International Masters of Science in Environmental Technology and Engineering

Master's dissertation submitted in partial fulfilment of the requirements for the joint degree of

EU Erasmus+ Master course organized by
University of Chemistry and Technology, Prague, the Czech Republic
IHE Delft Institute for Water Education, Delft, the Netherlands
Ghent University, Ghent, Belgium

Academic year 2018-2020

A NOVEL WAY OF WATER REUSE IN A DECENTRALIZED WASTEWATER TREATMENT SYSTEM, APPLICABLE IN THE CITY OF THE FUTURE

Host institutions: Ghent University, Ghent, Belgium & PureBlue Water, Hulst, the Netherlands

Luiz Henrique Da Silva Corrêa

ES-IMETE.20-20

Promotors: Mr. Kevin Van de Merlen, Msc & Prof. Dr. Ir. Erik Meers

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Abstract

The increase in the water and energy demand in urban cities comes with the need to develop smart eco-friendly solutions to promote the best use of these resources. Greywater reuse can contribute as an important practice in sustainable cities to reduce the pressure on water and energy resources. This study aimed to design and evaluate the performance of a decentralized pilot-treatment system composed of a moving bed biofilm reactor (MBBR) followed by an up-flow filter and UV disinfection to treat greywater from showers and hand basins for toilet flushing. Additionally, a heat exchanger was placed before the MBBR to study its performance on promoting energy recovery for water heating. The pilot was located in Hulst, the Netherlands, at the Pureblue Water company's installations. The monitoring of the overall system performance, as well as its units, in removing organic matter, nutrients, total suspended solids (TSS), and recovering energy from greywater were performed. Results showed that the system was able to reduce all the parameters analyzed (chemical oxygen demand - COD, total nitrogen -TN, total phosphorus (TP - PO_4-P), pH, and turbidity) to most of the greywater reuse safety standards found in the literature. Moreover, the system presented COD, TN, and TP removal efficiencies of 69%, 42%, and 53%, respectively corresponding to a population equivalent of 120 inhabitants. The filter showed TSS removal from 44% to 52% associated with a suspended solids loading capacity of 4 TSS COD g/L (with a breakthrough time of 21 hours). While the MBBR was able to treat the organic load of 2.58g COD/m^2.d. In addition, the heat exchanger presented from moderate to high efficiencies (from 39% to 92%) in recovering heat for water heating. The pilot plant showed to be an excellent way to promote sustainable water and energy use in the cities of the future.

Keywords: MBBR, filtration, UV disinfection, cities of the future, heat recovery, greywater reuse.

FACULTY OF BIOSCIENCE ENGINEERING

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List of Units

°C	Celsius degree
d	Day
g	Gram
J	Joule
K	Kelvin
kg	Kilogram
kton	Kiloton
h	Hour
L	Liter
m	Meters
m^2	Square meters
m^3	Cubic meters
min	Minute
mg	Milligram
mL	Milliliter
MPN	Most probable number
NTU	Nephelometric turbidity unit
S	Siemens
y	Year
kWh	Kilowatt-hour

List of Abbreviations

AC	Activated carbon
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DAF	Dissolved air flotation
DNA	Deoxyribonucleic acid
DO	Dissolved oxygen
EEC	European economic community
EEA	European economic area
F COD	Filtered COD
GW	Greywater
HE	Heat exchanger
HRT	Hydraulic retention time
MBBR	Moving biofilm bed reactor
P&ID	Piping and instrument diagram
TN	Total nitrogen
SALR	Surface area loading rate
SLR	Solid loading rate
TP	Total phosphorus
TSS	Total suspended solids
TSS COD	Total suspended solids chemical oxygen demand
UF COD	Unfiltered chemical oxygen demand
UV	Ultraviolet
RNA	Ribonucleic acid
SD	Standard deviation
SS	Suspended solids
VSS	Volatile suspended solids
WFD	Water framework directive
WHO	World health organization
WW	Wastewater
WWTP	Wastewater treatment plant

1 Introduction

1.1 Background

Water and energy resources are fundamental to social and economic development. Rapid urbanization, industrial activities, and agriculture growth have resulted in increased demand for these resources. (Fang & Chen, 2017). By 2050, there will be insufficient water and energy to satisfy the growing need at the global level. Global energy demand is estimated to increase by over 80%, while water demand is estimated to increase by 50%, causing insecurity in providing water and energy. The most affected zones by this process are the most populated areas, urban areas (Tsolakis & Anthopoulos, 2015). This is exacerbated by the shifts in the population lifestyle and an increase in the consequent need for water-energy demand (Tsolakis & Anthopoulos, 2015). The main consumers of water and energy resources for domestic use are cities and urban areas (Wanjiru & Xia, 2017). In the 2018 revision of World Urbanization Prospects by the United Nations, it was estimated that by 2050, 68.4% of the world's population will be residing in urban areas (United Nations, 2018). According to Bulkeley & Betsill, 2005, cities consume 70% of the world's resources. In addition, to the depletion of resources such as water and energy, cities are major contributors to water pollution, greenhouse gas emissions, air pollution, soil contamination among many others. The mechanism of how society consumes and discharges or wastes water-energy has to be changed. Innovative and more effective mechanisms in water technologies and infrastructure will be needed in these areas to mitigate the impacts of growing water shortages while ensuring water allocation efficiently and securely. From here emerged the need to develop a smart, sustainable, and eco-friendly way to use water and energy in urban areas to mitigate environmental, social, and economic problems threatening cities (Bibri & Krogstie, 2017).

Sustainable cities, the so-called green-cities or cities of the future, are cities designed with consideration for social, environmental as well as economic aspects aiming to achieve sustainability through the balance of resources consumption and minimization or mitigation of environmental adverse effects, environmental-friendly lifestyle, social equality, and sustainable urban management (Bibri & Krogstie, 2017; Liu & Jensen, 2018). One of the major challenges of these cities is how to supply potable water and energy sustainably (Wanjiru & Xia, 2017). Greywater treatment and recycling are the key practices to overcome these challenges.

Normally in a conventional centralized system, the treatment of greywater causes many adverse impacts on urban water management. Adding to that, the impact caused by heavy rainfall may decrease wastewater (WW) treatment performance in wastewater treatment plants (WTTP). Because not only stormwater can bring a high number of pathogens, but it also increases the wastewater flowrate to the WTTP exceeding its capacity and reducing by this mean the WTTP's effluent quality (McMahan, 2006). This because after reaching its full capacity, the WTTP would not be able to treat the incoming extra pollutants load, resulting in the pollution of water bodies (Díaz et al, 2016; Rashid & Liu, 2020).

On the contrary, when treated and recycled in a decentralized manner, this unconventional approach can bring many benefits. For example, positioning the wastewater treatment plant close to the WW contributors, in a decentralized manner would reduce the cost of WW transportation due to a smaller WW collection system. This guarantees an economic benefit, on the contrary to centralized treatment systems placed in remote areas. The other advantage is that the relocation of WW treatment would also allow the reuse of energy and treated WW by the decentralized system's contributors/users due to the proximity of the treatment plants which results in the dropping of potable water and energy demands (Wanjiru & Xia, 2017). Furthermore, examples of environmental benefits would be the reduction of WW discharges to water bodies, and pollutants load to the WTTP which avoids water bodies pollution when its capacity is exceeded because of heavy rainfalls (Wanjiru & Xia, 2017). These benefits emphasize the need to treat greywater in a decentralized manner and recover energy from the treated to optimize the energy-water consumption in the cities (Plappally et al.,2012; Ackerman et al., 2013; Feng et al., 2014; Spang et al, 2014). Thus, attention has been made worldwide and more specifically in Europe on decentralized systems combining both energy recovery and wastewater treatment (Wanjiru & Xia, 2017).

Besides the existence in Europe of a legal framework that supports greywater reuse and energy recovery (such as the Directive 91/271/EEC on urban wastewater treatment, the Water Framework Directive (WFD), 2000/60/EC, WFD, and the EU action plan for the circular economy) little is known yet on how to implement greywater treatment, greywater reuse limits, and energy recovery throughout this process. However, scientists, environmentalists, and policymakers commonly agree that greywater treatment and possible ways to recycle and reuse water are great examples of using water and energy sustainably in cities.

Many technologies, such as membrane reactors, filters, and electrocoagulation, may potentially be applied for greywater treatment and energy recovery (Barzegar et al., 2019, Parjane and Sane, 2011, Chrispim and Nolasco, 2017). Membrane technology, for example, can be applied in several sorts of wastewater treatment applications. However, although this technology is known by the production of high-quality effluent, it is also acknowledged as an expensive technology due to its high operational cost (Merz et al., 2007). Making its application for domestic greywater treatment less attractive (Boano et al., 2019). Other processes such as filtration and electrocoagulation, often applied to the removal of suspended solids in wastewater treatment, would not be able to reduce the dissolved organic pollutants from greywater significantly (Barzegar et al., 2019; Gross et al., 2007). Making their application in greywater treatment often accompanied by a second biological step, such as Moving Bed Biofilm Reactors (MBBR), for organic matter degradation and nutrient removal (Chrispim et al., 2017). Many studies showed that MBBR followed by filtration and a disinfection step is the optimal way to treat greywater for non-potable uses (McNabola & Shields, 2013; Van Blommestein et al. ,2013; Chrispim et al., 2017; Saidi et al., 2017; Mazhar et al., 2018). To achieve that, the greywater treatment system, proposed in this study, was designed to remove organic matter/nutrients (by a MBBR), suspended solids (by a filter), and kill pathogens (by UV disinfection) from the greywater originated in showers and hand basins for toilet flushing in buildings. Moreover, to promote energy recovery from the greywater shower, a heat exchanger was added to the system allowing an optimal recovery of energy (Saidi et al., 2017; Chrispim et al., 2017). The proposed system can be considered as an essential contribution to sustainable water and energy use in the cities of the future. Figure 1.1 shows a schematic layout of the proposed greywater treatment technology integrated with cities of the future.

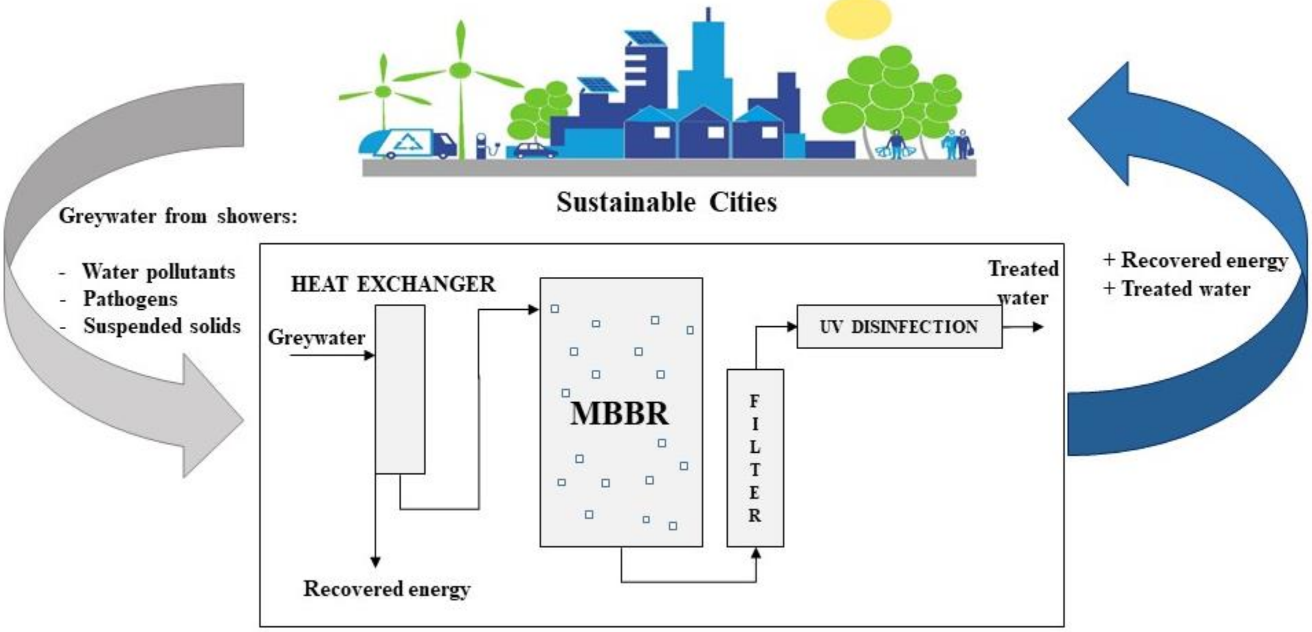


Figure 1.1 - Schematic Layout of Greywater Treatment Technology to Reuse Treated Greywater and Recover Energy from Buildings

In other words, this study, based on results obtained from a pilot plant at **PureBlue Water** facilities in Hulst, Netherlands, consists of a first attempt to promote water and energy savings in sustainable cities using a system that can treat greywater for toilet flushing, while recovering energy. The proposed research aims to test and evaluate the performance of this MBBR-Filter system by performing a physico-chemical analysis of the system's influent and effluent. The specific objectives were testing the MBBR performance in removing organic matter from synthetic greywater, at different feed concentrations, and test the filter performance in removing suspended solids from the MBBR effluent. Additionally, the efficiency of the heat exchanger at different flowrates rates was determined to find its optimal operational flowrate and temperature. Thus, the main goals of this study were to evaluate the pilot system performance in treating greywater (from showers and hand basins for toilet flushing) and recovering energy (for water heating).

1.2 Objectives

The main objective of this research was to study and develop a system for greywater treatment and energy recovery from buildings to promote sustainable water and energy reuse in the implementation of cities of the future. This goal has been reached through the design and evaluation of a pilot system composed of a moving bed biofilm reactor followed by a new up-flow filter concept and a disinfection unit for toilet flushing and a heat exchanger to recover energy.

This thesis was divided into 2 parts. The first part provides a review of technologies such as MBBR, filtration, and UV disinfection used to date in treating greywater for toilet flushing as well as the use of heat exchangers to recover energy from domestic wastewater. The second part deals with the performance analysis of the pilot plant to treat synthetic greywater and recover energy from it. For this purpose, the following specific objectives were defined:

- To evaluate the pilot MBBR performance in removing organic matter and nutrients (COD, TN, TP, NH_4-N, and NO_3-N) from synthetic greywater.
- To test and analyze the pilot filter performance in removing suspended solids from the MBBR effluent (TSS removal efficiency, turbidity removal, TSS COD loading capacity, and filter's saturation and breakthrough time).
- To determine and evaluate the pilot heat exchanger performance in recovering energy for water heating as well as its optimal operational flowrate and temperatures.
- To find the optimum operating conditions and determine and evaluate the overall system performance in treating synthetic greywater for toilet flushing (Pilot's influent versus effluent characterization, overall removal efficiencies, and mass balances).

2 Literature Review

This section consists of a literature review on a) the technologies applied in this study, b) advantages of decentralized systems to treat greywater in the cities of the future, c) the contribution of this study to the energy-water nexus, and d) the existing legal framework on water reuse and energy recovery.

2.1 Greywater Treatment Technologies

2.1.1 Greywater

Greywater (GW) is the amount of domestic wastewater except for toilet flushing and accounts for 75% of total household wastewater (Ghaitidak and Yadav, 2013). It is normally divided into two types: light GW, which sources are bathrooms, showers, tubs, and hand basins and dark GW which includes laundry facilities, dishwashers, and sometimes kitchen sinks (Boano et al, 2019; Fowdar et al, 2017; Hourlier et al, 2010). Usually, greywater contains personal care products (e.g. shampoo, shaving cream, and toothpaste), human-derived compounds (e.g. hair and skin), and traces of urine and feces (Eriksson et al., 2002). Though by definition greywater does not include feces and urine, some traces of them can be found in greywater, indicating urine and feces contamination. Dark GW contains high concentrations of chemical products, non-biodegradable fibers, food, oils, and fat, while light GW does not (Ghaitidak and Yadav, 2013). This facilitates the recycling of light GW because it reduces the complexity of the treatment needed. Table 2.1.1 shows the physico-chemical composition of domestic greywater in different countries (Boano et al, 2019).

Table 2.1.1 - Physico-Chemical Composition of Domestic Greywater in Different Countries

	Minimum-Maximum (Average)			
Country	**COD**	**TP**	**TN**	**pH**
	mg/L			
Belgium[c]	225 - 364	-	-	(7.6)
Brazil[a]	(1,031.4)	(21.15)	(14.4)	(8.9)
Canada[b]	301 - 557	-	-	6.7 - 7.6
France[c]	176 - 323	-	-	6.46 - 7.48
Germany[d]	(109)	(1.6)	(15.2)	(7.6)
Japan[d]	(675)	(1.1)	(25.6)	(-)
Marroco[e]	25 - 300	2.8 - 11.3	-	7.5 - 7.9
Netherlands[h]	425 - 1,583	5.7 - 9.9	17.2 - 47.8	(7.5)
Norway[f]	(241)	(1.03)	(10.61)	(7.1)
United Kingdom[d]	33 - 587	0.4 - 0.9	4.6 - 10.4	6.6 - 7.8
Western Europe[g]	25 - 1,583	0 - 11	3 - 75	6.1 - 9.6
Yemen[d]	1,200 - 2,000	-	-	6

Source (a: Pansonato et al, 2007; b: Finley et al., 2009; c: Hourlier et al, 2010; d: Ghaitidak and Yadav, 2013; e: Merz et al., 2007; f: Eregno et al, 2017; g: Boutin and Eme, 2016; h: Hernandez et al, 2007)

As seen in Table 2.1.1, greywater composition varies differently between the cited countries. No variations were found in the pH values because the greywater pH depends on a large extent on the water supply pH which is generally around 7 (Oteng-Peprah et al, 2018). COD values were observed in the order of some hundreds with only a few exceptions such as Yemen. Developing countries usually present high COD concentrations in greywater if compared to developed ones (Ghaitidak and Yadav, 2013). This shows a link between the greywater composition and the countries' characteristics. Additionally, total nitrogen and phosphorus were relatively low. Although many studies assessed greywater and provided extensive figure on the composition/sources, many important factors should be considered such as seasonal variations, greywater quality, country selected for the study, population lifestyle, wastewater infrastructure, water availability, population income, and environmental awareness among many others (Boano et al., 2017, Eriksson et al., 2002 and Ghaitidak and Yadav, 2013). As shown in Table 2.1.1. the greywater composition varies country-by-country. Therefore, greywater characterization should be performed before the treatment definition since it is hard to find a common pattern applicable to all countries

2.1.2 Conventional Technologies Applied to Treat Light Greywater for Domestic Purposes

Currently, the reuse and recycling of light greywater are receiving more attention not only due to the low levels of pathogens, nitrogen, and phosphorus but also because of the urge to reduce potable water demand (Li et al., 2004). Many studies were carried on different technologies that can be applied to treat greywater for non-potable applications (Boano et al., 2019; Cureau and Ghisi, 2019; Ghaitidak and Yadav, 2013; Li et al., 2009). Factors such as operational conditions and greywater composition seemed to be important parameters that determine the efficiency of the treatment (Boano et al., 2019). In an extensive literature review, Boano et al., 2019, summarized the main technologies used to treat greywater in the last 21 years. Table 2.1.2 shows the most relevant technologies applied in greywater treatment. The treatment technologies were classified according to the adopted processes: physical, chemical, and biological.

According to Table 2.1.2, coagulation presented high removal efficiency for phosphorus (>90%) and moderate for COD removal (>60%) from synthetic GW. Filtration generally had high efficiencies in the COD (>80%) and phosphorus removal (>70%) from synthetic GW. As expected, biological technologies showed high COD removal values (up to 90%) and from moderate to high values of nitrogen removal (from 40% to 72%) from real GW.

Boano et al., 2019, concluded that among chemical treatment processes coagulation and flocculation are the most commonly applied technologies to treat greywater (Ghaitidak and Yadav, 2013). Among the physical technologies, filtration is the most commonly applied in greywater treatments (Noutsopoulos et al., 2018). In the case of biological treatments, rotating biological contractors, MBBR, sequencing batch reactors, and membrane bioreactors are optimal technologies to treat greywater (Chrispim and Nolasco, 2017; Rodda et al., 2011; Wu, 2019).

