LOW LOAD GREYWATER AND MUNICIPAL WASTEWATER TREATMENT BY MEMBRANE BIOREACTOR

by

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BS. in Environmental Eng., Yıldız Technical University, 2005

Submitted to the Institute of Environmental Sciences in partial fulfillment of

the requirements for the degree of

Master of Science

in

Environmental Sciences

Boğaziçi University

2011

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my thesis supervisor Prof. Dr. Ayşen Erdinçler for her encouragement and support. I am thankful to my jury members Prof Dr. Turgut Tüzün Onay and Prof. Dr. Emine Ubay Çokgör for their constructive criticism and suggestions.

I would like to thank to Aktif Environmental and Renewable Energy Technologies Limited Company for their equipment and financial support.

I would like to give special thanks to my dear friend Murat Alpay and every single members of Epik family for their endless patience, support and love.

I am very grateful to my lovely friend Ayşe Akyapı for her friendship, kindness and support. I would like to express my deepest gratitude to Asu Ziylan and Moris Abolafya for their valuable friendships and being near to me whenever I need.

I am also very thankful to my dear Manager Alpöge Çamlıbel for his kindness and support during my study. Additionally, special thanks to my friend Yusuf Can Turan for his friendship and prayers.

At last, I would like to thank to Gülhan Özkösemen, Filiz Ayılmaz, Mehmet Ali Küçüker, Gül Geyik and Binnur Aylin Alagöz for their valuable helps and technical assistances during my laboratory studies.

"The world is changed. I feel it in the water. I feel it in the earth. I smell it in the air. Much that once was is lost, for none now live who remember it..."

The Lord of the Rings
J.R.R. Tolkien

To my Daddy, Mom and Brother…

ABSTRACT

Membrane Bioreactors (MBRs) have become popular in wastewater treatment. Offering excellent permeate quality and eliminating several treatment unit used in conventional wastewater treatment plants due to their special design have made MBRs preferable in reuse applications.

Reuse of domestic wastewater and especially greywater, a great part of domestic wastewater, is one of the most widespread reuse applications. Treated greywater can be used for non-potable purposes like toilet flushing, irrigation, washing of vehicles, fire protection, boiler feed water and concrete production. Safe reuse of greywater for non-potable purposes requires an appropriate treatment and the disinfection of the wastewater in terms of regulations and human concern over health and environment.

This study investigates the efficiency of Submerged Membrane Bioreactors (MBRs) in the treatment of low-load greywaters and domestic wastewaters. The quality of the treated greywater samples were evaluated based on the Regulations or Guidelines in Turkey and U.S.A to show the potential of these waters to be reused for non-potable purposes in Turkey and United States.

MBR was found to be successful in terms of low-load greywater and domestic wastewater treatment. In the treatment of greywater, the best results were achieved at highest MLSS concentrations. When the obtained results were compared with respect to the Regulations, it was observed that satisfactory results were fulfilled in most of the parameters in greywater treatment. However, despite higher removal efficiencies for fecal and total coliform, permeate concentrations were not satisfactory in terms of microbial quality requirements of some standards.

ÖZET

Membran Biyoreaktörler (MBR) atıksu arıtımında popüler hale gelmişlerdir. Mükemmel çıkış suyu kalitesi sunmaları ve geleneksel atıksu artıma tesislerinde kullanılan birçok arıtma ünitesi ihtiyacını ortadan kaldırmaları MBR'ları yeniden kullanım uygulamalarında tercih edilebilir kılmaktadır.

Evsel atıksuyun özellikle de evsel atıksuyun büyük bir parçası olan grisuyun tekrar kullanımı en yaygın yeniden kullanım uygulamalarından biridir. Arıtılmış grisu rezervuar suyu, sulama suyu, araç yıkama, yangından korunma, kazan suyu ve çimento üretimi gibi kullanma-suyu amaçlı alanlarda kullanılabilir. Grisuyun güvenli bir şekilde tekrar kullanılabilmesi için yasal düzenlemelere, insan sağlığı ve çevre üzerindeki sosyal kabullere uygun olmasını sağlayacak yeterli bir artım ve desenfeksiyon gerekmektedir.

Bu çalışmada Batık Membran Biyoreaktörlerin (MBR) düşük yüklü grisu ve evsel nitelikli atıksuların artımındaki etkinliği araştırmaktadır. Arıtılmış grisuyun kalitesi, bu suların Türkiye ve ABD'de tekrar kullanım potansiyelini göstermek amacıyla Türkiye ve Amerika Birleşik Devletleri'ndeki Yasal düzenlemeler veya kılavuzlar baz alınarak değerlendirilmiştir.

MBR düşük yüklü grisu atık su ve evsel atıksu arıtmında başarılı bulunmuştur. Grisu arıtımında en iyi sonuçlar en yüksek MLSS konsantrasyonlarında elde edilmiştir. Elde edilen sonuçlar Yönetmeliklerle karşılaştırıldığında, parametrelerin çoğunda tatmin edici sonuçlar olduğu gözlenmiştir. Bunun yanında, fekal ve toplam koliform için elde edilen yüksek giderme verimlerine rağmen, çıkışsuyu konsantrasyonları bazı standartların mikrobiyal gereklilikleri açısından tatmin edici bulunmamıştır.

