vol. 27, no. 6, pp. 653–663, 2006.

[153] R. Khalaphallah and Y. Andres, “The effect of various abiotic factors on the survival growth of Escherichia coli and Pseudomonas aeruginosa in bathroom greywater,” *J. Water Reuse Desalination*, vol. 2, no. 2, pp. 92–101, 2012.

[154] B. Zuma, R. Tandlich, K. Whittington-Jones, and J. Burgess, “Mulch tower treatment system. Part 1: overall performance in greywater treatment,” *Desalination*, vol. 242, pp. 38–56, 2009.

[155] J. B. Rose, G. S. Sun, C. P. Gerba, and N. A. Sinclair, “Microbial quality and persistence of enteric pathogens in graywater from various household sources,” *Soil, Water and Environmental Science*, vol. 25, no. 1, pp. 37–42, 1991.

[156] H.-S. Shin, S.-M. Lee, I.-S. Seo, G.-O. Kim, and J.-S. Sang, “Pilot-scale SBR and MF operation for the removal of organic and nitrogen compounds from greywater.,” *Water Science & Technology*, vol. 38, no. 6, pp. 80–88, 1998.

[157] E. Nolde, “Greywater reuse systems for toilet flushing in multi-storey buildings - over ten years experience in Berlin,” *UrbanWater*, vol. 1, no. 4, pp. 1-15, 2000.

[158] L. M. Casanova, C. P. Gerba, and M. Karpiscak, “Chemical and microbial characterization of household graywater,” *Journal of Environmental Science and Health*, vol. 36, no. 4, pp. 395–401, 2001.

[159] A. T. Laine, “Technologies for greywater recycling in buildings,” PhD Thesis, Cranfield University, UK, 2001.

[160] Hrudey and Raniga, “Greywater characteristics, health concerns and treatment technology,” in *Proceedings of the post IAWPR conference seminar*, 1980.

[161] S. Surendran and A. Wheatley, “Grey water reclamation for urban non-potable reuse - challenges and solutions a review,” *Journal of Colloid and Interface Science,* vol. 122, no. 2, pp. 382–397, 1998.

[162] A. Dixon, D. Butler, A. Fewkes, and A. Robinson, “Measurement and modelling of quality changes in stored untreated greywater,” *Urban Water*, vol. 1, no. 4, pp. 293–306, 1999.

[163] S. A. Prathapar, M. Ahmed, S. Al Adawi, and S. Al Sidiari, “Design, construction and evaluation of an ablution water treatment unit in Oman: A case study,” *International Journal of Environmental Studies*, vol. 63, no. 3, pp. 283–292, 2006.

[164] R. Liu, X. Huang, L. Chen, X. Wen, and Y. Qian, “Operational performance of a submerged membrane bioreactor for reclamation of bath wastewater,” *Process Biochemistry*, vol. 40, no. 1, pp. 125–130, 2005.

[165] M. Pidou, F. A. Memon, T. Stephenson, B. Jefferson, and P. Jeffrey, “Greywater recycling: A review of treatment options and applications,” *Engineereing Sustainaibility*, vol. 160, no. September, pp. 119–131, 2007.

Appendix A

Table A.1: Typical greywater characteristics.

References	[155]	[156]	[157]		[158]	[32]	[159]	[160]
Source	**Mixed**	**Mixed**	**Mixed**	**Mixed**	**Mixed**	**Mixed**	**Mixed**	**Mixed**
pH	6.54	7.00			7.247	6.4 – 8.1	7.47	
SS (mg/l)		185			35.09	48 – 120	100	162
Alkanity (mg/l)	158	118				24 – 43		
Hardness (mg/l)	144							
Turbidity (NTU)	76.3				43.0	60 – 240	100.6	
BOD_5 (mg/l)		5			64.85	76 – 200	146	149
BOD_7 (mg/l)			50 – 100	150 – 250				
COD (mg/l)		79	100 – 200	250 – 430			451	
TOC (mg/l)							72.6	125
Chloride (mg/l)	9.0				20.54	9.0 – 18		
T-N (mg/l)	1.7						8.73	
TKN (mg/l)		29.0	5 – 10			4.6 – 20		11.3
NH_4-N (mg/l)	0.74	9.0				<0.1 – 15		1.7
NO_3-N (mg/l)	0.98					<0.05 – 0.2		0.12
T-P (mg/l)		1.7	0.2 – 0.6			0.11 – 1.8		
PO_4-P (mg/l)	9.3						0.4	1.4
Total Coliforms (CFU/100ml)	56 - 10^5		10^2 - 10^3	10^4 – 10^6	8.03 x 10^7	500 – 2.4 x 10^7	7387	2.4 x 10^7
FC (CFU/100ml)	25 – 6 x 10^3		10^{-1} – 10^1	10^4 – 10^6	5.63 x 10^5	170 – 3.3 x 10^3		1.4 x 10^6
Fecal Streptococci (CFU/100ml)					2.38 x 10^2	79 – 2.4 x 10^3		
E. coli (CFU/100ml)							2022	