Though, many technologies seem to be suitable to treat light greywater. Li et al. ,2009, showed that physical treatments alone cannot reduce organics and surfactants to safe standards. While, for example, chemical treatments can efficiently remove them. Therefore, the authors concluded that the combination of an aerobic biological treatment with physical filtration, and disinfection is the most economical and feasible solution to treat and recycle greywater for domestic use.

Having that in mind, MBBR technology (aerobic biological treatment) followed by an up-flow filter (physical filtration), and UV disinfection was the treatment combination chosen in this thesis to treat greywater from buildings in the cities of the future. This study will discuss in-depth the MBBR, physical filtration, and UV disinfection technologies in further sections.

Table 2.1.2 - Conventional Technologies to Treat Greywater (Source: Boano et al., 2019)

Conventional/Advanced Process		GW Origin	Treatment Efficiency Minimum-Maximum (Average)					Reference
			COD	TP	NO_3^--N	NH_4^+-N	pH	
			%					
Chemical	Coagulation: FeSO4	Synthetic GW: shower and sink	(63.59)	(96.39)	(8.96)	-	-	Pidou et al., 2008
	Coagulation: Al2(SO4)3	Synthetic GW: shower and sink	(63.72)	(94.58)	(14.93)	-	-	Pidou et al., 2008
	Electro-coagulation O3	Real GW: shower and sink	(85)	-	-	-	-	Barzegar et al., 2019
Physical	Filtration: crushed dolomite and plastic filter media	Synthetic GW: bath, laundry, and kitchen	-	(73.68)	(48.57)	(16.67)	-	Gross et al., 2007
	Filtration: coconut shell, sawdust, and charcoal	Synthetic GW: kitchen	(82.26)	(100)	(68.66)	(73.42)	-	Parjane and Sane, 2011
	Filtration: AC	Synthetic GW: bath and laundry	-	-	-	-	6.1-7.8	Ghaitidak and Yadak, 2013
Biological	Rotating Biological Contactor	Real GW: laundry, bath, and kitchen	21.48-60.36	-	-	-	-	Xio et al.,2018
	MBBR	Synthetic GW: bath and laundry	(70)	(12)	-	-	-	Chrispim and Nolasco, 2017
	Membrane Bioreactor	Real GW: shower	(86.24)	(18.75)	-	(72.03)	-	Merz et al., 2007
	Sequencing Batch Reactor	Synthetic GW: shower	(90)	-	-	-	-	Weitao et al., 2006
	Up-flow Anaerobic Sludge Blanket	Real GW: shower	(51)	-	-	(47)	-	Hernandez Leal et al., 2011

2.1.3 Moving Bed Biofilm Reactor – MBBR

The MBBR has its origin in Norway and emerged from the need to address pollution control in small Norwegian communities. The need to upgrade existing wastewater treatment was the main driver behind its development (Di Biase et al., 2019). Currently, more than 400 large-scale wastewater treatment facilities in 22 different countries operate with MBBR technology (Rusten et al., 2006). In 2014, more than 1,200 wastewater treatment installations used MBBR technology serving as a great example of the success of MBBRs in the wastewater treatment sector (Biswas et al., 2014).

A MBBR is a biological technology for high organic matter degradation and nutrient removal (Chrispim et al., 2017). The degradation/removal mechanisms are based on biofilms attached growth on carriers that are kept in suspension by the aeration system. The carriers are small polyethylene with a high surface area that accommodates biofilm development. The bacterial growth in the MBBR is described by four phases: lag phase, exponential phase, stationary phase, and death phase. The biomass and growth kinetics are described by the Monod curve, a curve that relates microbial growth with the concentration of limiting nutrient (Kawan et al., 2016). The lag phase corresponds to the acclimatization stage where the microorganisms adapt themselves to growth conditions. During the exponential phase, the cells grow by doubling due to the excess of nutrients. As soon as the nutrient concentration is limited the stationary phase is reached. The population dies then because of inappropriate living conditions. This is the death phase. Figure 2.1.3 illustrates the biofilm devolvement of *Pseudomonas aeruginosa*. Figure 2.1.3.1 shows the MBBR technology process diagram. According to Kawan et al., 2016, more than 90% of the biomass stays in the system. Hence, there is no need for sludge recirculation. This is one of the many advantages of MBBR. Table 2.1.3 lists the advantages and limitations of MBBR systems.

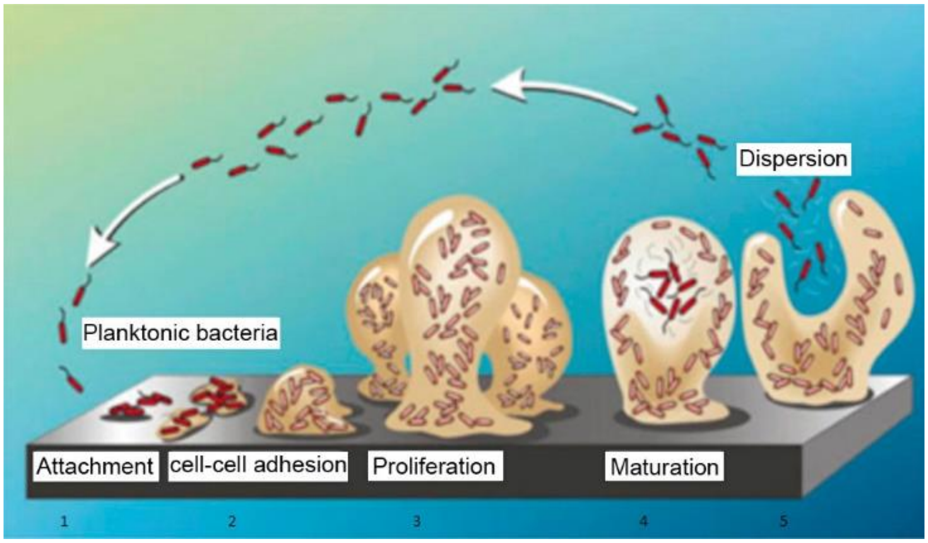


Figure 2.1.3 - Stages of Pseudomonas aeruginosa Biofilm Development [acclimatization stage: attachment and cell-cell adhesion; exponential phase: proliferation; stationary phase: maturation; death phase: dispersion] (Source: Karaguler et al., 2017)

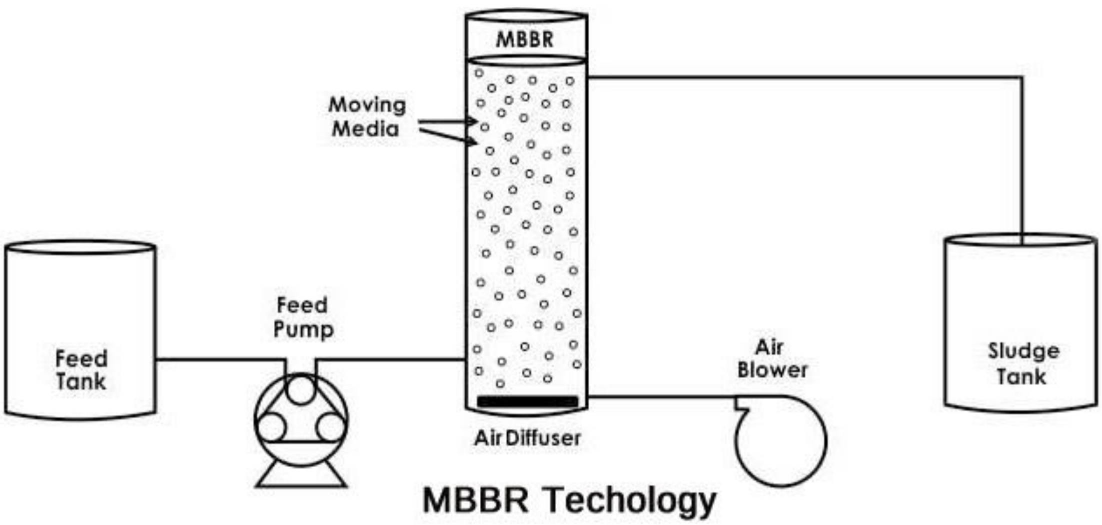


Figure 2.1.3.1 - MBBR Technology Process Diagram (Bionics Consortium, 2019)

Table 2.1.3 - Advantages and Limitations of MBBR Technology

Advantages	Limitations
Possibility to upgrade existing wastewater treatment plant with low cost [a]	High energy cost due to aeration and carriers mixing [c]
Sludge does not need recirculation since the biomass is retained on the carriers [a]	Long time for biomass cultivation might be required [b]
	Long start-up period may be required [b]
Small footprint [a]	
The biofilm is resilient to variations in the influent characteristics such as load, pH, and temperature [a]	
Low sludge production [b]	
Low maintenance required [b]	
No clogging problems [b]	
Easy and simple design to operate [b]	

Source : a: Dezotti et al., 2018; b: Kawan et al, 2016; c: Ødegaard, 2016.

Many researchers agree that MBBR performance may be affected by many factors. These are carrier size and shape, carrier percent fill, hydraulic retention time (HRT), surface area loading rate (SALR), dissolved oxygen (DO), mixing, and aeration rate. Odegaard et al., 2000 studied the influence of carries' sizes and shape on the MBBR performances. The authors concluded that no distinction in the treatment efficiency happened in carriers with different shapes and the same surface area. Other researchers investigated the relation between carrier percent filling and removal of contaminants. They estimated that the optimum carrier filling percentage for COD removal was approximately 50%. Moreover, it was recommended that the DO levels should be maintained higher than 2 mg/L for optimal COD removal (Hajipour et al., 2011; Wang et al, 2005).

Additionally, Hajipour et al., 2011, advised HRTs from 12 to 16.5 hours to guarantee higher pollutants removal in MBBRs. Moreover, Aygun et al, 2008, in a lab-scale experiment found that a rise in organic loading from 6 to 96 g COD/m^2/d was followed by a decline in organic removal from 95.1 removals to 45.2%. The mixing in MBBRs is done by aeration; requiring an extra cost and adding a disadvantage to the technology (Di Biase et al., 2019).

As a result, MBBR is an excellent technology to treat greywater due to its many benefits. However other factors such as DO level, carrier filling, HRT, aeration rate, and others could affect the MBBR performance. These factors need to be taken into account in the MBBR designing. Normally MBBR technology is followed by additional steps to achieve quality standards more specifically when the purpose is for domestic greywater treatment. The polishing steps are commonly filtration and disinfection. Thus, these steps will be discussed in the next sections of this literature review.

2.1.4 Filtration

Filtration consists of a separation process in which a liquid passes through a medium or layer such as sand, gravel, activated carbon, pine bark, to be purified. Filtration, in the context of greywater treatment and recycling, aims to remove particulate matter that was not removed by prior steps in the greywater treatment. Filtration can be done by physical or biological means (Ghaitidak and Yadav, 2013). Physical filtration for removal of solids is applied to the greywater treatment, more frequently. Like any technology, filtration presents advantages and limitations. The following table summarizes the most relevant advantages and drawbacks of filtration on greywater treatment and recycling.

Table 2.1.4 - Advantages and Limitations on Treatment and Recycling of Greywater Filtration

Advantages	Limitations
Simple operation	Not all germs and contaminants are removed
High particulate matter removal	Surface loading rate: 3 - 5 m/h
Inexpensive	Solids Loading Rate: 30 - 50 mg/L.VSS
Effluent with potential for reuse	Backwash volumes: 2.5 - bed volumes
Properly designed vertical flow bed systems can remove 90% of BOD and 80% COD, approximately	Clogging problems
Small footprint	

Source (Ghaitidak and Yadav, 2013; Verma et al., 2017; Noutsopolos et al., 2018; Hamoda et al, 2002; Rajala et al., 2003)

Many factors might interfere in the performance of a filter such as greywater characteristics, surface loading rate (3 - 5 m/h), total suspended solids load (150 mg/L TSS), chemical addition (to boost TSS removal efficiencies), and media characteristics (Verma et al., 2017; Noutsopolos et al., 2018). For example, Rajala et al., 2003, studied the application of a rapid sand filter followed by UV disinfection to remove suspended solids from wastewater. They evaluated the filter's performance with two different surface loading rates of 5 m/h and 10 m/h, respectively. The researchers observed that at the higher surface loading rate (10 m/h), the filter presented lower TSS removal efficiencies (from 30% to 80%) if compared to the SRL of 5 m/h (50% to 80%). In the same line, Hamoda et al, 2002, studied the performance of a full-scale rapid sand filter (SRL of 5 m/h) in removing suspended solids from three wastewater treatment plants in Kuwait. The filter presented COD removal efficiencies lower than 30% and TSS removal efficiencies lower than 70%. They attributed those efficiencies to the fact that just a pre-chlorination step was placed before the filter to prevent clogging due to algae. Additionally, Noutsopolos et al., 2018, studied different factors that can interfere in a sand filter's TSS removal performance. The authors observed that high TSS COD (Total Suspended Solids' Chemical Oxygen Demand) loads were accompanied by low TSS reductions. The researchers also concluded that filtration combined with aluminum chemicals can boost suspended solids removal efficiencies. In the same study, the filtration without chemical additions presented effluent's turbidity and TSS concentration higher than 10 NTU and 10 mg/L, respectively. While, the filtration with the incorporation of coagulation dropped the effluent's turbidity and TSS concentration to 2 NTU and 3 mg/L, respectively. The same differences were observed by Hamoda et al, 2002. Therefore, the examples aforementioned indicate a correlation between the filtration performance in removing TSS and parameters such as SRL, coagulants addition, and TSS COD load. Therefore, the filter applied in this study was designed to overcome such limitations.

Many studies were found in the literature on filtration as a polishing step on greywater treatment. In a study, Friedler et al, 2005, investigated a pilot plant consisting of a biological reactor followed by sand filtration and disinfection units to treat light greywater from seven flats. The results showed that the TSS, turbidity, BOD, and COD were reduced by 82%, 98%, 96%, and 75%, respectively, resulting in an effluent with quality standards for toilet flushing. Additionally, Jabri et al, 2019, investigated the performance of a full-scale MBRR, followed by filtration and UV disinfection, to treat domestic greywater for toilet flushing. The system showed COD, BOD, TN, and TSS removal of 93%, 99%, 78%, and 98.8%. Moreover, in a study Al-Hamaiedeh and Bino et al., 2010, tested the use of filtration as the only technology to treat greywater. The system applied four barrels of up-flow filtration units in series. The first, second, and third barrel removed grease, oil, pollutants, and suspended solids. The fourth barrel functioned as a polishing step. The results showed that the correspondingly initial influent concentrations of COD, BOD, TSS, and TN of 1,172 mg/L, 942 mg/L, 275 mg/L, and 52 mg/L were reduced to 489 mg/L, 108 mg/L, 128 mg/L, and 11 mg/L, respectively. Although the final effluent concentrations did not reach the standard limits for domestic greywater reuse, the study was a good example to show the influence of filtration in the reduction of pollutants in domestic greywater treatment. The table below summarizes the filtration efficiency as a polishing step for greywater treatment and recycling from different studies mentioned previously

Table 2.1.4.1 - Treatment Efficiencies for Filtration as Greywater Treatment Technology

Parameters (mg/L)	**Percentage Removal**
Total Suspended Solids (TSS)	53 - 93%
BOD_5	89 - 98%
COD	37 - 94%
TN	5 - 98%
TP	Up to 100%

Source: Oteng-Peprah et al., 2018; Al-Hamaiedeh and Bino, 2010; Dalahmeh et al.,2012; Finley et al., 2009; Gross et al., 2008

It can be seen that filtration is a fundamental step in greywater treatment and recycling in green cities. It is important to mention that filtration helps to reduce the number of pathogens from wastewater, but it cannot eliminate them. Thus to guarantee safety in the domestic greywater reuse, in the cities of the future, an additional disinfection step is necessary (Jabri et al, 2019). A brief discussion of disinfection will be done in the next section of this literature review.

2.1.5 UV Disinfection

After the biological (MBBR) and physical (Filtration) steps, a low concentration of pathogens such as bacteria, viruses, and microbes might be found on treated light greywater (Jabri et al, 2019). Their removal depends on many factors such as type of media, the thickness of the filtration layer, hydraulic retention time. Although filtration might be able to remove efficiently bacteria and viruses, a disinfection step is still needed to promote the reuse of domestic greywater. A well-established method for disinfection should be applied in the greywater treatment ensuring safe domestic reuse (Gibson et al., 2017). Among many technologies used to kill or inactivate microorganisms, many studies proved that Ultraviolet (UV) disinfection is an efficient step for a total elimination or inactivation of pathogens making this technology applied commonly on full-scale installations (Oh et al., 2018; Gibson et al., 2017; Couto et al., 2013).

UV disinfection damages the DNA and RNA of microorganisms and prevents replication and inability to infect in treated wastewater (Gibson et al., 2017). Figure 2.1.5 illustrates the UV disinfection process and Table 2.1.5 shows the advantages and limitations of the ultraviolet disinfection technology in greywater treatment.

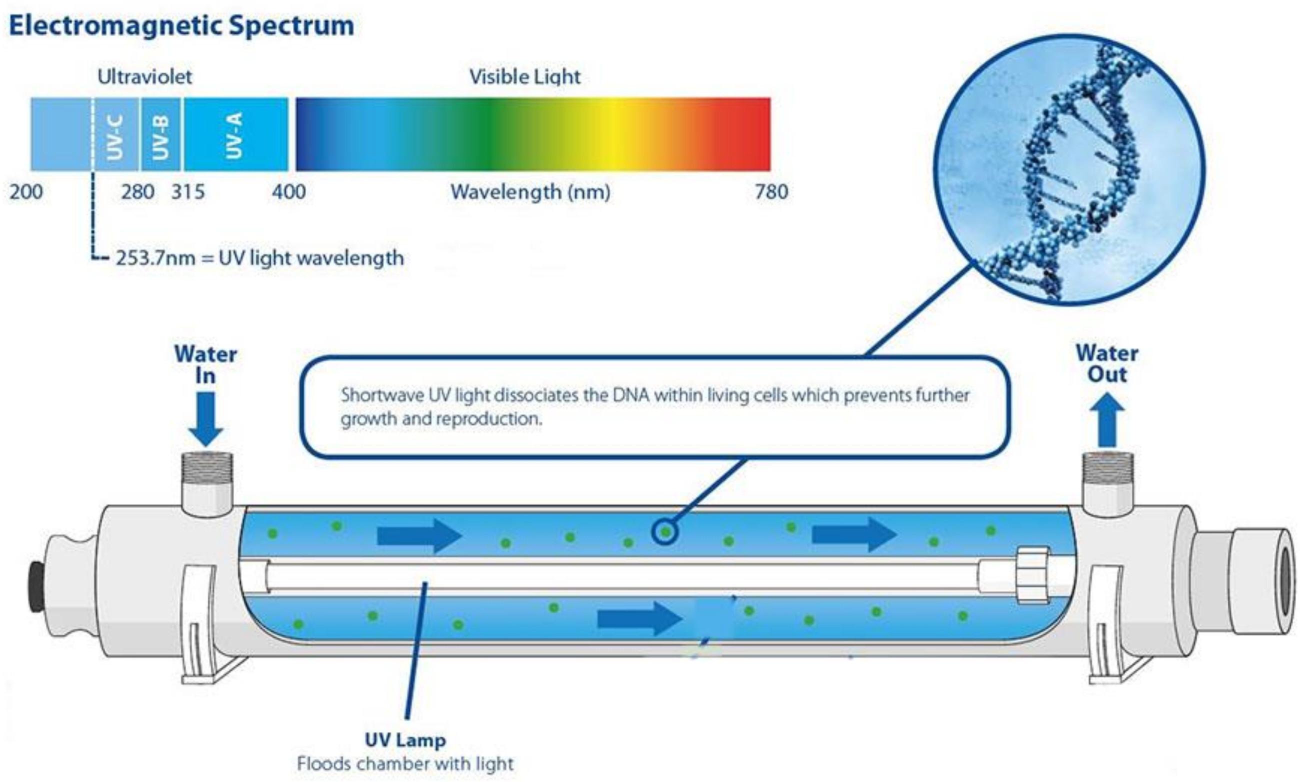


Figure 2.1.5 - UV Disinfection Process (Alfaauv, 2019)

Table 2.1.5 - Advantages and Limitations of UV Disinfection on Greywater Treatment and Recycling

Advantages	Limitations
Kill pathogens in seconds	Pathogens might develop resistance
No hazardous by-products formation	High TSS and turbidity might reduce the effectiveness of UV disinfection
No chemicals needed	Expensive if compared to chlorination[1]
Low maintenance and easy operation	
Low operation cost	

1 – Chlorination is a disinfection method in which chlorine is added to water to kill bacteria and other microbes.