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1. INTRODUCTION

The world's water resources are under pollution and depletion threat (Anderson et al., 2003). Climate change, growing population, industrial activities and overconsumption of freshwater limits the amount and quality of available water for many regions of the world. The growing demand on water makes protection of water supplies more important subject. Improper use of water can only be minimized by developing water management strategies and water reuse practices (Jackson et al., 2001; Bixio et al., 2006; Karr et al., 1991; Sauer et al., 2008; Shiva et al., 2002).

Separate collection and recycling of different stream of domestic wastewater such as greywater and blackwater is one of the considerable water management strategies (Müllegger et al., 2003; Scheumann et al., 2007). Treatment and reuse of greywater has been widely preferred because the total greywater fraction constitutes a major portion of the domestic wastewater (50%-80%) (Lamine et al., 2007; Friedler et al., 2006).

Reuse of greywater and municipal wastewater is a worldwide application and both of them can be used for non-potable purposes like urinal and toilet flushing, irrigation of lawns, cemeteries, parks and golf courses, washing of vehicles and windows, fire protection, boiler feed water and concrete production (Anderson et al., 2003; Angelakis et al., 2001; Friedler et al., 2001). Despite reclaimed greywater can also be used for agricultural irrigation, municipal wastewater is preferred because of its higher nutrient content (Eriksson et al., 2002; Jefferson et al., 2004; Winward et al., 2008). Recycled water to be reused have a particular physical, chemical and microbiological quality (Jefferson et al., 2004; Jefferson et al., 2001).

The most significant threat of reuse of wastewaters is the existence of fecal contaminants (Wintgens et al., 2005). Safe reuse of greywater and wastewater for non-potable purposes requires an appropriate treatment and the disinfection of the wastewater in terms of regulations and human concern over health and environment (Pcote et al., 2004). Despite it does not include urine or fecal matter different from wastewater or blackwater, greywater has faeces sourced from processes like hand washing after toilet use or diaper washing. *Escherichia coli* are the most common indicators of fecal contamination. *E-coli* ratio of water provides useful information for the reusability assessment of water in terms of human health. Selecting acceptable water treatment technologies and disinfection of wastewater are important to provide safe water for reuse (Eriksson et al., 2002; Winward et al., 2008; Jefferson et al., 2001). Especially in house reuse applications bring disinfection need to remove microbial contaminants because of the potential for human contact to the water (Lamine et al., 2007).

In conventional treatment systems, disinfection is realized in separate units with the addition of certain chemicals. Alternative technologies like Membrane Bioreactors (MBRs) present economical opportunities for wastewater disinfection without any chemical addition (Marrot et al., 2004; Jefferson et al., 2000; Jefferson et al., 2001; Bixio et al., 2006).

MBRs have become one of the popular technologies in wastewater treatment offering excellent effluent quality compact treatment systems. MBRs provide disinfection due to their low pore size (Dijk et al., 1997). Ultrafiltration (UF) or microfiltration (MF) membranes have a pore-size of 0.2 μm or less. Depending on their low pore size, all the bacteria and even most of the viruses are retained within the UF or MF MBRs (Rosenberger et al., 2002; Ciardelli et al., 2000).

MBRs have also been preferred for wastewater treatment instead of conventional wastewater treatment methods because they eliminate several treatment unit (e.g. sedimentation tank) requirements due to their special design. MBRs treat the wastewater both biologically and physically at same treatment unit including membrane and bioreactor. Biological reduction of organic matter is provided by bioreactor with the help of microbial activity. Membrane presents physical separation for suspended solid, bacteria and viruses by filtration (Kitis et al., 2005; Rosenberger et al., 2002; Karakulski et al., 1998; Gryta et al., 2001).

This study investigates the efficiency of MBRs having a plate type membrane filter module in the treatment of the low-load greywater and the municipal wastewater. The quality of the treated greywater samples were evaluated based on The Regulations and

Guidelines of Turkey and United States to show the potential of these waters to be reused for non-potable purposes in Turkey and U.S.A.

The objectives of this study are:

- Characterization of low-load greywater samples.
- Determination of filtration performance of membrane filters in greywater treatment.
- Determination of the efficiency of MBR in the treatment of greywater at three different Mixed Liquor Suspended Solid (MLSS) concentrations.
- Evaluation of greywater effluents whether it can be reused or not for non-potable purposes with respect to "The Regulation Concerning Water Intended for Human Consumption" and "Water Pollution Control Regulation of Turkey" in Turkey and "U.S. Environmental Protection Agency, Guidelines for Water Reuse" or not.
- Characterization of wastewater samples.
- Determination of the efficiency of MBR in treatment of wastewater at a constant MLSS concentration.

2. BACKGROUND

2.1. Water Scarcity and Alternative Water Sources

Growing urbanization and increasing water demands for domestic, industrial, commercial, and agricultural purposes cause water scarcity both in Turkey and in the world. Figure 2.1 demonstrates the rapid growth of the urban population worldwide (US EPA, 2004). Turkish statistical institute reported the mid-year population estimate of Turkey between 1927 and 2025 (see Figure 2.2) (TSI, 2010). Capital Regional District Water Advisory Committee (2003) reported that an approximate population growth rate of 2.3% increases demand on the water supply and from approximately 2013 to 2015 water supply will begin to descend below the accepted reliability level (96%).