References	[161]	[159]	[162]	[157]	[159]	[163]	[164]	[165]
Source	**Bath & Shower**	**Bath**	**Bath**	**Shower**	**Shower**	**Shower**	**Shower**	**Shower**
pH	7.6		7.5		7.52	7.4		7.2 ± 0.1
SS (mg/l)	76	54	47		89	353	15 – 50	
Alkanity (mg/l)						15		
Hardness (mg/l)								
Turbidity (NTU)	92		46.1		84.8	375		21 ± 6
BOD_5 (mg/l)	216				146	130	99 – 212	100 ± 23
BOD_7 (mg/l)				70 – 300				
COD (mg/l)	424	184	685	113 – 633	420	294	130 – 322	292 ± 68
TOC (mg/l)	104				65.3	83.5		
Chloride (mg/l)								
T-N (mg/l)					8.7			13.5 ± 3.3
TKN (mg/l)								
NH_4-N (mg/l)	1.56	1.1					0.6 – 1.0	
NO_3-N (mg/l)	0.9	4.2				28.7		
T-P (mg/l)								
PO_4-P (mg/l)	1.63	5.3			0.3			
Total Coliforms (CFU/100ml)	6×10^6		370	$10^1 – 10^3$	6800			
FC (CFU/100ml)	600		0	$10^{-1} – 10^1$		>200.5		
Faecel Streptococci (CFU/100ml)								
E. Coli (CFU/100ml)						>200.5		

Table A.2: Typical standards for non-potable greywater reuses and applications [30], [47]-[1].

Categories	Reuse Type	Treatment Objective	Application
Recreational (impoundments, lakes)	Unrestricted	BOD_5: ≤ 10 mg/l TN: ≤ 1.0 mg/l TP: ≤ 0.05 mg/l Turbidity: ≤ 2 NTU	Water fountains, recreational impoundments, lakes and ponds for swimming
	Restricted	BOD_5: ≤ 30 mg/l TN: ≤ 1.0 mg/l TP: ≤ 0.05 mg/l TSS: ≤ 30 mg/l Fecal coliform: ≤ 10 mg/l Total coliforms: ≤ 100 mg/l	Recreational lakes and pond with no skin contact
Urban reuses and agricultural irrigation	Unrestricted	BOD_5: ≤ 10 mg/l Turbidity: ≤ 2 NTU pH: 6-9 Fecal coliform: ≤ 10 mg/l Total coliforms: ≤ 100 mg/l Residual chlorine: ≤ 1 mg/l	Toilet flushing, laundry, air conditioning, process water, landscape irrigation, food crops and vegetables, street washing and construction
	Restricted	BOD_5: ≤ 30 mg/l Detergent (anionic): ≤ 1 mg/l TSS: ≤ 30 mg/l pH: 6-9 Fecal coliform: ≤ 10 mg/l Total coliforms: ≤ 100 mg/ Residual chlorine: ≤ 1 mg/l	Landscape irrigation, location where public access is limited or controlled, non-food crops and vegetables that are consumed after processing

Vita

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In September 2017, Ms. Fatima began her Master's program at the American University of Sharjah. She also worked alongside for Jacobs Engineering Group as a Water Design Engineer. Currently she holds 5 years' experience working in the field of wet utilities design including designing of storm water drainage networks, sewerage networks, pressure mains. Her area of expertise is conducting hydrology studies and preparing flood protection work schemes.