Source: Gibson et al., 2017

The advantages of UV disinfection as shown in Table 2.1.5 make this technology an interesting option to be applied in greywater treatment in green cities. Although its application might be expensive when compared to other disinfection steps such as chlorination, UV disinfection presents high efficiency in removing pathogens without the necessity of chemical addition. Additionally, the development of pathogens' resistance could be overcome by increasing the applied radiation dose. Thus, making this technology an efficient way to disinfect greywater with low-cost maintenance and easy operation (Gibson et al., 2017).

Some studies showed that UV disinfection is commonly applied after MBBR and filtration steps (Jabri et al, 2019; Saidi et al., 2017, Jabornig et al, 2013). Friedler et al, 2010, evaluated the performance of a UV disinfection step, preceded by biological and filtration steps, on pathogens removal to treat light greywater for toilet flushing. The results indicated that the UV phase was efficient to remove completely fecal coliforms and *Staphylococcus aureus*. In addition, UV removed all the viral indicators injected into the system. Moreover, in a review of technologies to disinfect light greywater for domestic reuse, Oh et al., 2018, indicated that UV light disinfection is capable of eradicating pathogenic bacteria. Furthermore, Couto et al., 2013, proved in a study on greywater from a mid-size airport in Brazil that UV light disinfection removed 100% of E. coli from 80% of the greywater samples (in the other 20% of samples, E. coli concentrations were found to be lower than of 1 MPN/100 mL). The authors concluded that the treated greywater met the non-potable water reuse limits and its use provided great water savings in the airport. Therefore, UV disinfection showed to be an essential step after the MBBR and filtration system for domestic greywater treatment and recycling. Thus, its application justifies the use of disinfection to promote sustainable water reuse in sustainable cities.

2.2 Advantages of Decentralized Greywater Treatment System for the Sustainable Urban Water-Energy Management: Cities of the Future

This section provides some examples of existing decentralized infrastructures of greywater treatment to have a better idea of how water and energy should be managed in the so-called sustainable cities.

Nowadays expensive conventional centralized water and energy management are being replaced by decentralized solutions for recycling and reuse of water and energy close to the site of origin (Díaz et al, 2016). This shifting to a decentralized water treatment and energy recovery system relies on the many benefits that a decentralized approach brings (Wanjiru & Xia, 2017). These advantages are cost reduction (on the sewage system, drinking water, and wastewater treatment collection), resource efficiency improvement (by optimizing water and energy consumption), and environmental benefits over centralized systems (by minimizing untreated wastewater discharges on water bodies due to stormwater overflow) (Wanjiru & Xia, 2017). Ni et al., 2012, demonstrated that decentralized systems seem to be the most efficient way to recover energy and recycle water. The researchers analyzed the feasibility of a residential greywater energy recovery system for domestic use in 14 cities in the United States. Their results showed that the energy and the potable water consumption in those cities would be reduced by 17- 57.9% and 14 – 34.1%, respectively when decentralized systems in the buildings to recover water and energy from greywater are adopted. Furthermore, a pilot study in the Netherlands showed that recovery heat from greywater, in a decentralized system, can save 4% of the total annual energy consumption in Amsterdam and help to reduce 54 kton per year of CO_2 emissions in the city. The same study proved that the heat recovery remains the same in both winter and summer periods and has an estimated payback period of 4 years for 4 people size households and 2 years for multi-family habitations. (Deng et al., 2016). Thus recovering energy from greywater, in a decentralized system, reduces the energy consumption of cities and its carbon footprint. This will take the cities of the future to another level of sustainability by optimizing their resources from water to energy to waste allowing their preservation for future generations.

In a case study, Lam at al., 2017, evaluated the economic and environmental aspects of four water management options to reuse non-potable water for toilet flushing in domestic buildings in Hong Kong, China. These were a) a freshwater flushing system; b) a seawater flushing system; c) an aerobically treated greywater flushing system, and d) an anaerobically greywater flushing system. The eco-efficiency analysis revealed that the scenarios in which greywater was treated aerobically or anaerobically by bioreactors were the most eco-efficient water management options to reuse domestic greywater. The latter reduced the volume of sewage treated as well as the supply of freshwater while minimizing the cost. Thus, greywater reuse and recycling should be at the core of sustainable water management in green cities (Al-Jayyousi et al., 2003; Figuères et al., 2003; Lam at al., 2017).

Another study was conducted by Cureau at al. in 2019 in Joinville, Brazil to assist the decision-making on water management and reduce potable water consumption and sewage generation. Four strategies were studied and compared a) the replacement of the potable water use for toilet flushing by rainwater harvesting; b) the reuse of treated greywater for toilet flushing; c) the application of dual-flush toilet flushing; and, d) the combination of the three strategies. The results showed that the potential for potable water savings ranged from 1.7% to 50.5%, and the potential for sewage generation reduction ranged from 2.1% to 52.1%. In conclusion, the authors indicated the greywater reuse as the best viable strategy to save water for non-potable use such as toilet flushing, and when a large catchment area is available rainwater harvesting is recommended.

In European countries, drinking water and wastewater treatment present net energy consumption of 34 and 88 kWh/y/person respectively, accounting for 7.6% of the overall energy consumption (EEA, 2014). Many researchers agreed that this ratio can be reduced if greywater recycling and energy recovery are adopted (Plappally et al.,2012; Ackerman et al., 2013; Feng et al., 2014; Spang et al, 2014). Wakkel et al., 2016, made a review and compared several studies tackling energy consumed within the water sector. They concluded that energy should be taken into account when managing water resources is fundamental to promote sustainability in sustainable cities. Therefore, greywater has to be perceived as a valuable source of water and energy for non-potable uses in the cities of the future (Wong et al., 2010; Meggers et al., 2011; Van Blommestein et al., 2013; Mazhar et al., 2018).

2.3 Energy-Water Recovery: Greywater Reuse and Energy Recovery in Buildings

The advantage of a compact treatment unit with high pollutant removal efficiency makes MBBR technology an interesting option to treat domestic greywater. In this perspective, biological treatments are the most appropriate methods for greywater treatment due to high organic removal (Jefferson et al., 2004; Patil, et al., 2016). The post-treatment after a biological treatment for greywater reuse is usually defined by the use of the treated wastewater. Filtration or settling after the MBBR is commonly applied for uses such as irrigation (Hadei et al., 2015; Al-Wasifya et al., 2018). Furthermore, for greywater reuse in households an additional step of disinfection, such as UV technology or chemical dosing, should be applied (Jabornig et al, 2013; Saidi et al., 2017; Jabri et al., 2020).

A 6-months pilot study performed in Brazil to verify the viability of greywater recycling, tested different types of synthetic greywater in a MBBR of 83.3 L followed by a settling tank implemented in a building at the University of Sao Paulo. The results showed that the MBBR system removed 59% and 70% of BOD and COD, respectively in a system with the influent flow rate of 300 L/d. The raw greywater presented an average initial COD concentration of 270 mg/L. While the system effluent presented 11 mg/L of COD concentration. This allowed the greywater to be used in irrigation, pastures, cereals, and other crops considering the Brazilian safety standards. Though, the treated wastewater did not meet the safety criteria to be used for domestic purposes (Chrispim et al., 2017). This confirms the need for a disinfection step to promote the reuse of treated greywater for domestic purposes such as toilet flushing.

Saidi et al., 2017, performed a detailed investigation on a full-scale MBBR of 11.7 m^3 followed by sand filtration and UV disinfection used to treat and recycle domestic greywater from a small community of 223 inhabitants that been operating in Berlin since 2006. The results showed that the average loading rate was 3.7 kg COD/d. While the removal rate was 3.4 kg COD/d. In terms of BOD, the loading rate of 2.8 kg BOD/d was almost completely removed. The system with an area of 0.15 m^2/person was used to treat greywater for toilet flushing. Therefore, this study showed that the configuration of MBBR technology followed by filtration and disinfection is an excellent way to promote sustainable water use in smart cities.

In a literature review, Arora et al., 2016, investigated many treatment configurations for greywater recycling. The researchers showed that the MBBR followed by the DAF system could be an excellent alternative to treat greywater for non-potable use. On the other hand, Ødegaard et al., 2012, studied the MBBR followed by DAF for greywater reuse in a pilot study in Norway. The results showed that the treatment configuration presented a compact efficient solution for greywater recycling. However, few studies have been found on the application of a MBBR followed by DAF for greywater treatment.

Regarding energy recovery from domestic greywater, a heat exchanger is commonly applied to recover energy in buildings from showers, washbasins, and wash machines (McNabola & Shields, 2013; Van Blommestein et al. ,2013; Mazhar et al., 2018). A great amount of the energy used in a household is consumed for heating water (Meggers et al., 2011). As an example, the temperature of water discharged from a typical shower varies between 30 and 38 °C and reaches 60 °C when discharged from washing machines (Wong et al., 2010). To date, only heat exchangers and heat pumps are viable options to recover energy from non-industrial use (Mazhar et al., 2018). Both technologies are applied in different scales, with heat exchanger more commonly applied in smaller scales. Figure 2.3.1 illustrates a simple heat exchanger commonly applied in buildings.

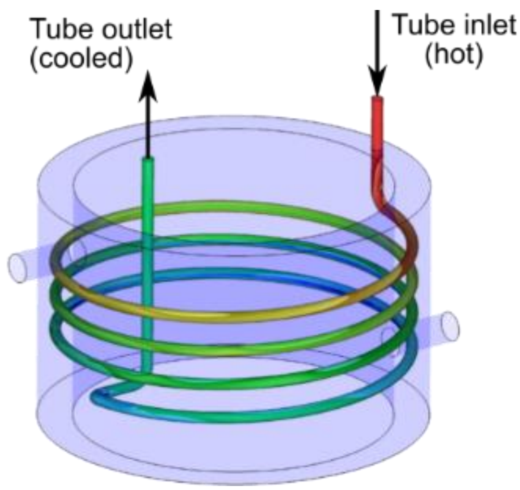


Figure 2.3.1 - Stainless Steel Coil Heat Exchanger Diagram (Source: Azore CFD, 2019)

The potential of energy recovery from greywater is quite high and reaches in some cases 3.5 kWh/person/day (Mazhar et al., 2018). In a study, McNabola & Shields, 2013, evaluated the performance of a heat exchanger in a water heat recovery system from showers for domestic use. The results showed efficiencies over 50% in heat recovery. Moreover, the assessment of energy and economic savings proved the viability of the system to recover energy from greywater.

Hence, greywater reuse and energy recovery in buildings are crucial practices that decrease the demand for potable water and energy. Greywater reuse may decrease all the infrastructure needed to collect, transport, and treat greywater. Consequently, decreasing the urban wastewater discharge and environmental impacts in the whole life cycle of water and energy production-consumption (Chrispim et al., 2017).

2.4 European Legislation: Recycled Water Applications Limits in Europe

The quality requirements for greywater reuse depends on the type of water used, the source of greywater, and the likelihood of human contact with the recycled water (Boano et al, 2019). Edwin et al., 2014, showed in a study that there are many recycled greywater standards for different countries.

- In Europe, the Directive 91/271/EEC on urban wastewater treatment and the Water Framework Directive (WFD) (2000/60/EC, WFD) encourages greywater reuse., The EU action plan for the circular economy also includes water reuse of treated wastewater for irrigation and aquifer recharge.
- Directive 91/271/EEC aims to protect the environment, especially in nutrient-sensitive areas, from adverse effects due to discharges from urban wastewater from households and industries. Moreover, this Directive states that all treated wastewater should be reused whenever appropriate and the Member States should minimize any environmental effect caused by wastewater reuse.
- The WFD established a framework, to protect water bodies, that provides guidelines to integrate water reuse and water management.

One of the barriers to promoting domestic greywater reuse is the lack of a clear and precise legislative framework to tackle that matter within the European Union (Li et al., 2009). For instance, many countries such as Germany, Italy, and Slovenia developed their standards for greywater reuse while others such as the Netherlands and Belgium, follow other developed countries' standards (e.g. the US EPA greywater reuse limits). This reveals that the EU legislative framework on domestic greywater reuse should be developed. Although, as discussed previously, the greywater characteristics may vary in country-by-country, a greywater reuse guideline for the whole EU would blaze a trail to the European countries which did not develop a reuse standard to reuse greywater. As an example, the United States has a stringent guideline for greywater reuse that is applied for the entire country. However, some American states (e.g. California) have developed their own standards, adapted to local greywater characteristics, that could be more stringent or not than the US EPA guideline for greywater reuse (Cook, 2016). Similarly, it would be helpful to have a general guideline for Europe as well as national legislation adapted to each EU country. In other words, although many directives promote the reuse of treated greywater, none of these provides specific guidelines of how greywater recycling should be done or defines the limits for greywater reuse. For instance, the guideline for the safe use of wastewater, excreta, and greywater by the World Health Organization (WHO) lacks standards or limits for greywater reuse (WHO, 2006). Thus, there is an urgent need to set clear standards for greywater recycling for all EU Member States. Therefore, policies, legislations, specific guidelines need to be created and shared to popularize greywater reuse for the current and future generations.

Table 2.4.1 below shows the limits of a few European and Non-European countries for greywater reuse.

Table 2.4.1 - Limits for Greywater Reuse

	Minimum-Maximum (Average)				
Country	**COD**	**TP**	**TN**	**pH**	**Turbidity**
		mg/L			**(NTU)**
Canada	(280)	-	-	7 - 9	< 2
China	(15)	-	10 - 20	6 - 9	< 10
Germany	-	-	-	6 - 9	Near Clear
India	(250)	-	-	6 - 9	-
Japan	-	1 - 4	20 - 30	6 - 9	Clear
Italy	(100)	(2)	(15)	6 - 9.5	-
Slovenia	(200)	(1)	-	7 - 9	-
US EPA	20 - 90	-	1 - 30	6 - 9	< 5

Source (Boano et al., 2019; Camp Dresser & McKee, 2004; Hernandez et al, 2007)

3 Material and Methods

3.1 Site Description and Material Set-Up

A pilot experiment unit for greywater treatment and energy recovery was built in the frame of this study, in the facilities of the company PureBlue Water in Hulst, the Netherlands. The pilot set-up took 50 days to be finalized, approximately. After that, the carriers (type K5) with the attached biofilm from the company's full-scale bioreactor were added into the MBBR. During the system's operation, influent and effluent were sampled regularly for a period of 2 months. The pilot set-up consisted of a feed tank, shower, an equalization tank, a biological wastewater treatment unit (an aerobic MBBR), an up-flow filter (called LigoFlux), a DAF, one heat exchanger, two heaters, two coolers, and five plastics reservoirs (one cubic meter each). Figure 3.2.2 illustrates the pilot experiment set-up. Pictures of the pilot plant can be found in appendix 2.

As seen in the schematic Figure 3.2.2, the synthetic greywater (soap, shampoo, carbon source, toothpaste, shaving cream, and ammonium chloride) was added to the feed tank and pumped to the first reservoir (shower reservoir) to simulate a shower. Warm water was pumped to the first reservoir through the shower from the heating reservoir. Then, after the greywater mixing in the shower reservoir, the greywater was conducted to an equalization tank by gravity. Subsequently, the greywater was pumped to the MBBR (for nutrient removal) passing through a heat exchanger (for heat recovery). After the biological treatment unit, the flow was divided equally between the DAF and the filter (for the removal of particulate matter). After the filtration and flotation, the treated wastewater was sent to a reservoir for cooling, and the sludge was sent to two collection reservoirs. In the cooling reservoir, tap-water was added only to compensate water losses (e.g. water leaves the system when sludge is removed from the DAF and the filter ensuring a constant level of water). Then, the water from the cooling reservoir, containing the treated cooled water, was pumped to the heating reservoirs through the heat exchanger. Finally, the water was heated up in the heating reservoir and pumped up back to the shower, closing the system loop.

3.2 Operational Conditions of the MBBR and Filter

Before going into details on the operation conditions of the MBBR reactor and filter, which are described in this section, it is important to mention that the study of the DAF system (with an inner diameter, height, and nozzle's height are 0.215m, 1.68m, and 0.62m, respectively) is out of the scope of this study. The system investigation is focused on the MBBR system followed by filtration only. The presence of the DAF in the system was used to feed the company's database. Therefore, although the DAF is present in the pilot system, its description and analysis will not be discussed in this study.

In this way, moving to the MBBR/Filter system description. The bioreactor had a total active volume of 1.6 m^3. A volume of 0.5 m^3 carriers (type K5, biofilm surface is of 800 m^2/m^3) was used for the MBBR, this means a filling ratio of 31,25%. The same type of carrier was used for the filter. Figure 3.2.1 illustrates the disc carriers used in the filter and MBBR. The DO levels in the MBBR were kept from 2 mg/L to 4 mg/L, while the temperature at 27.5 °C, throughout all the pilot plant operation. The greywater flowrate to the bioreactor was set on 300 L/h, to be later on increased gradually to 600L/h. Furthermore, the filter (inner diameter of 0.27 m) had an active volume of 82.7 L. The active filter volume is the volume between the screens (at the bottom of the filter) and the top of the carrier bed layer. The carrier volume in the filtration unit was 52 L, thus the filling ratio was 62.85%. Normally, a higher filling ratio would not allow a proper backwash of the filter due to not enough room for the carriers to move. The LigoFlux, filter designed by PureBlue Water, was set at a filtration speed and HRT of 5 m/h and 11 min, respectively. The wastewater flowrate to the filter was 300 L/h (because after the MBBR, the flow was equally divided between the DAF and the filter).