Imbalance between rapid growth and fresh water amount has directed institutions and people to alternative water sources (Jackson et al., 2001; Gross et al., 2007). Water scarcity and the growing stress on water supply resources have prompted considerable interest in water recycling. The emphasis is, however, mostly on domestic wastewater (Nghiem et al., 2006) because domestic wastewater is one of the most significant causes of water pollution (Soontarapa et al., 2001). US EPA (2004), Water Pollution Control Regulation of Turkey (2004) and Capital Regional District Water Advisory Committee (2003) reported that reclaimed water has been considered as a new source offering the potential use of many areas such as urban, industry, and agriculture.

2.2. Reuse of Domestic Wastewater

Reuse of municipal wastewater is a very common practice in worldwide and has many reuse opportunities like reducing the demand for fresh water and the amount of wastewater (Kim et al., 2009; Jefferson et al., 1999).

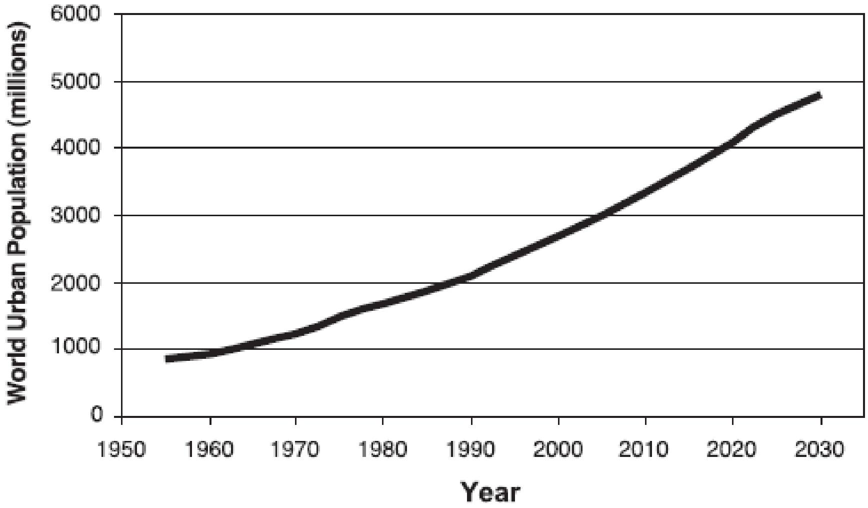


Figure 2.1. Estimated and Projected Urban Population in the World (US EPA, 2004)

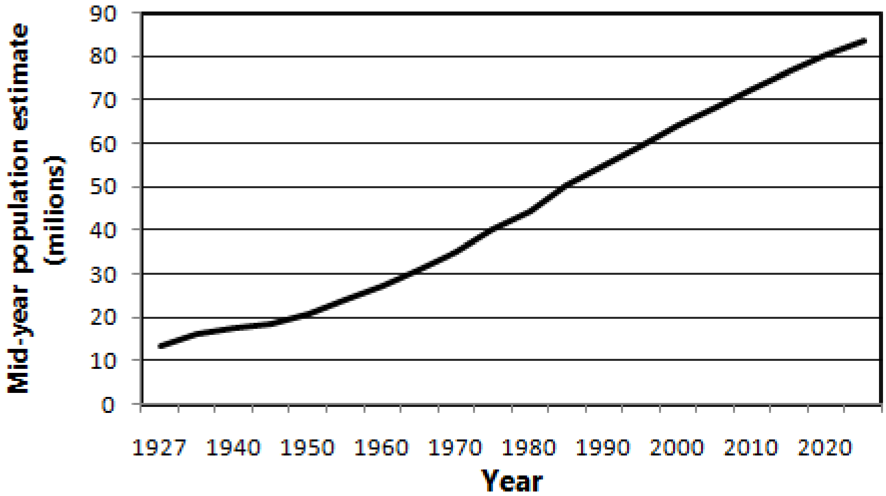


Figure 2.2. Estimated mid-year population of Turkey, 1927-2025 (TSI, 2010)

Reclaimed wastewater can be used for urinal and toilet flushing, irrigation of lawns on college campuses, athletic fields, cemeteries, parks and golf courses, washing of vehicles and windows, fire protection, boiler feed water and concrete production (Eriksson et al., 2002; Jefferson et al., 2004; Winward et al., 2008; Ogoshi et al., 2001).

2.2.1. Major Parts of Domestic Wastewater

Domestic wastewater consists of two main fluxes; greywater and blackwater (Tarasenko, 2009; March et al., 2004).

2.2.1.1. Greywater. Greywater is basically defined as a part of domestic wastewater coming from bathing, wash basins or sinks, washing machines, dish washing, kitchen etc. Reported discharge amounts are ranges between 60 and 120 l/capita/day. Greywater or hygiene water (Garland et al., 2000; Friedler et al., 2006) constitutes a major portion of the domestic wastewater (Schafer et al., 2006) and contains lower concentrations of organic matter and nutrients than domestic wastewater since it does not include urine, faeces and toilet papers (Ramon et al., 2004; Eriksson et al., 2002; Jefferson et al., 2004). It also includes relatively low suspended solids and turbidity, indicating that a greater proportion of the contaminants are dissolved (Jefferson et al., 1999). Müllegger et al., (2003) reported BOD_5:N:P ratio as about 100:4:1 for greywater while it is 100:5:1 for typical domestic wastewater. Therefore, biological treatment of greywater without addition of nutrients is possible. However, another study reported the lower COD:NH_3:P value of greywater as 1030:2.7:1 indicating imbalance between biodegradable organic matter and the nutrient which limits biological treatment (Jefferson et al., 1999).