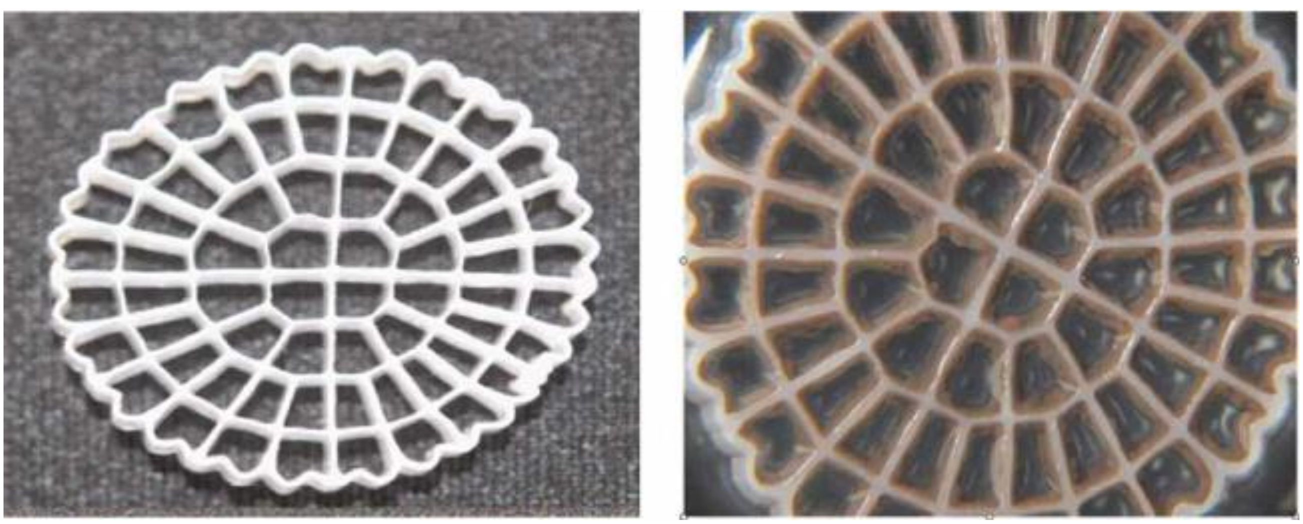
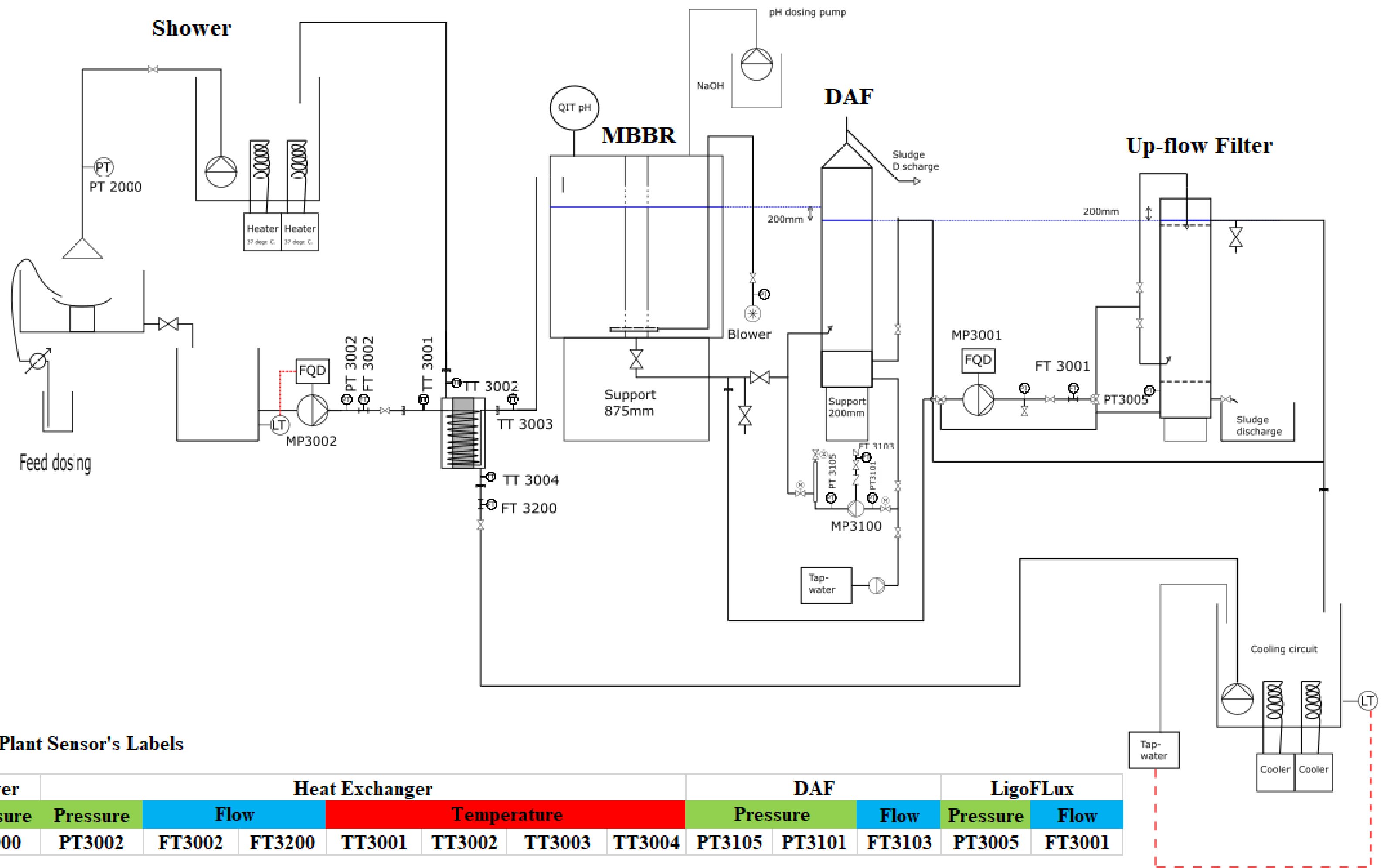


Figure 3.2.1 - Carrier, Type K5 (Source: Chan et al., 2014)

Pilot Plant



Pilot Plant Sensor's Labels

Shower	Heat Exchanger							DAF			LigoFLux	
Pressure	Pressure	Flow		Temperature				Pressure		Flow	Pressure	Flow
PT2000	PT3002	FT3002	FT3200	TT3001	TT3002	TT3003	TT3004	PT3105	PT3101	FT3103	PT3005	FT3001

Figure 3.2.2 - PID Layout of the Pilot Experiment Set-up

3.3 Analysis

3.3.1 Biofilm Cultivation

Prior to the experiment, the carriers with the cultivated biofilm from the company's full-scale MBBR reactor, to treat greywater for ships, were used to start up the system (a picture of the full-scale reactor can be found in appendix 2). The tank of 15 m^3 was filled with synthetic greywater and carriers. The system was fed with synthetic greywater continuously for 3 months, approximately.

3.3.2 Feed Composition

The synthetic greywater formulation, used to understand the performance of the present pilot system, originated from the synergy of many studies (Boano et al., 2019; Scheumann and Kraume, 2009; Liu and Mabury, 2019; Spychała et al., 2019; Eriksson et al., 2003; Ghaleh Khondabi et al, 2019). Table 3.3.2.3 shows the synthetic greywater formulation used in the experiment. The average water consumption, for showering and bathroom sinks, considered in the study was approximately 60 L/person/day. The number of inhabitants first assumed, in this study, was 240 inhabitants.

To calculate the product loads to the system shown in Table 3.3.2.2, the following procedure was performed: As a first step, COD, total nitrogen, and total orthophosphate of the products (shampoo, shower gel, toothpaste, and shaving cream) were measured to have an idea of the synthetic greywater composition in this study. The measurements followed the procedure described in Appendix 1. The following table shows the results for the feed composition:

Table 3.3.2.1 - Product Composition

Product	**Brand**	**COD**	**TN**	**Orthophosphate**
			g/L	
Shampoo	jumbo	184	1,412	27.8
Shower gel	jumbo	260	1,848	50.8
Toothpaste	jumbo	520	620	604.8
Shaving Cream	jumbo	376	3,820	106.4

Considering the greywater maximum flowrate for the pilot experiment as 600L/d (14.4 m^3/d) and assuming that the greywater's COD concentration from a 240 inhabitants-system as 150 mg/L (Boutin and Eme, 2016), the pilot COD load was calculated by multiplying the pilot flowrate and the influent's COD concentration: 2.16 kg/d of COD.

From the product composition (Table 3.3.2.1), loads of COD, N, and P per day of the products from a system of 240 inhabitants were calculated as showed in Table 3.3.2.2. It is important to notice that a carbon source (methanol; trade name: carbo 60) was added to reach the total load of 2.16 kg/d of COD. Moreover, ammonium chloride (NH_4Cl; load: 112 g/d of N) was added to simulate urea. Furthermore, the C/N/P ratio aimed in this study was 144/6.48/1. To achieve the latter, 5 grams of monosodium phosphate and 17 grams of sodium dihydrogen phosphate dehydrate were daily added to the GW formulation.

Table 3.3.2.2 - Product Loads

Parameter	**Value**	**Unit**
Daily average water consumption	60	Liter/person
Number of Inhabitants	240	Inhabitants
COD load from products	503.11	g/d of COD
N load from products and NH_4Cl	116.11	g/d of N
P load from products	0.14	g/d of P
COD load from carbo 60	1,656.89	g/d of COD

Finally, the maximum amount of product to be fed into the system was calculated to obtain the desired loads (Table 3.2.2.3). The system's feeding started at an organic load corresponding to 24 inhabitants which was gradually increased to the maximum feed concentration that the system could handle.

Table 3.3.2.3 - Daily Synthetic Greywater Formulation

Products	**Quantity**	**Unit**
Shower gel	600	mL
Shampoo	600	mL
Toothpaste	66.12	mL
Shaving cream	538.12	mL
Carbo60	1.74	L
NH_4Cl	428	g
NaH_2PO_4	5	g
$NaH_2PO_4.2H_2O$	17	g

3.3.3 Bioreactor Performance: Greywater Analysis

The synthetic greywater was fed to the system continuously for approximately two months for the organic loads corresponding from a population of 24 inhabitants to 168 inhabitants. During this 73-days pilot experiment (from May 13th, 2020 until July 24th,2020), the samples were taken from the following points: the heating tank, the MBBR reactor (influent and effluent), the filter (influent, effluent, and backwash), and the cooling tank.

To assess the system effectiveness, the following parameters were analyzed in wastewater samples

- pH, dissolved oxygen (DO), and conductivity using a multi-meter device for Hach (model HQ40d) with automatic calibration directly after sampling. For each parameter, a specific probe was used and results were obtained in mg/L for DO and µS/cm for Conductivity.
- COD, total ammonium, total nitrate, and total orthophosphate using Nano Color test tubes from the company Macherey Nagel (Macherey Nagel, 2020). A description of these experiments can be found in Appendix 1.

3.3.4 Flow Measurements

The flow measurements of the pilot-scale were done by the flowmeter sensors, which computed all the measured data into an Excel file. The flowmeters were labeled as FT3002, FT3200, FT3103, and FT3001 as shown in Figure 3.2.2. Figure 3.3.4 shows the flowmeter used in this study.

Figure 3.3.4 - Flowmeter

3.4 Filter Performance

The procedures to evaluate and optimize the filter performance are described in the following sections. Table 3.4.1 shows the specifications of the up-flow filter (LigoFlux) used in this study.

Table 3.4.1 - Filter's Specifications

Parameters	**Values**	**Units**
Internal diameter	0.27	m
Surface area	0.057	m^2
Bed height	0.91	m
Filling capacity	65	%
Total volume	0.080	m^3
Surface Loading Rate	5	m/h

3.4.1 TSS Removal Performance and TSS COD Load Capacity

Method

The objective of this phase was to evaluate the filter performance in removing suspended solids from the MBBR effluent, in terms of the TSS COD mass retained in the filter, at the optimum organic load in the pilot. Then, this TSS removal efficiency was associated with a TSS COD load (TSS load in terms of COD). For that, the filter's TSS removal efficiency was calculated in two different ways.

The first approach was to estimate the TSS COD of the influent and effluent by the difference between their respective filtered and unfiltered COD concentrations hourly. Then considering that the TSS COD was constant over one-hour intervals, a TSS mass in terms of COD was calculated hourly during the filter's operation time. Afterward, an average value for the incoming TSS and retained TSS (influent's TSS subtracted from the effluent's TSS) was estimated. Hence, the estimated TSS removal efficiency was found by the estimated TSS COD mass over the incoming TSS COD mass.

The second approach was to calculate the actual filter's TSS removal efficiency. This was done by measuring the filter's backwash COD subtracted from the influent filtered COD times the filter's backwash volume. In this way, the observed TSS efficiency was determined by the TSS COD mass in the filter's backwash water over the estimated incoming TSS mass.

Finally, a TSS COD load was calculated for each test by the filter's flowrate (sensor FT 3001) times the filter's backwash TSS COD.

Procedure

- The experiments consisted of four tests on different days when the MBBR was fed by an organic load corresponding to 120 inhabitants. Additionally, an extra test was added for a 144-inhabitants load;
- The unfiltered and filtered COD of the filter's influent and effluent were measured as described in appendix 1;
- Then, the unfiltered COD of the filter's backwash water was measured and subtracted from the average influent filtered COD concentration;
- Afterward, the TSS COD mass of the filter's influent and effluent was calculated as the difference between the unfiltered and filtered COD concentrations times the average filter influent rate times the filter's operational time;
- Furthermore, the incoming TSS, estimated retained TSS, and measured retained TSS were calculated;
- From these values, the TSS removal efficiency measured and estimated were calculated and compared;
- Finally, the TSS COD load was calculated for each test as previously described.

3.4.2 Turbidity versus TSS COD

Method

According to the device's manual, the turbidity measurement is based on ISO 7027 (Water Quality – Determination of Turbidity). The principle consists in the measurement of the turbidity from the detection of the scattered light emitted from the sample. The test measuring ranges from 0.01 to 1100 NTU (Lovibon, 2020). This test was performed for one of the four tests (corresponding to a 120-inhabitants load) described in section 3.4.1.

Procedure

- 15 mL sample, from the filter's influent and effluent, was added into the turbidity test tube and inserted in the turbidimeter (Model TB300 IR, Lovibind);
- Then, the test tube was cleaned and its content was measured in the device;
- The turbidity of the filter's influent and effluent was measured hourly per 7 hours as well as the TSS COD;
- Then, the TSS COD versus turbidity was plotted on Excel to check the correlation between these parameters.

3.4.3 Filter's Breakthrough and Saturation Time

Method

The filter's saturation point was determined as the time in which the measured TSS COD concentration was the same in the filter's influent and the effluent (Hawari & Alnahhal, 2016). While the breakthrough point was the time in which a step-increase that resulted in these equaled concentrations was first observed (Hawari & Alnahhal, 2016). For that, the filter was tested at the pilot's optimum feed concentration over a constant flowrate. The TSS COD and turbidity in the influent and effluent were measured hourly until it was observed that the TSS COD concentration in the filter's inlet was equal to its outlet concentration (Hawari & Alnahhal, 2016; Shiue et al., 2018). Then, the saturation and breakthrough time were determined accordingly.

Procedure

- The filter's TSS COD concentrations and turbidity were measured as described in section 3.4.1 and 3.4.2, respectively.

3.5 Heat Exchanger Performance

The stainless steel coil heat exchanger (diameter: 24 cm; height: 115 cm; spiral tube diameter 15 mm; and spiral diameter: 230 cm) performance analysis was based on the heat energy transferred from warm water at 38 °C or 35 °C (simulating the greywater from showers) to cold water at 22 °C (simulating the treated water) at different flowrates. During the tests, the system could not be operational because elements from the pilot plant were used to perform the heat exchanger experiment. Moreover, the tests were performed with tap-water instead of greywater and treated greywater since the system had to be shut down for this experiment.

The warm water came from a plastic tank (1m^3), while the cold water came from a tap. The sensors TT3001 and TT3003 measured the temperature difference in the hot water, coming from the heating reservoir, before and after the heat exchanger. Likewise, TT3002 and TT3004 registered the temperature difference in the cold flow. Moreover, warm and cold-water flows were measured by the sensors FT3002 and FT3200, respectively. Figure 3.5.1. shows the heat exchanger's P&ID with the water fluxes in the experiment. Figure 3.5.2 illustrates the temperature sensor used in this study. In appendix 2, pictures of the experimental setup can be found.

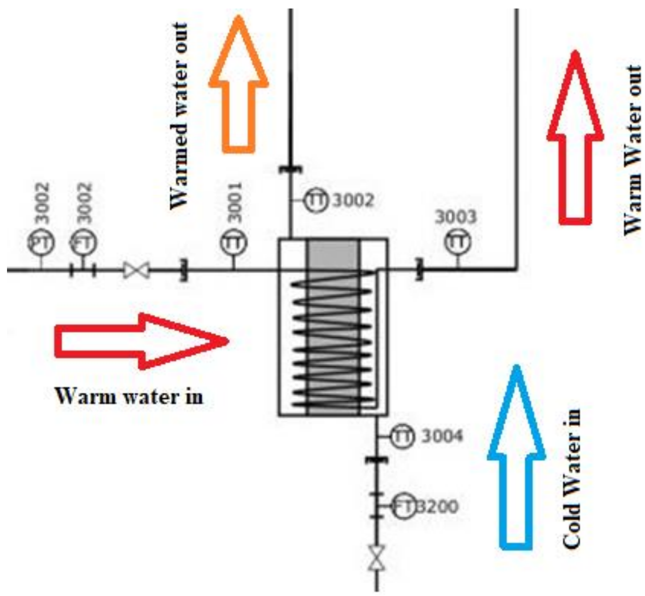


Figure 3.5.1 - Heat Exchanger's P&ID with the Water Fluxes During the Experiment

Figure 3.5.2 - Temperature Sensor

Method

Specific Heat Formula

$$\mathbf{Q= m.c. \Delta T} \quad \text{(Eq.1)}$$

With: Q: Heat (J)
m: Mass (kg)
c: Specific heat capacity of water (4.18 J/g.°C)
ΔT: Final temperature – Initial temperature (K)

Considering the mass flow rate as volumetric flowrate times the density of water, the specific heat exchanger formula for the heat exchanger becomes:

$$Q\ (kJ/h) = Q\ (m^3/h) \text{ X Delta T } (°C) \text{ X } 4.18\ (J/g.°C) \text{ X } 1000\ (kg/m^3) \quad \text{(Eq.2)}$$

Procedure

- The specific heat of the cold and warm waters was calculated at four different settings:

Table 3.5.1 - Heat Exchanger Setups

Test	Warm Water Temperature (°C)	Warm water Flowrate (m^3/h)	Cold Water Temperature (°C)	Cold Water Flowrate (m^3/h)	Time
1	38	0.30	22	0.15	8:30 a.m. to 9:40 a.m.
2	38	0.30	22	0.30	9:40 a.m. to 10:50 a.m.
3	35	0.30	22	0.07	01:40 p.m. to 02:10 p.m.
4	35	0.15	22	0.07	02:13 p.m. to 03:10 p.m.

- The data were measured by the temperature sensors (TT3001, TT3002, TT3003, and TT3004) and flowmeters (FT3002 and FT3200).
- The data were compiled into an Excel file.
- Average flowrates and temperatures at steady-state conditions (when the temperatures and flowrate values were constant for 30 minutes) were calculated on Excel.
- The differences between the average temperatures (ΔT) before and after the heat exchanger for the warm water flow and cold water flow were calculated.
- The specific heat was calculated by multiplying the average flow rates and the differences between the temperatures by the water-specific heat capacity and density of the water.

- Different specific heat values were calculated for different flows and temperatures to find the optimal heat exchanger operational flowrate.

3.6 Overall Performance

3.6.1 Pilot's Influent Versus Effluent Quality

To assess the performance of the pilot plant in removing pollutants from the synthetic greywater, the water analysis of the overall system's influent and effluent was performed. For that, it was followed the same greywater analysis methodology applied for the study of the bioreactor performance (described in section 3.3.3). The average values of pH, conductivity, COD, total ammonium, total nitrate, turbidity, and total orthophosphate were measured for the pilot's influent and effluent, at the optimum feed concentration, over 6 samples.

3.6.2 Mass Balance

To evaluate the overall performance of the pilot plant in converting the incoming total COD to CO_2, an unfiltered COD mass balance was done considering a system boundary-layer around the entire pilot plant during a 3-days cycle. It was assumed steady-state conditions, no accumulation, no production, nor destruction of COD. In this way, the mass of unfiltered COD leaving the system is the same as the COD amount entering it. Furthermore, as an alternative way to evaluate the filter performance, a TSS COD mass balance for the filter was done. For that, it was assumed steady-state conditions, no production, or destruction of TSS COD. Thus, the TSS COD retained by the filter was equal to the TSS COD entering subtracted from the TSS COD leaving the filter.

Method

For the overall pilot system:

- *Water Mass Balance*:

$$\text{Volume}_{\text{tap-water}} = \text{Volume}_{\text{filter's backwash}} + \text{Volume}_{\text{DAF flushing}} + \text{Volume DAF}_{\text{extra water loss}} - \text{Volume}_{\text{feed}} \quad \text{(Eq.3)}$$

- *Unfiltered COD Mass Balance:*

$$Mass_{\text{COD converted to CO2}} = (V_{TW} * COD_{TW} + V_F * COD_F + V_{RW} * COD_{RW}) - (V_{FB} * COD_{FB} + V_{\text{DAF's flushing}} * COD_{\text{DAF's flushed water}} + V_{\text{DAF's extra water loss}} * COD_{\text{DAF's effluent}}) \quad (Eq.4)$$

With: $Mass_{\text{COD converted to CO2}}$: COD mass of the feed that was converted to CO_2 (g)

$V_{\text{Tap-water (TW)}}$: volume of tap-water added to the system (L)

$COD_{\text{Tap-water}}$: COD of tap-water (negligible)

$V_{\text{Feed (F)}}$: volume of the feed added to the tank (25.7 L)

COD_{Feed}: feed's COD (g/L)

$V_{\text{Recycled-Water (RW)}}$: volume of the recycled water to the shower (2,894 L)

$COD_{\text{Recycled-Water}}$: COD of the water from the shower (mg/L)

$V_{\text{Filter's Backwash (FB)}}$: volume of the filter's backwash (88 L)

$COD_{\text{Filter's Backwash}}$: COD of the filter's backwash (g/L)

$V_{\text{DAF's flushing}}$: volume of the DAF' flushing (40 L)

$COD_{\text{DAF's flushed water}}$: COD of the DAF flushed water (g/L)

$V_{\text{DAF's extra water loss}}$: volume of water loss due to DAF's air flushing (3,870 L)

$COD_{\text{DAF's effluent}}$: COD of the DAF's effluent (mg/L)

For the filter's TSS mass balance in terms of TSS COD:

- *TSS COD mass balance:*

$$TSS_{\text{retained}} = TSS_{\text{influent}} - TSS_{\text{Effluent}}$$

$$TSS\ COD_{\text{filter's backwash}} * V_{\text{filter's backwash}} = TSS\ COD_{\text{influent}} * V_{\text{influent}} - TSS\ COD_{\text{effluent}} * V_{\text{effluent}} \quad (Eq.5)$$

With: TSS COD filter's backwash = COD of the filter's backwash (mg/L)

$V_{\text{filter's backwash}}$ = volume of the filter's backwash (88 L)

$TSS\ COD_{\text{influent}}$ = influent's unfiltered COD subtracted from its filtered COD (mg/L)

V_{influent} = average influent flowrate times the operation of the filter (L)

$TSS\ COD_{\text{effluent}}$ = effluent's unfiltered COD subtracted from its filtered COD (mg/L)

V_{effluent} = average effluent flowrate times the operational time of the filter (L)

Procedure

Overall System COD Mass Balance:

- All the volumes in Eq. 3 were known except for the volume of tap-water. This volume was easily calculated by Eq. 3.
- Then, all the unfiltered COD from all streams showed in Eq. 4 were measured as described in appendix 1.
- Finally, the COD consumed for CO_2 conversion (from the system's feed) was calculated by Eq. 4

Filter's TSS COD mass balance:

- First, the unfiltered and filtered COD of the filter's influent and effluent were measured hourly for 7 hours. From those measurements, an average unfiltered and filtered COD was found.
- Then, the difference between filtered and unfiltered COD was multiplied by the filter's average flowrate (sensor FT3001) and the filtration operation time (7 hours). Resulting in an estimated amount of TSS mass in terms of COD retained by the filter.
- Finally, its value was compared with the actual amount of TSS retained by the filter. This amount is found by the filter's TSS COD backwash concentration (unfiltered backwash' COD subtracted from the filtered influent COD) times the filter's backwash volume.