The characteristics of greywater vary significantly source to source (Nghiem et al., 2006; Ramon et al., 2004), and generally mentioned as suspended solids (SS), turbidity, chemical oxygen demands (COD), biological oxygen demand (BOD), total dissolved solid (TDS), total organic carbon (TOC) and nutrients (nitrogen and phosphorus) (Schafer et al., 2006). Based on their sources, greywaters are divided into different categories; bathroom, laundry, kitchen, washbasin and greywater of mixed origin. The source of greywater is highly important for the evaluation of its reuse potential. Greywaters are defined as high-load and low-load according to their pollutant concentrations. High-load greywater includes wastewater coming from kitchen, washing machine and dish washer and presents complex chemical composition including pollutants like detergents, soaps, personal care products and other chemicals (Ramon et al., 2004; Nolde, 1999; Eriksson et al., 2002; Sandec, 2006).

Fecal bacteria concentration is another important parameter in characterization of greywater. Fecal contamination of greywater is remarkably lower than wastewater since toilet waste is not included in greywater. The presence of coliforms in greywater is a result of introduction of fecal bacteria into the system during body hygiene and washing of contaminated items like baby diapers (Schafer et al., 2006). Gastrointestinal bacteria, such as *Salmonella* and *Campylobacter*, can introduce due to food-handling in the kitchen (Ottoson et al., 2003a; Ottoson et al., 2003b).

Low-load greywater is sourced from bath, shower and wash basin wastewater and it includes naturally low concentrations of pollutants than high-load greywater, domestic wastewater and blackwater. Table 2.1 shows general characteristics of low-load greywater reported in the literature. Average COD concentrations are given in a range between 244 mg/L and 371 mg/L. Ammonia concentration is 0.3 mg/L in handbasin greywater while it is higher in bathroom and shower based greywater because of urine. Phosphorus concentrations range between 2.58 mg/L and 19.2 mg/L. Fecal contamination can also be found in low-load greywater despite it is relatively lower than blackwater (Lamine et al., 2007; Merz et al., 2007; Ramon et al., 2004; Nolde et al., 1999; Atasoy et al., 2007; March et al., 2004; Jefferson et al., 1999; Almeida et al., 1999).

Table 2.2 shows general characteristics of *high-load greywater* reported in the literature. Average COD values of high load greywater vary from 483 to 1164 mg/L in the literature. While COD concentration of greywater coming from kitchen or mixed origin (bathroom and kitchen) changes between 483 and 644, washing machine based greywater includes 1164 mg/L COD value indicating high concentrations of detergents and chemicals in washing waters. Phosphorus and nitrogen concentrations also represent differences source to source. The major portion of nutrients (N and P) comes from kitchen sink in greywater flow (Almeida et al., 1999).

NH_4^+-N concentration is 5.7 mg/L for kitchen and bathroom based greywater, while it is 2 mg/L for greywater coming from washing machine origin greywater. Phosphorus concentrations are also high in almost all sources that it is 7.4 mg/L for bathroom and kitchen water, 26 mg/L for kitchen wastewater, 8.4 mg/L for mixed origin, and 21 mg/L for washing machine. (Lesjean et al., 2006; Almeida et al., 1999 Trasenko, 2009; Gross et al., 2007; Jefferson et al., 1999).

Table 2.1. General characteristics of low-load greywater

Parameter	**Shower and Bath** (Lamine et al., 2007; Merz et al., 2007; Ramon et al., 2004; Nolde et al., 1999; Atasoy et al., 2007; Almeida et al., 1999)		**Handbasin** (March et al, 2004*; Jefferson et al., 1999; Almeida et al., 1999)		**Mixed** (Atasoy et al., 2007)	**Mixed** (Jefferson et al., 1999)
	Average	Range	Average	Range	Average	Average
COD, mg/L	296	100-633	244	171-298	245	371
NH_4^+-N, mg/L	9.25	6.70-11.80	-	-	1.30	-
NH_3-N, mg/L	1.15	1.10-1.20	0.30	-	-	1
NO_2^--N, mg/L	0.20	-	-	-	-	-
NO_3^--N, mg/L	3.60	0.20-6.30	6	-	-	-
TN, mg/L	-	-	9.60	-	9	-
TP, mg/L	9.30	3.50-19.20	7.94	2.58-13.30	7.30	0.36
Al, µg/L	30	-	-	-	-	-
Fe, µg/L	130	-	-	-	-	-
Mn, µg/L	<20	-	-	-	-	-
Turbidity, NTU	26	23-29	20	-	-	-
TOC, mg/L	32.60	-	58	-	-	69
pH	7.6	7.5-7.6	7.60	-	7.1	-
Fecal Coliform/100 mL	-	10-140.000	-	-	3565	$1.5x10^6$
Total Coliform/100 mL	-	10^4-10^6	-	-	13634	-

**Handbasin and bathtubs.*

Table 2.2. General characteristics of high-load greywater

Parameter	**Bathroom and Kitchen** (Lesjean et al., 2006)	**Mixed** (Trasenko, 2009; Gross et al., 2007)		**Kitchen** (Almeida et al., 1999)	**Washing Machine** (Almeida et al., 1999)
		Average	Range		
COD, mg/L	483	580	200-839	644	1164
NH_4^+-N, mg/L	5.70	-	-	-	-
NH_3-N, mg/L	-	-	-	0.30	2
NO_2^--N, mg/L	-	3	-	5.80	2
TN, mg/L		24.10	8-34.30	-	-
TP, mg/L	7.40	10.60	2-22.80	26	21
Fecal Coliform/100 mL	-	$5x10^7$	-	-	-

2.2.1.2. Blackwater. Remaining part of the domestic wastewater is called as blackwater which includes higher concentration of pollutant than domestic wastewater due to concentrate urine and sewage ingredients (March et al., 2004). General characteristics of blackwater are presented in Table 2.3. Average COD concentration of domestic wastewater is reported as 392 mg/L while this value is remarkably lower than blackwater (average 1206 mg/L). Nutrient concentrations are also higher in blackwater indicating that significant part of the phosphorous and nitrogen is coming from feces in domestic wastewater (Sarioglu et. al., 2007; Ueda et al., 1998; Tarasenko, 2009; Atasoy et al., 2007). 90% of the nitrogen and 70-80% of the phosphorus is found in the blackwater (Jenssen, 2005; Müllegger et al., 2003).

2.2.2. Source Separation of Domestic Wastewater

In conventional wastewater treatment systems greywater and blackwater are collected and treated together (see Figure 2.3a). However, an alternative approach, separation and treatment of different wastewater streams have been frequently used in wastewater treatment.

Table 2.3. General characteristics of wastewater and blackwater

Parameter	**Domestic wastewater** (Sarioglu et. al., 2007; Ueda et al., 1998)		**Blackwater** (Tarasenko, 2009; Atasoy et al., 2007)	
	Average	Range	Average	Range
COD, mg/L	392	-	1206	900-1500
NH_4^+-N, mg/L	44	-	155	-
TN, mg/L	44.50	34-55	196	100-300
TP, mg/L	4	-	27.10	20-40
pH	-	-	7.60	-
Total Coliform/100 mL	$6.9x10^7$	-	$>10^6$	-

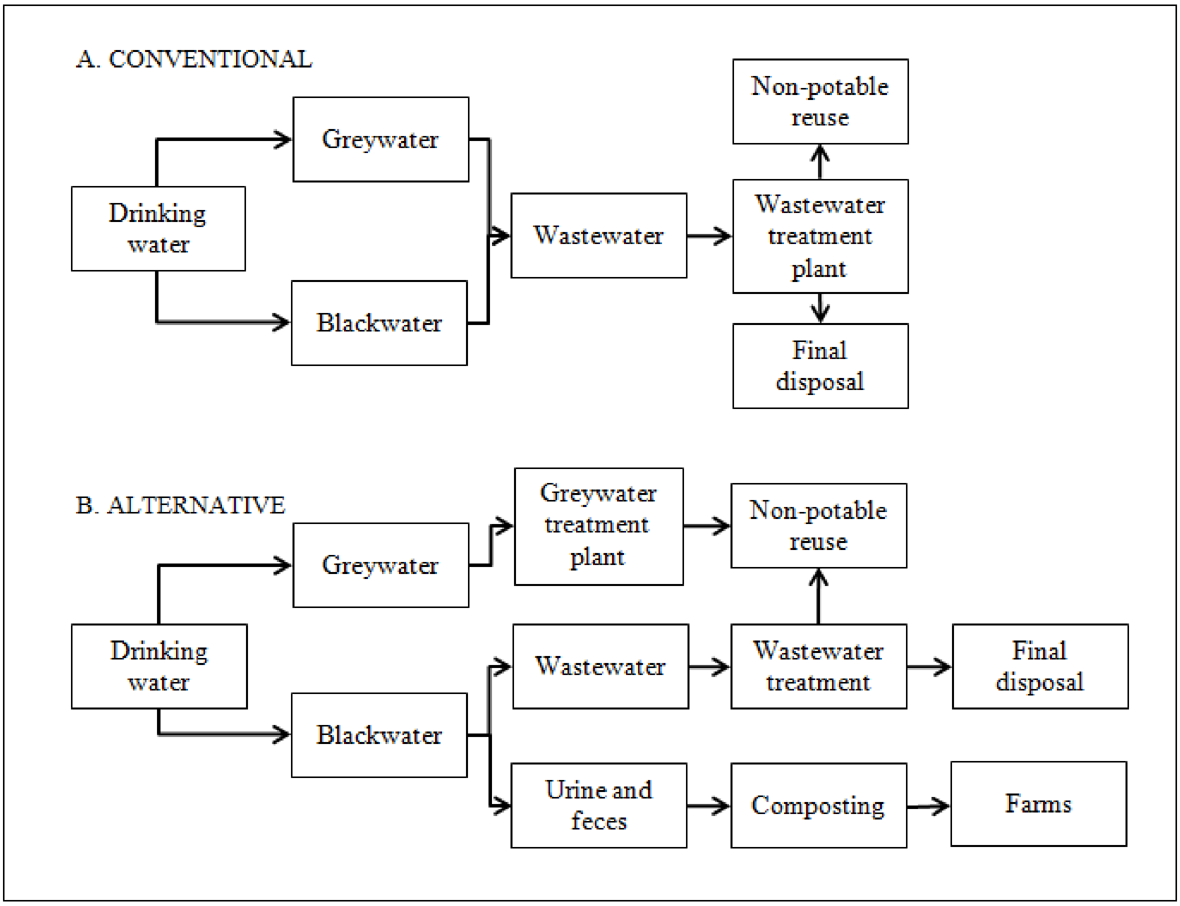


Figure 2.3. Conventional and alternative design for water use and treatment (March et al., 2004; Telkamp et al., 2003; SWITCH, 2006; Agudelo et al., 2003).