Finally, based on the results of all the measurements performed in this pilot experiment, the potential of water reuse for toilet flushing and energy recovery from greywater was assessed based on the technological aspects, and national and international regulations for water reuse.

4 Results

In this section, results of the pilot plant will be presented in 5 main sections: a) the performance of the MBBR in removing organic matter and nutrients, b) its optimum feed concentration, c) the performance of the filter in removing suspended solids, d) the performance of the heat exchanger in recovering energy for water heating, and, e) the ability of the overall system in treating greywater from 120 inhabitants equivalent.

4.1 MBBR Performance on Organic Matter and Nutrient Removal: Definition of the Optimal Loading Rate in Inhabitants Equivalent

In this section, the results of the MBBR's performance in removing organic matter (in terms of COD removal) and nutrients for different numbers of inhabitants over 73 days is presented. Table 4.1.1 shows the bioreactor's influent and effluent concentrations. Table 4.1.2 presents the MBBR efficiencies on organic matter and nutrient removal.

As explained in section 3.3.2, the system organic load was intended to be increased (by incrementing the system's feed concentration) gradually until its maximum value was achieved. The same can be said for the pilot incoming flowrate, which started at 300 L/h to be increased to 600 L/h, when the maximum feed concentration would be reached. The maximum organic load was initially estimated for 240 inhabitants equivalent. For the case that the maximum load, which the pilot plant could treat, was reached before the initial maximum estimated load, the water analysis measurements would be stopped. And, the system would be set back to the new-found operational feed concentration. During the experiments, the follow-up on the influent and effluent concentrations showed in Table 4.1.1, it was clear that the pilot system could not handle an organic load for more than 120 inhabitants equivalent. This because for a load corresponding to 168 inhabitants equivalent, filtered COD in the influent and effluent were the same, and low ammonium removal was observed. Furthermore, for a 144-inhabitants load, it was noticed a lot of foaming and bad flocculation in the MBBR effluent. These signs indicate an overload of the MBBR system. Therefore, after the pollutant load corresponding to 168 inhabitants was reached, the system was set back to the 120-inhabitants load. Which was known to be the maximum load that the bioreactor could handle. Because this maximum load corresponds to 120 inhabitants equivalent, the system flowrate was kept at 300L/h. For these reasons, the MBBR's water analysis will be presented only from loads corresponding from 24 to 168 inhabitants equivalent.

Table 4.1.1 - The MBBR Influent and Effluent Water Analysis for Different Numbers of Inhabitants Equivalent

Bioreactor Parameters	Inhabitants Equivalent	pH	Conductivity	COD		TN	NH_4-N	NO_3-N	PO_4-P
				UF	F				
			µS/cm	mg/L					
Influent	24	7.07	865.00	48.80	39.00	8.37	-	2.49	0.356
Influent	96	7.04	764.00	152.60	117.20	-	18.20	0.89	0.319
Influent	120	7.58	853.00	238.00	168.00	19.10	13.50	2.11	0.612
Influent	144	7.71	1308.00	300.00	127.00	57.40	27.70	2.35	1.652
Influent	168	7.56	1033.00	417.00	194.00	-	33.90	6.00	1.808
Effluent	24	7.15	876.00	46.40	16.80	7.59	-	2.49	0.254
Effluent	96	6.76	768.00	81.80	50.10	-	16.80	0.75	0.051
Effluent	120	7.50	829.00	147.00	31.40	10.90	6.52	2.11	0.384
Effluent	144	7.78	1511.00	204.00	60.80	53.40	24.00	1.88	1.348
Effluent	168	7.77	1008.00	287.00	194.00	-	30.70	6.00	1.400

Note: UF - Unfiltered; F – Filtered; and TN- Total Nitrogen

Table 4.1.2 - MBBR's Removal Efficiency for Different Numbers of Inhabitants Equivalent

Inhabitants Equivalent	COD	TN	NH_4-N	NO_3-N	PO_4-P
24	65.57	9.32	-	0.00	28.65
96	67.17	-	7.69	15.45	84.01
120	86.81	42.93	51.70	0.00	37.25
144	79.73	6.97	13.36	20.00	18.40
168	53.48	-	9.44	0.00	22.57

As seen in Table 4.1.2, from the 24 to 144-inhabitants load, all the COD removal efficiencies were above 65%. The maximum COD removal was observed at the load corresponded to 120 inhabitants. The values of the influent unfiltered (UF) and filtered (F) COD ranged from 48.80 mg/L to 417.00 mg/L and 39.00 to 194.00 mg/L, respectively. While the bioreactor's effluent F and UF COD varied from 46.40 to 287.00 mg/L and from 16.80 to 194.00 mg/L. The pH values remained around 7 and the conductivity remained around 1 mS/cm, for all pollutant loads. The orthophosphate concentrations varied in the influent and the effluent from 0.319 to 1.808 mg/L and 0.254 to 1.400 mg/L, respectively. Making, the high phosphorus removals observed in the bioreactor a result of small orthophosphate reductions.

Regarding nitrogen removal, the nitrate concentrations in the MBBR influent and effluent were very similar, from 0.75 to 2.35 mg/L (except for the 168-inhabitants equivalent load). Resulting in observed nitrate removal efficiencies from the MBBR's influent lower than 20%. In addition, ammonia removal ranged from 9.44 to 51.70%. The best ammonia removal efficiency was achieved at the 120-inhabitants load. The total nitrogen concentrations in the reactor's influent and effluent varied from 8.37 to 57.40 mg/L and from 7.59 to 53.40 mg/L, respectively. In this way, considering all the pollutant loads, the MBBR presented from 6.97 to 42.93% of total nitrogen removal efficiencies. The lowest nitrogen removal observed was at the 144-inhabitants load. While the maximum total nitrogen removal observed was at the 120-inhabitants load. Therefore, because the pollutant loads corresponding to a number of inhabitants higher than 120 resulted in low nitrogen removal (144-inhabitants load) and low organic matter degradation (168-inhabitants load), the 120-inhabitants equivalent load was identified as the MBBR optimal loading rate.

4.2 Water Analysis of the Optimal System's Feed and Synthetic Greywater Composition

As highlighted in the previous section, the maximum pollutant load that the pilot could handle corresponds to a population equivalent of 120 inhabitants. This load was achieved by adding half of the greywater formulation initially estimated for 240 inhabitants. Thus, this section will provide the water analysis results for the optimum feed concentration (120 inhabitants equivalent) for the pilot system.

The system's feed (for 120 inhabitants) was prepared for seven days, throughout all the experiments. Table 4.2.1 shows the system feed's water analysis for 7 days, with the dosing pump flow of 357 mL/h.

Table 4.2.1 - The Feed's Water Analysis for the 120-Inhabitants Load

	pH	Conductivity	UF COD	TN	NH_4-N	NO_3-N	Orthophosphate
		mS/cm			g/L		
Feed for 7 days	7.37	50.20	163.00	5.74	5.62	0.04	0.43

Table 4.2.2 shows the water analysis of the synthetic greywater fed to the bioreactor. This GW has resulted from the feed described in Table 4.2.1.

Table 4.2.2 - The Average Synthetic Greywater Composition for the 120-Inhabitants Load

Greywater	**pH**	**Conductivity**	**COD**		**TN**	**NH_4-N**	**NO_3-N**	**PO_4-P**	**Turbidity**
			UF	**F**					
		µS/cm			**mg/L**				**NTU**
Shower	7.69	768.00	57.00	29.00	9.61	4.82	2.11	0.172	7.48
MBBR Influent	7.58	853.00	238.00	168.00	19.10	13.50	2.93	0.612	38.50

According to Table 4.2.2, the synthetic greywater fed to the system (MBBR influent) presented moderate values of unfiltered and filtered COD, 238.00 mg/L, and 168.00 mg/L, respectively. Low content of total phosphorus of 0.612 mg/L and moderate total nitrogen content of 19.10 mg/L. Moreover, the turbidity measured in the influent was 38.50 NTU. Additionally, because the pilot recycled water from the DAF and the filter to the shower, this water presented COD, TN, and PO4-P concentrations of 57.00 mg/L, 9.61 mg/L, and 0.172 mg/L, respectively. Conductivity and pH values were found to be around 1mS/cm and 7, respectively, in the shower's water and MBBR influent.

4.3 Filter Performance

In this section, the filter performance in removing total suspended solids, at the optimal MBBR feed concentration (120 inhabitants), in terms of TSS COD will be presented in 3 parts: First, the results for the filter's TSS removal capacity will be presented. Second, the filter's breakthrough time will be verified. Then, TSS COD versus turbidity correlation will be presented.

4.3.1 The Filter's TSS Removal Efficiency

The filter's average influent versus effluent unfiltered, filtered, and TSS COD at the pilot's feed concentrations corresponding to 120 and 144 inhabitant equivalent can be found in Table 4.3.1. The results showed that the tests 1, 2, and 4 presented similar values of TSS COD in the influent (from 73.00 mg/L to 86.67 mg/L) and in the effluent (from 18.77 mg/L to 36.83 mg/L). The same can be said for unfiltered and filtered COD values, which ranged from 114.00 to 128.50 mg/L (influent) and 52.16 to 78.67 mg/L (effluent). However, tests 3 and 5 presented higher TSS COD and UF COD values if compared to tests 1, 2, and 4. This because, during test 3, the dissolved oxygen was found at 1.3 mg/L, which was increased to 5.89 mg/L during this experiment. This increase in the DO level resulted in a higher mixing in the MBBR, thus affecting the filter's influent TSS COD and UF COD values in test 3. While in test 5, the differences in the influent's TSS COD and UF COD values from tests 1, 2, and 4 were due to the higher pollutant load (144 inhabitants) associated with this test. Nevertheless, filtered COD values were similar in all tests.

Table 4.3.1 - The Filter's Average Influent versus Effluent Unfiltered, Filtered, and TSS COD Values

		Influent (in)			**Effluent (eff)**	
		mg/L			**mg/L**	
Test	**Inhabitants**	**UF COD_{in}**	**F COD_{in}**	**TSS COD_{in}**	**UF COD_{eff}**	**TSS COD_{eff}**
1	120	128.50 ± 16.38	41.83 ± 11.62	86.67 ± 23.21	78.67 ± 15.81	36.83 ± 20.62
2	120	114.00 + 19.32	41.00 ± 5.21	73.00 ± 22.87	71.50 ± 19.40	30.50 ± 16.69
3	120	270.00 ± 99.96	36.90 ± 6.54	233.10 ± 80.47	186.33 ± 82.40	149.43 ± 67.56
4	120	115.86 ± 9.60	33.39 ± 3.58	82.47 ± 11.23	52.16 ± 4.38	18.77 ± 5.68
5	144	241.30 ± 60.96	34.67 ± 8.49	206.63 ± 60.87	181.03 ± 10.30	146.37 ± 9.14

Furthermore, the efficiency of the filter in removing suspended solids is presented in Table 4.3.2. The results showed that the test 1, 2, and 4 presented similar values. In these tests, the incoming total suspended solids estimated values ranged from 127.51 to 145.50 g COD. The estimated retained TSS, from 74.28 to 112.38 g COD, and measured retained values from 57.99 to 76.26 g COD. The TSS COD load varied from 177.13 to 218.39 g TSS COD/h. In addition, the TSS removal efficiencies estimated and measured ranged from 57.50 to 77.44% and 44.07 to 52.41%, respectively. In the case of tests 3 and 5, the incoming TSS and retained TSS (estimated and measured) presented higher values (if compared to tests 1, 2, and 4). Additionally, in these tests, the filter presented the lowest TSS removal efficiencies. It was also observed that the TSS COD loads ranging around 200 g/h (test 1,2, and 4) values presented the best TSS removal efficiencies. While the TSS COD higher than 250 g/h (tests 3 and 5) presented the lowest suspended solids removal efficiency.

Table 4.3.2 - The Filter's Efficiency in Removing Suspended Solids

Test	Measured Flow	Backwash TSS COD	TSS COD Load	Filtration Time	Incoming TSS (estimated)	Retained TSS (estimated)	Retained TSS (measured)	TSS removal efficiency (estimated)	TSS removal efficiency (measured)
	L/h	mg/L	g/h	h		g		%	
1	260.80	679.17	177.13	6	135.62	77.98	59.77	57.50	44.07
2	291.12	659.00	191.84	6	127.51	74.24	57.99	58.22	45.48
3	237.92	1463.10	348.10	7	388.21	139.34	128.75	35.89	33.64
4	252.04	866.61	218.39	7	145.50	112.38	76.26	77.24	52.41
5	296.00	874.33	258.80	6	366.98	107.03	76.94	29.17	20.97

4.3.2 Filter's Breakthrough and Saturation Time

Figure 4.3.2 shows the filter's influent and effluent TSS COD concentrations follow-up. While Figure 4.3.2.1 shows the influent and effluent respective turbidity measurements during the experiment. As the results indicated, the breakthrough time of the filter was observed at 21 hours. Since this was the time in which it was observed a step-increase in the TSS COD and turbidity measurements. Before, the breakthrough time the average TSS COD values in the filter's influent and effluent were 102.52 mg/L and 20.30 mg/L, respectively. Moreover, the filter reached its saturation point at 26 hours, time in which the TSS COD influent and effluent concentrations were the same. Additionally, the filter's measured flowrate and backwash water's TSS COD were 249.69 L/h and 3.17 COD g/L, respectively.

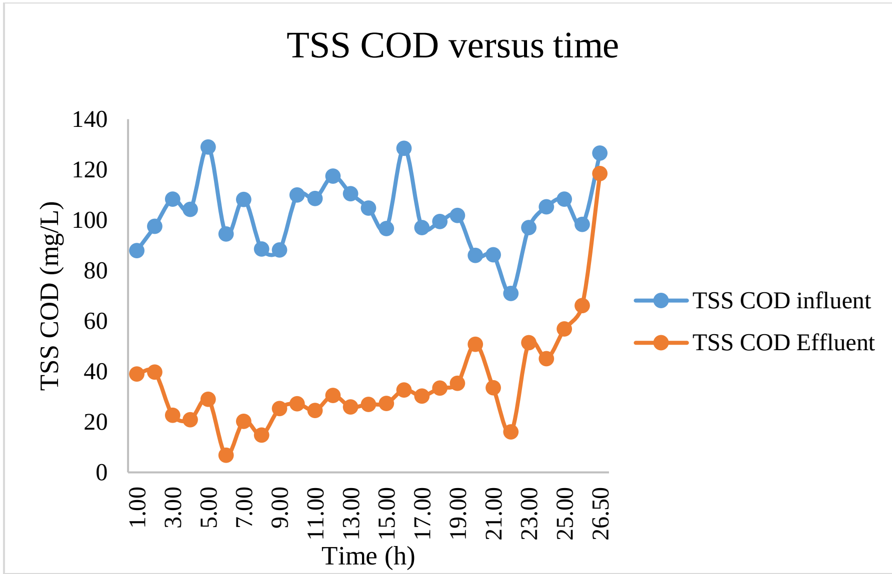


Figure 4.3.2 - Filter's Influent and Effluent TSS COD Concentrations Over 27 Hours

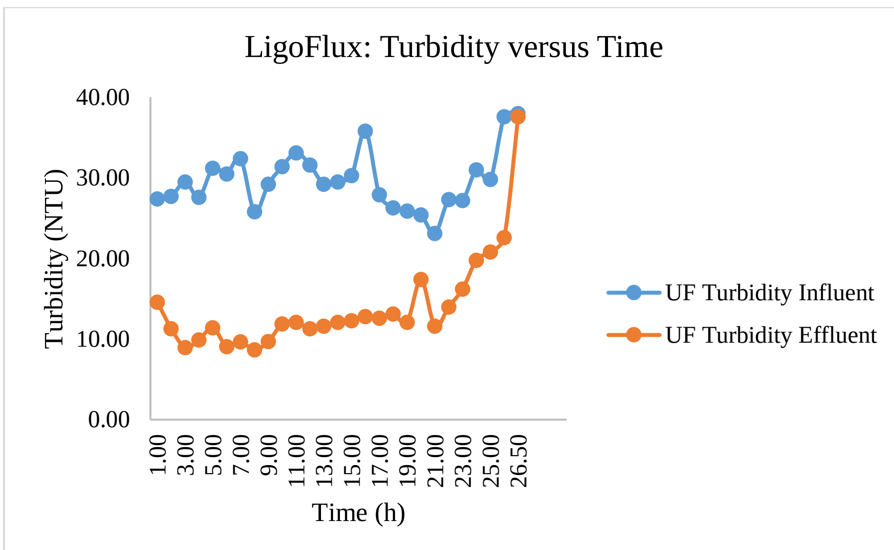


Figure 4.3.2.1 - Filter's Influent and Effluent Turbidity Over 27 Hours

4.3.3 Turbidity and TSS COD Correlation

During test 4 (section 4.3.1), the turbidity and TSS COD from the filter's effluent and influent were measured hourly for 7 hours. Figure 4.3.3. shows the correlation between the turbidity and the total suspended solids COD. The results showed that there is a high correlation between turbidity and TSS COD values, presenting a correlation factor above 95% in both influent and effluent.

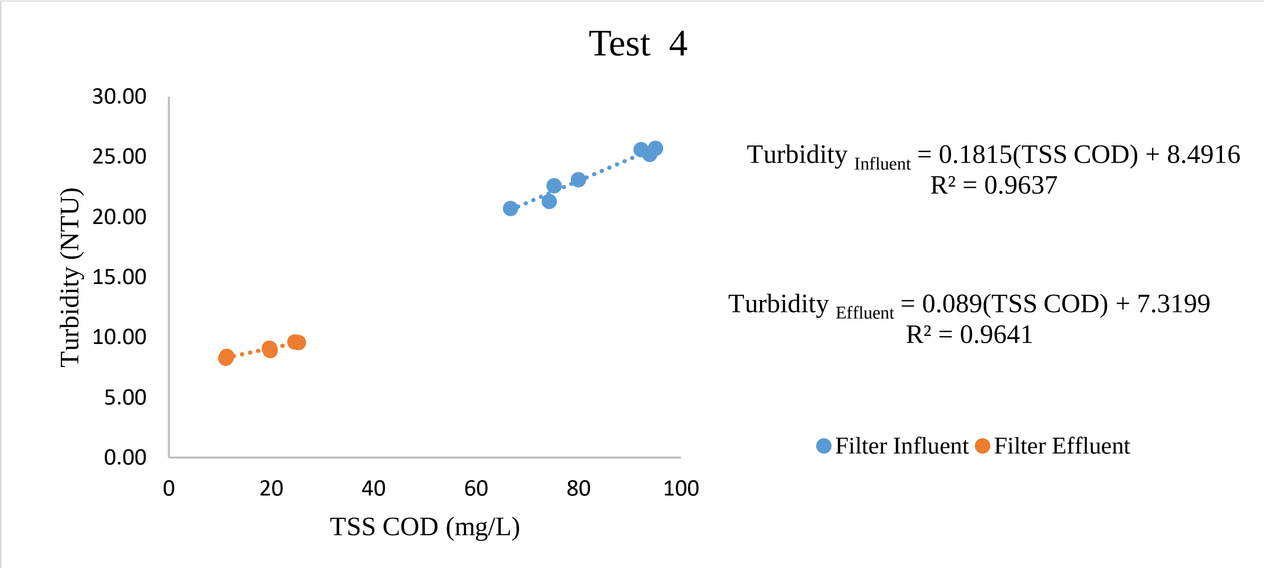


Figure 4.3.3 - The Turbidity and TSS COD Correlation

4.4 Heat Exchanger

In this section, the heat exchanger performance will be presented at different warm and cold water flows and temperatures.