A number of sanitation system based on source-separation have been realized inside and outside of the Europe. Source separating systems can be divided into two basic approaches. In the first approach, greywater and blackwater are separately collected and treated (see Figure 2.3b). In the second approach, urine is separately collected and treated or used as fertilizer. The first approach, separation of black and greywater, has been widely preferred in water reuse applications. Especially greywater has been regarded as a valuable resource and reuse of greywater leads up to saving of almost 60% of water (Telkamp et al., 2003; SWITCH, 2006; Agudelo et al., 2003).

Separate collection and treatment of greywater provide financial, environmental and social benefits (Ramon et al., 2004; Nolde, 1999; Eriksson et al., 2002, Sandec, 2006; Nghiem et al., 2006). Separation of greywater and blackwater provide water nutrient recovery, minimize emissions into the environment, load of sewerage flow and dilution of pollutants, and consequently costs for transport and treatment (Agudelo et al., 2003; Mels et al., 2007; SWITCH, 2006; CRD, 2003; Ottoson et al., 2003b). Due to the substantial difference in their qualities, separating greywater and blackwater, allows more effective wastewater treatment and reuse (Gross et al., 2007). For example, despite greywater can also be used for agricultural irrigation, because of its higher nutrient content municipal wastewater reuse in for this purpose is more suitable (Eriksson et al., 2002; Jefferson et al., 2004; Winward et al., 2008; Ogoshi et al., 2001). However, greywater recycling is more easily accepted by both people and regulations than blackwater due to the lack of urine and faeces concentrations as well as lighter chemical contaminants in greywater (Schafer et al., 2006; Gross et al., 2007).

2.2.2.1. Drivers and Barriers of Source Separation. Higher investment costs, already having conventional sanitation systems of most of urban areas, maintenance requirements, health concerns, potential of odor and some operational problems like clogging were found as main barriers of the separation systems in previous studies (Mels et al., 2007; Agudelo et al., 2003). Jefferson et al. (1999) stated the large variation of greywater composition as the major difficulty for separate treatment. Blackwater, a predictable flow, is easier to treat than greywater (CRD, 2003). However, user acceptance is a key issue in separate collection and treatment of wastewater and greywater is more acceptable than blackwater due to the lack of urine and faeces concentrations as well as lighter chemical contaminants in greywater (Telkamp et al., 2003; Schafer et al., 2006; Gross et al., 2007).

While in some cases compared to the conventional sanitation system separate collection and treatment applications were found as having higher investment costs, the yearly capital and operation cost of some other cases were found to be lower than the conventional system (Mels et al., 2007; Agudelo et al., 2003). Drivers of the systems, noted as water saving, providing nutrient recycling, reduction of water emissions, groundwater and surface water protection, can balance the investment cost of the systems (Mahmoud et al., 2003; Agudelo et al., 2003).

<u>2.2.2.2. Wastewater Separation and Reuse Applications.</u> In Netherlands and Sweden between 1993 and 1998 different source separation systems were established in five sites called as "*Het Groene Dak", "Polderdrift", "Understenhöjden", "Ekoporten"* and *"Gebers*" for 66, 40, 44, 18 and 9 houses, respectively. Special sanitation systems were established based on separation of grey, black, and rainwater and also urine and feces. Greywater is treated in a process consisting of sedimentation, trickling filters, fat removal, and surface-flow constructed wetland and UV for disinfection. The treated greywater was used for toilet flushing, if effluents complied with local regulations. The blackwater is discharged into the municipal sewer or separated urine was transported to the local farms and after removal of pathogens the urine is used to fertilize cereal crops. The separated feces were mixed and composted with organic waste and wood chips. These investigations showed that the establishment of source-separating sanitation provides reducing of tap water consumption (up to 40%) and sewage overflows, recover of nutrients for agricultural use, reduction of pollutant emissions (Mels et al., 2007).

Mahmoud et al. (2003) carried out a research to assess the impact of separation systems on the environment, health and socio-economic factors. A house onsite sanitation project was implemented at 47 houses in Qebia village in the West Bank, Palestine. The system consisted of onsite greywater treatment and reuse units. Greywater was treated at an anaerobic pre-treatment step followed by an 'aerobic' multi-layer filter (sand, coal, gravel). The treated greywater was reused for irrigating home gardens plants, fruit trees and eaten vegetables. The blackwater was discharged into the existing septic tanks.

Beijing, one of the driest cities in the world (Jia et al., 2005), had an integrated strategy on water-recycling. Different decentralized wastewater re-use systems (DWRSs) was established and operated in the city. Two of the studies only treated greywater, while the other three treat the total flow of domestic water (grey and blackwater). Various treatment techniques were used (i.e. activated sludge), contact oxidation and an aerated ceramic filter. The treated wastewater was locally used for toilet flushing, landscape irrigation and urban river recovery and road cleaning) (Guo et al., 2003).

Agudelo et al. (2003) reviewed several sewage separation systems built in Netherlands, Norway, and Germany between 1993 and 2000. Constructed wetlands were selected as treatment method and installed on various sites. The implementation of on-site greywater treatment systems combined with reuse of reclaimed water led up to 57% less drinking water consumption.

2.2.3. Water Quality Considerations for Reuse

Reuse applications include determining the water quality for intended purpose, selection of necessary treatment to achieve desired water quality and assessment of reclaimed water depending on the acceptable levels of chemical constituents and microbial organisms defined in regulations and guidelines (US EPA, 2004). Public health, environmental sustainability, quality of food products, social acceptance, treatment technology capability and reliability, monitoring systems, economics of recycling, and availability of expertise are also main issues in water reuse (Dillon, 2000). The acceptability of recycled water for any particular end use depends on its physical, chemical and microbiological quality (Jefferson et al., 2004; Jefferson et al., 2001).

US EPA (2004) lists required parameters monitored for safe use of reclaimed water for miscellaneous purposes as BOD, SS, coliforms, nutrients, toxic organics and metals. Desired concentrations change depending on the demanding quality of reused water. For example; while nitrogen and phosphorus in recycled water is an advantage for certain irrigation, these nutrients may cause problems like fouling or corrosion promoting biological growth in industrial reuse. Moreover, according to The Water Control Regulation of Turkey (2004) recycled water used for irrigation of lawn or urban irrigation must be well disinfected while a trace amount of coliform can be ignored in other areas where contact of the people is limited. Table 2.4 shows a summary of water quality requirements for different purposes in Turkey and USA. The Regulation Concerning Water Intended for Human Consumption of Turkey (2009) aim to regulate waters intended for drinking, cooking, food preparation, or other in-house uses. The Regulation includes more strict items than other the regulations in terms of chemical and microbiological quality of water (see Table 2.5)**.**

Treatment and disinfection of wastewater are important to provide safe and aesthetically acceptable water. Inadequately treated or disinfected wastewater presents a risk of infection to end users from pathogens in the reused water (Winward et al., 2008; Wintgens et al., 2005).

<u>2.2.3.1. Disinfection Requirements.</u> One of the most critical objectives in any reuse case is public health protection and achieved in three ways; eliminating pathogenic bacteria and viruses, controlling concentrations of chemicals in reclaimed water, and prevent people to contact with recycled water (US EPA, 2004; WPCR NTM of Turkey, 2010; Jefferson et al., 2001). In urban uses, where there is a high potential for human contact to reclaimed water like landscape irrigation, toilet flushing etc. reclaimed water should be treated to a high degree prior to its use. The Regulation Concerning Water Intended for Human Consumption of Turkey (2009) exactly required 0 CFU/100 mL levels of fecal bacteria quality. The toilet tank is described as a natural incubator for bacterial growth. Water quality for toilet flushing should therefore equal bathing water criteria (CRD, 2003).

Pathogenic bacteria are normally exist in the municipal wastewater and can be introduced into greywater by hand washing after toilet use, washing of babies and small children connected with diaper changes and diaper washing etc. (Eriksson et al., 2002; Winward et al., 2008). *Salmonella sp*, *Shigella sp.* and *Escherichia coli* are the most common bacterial pathogens found in wastewater. *Escherichia coli* and Total coliform are commonly used as indicators of fecal contamination (Ottoson et al., 2003a; Feng et al., 1982).

Table 2.4. USA EPA Suggested Guideline and Turkey standards of water reuse for different purposes

Regulation& Guideline	Reuse Area	Residual Cl_2 (mg/L)	pH	BOD_5 (mg/L)	TSS (mg/L)	Turbidity (NTU)	Fecal coliform/100 mL)
US EPA Suggested Guidelines for Water Reuse	*Urban Reuse*-All types of landscape irrigation (e.g golf courses, parks, cemeteries), vehicle, washing, toilet flushing, use in fire protection systems and commercial air conditioners, and other uses with similar access or exposure to the water	1	6-9	≤10	-	≤2	Not detectable
	Restricted Access Area Irrigation -Sod farms, silviculture sites and other areas where public access is prohibited			≤30	≤30	-	≤200
	Agricultural Reuse- Food crops not commercially processed-Surface or spray irrigation of any food crop, including crops eaten raw			≤10	-	≤2	Not detectable
	Agricultural Reuse- Food crops commercially processed-Surface irrigation of orchards and vineyards			≤30	≤30	-	<200
	Agricultural Reuse-Non food crops-Pasture for milking animals; fodder, fiber and seed crops			≤30	≤30	-	<200
Water Pollution Control Regulation of Turkey, Notification of Technical Methods	Urban Reuse, irrigation of parks, golf areas etc.	<1		< 20	-	< 2	0
	Food crops not commercially processed						
	Food crops commercially processed			<30	<30	-	< 200
	Lawn production, cultural agriculture irrigation (limited public contact)						
	Feeding ground irrigation						