4.4.1 Flowrates and Temperatures Measurements: Heat Exchanger

The temperatures and flowrates measurements of the heat exchanger tests, from test 1 to test 4, can be found in Figure 4.4.1. From this figure, the steady-state conditions (the period in which the temperatures and flowrates are constant for 30 minutes) from tests 1 to 4 could be identified to calculate the specific heat values for each test. The results showed that tests 1 – 4 achieved the steady-state conditions in the following intervals: 09:00 - 09:30 a.m., 10:20 – 10:50 a.m., 01:40 – 02:10 p.m., and 02:30 – 03:00 p.m., respectively. Because the temperature of the warm water from tests 1 and 2 (38°C) was different from tests 3 and 4 (35 °C), it took two hours (from 11:00 a.m. to 13:00 a.m.) to adjust the warm water temperature from 38 to 35°C. Resulting in a 2 hours wait to restart the temperature and flowrate measurements, as it can be noticed from Figure 4.4.1.

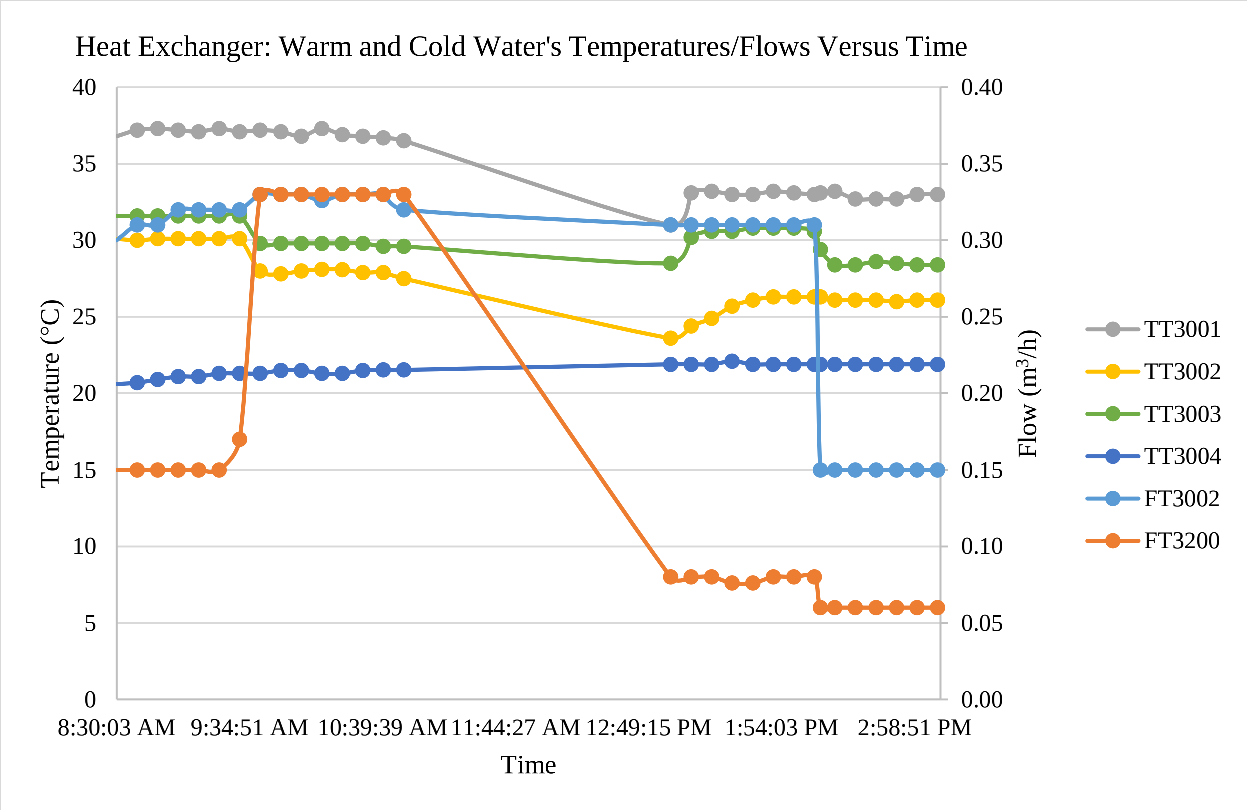


Figure 4.4.1 - Temperatures of Warm and Cold Water Flows Before and After the Heat Exchanger

4.4.2 Heat Exchanger Efficiency at Different Flowrates and Temperatures

From the 30 minutes' intervals (steady-state) in which the temperature and flowrate did not change, the heat specific values and heat exchanger efficiencies were calculated. Table 4.4.2. shows the fluid's average temperatures and flowrates at steady-state conditions, the specific heat from the warm and cold water, and the heat exchanger efficiency from each test. These efficiencies were calculated based on the amount of specific heat transferred from the warm water to the cold water.

Table 4.4.2 - The Heat Exchanger Efficiency at Different Flowrates

	Test 1	Test 2	Test 3	Test 4	Unit	Notes
FT3002	0.32	0.33	0.31	0.15	m^3/h	Warm water Flowrate
FT3200	0.15	0.33	0.08	0.06	m^3/h	Cold water flowrate
TT3001	37.18	36.73	33.08	32.78	°C	$T_{warm,in}$
TT3002	30.10	27.85	26.25	26.08	°C	$T_{cold,out}$
TT3003	31.60	29.70	30.75	28.48	°C	$T_{warm,out}$
TT3004	21.20	21.47	21.90	21.90	°C	$T_{cold,in}$
ΔT_{warm}	5.58	7.02	2.33	4.30	K	
ΔT_{cold}	8.90	6.38	4.35	4.18	K	
Q_{Warm}	7457.12	9616.87	3012.74	2696.10	kJ/h	
Q_{Cold}	5766.30	8800.60	1436.50	1047.10	kJ/h	
Q_{Warm}	2.10	2.70	0.80	0.70	kWh	
Q_{Cold}	1.60	2.40	0.40	0.30	kWh	
Efficiency	77.30	91.50	47.70	38.80	%	

According to Table 4.4.2, average temperatures of the incoming warm water from tests 1-2 (37.18°C and 36.73°C) and tests 3-4 (33.08°C and 32.78°C) were slightly different from the temperature set at the heating tank (38°C). This due to heat losses (resulted from the pipes, connections, and heat loss to the surroundings) from the warm water tank to the heat exchanger. The same can be said for the cold water (tap water) temperatures (TT3004 values). Moreover, the flowrates of warm and cold water (FT3002 and FT3200 values) were quite consistent with the desired flowrate values set for this experiment.

From the heat specific formula, Q_{Warm} (the heat lost by the warm water) and Q_{Cold} (the heat increase observed in the cold water) were calculated for each test in kilojoule per hour (kJ/h) and converted to kilowatts hours (kWh). The results showed that the heat exchanger efficiencies from test 1 to test 4 were 77.3%, 91.5%, 47.7%, and 38.8%, respectively. Showing that with the increase of the cold water flow, for the same warm water flow, the efficiency of the heat exchanger increased. For example, from test 1 (warm flow:0.32 m^3/h; cold flow: 0.15 m^3/h) to test 2 (warm flow:0.33 m^3/h; cold flow: 0.33 m^3/h), the heat exchanger efficiency increased from 77.3% to

91.5%. The lowest heat exchanger's efficiency was obtained when the warm water flow and the cold water flow were decreased to 0.15m^3/h and 0.06 m^3/h, respectively. On the contrary, the best efficiency of 91.5%, observed in test 1, was obtained when the flowrates and warm water temperature were at the highest experiment's setting values (38°C and 0.30 m^3/h) showing that the optimal heat exchanger operational flowrate was 0.3 m^3/h.

4.5 System Performance

In this section, the overall performance of the system will be assessed. First, the average influent and effluent water analysis, and the system removal efficiencies will be presented. Then, as another way to represent the pilot's capacity in removing pollutants, the overall pilot and filter mass balances will be provided.

4.5.1 The System Performance Water Analysis (Bioreactor + Filter)

Table 4.5.1 shows the system's average effluent and influent water analysis over different random days for a pollutant load corresponding to 120 inhabitants. Results showed that the influent and effluent average unfiltered COD concentrations were 216.75 mg/L and 66.94 mg/L, respectively. Filtered CODs observed were 112.73 mg/L (influent) and 37.76 mg/L (effluent). In addition, the total COD presented removal efficiency above 65%. Moreover, the turbidity decreased significantly (86.74%) from the influent to the effluent. In regards to nitrogen removal, the pilot plant, mainly due to nitrogen conversions in the MBBR, presented total nitrogen and ammonium reductions above 40%. The influent and effluent total nitrogen values were 19.90 mg/L and 11.63 mg/L, respectively. While, the ammonium concentrations were 13.57 mg/L (influent) and 7.83 mg/L (effluent), respectively. No significant nitrate removal from the system's influent was observed. The same can be said for orthophosphate with influent and effluent concentrations of 1.02 mg/L and 0.47 mg/L, respectively. Furthermore, the pH and conductivity values remained quite stable around 7 and 1 mS/m.

Table 4.5.1 - Pilot Plant Overall Average Treatment Performance (6 samples)

Parameters		pH	Conductivity	COD		TN	NH_4-N	NO_3-N	PO_4-P	Turbidity
				UF	F					
			uS/cm	mg/L						NTU
Influent	Mean	7.49	872.67	216.75	112.73	19.90	13.57	1.62	1.020	64.23
	S.D.	0.14	148.28	34.52	49.24	2.98	1.30	0.76	0.400	22.47
Effluent	Mean	7.63	864.67	66.94	37.76	11.63	7.83	1.44	0.470	8.52
	S.D.	0.38	145.11	3.59	1.31	0.75	1.56	0.62	0.260	0.73
Removal Efficiency (%)		-	-	69.12	-	41.54	42.29	10.91	53.91	86.74

S.D.: Standard Deviation

4.5.2 System and Filter Mass Balance

In this section, it will be presented the system unfiltered COD mass balance over a 3 days' cycle (from July 21st to July 24th, 2020) as a different way to report the system's COD removal efficiency. For that, a mass balance of the overall system performance (Figure 4.5.2.1) was done to verify the feed COD conversion to CO_2 due to the organic degradation (happening in the MBBR). Additionally, a mass balance for the filter, as shown in Figure 4.5.2.2, was done to demonstrate the filter removal efficiency in removing total suspended solids.

As shown in Figure 4.5.2.1, the COD converted by the system was 3,088 g in three days. This value was calculated from the UF COD mass balance. Which was done by measuring the unfiltered COD concentrations and volume (measured flowrate times 3 days) values of all water streams in the pilot. The pilot's mass balance showed that 73% of the incoming COD mass (4,231.52 g COD) was converted to CO_2. Since the pilot COD conversion to CO_2 is attributed to the MBBR, the mass balance showed that the pilot bioreactor presented a high organic matter removal efficiency (73%).

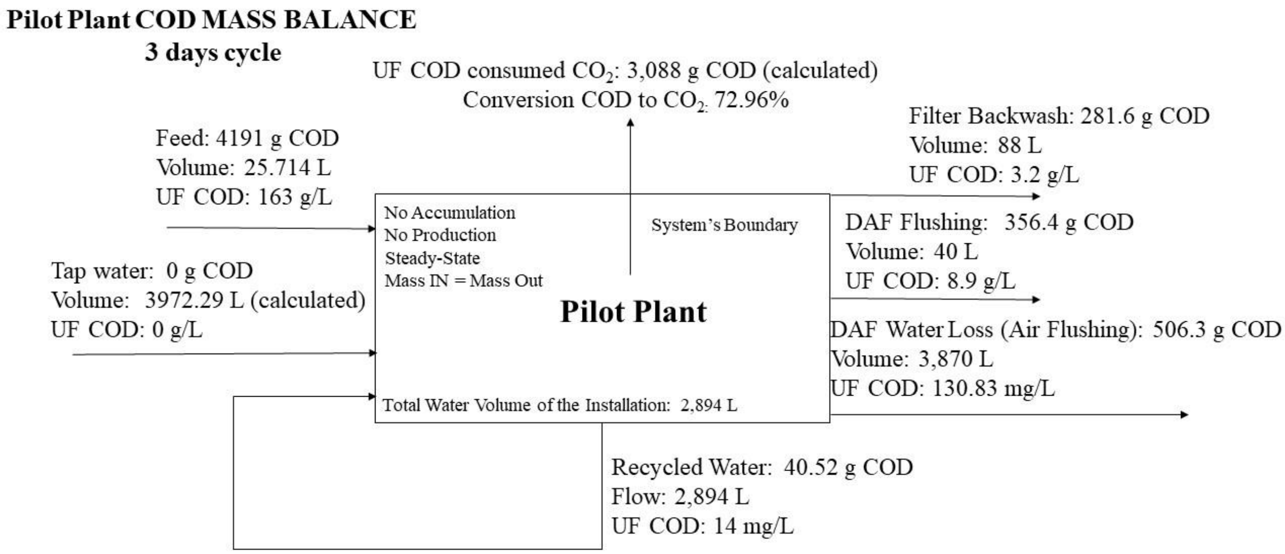


Figure 4.5.2.1 - Pilot Plant's Mass Balance (72-hours Cycle)

Furthermore, the filter mass balance indicated that the measured TSS removal efficiency of the filter is 52.41%, as shown in Figure 4.5.2.2. Along with, the mass balance (for the filter operation of 7 hours) also shown that the estimated retained suspended solids, in terms of COD, (112.38 g) was higher than the actual amount of TSS retained by the filter (76.26 g). It is important to notice that this mass balance represents a visual illustration of the results already represented in section 4.3.1.

Figure 4.5.2.2 - Filter's Mass Balance Filter (7-hours Cycle)

5 Discussion

In this chapter, a discussion of all 5 result sections will be provided on the ability of the pilot plant in treating light GW (from showers and bathroom hand basins) to be reused for toilet flushing. Furthermore, the discussion will be divided into five parts. First, a discussion on the synthetic greywater characterization formulated for 120-inhabitants equivalent will be provided. Then the performances of the bioreactor, filter, heat exchanger, and overall system will be discussed.

5.1 Synthetic Greywater Characterization

In this study, the total phosphorus content of the synthetic greywater (0.612 mg/L) was lower than the average values (approx. 5.7 mg/L) found in the literature for the Netherlands (Hernandez et al, 2007). Probably because these values were estimated based on light and dark greywater, instead of greywater solely coming from showers and washbasins like in this pilot experiment. This shows that greywater from showers and washbasins do not present high concentrations of phosphorus (Boano et al., 2019). For example, for all pollutant loads, in this study, the synthetic greywater's total phosphorus concentration did not exceed 1.8 mg/L. This value is considered to be low since it is lower than all greywater reuse limit values found for TP (Hernandez et al, 2007, Boano et al., 2019). According to Noutsopoulos et al., 2017, the major source of phosphorus in greywater is dishwashers (due to detergents). Regarding the unfiltered COD value of 238mg/L (obtained at the 120-inhabitants load), the system synthetic greywater presented similar values found in the literature for real greywater (Boano et al., 2019). In a pilot study, Chrispim et al., 2017, measured the COD values of raw greywater, from showers in a university building, as 272.8 mg/L. The authors also measured the turbidity value of the greywater, which was 40 NTU. These measurements are very similar to the greywater's turbidity (38.5 NTU) and COD values measured in this study.

Other parameters such as total nitrogen, nitrate, ammonium, and pH values were consistent with values found in real greywater when compared to previous studies (Saidi et al., 2017; Chrispim et al., 2017; Hernandez et al, 2007). For instance, Saidi et al., 2017, in a study in Germany on a full-scale MBBR system followed by filtration, measured real greywater for 223 inhabitants with the following influent concentrations and pH: TN: 13 mg/L, PO_4-P: 1.9 mg/L, and pH: 7.6.

In this way, the values measured in the synthetic greywater in this study (Table 4.2.2) were similar to the nutrient concentrations expected from real raw greywater.

Furthermore, the C:N:P ratio according to the measurements presented in Table 4.2.2 was 120:10:1 close with the C:N:P ratio pre-determined in section 3.3.2. In this study, the C:N:P ratio encountered for the system's influent synthetic greywater shows that nutrients are not a limitation for the biofilm growth indicating high greywater biodegradability (Chrispim et al., 2017; Saidi et al., 2017).

5.2 Bioreactor Performance

The main goal of the MBBR in the pilot plant was the biodegradation of the organic matter from greywater since it is the main load present in it (Saidi et al., 2017). The load regarding the suspended solids (the difference between the unfiltered COD load and filtered COD load) was to be removed by the filter. The results showed that MBBR could treat significantly the load from 120 inhabitants. At this optimum operational organic load, the bioreactor of the total active volume of 1.6 m^3 (carriers' volume: 0.5 m^3) presented high COD removal efficiency (above 86%) as shown in Table 4.1.2. and Table 4.5.1. From the pilot mass balance (Figure 4.5.2.1), it was observed that the COD removal efficiency due to the MBBR was 73%. Thus, the mass balance indicated the actual amount of COD converted to CO_2 by the MBBR. Meaning that this is the real COD removal efficiency of the MBBR. In other words, the mass balance indicated that the MBBR removed 2.58g COD/m^2.day (considering a carriers' surface area of 400 m^2, section 3.2). The difference between this efficiency and the one found in Table 4.1.2. was because when the latter was calculated with average COD concentrations, the COD conversion into CO_2 was overestimated. This because the estimated amount of COD assumed just for the CO_2 conversion would actually be the COD converted into CO_2 and biomass (Kawan et al., 2016).

Despite the COD removal differences observed in the MBBR real (73%) and estimated (86%), these COD reduction values accounted for a high total COD removal efficiency. Probably, even higher COD removal efficiencies could be achieved if the present MBBR carrier's percent filling (31.25%, section 3.2) was increased to 50% (Wang et al, 2005). Lower total COD removal efficiencies were found by Saidi et al., 2017, which evaluated the performance of a full-scale system composed of 9 MBBR reactors in series (total MBBR system volume of 11.7 m^3) to treat greywater. The researchers found that the three most efficient MBBR reactors in the system presented a total COD removal efficiency of 64%. Though, it is important to bear in mind that the efficiency of the MBBR-system can vary due to many parameters such as organic load, the number of MBBR reactors, carrier volume, and HRT as discussed in section 2.1.3. Thus, based on the good performance of the MBBR in this study in degrading organic matter, the MBBR showed to be a feasible technology to greywater, promoting by then its reuse. Though, a further step seemed to be needed to reduce the total COD levels in the MBBR's effluent (147 mg/L; 120 -inhabitants load) for domestic uses (Boano et al., 2019).

Regarding nitrogen degradation, the best nitrogen removal performance (42%) by the MBBR was observed at the 120-inhabitants equivalent load. For instance, as observed in Table 4.1.1, the bioreactor could reduce an influent TN concentration of 19.1 mg/L to 10.9 mg/L. This effluent concentration allows the treated GW reuse for toilet flushing by many of the limits found in the literature (Boano et al., 2019; Camp Dresser & McKee, 2004; Hernandez et al, 2007). The results presented in Table 4.1.1 and Table 4.5.1 indicated that the reduction in the total nitrogen was mostly attributed to the removal of ammonium from greywater which presented removal average efficiency above 40% attributed to the 120-inhabitants load. The stable nitrate concentrations in the influent and effluent at this pollutant load showed that all the NO_3 resulted from nitrification was converted to nitrogen gas by denitrification. Similar results were found by Saidi et al., 2017, in which the nitrate concentration in the influent and effluent from a full-scale MBBR system did not change significantly. Thus, since the MBBR nitrogen degradation from ammonium to nitrogen gas is done by the nitrification/denitrification process, it is expected the removal of ammonium was the most significant for the TN reduction (Ghaitidak and Yadak, 2013). In wastewater treatment, when nitrate concentration needs to be removed more efficiently, usually an additional tank to place denitrification is added in the treatment train (Ghaitidak and Yadak, 2013). Nitrification/Denitrification is possible in MBBR systems by introducing highly aerated periods and low aerated periods Though, it is not the case of this study since as showed in Table 4.1.1, the final MBBR effluent is already suitable for reuse (Boano et al., 2019).

The removal of orthophosphate in wastewater treatment is usually done by chemical precipitation or membrane techniques (Boano et al., 2019; Saidi et al, 2017). Therefore, it was not expected to find high removal efficiencies of phosphorus compounds in MBBRs. The results presented in Table 4.1.1 and Table 4.5.1 supports that fact. In case a more efficient removal of orthophosphate is intended, precipitation could be added to the treatment train (Saidi et al, 2017). Though, this is not the case, since for all the bioreactor effluents measured in this study, no orthophosphate concentrations, which often used as a parameter to indicate the total phosphorus content in WW, were found above the limit standards for greywater reuse (Boano et al., 2019; Camp Dresser & McKee, 2004; Hernandez et al, 2007).

Therefore, due to the high removal of organic matter and moderate removal of total nitrogen which allows the reuse of the greywater based on many reuse limit standards found in literature, the use of the MBBR was satisfactory and its presence in the pilot treatment system is justified (Boano et al., 2019). Though, to be able to reach the most stringent COD limits for GW reuse, it was observed that the necessity of a further step after the MBBR. As mentioned, for this study, the filter was chosen to be this step and its performance will be discussed in the next section.

5.3 Filter Performance

In section 4.3.1, no significant difference in the measured TSS removal efficiencies was found in the tests performed except for tests 3 and 5. This because a disturbance in the carrier's mixing (due to an increase in aeration) affected the MBBR effluent TSS COD concentrations during test 3. While during test 5, the pollutant load to the MBBR was higher than its optimum operational load (the 120-inhabitants load). These results indicate that the well-functioning of the filter, in the pilot plant, depends on the well-functioning of the MBBR. For the reason that the effluent of the MBBR is the influent of the filter. Furthermore, important patterns from tests 1 to 5 could be identified. The test 1, 2, and 4 showed that the measured TSS removal efficiency in the filter, when the MBBR is operating in stable conditions, seemed to be stable ranging from 44.07% to 52.41%. Indicating that the efficiency of the filter relies on this range, considering the pilot's operational conditions. Hamoda et al., 2004, studied a rapid sand filter (60cm of the sand layer and 40cm gravel layer) performance in removing suspended solids from wastewater, which had the same surface loading rate from the present filter (5 m/h, section 3.4). While the filter's influent TSS concentrations were lower in comparison with this study (from 8.5 to 13.9 mg/L). They observed that the sand filter, placed after a clarifier, presented higher TSS removal efficiencies (from 58% to 70%) if compared to the results found in Table 4.3.2. Probably, because the filter in Hamoda et al., 2004, had a pre-chlorination step before it to prevent clogging. Thus, increasing the filter's average TSS removal efficiencies. However, without any chemical additives, the filter in this study presented moderate TSS removal efficiencies around 50%. Reductions not that far from the results found by Hamoda et al., 2004. Furthermore, for a lower surface loading rate (1.4 m/h) than this study, Noutsopoulos et al., 2018, analyzed a lab-scale sand filter performance in removing TSS from greywater from showers and hand basins. The authors found that the TSS removal efficiencies of the filter were 40% approximately. This efficiency is similar to the values found in Table 4.3.2.

Regarding the differences between calculated and estimated TSS removal efficiencies. The calculated TSS removal efficiencies (from 35.89% to 77.24%) showed to be higher than the measured ones (from 33.64% to 52.41%). This because it was assumed that TSS COD concentrations in the influent and effluent remained constant over one-hour intervals. Resulting in an average of incoming TSS and retained TSS values higher than the actual TSS COD concentrations observed from the filter's backwash COD measurements. Because the difference between unfiltered and filtered COD from the filter's backwash indicates the actual amount of TSS in the filter. Hence, the latter was used to calculate the suspended solids retained by the filter. Therefore, the results in Table 4.3.2 indicated that the TSS entering and leaving the system are not constant within one-hour intervals as assumed. As a result, TSS removal efficiencies calculated and estimated differed.

Although, tests 3 and 5 presented the lowest TSS removal efficiencies a lot can be learned from them. These tests showed a limitation for the filter in operating with high TSS COD loading capacities. Because during tests 3 and 5, the filter efficiency was reduced significantly when operated in loads higher than 250 g TSS COD/ h. Making the filter effluent in the tests not suitable for greywater reuse due to a high COD level (test3: 186.33 mg/L; test 5: 181.03 mg/L) in the most stringent limits found in the literature (Boano et al, 2019). While tests 1, 2, and 4 could reduce the filter's influent COD concentrations to the most restrictive reuse limits for non-potable purposes (Noutsopoulos et al., 2018). Showing that this filter seemed to be a good technology for removing suspended solids to promote the greywater reuse for toilet flushing.

It must be pointed out that in the seven hours of operation in the tests 1-5, presented in Table 4.3.2, the filter's saturation and breakthrough time were not observed. This because the TSS average incoming mass did not match the TSS average outcoming mass values. Since these are important parameters for the up-scaling of the filter, an additional test needed to be performed. As shown in Figure 4.3.2 and Figure 4.3.2.1, the filter's saturation and breakthrough time are 26 hours and 21 hours, respectively. These parameters indicate that the filter needs to be back washed after 21 hours of filtration for the operational conditions observed in the pilot. Similar backwashing frequency was found by Hamoda et al., 2004, for a full-scale rapid filter with the same surface loading rate as the present filter. Additionally, according to the average filter's TSS COD concentrations (influent and effluent) before the breakthrough point showed in section 4.3.2, the filter presented a TSS COD loading capacity of 4 TSS COD g/L. This considering the filter's carrier's volume of 52 L (section 3.2). Lower suspended solids loading capacity (2.4 TSS g/L) was found by Rajala et al., 2003, for a pilot rapid sand filter with a surface loading rate of 7.7 m/h. Indicating that the present filter presents comparable performance and operational parameters to full and pilot scale filter applications.

Furthermore, it was noticed during the filter's COD follow-up experiments that it is quite expensive to perform the COD tests every hour within the filter operational time. The results from section 4.3.3 showed that there is a high correlation between TSS COD and turbidity. This means that the COD measurements can be done in longer intervals than this study (Saidi et al, 2017). Because, if the turbidity is measured in faster intervals, the unknown COD values can be found by the COD/Turbidity correlation equation. This would reduce the cost of the filter's COD follow-up measurements. Similar correlations (above 95%) were found by Saidi at al., 2017. Though, it is important to notice that the COD has to be measured so a correlation equation between TSS COD and turbidity can be established for the experiment. This because, although turbidity measurements can be used to control the COD monitoring, it cannot substitute the COD follow-up measurements (Saidi et al, 2017).

Based on the results here discussed, the filter in this study showed moderate TSS removal efficiencies which for an average influent concentration of 200 mg/L can be reduced to greywater reuse levels like showed in Table 2.4.1. Hence, the filter showed to be a crucial step to promote sustainable water use. However, a better TSS removal performance can be achieved by adding a coagulation step before the filter, for example. Alternatively, increasing the carrier filling ratio would also be a way to increase the pilot filter's efficiency. However, as described in section 3.2, this increase is not recommended since a higher carrier filling in the filter would not allow an efficient backwashing. In this way, another carrier type with a higher surface area, corresponding to the same carrier filling ratio, is recommended for the pilot filter.

5.4 Heat Exchanger Performance

As it could be appreciated in Table 4.4.2., the highest efficiency (91.5%) of the heat exchanger (HE) was found at warm and cold flowrates of 0.3 m^3/h, the same flowrate as the optimum operational flowrate of the pilot plant, and temperatures of 21°C and 38°C. It was noticed that the HE efficiencies were affected by variable flowrates and temperatures. Thus, the HE efficiencies varied from 38.8% to 91.5%. In a literature review, Mazhar et al., 2018, concluded that the HE performance depends on the flowrate and temperature. Furthermore, optimum efficiency can be determined by testing different flowrates and temperatures of cold and warm water. As in this study, the average maximum flowrate and temperature of warm water and cold water were 300 L/h, 20°C and 38°C, respectively, the optimum HE operational parameters found for the HE were flowrate of 0.33 L/h, warm and cold temperatures of 21°C and 38°C. Compared to other studies on GW heat recovery technologies, similar heat exchanger efficiencies (from 70% to 90%) were found by Alnahhal and Spremberg, 2016; Neugebauer et al, 2015; and Kordana, 2017. Furthermore, McNabola & Shields, 2013, in a study with different warm/cold water flowrates (360 L/h) and water temperatures (11.3 °C and 37.0 °C), if compared to this study, presented lower efficiencies (from 49.1 to 55.5%). Most probably, due to the difference observed in the temperatures and flowrates in the experiment, which as discussed, are parameters that interfere in HE efficiencies. Therefore, based on the HE performance showed in Table 4.4.2, the heat exchanger showed as a good way to promote heat recovery from showers.

The moderate and high HE efficiencies observed in Table 4.4.2 can be translated into a reduction in the electricity demand for water heating due to energy savings (Mazhar et al., 2018). In other words, for example, considering that in the Netherlands the electricity costs 23 cents per kWh, with the use of the present HE from 9 to 21 c €/kWh would be saved (for the HE efficiencies of 38.8% and 91.5%, respectively) (Gercek and Reinders, 2019). Assuming that a shower of 10 min (5 L/min) spent from 0.4 kWh to 1.1 KWh per person in the Netherlands (values corresponding of summer and winter periods), in one month (assuming each person takes one shower per day) the electricity bill savings due to the HE of a Dutch household of 4 residents would be from 4 to 28 euros per month (Deng et al., 2016). Yearly, 48 euros to 336 euros for water heating per household (4 residents) would be saved. Similar values were found by Deng et al., 2016, justifying the use of the heat exchanger to recover energy in this pilot study. It is important to notice that the example mentioned is just an illustration. Actual electricity savings may vary due to the number of showers, summer/winter season, the pilot plant allocation, heating storage, etc.

However, the results from Table 4.4.2 also revealed that the efficiency may vary (from 38.8% to 91.5%, in this study) depending on factors such as cold/warm water temperatures and flowrates (Mazhar et al., 2018). Moreover, it is noteworthy that the heat exchanger efficiencies might differ from the values calculated in this study. This because the experiment was performed with tap-water instead of greywater. Since the heat transfer also depends on the characteristics of the fluids, the actual heat exchanger efficiency for GW might differ from the value calculated. The heat recovery from greywater offers an extra challenge if compared with the energy recovery from tap water. Because HE performance might be lower when the heat is recovered from greywater due to foaling. This was the case of this study, that because of the HE fouling, it had to be removed from the treatment plant. This to avoid the reduction of the pilot system's greywater treatment performance. Though, there are anti-fouling mechanisms that can be applied to tackle the fouling problem in HEs. For instance, the pipes carrying GW could be dipped and baked in chemical coatings, regularly cleaned/flushed, and pipeline strainers could have been placed before the HE (Mazhar et al., 2018). In this way, these small adaptations would allow the long-term application of the studied HE in the pilot.

Despite that, the experiment performed in this study provided an idea of how the heat exchanger efficiencies are. Since it is expected that the heat exchanger efficiencies with greywater and water are very similar (Mazhar et al., 2018). Though, further experiments with real or synthetic GW should be performed to identify the exact GW heat recovery values by the pilot.

Therefore, heat recovery from greywater is advantageous and could be applied in the treatment system with large benefits as showed in this study. Promoting the sustainable use of energy for heating water in sustainable cities.

5.5 System Performance

The results of the overall pilot plant in treating synthetic greywater from a population of 120 inhabitants in Goes, Netherlands, presented in Table 4.5.1, showed to be efficient in reducing almost all parameters to the greywater reuse limit levels found in the literature (Boano et al., 2019; Camp Dresser & McKee, 2004; Hernandez et al, 2007). The system represented overall removal efficiency for COD, TN, ammonium, nitrate, and PO_4-P of 69.12%, 41.54%, 42.29%, 10.91%, and 53.91%, respectively. Efficiencies that reduced the average influent values presented in Table 4.5.1 of total COD, TN, and TP (PO_4-P) to average effluent concentrations of 69.94 mg/L, 11.63 mg/L, 7.83, and 0.47 mg/L, respectively. Consequently, according to Table 4.2.1, the pilot's effluent presented COD, TN, and TP (PO_4-P) concentrations lower than all greywater reuse limits found in the literature for domestic non-potable use, except for the limit of total COD concentration in China (COD lower than 15 mg/L). Saidi et al., 2017, studying a full-scale MBBR/Filter/UV disinfection system to treat greywater from 223 inhabitants in Berlin found higher removal efficiencies for COD and nitrogen removal if compared to this pilot system. Those authors observed that the full-scale systems had total nitrogen and ammonium reductions from 13.00 mg/L and 7.15mg/L to 4.80 mg/L and 0.02 mg/L, respectively. Additionally, the overall system presented a COD conversion efficiency of 94.5% (Saidi et al., 2017). This because, the full-scale MBBR/Filter/UV system presented a total MBBR volume of 11.7 m^3, significantly higher than the MBBR volume in the present study (1.6 m^3). Moreover, one of the MBBRs was used as a settling tank. However, the pilot plant in this study achieved similar COD removal efficiencies if compared to the study of Chrispim et al., 2017. The researchers evaluated a pilot MBBR (88.3L) followed by a settling tank to treat a total COD load of 0.074 Kg/day from synthetic light greywater. The total COD reduction observed by the authors was 70%. In respect of phosphorus concentrations in the treated GW, the pilot's effluent presented concentration lower than all reuse standards found in the literature (Boano et al., 2019; Camp Dresser & McKee, 2004; Hernandez et al, 2007).

Furthermore, the pH values found for the system's effluent are within all the limits levels found in literature, as shown in Table 2.4.1. Yet, presenting average effluent turbidity of 8.52 NTU, the pilot's effluent seemed not to meet the most stringent limits for domestic GW reuse found in Table 2.4.1 such as the American and Canadian standards. Even though the system's effluent is able to be used for other purposes such as garden irrigation (Hamoda et al., 2004; Noutsopoulos et al., 2018) Furthermore, comparing the effluent's unfiltered and filtered COD in the overall system (Table 4.5.1), there are still some suspended solids that can be removed. Showing that the filter's operation can still be optimized. On the other hand, in European countries with more flexible GW reuse limits such as Germany, Italy, and Slovenia, the pilot effluent's turbidity nor other parameters would not find any restrictions that limit its use for toilet flushing. Turbidity also seemed to be a barrier to be overcome by the MBBR/settling tank system to treat greywater from showers studied by Chrispim et al., 2017. The researchers observed that the pilot's system presented the average effluent turbidity level of 11 NTU. Not allowing the greywater reuse for non-potable purposes in Brazil which had a limit for the turbidity of 10 NTU. Noutsopoulos et al., 2018, that applied a rapid sand filter to remove suspended solids from light GW, also observed effluent's turbidity above 10 NTU. In this way, if compared to the systems aforementioned, the filter in this study, presented better turbidity removal performance.

Another parameter to be considered for the domestic greywater reuse is the presence of pathogens in the treated water. Although it is expected a low pathogen concentration in light GW, the concentration of E. coli levels might present an obstacle for greywater reuse (Jabri et al, 2019; Saidi et al., 2017, Jabornig et al, 2013). For this reason, for a matter of safety, this study included UV disinfection in the pilot. Though, since the pilot experiments were only conducted with synthetic greywater, no experiments with UV disinfection were conducted. Hence, further experiments to evaluate the effluent quality, in regards to pathogens, should be done.

It is important to notice that the pilot plant can handle pollutant loads higher than the feeding corresponding to 120 inhabitants to some extent. This because the effluent from the DAF and the filter were recycled to the shower. Resulting in an increase of the incoming pollutant load to the plant. This shows the flexibility of the pilot in treating GW with possible variations in the incoming pollutant load. Thus, based on all the results here discussed, it can be concluded that the pilot plant showed to be an excellent way to treat light GW for toilet flushing in sustainable cities.

6 Conclusion and Recommendations

The pilot decentralized wastewater system seemed to be an excellent way of promoting sustainable water and energy use in the cities of the future. The pilot presented from moderate to high organic matter and nutrient reductions with COD, TN, and TP (PO_4-P) removal efficiencies of 69%, 42%, and 54%, respectively. As a result, the MBBR unit was able to treat the organic load of 2.58g COD/m^2.d, from the 120-inhabitants equivalent load, optimum loading rate, and flowrate of 300 L/h. While the filter presented a suspended solids loading capacity of 4.00 TSS COD g/L (TSS removal efficiencies up to 52%) with breakthrough and saturation time of 21 hours and 26 hours, respectively, for the same operating conditions than the MBBR. Furthermore, the heat exchanger in the pilot presented heat recovery efficiencies from 38% to 92% with optimum flowrate and warm/cold water temperatures of 0.30 m^3/h, 22°C, and 38°C, respectively. In order words, these efficiencies can be translated into the quality of the pilot's final effluent (COD< 66.9 mg/L, TN < 11.7 mg/L, and TP< 0.5 mg/L), which allows it to be reused for toilet flushing. And, the amount of energy that can be harvested from it (up to 2.7 kwh), which can be used for water heating. Thus, reducing the potable water and energy demands. Then, promoting the sustainable use of those resources in sustainable cities. Hence, the pilot showed a good performance in reducing the pollutant load to safe levels in many GW reuse limit standards found in the literature. Moreover, the HE presented a great performance in recovering energy from light GW. These results epitomize the outstanding pilot plant's ability in treating light GW for toilet flushing and recovering energy for water heating.

Nevertheless, it was noticed that in few non-European countries such as the U.S. and Canada, the pilot's effluent would not be permitted to be reused for toilet flushing due to the turbidity parameter which presented an average value of 8.20 NTU (turbidity removal of 86%). On the other hand, the pilot's effluent did find any problems meeting other non-potable water uses such as garden irrigation. It is noteworthy that small adjustments in the filter parameters such as chemical addition (coagulants) or change in the carrier type could reduce the turbidity levels to safety. Since the average turbidity level for toilet flushing is not much distant from the most restrictive limit standard found in the literature (< 2 NTU, Canada). Moreover, many European countries such as Germany, Italy, and Slovenia would allow the pilot's effluent to be reused for toilet flushing. Additionally, some important aspects of the pilot plant performance were left out of this study such as operational and investment costs, maintenance, on-site performance, UV disinfection tests, and integration of the heat exchanger with the pilot plant. Therefore, further studies should be performed to promote a better understanding of those aspects.

In conclusion, the pilot's overall performance showed that the plant presented comparable removal efficiencies to full-scale and pilot-scale applications. And, considering the fact that it successfully met the goals of treating light greywater, for a population equivalent of 120 inhabitants, for toilet flushing, and the recovering energy for water heating. It can be concluded that the decentralized system in this study, showed to be an excellent way to promote the water reuse and energy recovery in the cities of the future.

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7 Appendices

7.1 Appendix 1

Chemical Oxygen Demand

Figure A1.1 - MACHEREY-NAGEL COD 1500 test box

The COD test fulfills the requirements of DIN ISO 15705. The test and reference numbers are 029 and 985029, respectively. The COD 1500 test measuring range is from 100 to 1500 mg/L O_2 and follows the potassium dichromate method.

Method

The organic compounds of the greywater sample are oxidized by heating it (Figure A1.2) in a mixture of sulfuric acid and potassium dichromate. The COD of the sample will be the concentration of oxygen that is equivalent to the amount of dichromate consumed (Macherey Nagel, 2020). The latter is determined by the photometer as shown in Figure A1.3.

Procedure

- 2 mL of greywater sample was added into the test tube filled with a 2 mL mixture (weight percentages: sulfuric acid: 80 - <98 %; potassium dichromate: 0.38 - <1.26 %; silver sulfate: 0.1 - <1 % ; and mercury(II) sulfate: 0.74 - <1.5 %)
- The test tube was sealed and shaken vigorously
- The sample was heated for 30 minutes at 160 °C
- The tube was taken out of the heating block and shaken again while still warm
- The tube was cooled to room temperature
- The tube was cleaned

- The COD of the sample was measured in the photometer

Figure A1.2 - MACHEREY-NAGEL Heating Blocks

Figure A1.3 - MACHEREY-NAGEL Photometer

When the COD readings were below or above the COD 1500 ranges, the COD 160 test (measuring range: 15 to 160 mg/L O; test number:026; reference number: 985026) or the COD

15000 test (measuring range: 1.0 to 1.5 g/L O_2; test number:028; reference number: 985028) were performed.

Procedure

- COD 160 test: 2 mL of greywater sample was added into the test tube filled with a 2 mL mixture (weight percentages: sulphuric acid: 80 - <98 %; potassium dichromate: 0.00126 - <0.1 %; silver sulfate: 0.1 - <1 %; and mercury(II) sulfate: 0.74 - <1.5 %)
- COD 15000 test: 0.2 mL of greywater sample was added into the test tube filled with a 4 mL mixture (weight percentages: sulphuric acid: 51 - <65 %; potassium dichromate: 0.32 - <0.38 %; silver sulfate: 0.1 - <1 %; and mercury(II) sulfate: 0.37 - <0.74 %
- Same further steps than the COD 1500 test.

Total Nitrogen

The total nitrogen test and reference numbers are 088 and 985088, respectively. The TN test measuring range is from 5 to 220 mg/L N and follows the 2,6-Dimethylphenol method.

Method

The total nitrogen method consists of the oxidative decomposition of the greywater in the heating block followed by interference compensation and photometric determination with 2,6-dimethylphenol in sulfuric acid / phosphoric acid mixture (Macherey Nagel, 2020).

Procedure

The total nitrogen procedure was performed in two steps:

A) Decomposition step

- 500 µL of greywater and 0.2 grams of the decomposition reagent (weight percentages: potassium peroxodisulfate 60 - <80 % and sodium carbonate 20 - <50 %) were added into the decomposition test tube A filled with a 4.5 mL mixture (weight percentage: water: 90 - <100 %)
- The test tube A were sealed and shaken vigorously
- The sample was heated for 30 minutes at 120 °C
- The tube A was removed from the heating block and left to cool until room temperature
- 14 mg of the compensation reagent (weight percentage: sodium sulfite 70 - <100 %) was added into the tube and shaken vigorously
- This resulted in the decomposed solution

B) Analysis step

- 500 μL of the decomposed solution was added into the test tube B filled a 4mL mixture (weight percentages: sulfuric acid: 51 - <65 %; and o-phosphoric acid: 25 - <40 %)
- 500 μL of the reagent NANOFIX R2 (weight percentages: 2-propanol: 35 - <50 %; and 2,6-dimethylphenol: 0.1 - <1 %) was added into the tube B and shaken gently
- After 10 minutes, the tube B was cleaned and its content was measured in the photometer

Total Ammonium

The total ammonium test and reference numbers are 008 and 985008, respectively. The test measuring ranges are from 4 - 80 mg/L NH_4-N and 5 - 100 mg/L NH_4^+/ NH_3. The test follows the Indophenol method.

Method

At high pH values, ammonium reacts with hypochlorite and salicylate (with sodium nitroprusside as the catalyst) to form indophenol. Then the photometric determination of Indophenol is performed. From the concentration of Indophenol, the ammonium concentration is determined in the photometer (Macherey Nagel, 2020).

Procedure

- 500 μL of the sample was added into the test tube filled with an 8mL mixture (weight percentages: sodium hydroxide solution /diluted < 2 %: 0.1 - <0.5 %; and trisodium citrate: < 1,00 %)
- 18 mg of the reagent NANOFIX R2 (weight percentages: sodium nitroprusside 15–33 %; and dichloroisocyanuric acid sodium salt 10–20 %) was added to the test tube
- The tube was closed and mixed gently
- After 15 minutes, the tube was cleaned and its content was measured in the photometer

Total Nitrate

The total nitrate test and reference numbers are 066 and 985066, respectively. The test measuring ranges are 4–60 mg/L NO_3-N and 20–250 mg/L NO_3. The total nitrate test also follows the 2,6-Dimethylphenol method.

Method

Photometric determination with 2,6-dimethylphenol in sulfuric acid / phosphoric acid (Macherey Nagel, 2020).

Procedure

- 0.2 mL sample was added into the test tube filled with a 4 mL mixture (weight percentages: sulfuric acid 51–65 % and o-phosphoric acid 25–40 %)
- 0.5 mL of the reagent R2 (weight percentages: 2-propanol 35–50 %; and 2,6-dimethylphenol: 0.1 - <1 %) was added into the test tube and mixed gently
- After 10 minutes, the test tube was cleaned and its content was measured in the photometer

Total Ortho-Phosphate

The total ortho-phosphate test and reference numbers are 076 and 985076, respectively. The test measuring ranges are 0.2–5.0 mg/L PO_4^{3-} and 0.03–2.50 mg/L PO_4^{3-}. The total ortho-phosphate test follows the Phosphomolybdenum blue method.

Method

The test method is equivalent to the EPA method 365.3. Ortho- phosphates react with molybdate anions to form a yellow colored complex. The latter is reduced to a molybdenum blue species by ascorbic acid. This process occurs at temperatures between 100 to 120 °C. From the concentration of molybdenum blue species, the ammonium concentration is determined in the photometer (Macherey Nagel, 2020).

Procedure

- 4.0 mL of sample was added to the tube test filled with a 1 mL mixture (weight percentage: sulfuric acid 5–15 %)
- 27 mg of the reagent NANOFIX R3 (weight percentage: ascorbic acid: 90 - <100 %) was added to the tube test
- 200 µL of the reagent NANOFIX R4 (weight percentages: sulfuric acid 5–15 %; and ammonium heptamolybdate: 2 - <5 %) was added to the tube test and mixed vigorously
- After 10 minutes, the test tube was cleaned and its content was measured in the photometer

Remark on the Water Analysis Concentrations Expressed in Weight Percentages

When not listed, mixtures are added with water [CAS No. 7732-18-5] to 100% (Macherey Nagel, 2020).

7.2 Appendix 2

In this appendix, pictures of the pilot plant and experiments can be found.

Figure A2.1 - Full-scale Bioreactor in Which the Biofilm Was Cultivated

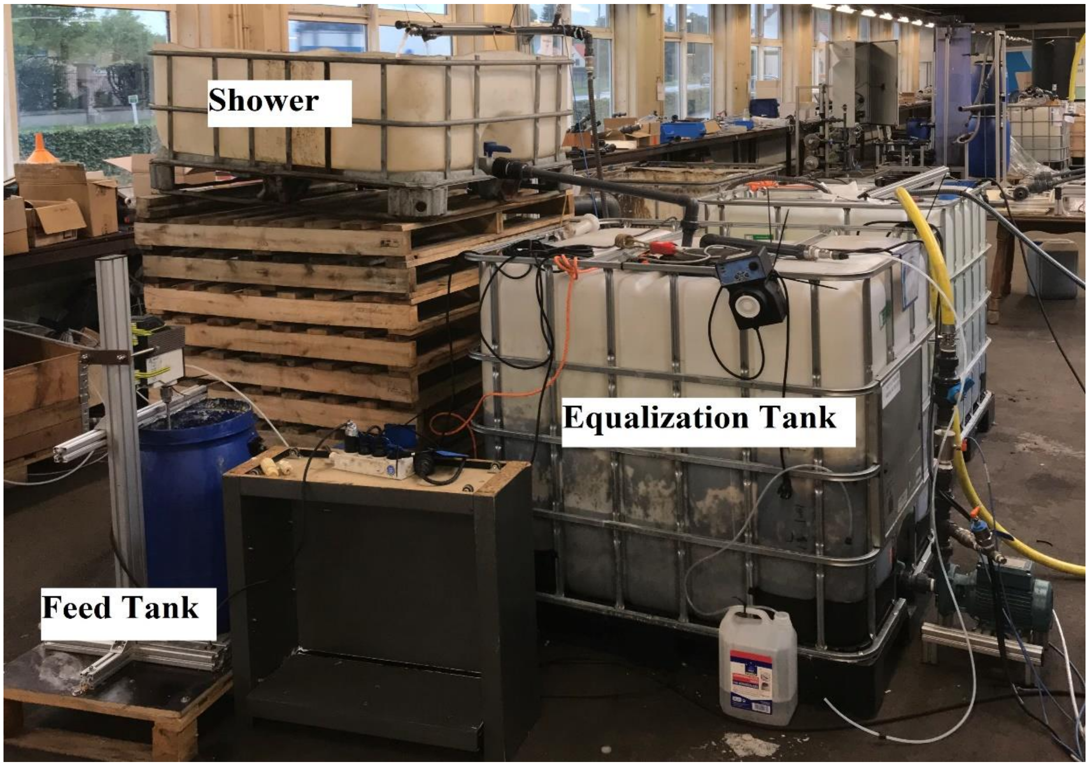

Figure A2.2 - Shower, Feed Tank, and Equalization Tank

Figure A2.3 - Emptied Filter, LigoFlux

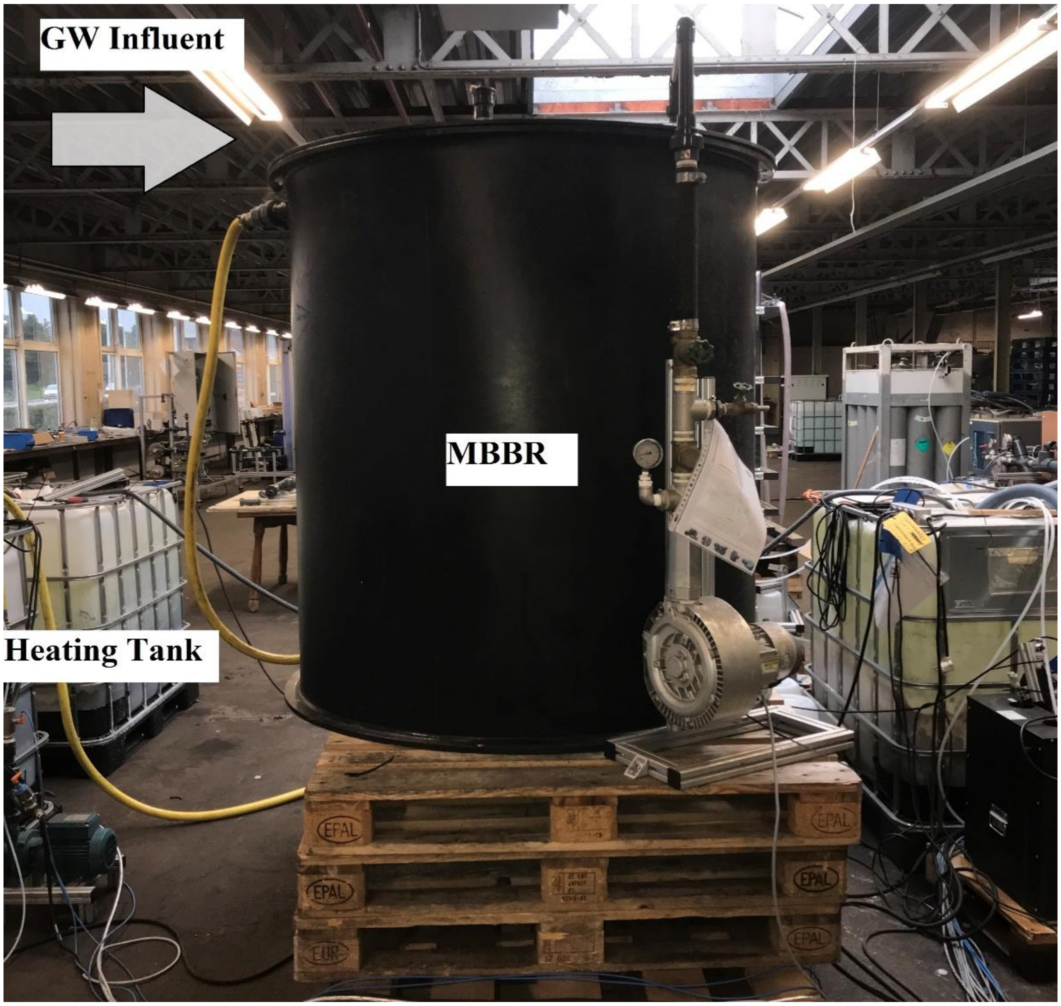

Figure A2.4 - Heating Tank and Bioreactor

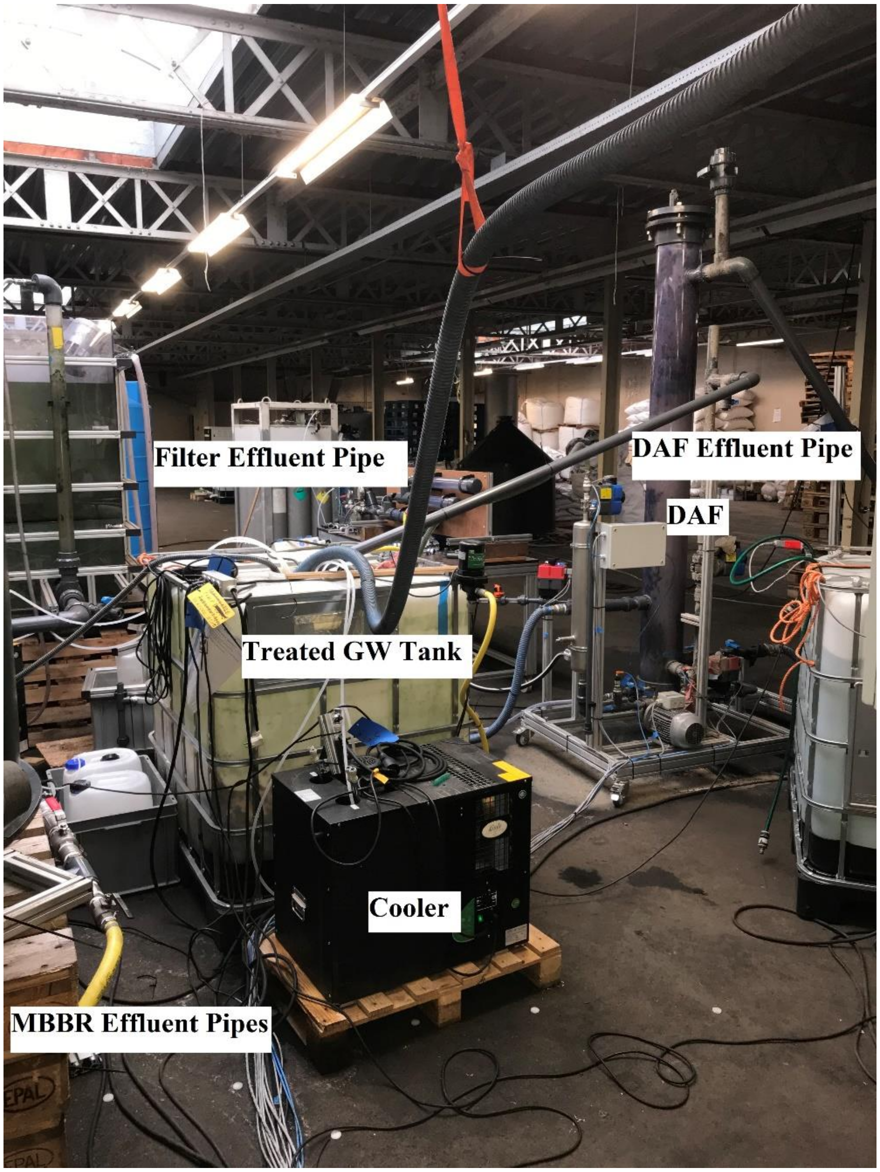

Figure A2.5 - MBBR/DAF/Filter Effluent Pipes, Cooler, Treated GW Tank, and DAF

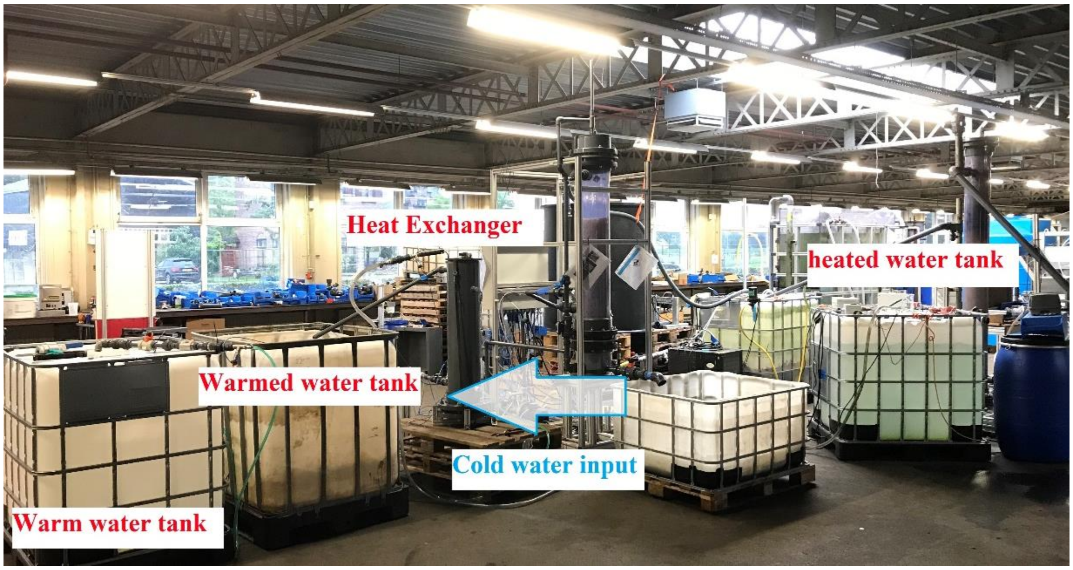

Figure A2.6 - Heat Exchanger Experiment Setup

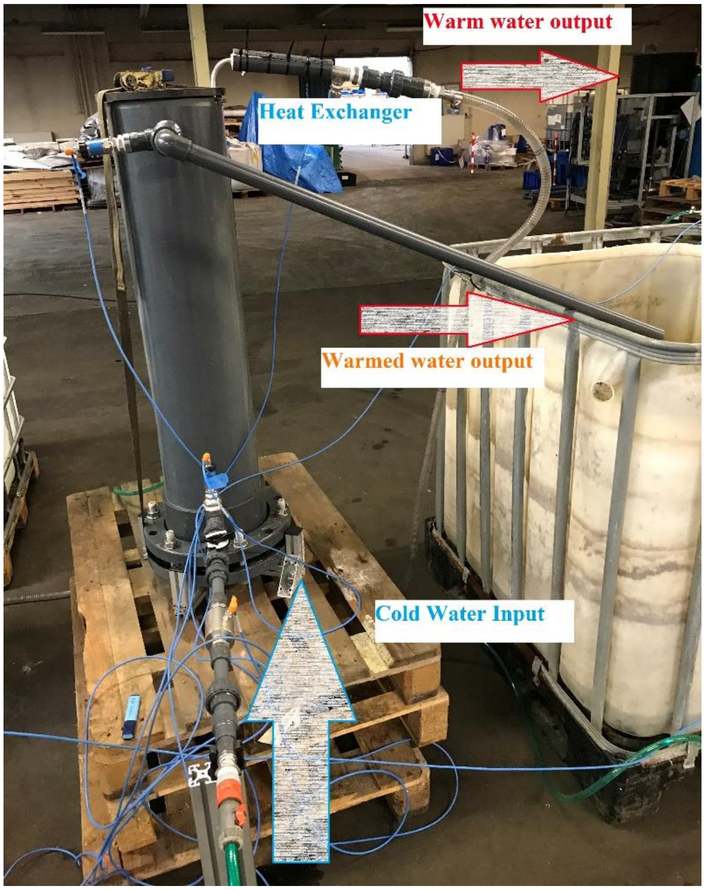

Figure A2.7 - Heat Exchanger