Table 2.5. Limits of the Regulation Concerning Water Intended for Human Consumption of Turkey

NH_4^+ mg/L	Nitrite mg/L	Turbidity NTU	TOC mg/L	Al µg/L	Fe µg/L	Mn µg/L	pH	*E.coli* CFU/100 mL	T. Coliform CFU/100 mL
0.50	0.50	1	No abnormal change	200	200	50	$6.5 \leq$ ≥ 9.5	0	0

<u>2.2.3.2. Industrial Reuse.</u> Reclaimed water quality for industrial processes changes depending on the expectation of the industry. While some industries require water of almost distilled quality others can use relatively low-quality water. Cooling water, for example, is the largest use of low-quality reclaimed water. Every industrial process requires significant process water quality (WPCR NTM of Turkey, 2010; US EPA, 2004). US EPA (2004) presents water quality requirements for several industries like textile, chemical, paper etc. Remarkable parameters are dissolved solids, dissolved organic material, chlorides, phosphates, and nutrients concerning the occurrence of corrosion, scaling, biofouling or other problems in process water.

<u>2.2.3.3. Agricultural Reuse.</u> US EPA (2004) reported recommended limits for constituents in irrigation water (see Table 2.4). Residual Cl_2, BOD_5, TSS, turbidity, pH, and fecal and total coliform values are described as significant parameters in water reuse in irrigation process. Other chemical constituents in reclaimed water of concern for agricultural irrigation are salinity, sodium, trace elements, excess chlorine, nutrients and trace metals in high concentrations.

Water Pollution Control Regulation of Turkey (2004) constitutes two classes of water quality for irrigation purposes. Irrigation of food crops not commercially processed that people can easily contact with plants requires high quality reclaimed water. However, in irrigation of food crops commercially processed, lawn production, cultural agriculture irrigation and feeding ground irrigation reclaimed water can be lower quality due to limited human contact. These criteria are minimum necessities that additional requirements can be apply in some special applications (see Table 2.4).

2.2.3.4. Urban and Indoor Reuse. Water Pollution Control Regulation of Turkey, Notification of Technical Methods (2010) reported that irrigation of urban areas (parks, golf areas etc.), vehicle washing, toilet flushing, fire protection systems that people can easily contact with plants or water require high quality reclaimed water. Reclaimed water should be colorless and odorless to ensure that it is aesthetically acceptable to the users. Heavy metal concentrations should be taken into consideration in certain applications. Table 2.4 shows minimum requirements for urban reuse. Additional requirements can be apply in some special applications.

2.2.3.5. Human Consumption. The Regulation Concerning Water Intended for Human Consumption of Turkey (2009) states that water intended for drinking, cooking, food preparation or other in-house purposes. According to the regulation, human consumption requires definitely high water quality to prevent people from disease (see table 2.5). The presence of *e-coli* and total coliform in water is completely prohibited. TOC, turbidity, nitrite, trace metals etc. are limited by the Regulation.

2.2.4. Technology Selection

Any system is not unique solution for treatment and reuse of wastewater. Choice of wastewater treatment methods depends on many factors like water quality for intended purpose, quantity of influent, social aspects, regulations, wastewater characteristics etc. (Agudelo et al., 2003; Tarasenko, 2009; US EPA, 2004; Jefferson et al., 1999). Considering acceptable levels of chemical constituents and microbial content, different treatment technologies such as filtration, disinfection, flotation etc. are applied to wastewater to achieve desired water quality. Table 2.6 shows different treatment technologies and pollutants potentially removed by them (WPCR NTM of Turkey, 2010).

Methods of wastewater treatment can be divided into mechanical or physical, physicochemical and biochemical. Mechanical sewage treatment is intended for removing of nonsolute contaminants and include bar screens, sand catchers, sedimentation tanks and filters. Mechanical treatment reduces concentration of suspended substances for 40–60%, which leads to reduction of BOD value for 20–40%. Biological sewage treatment methods, like activated sludge process provide reduction of BOD contamination values for 80–95%.

While physicochemical (e.g. chemical coagulation and chemical precipitation) and biological methods provide advanced removal of nitrogen and phosphorus compounds, compalate cleaning of suspended substances requires application of filtration that reduces 50-80% of suspended solid contents (Tarasenko, 2009; Chang et al., 2002).

Table 2.6. Treatment technologies and the pollutants potentially removed by them (WPCR NTM of Turkey, 2010)

Treatment units	Suspended Solid	Colloidal matter	Particulate organic matter	Soluble organic matter	Nitrogen	Phosphorus	Trace matters	Total soluble substances	Bacteria	Protozoa	Viruses
Secondary treatment	√			√							
Nutrient removal				√	√	√					
Filtration	√								√	√	
Surface filtration	√		√						√	√	
Microfiltration	√	√	√						√	√	
Ultrafiltration	√	√	√						√	√	√
Flotation	√	√	√							√	√
Nanofiltration			√	√			√	√	√	√	√
Reverse osmos				√	√	√	√	√	√	√	√
Electrodialysis		√						√			
Carbon adsorption				√			√				
Ion exchange					√		√	√			
Advanced oxidation			√	√			√		√	√	√
Disinfection				√					√	√	√

<u>2.2.4.1. Technologies Applied in Wastewater Treatment.</u> Jia et al. (2005) studied 21 systems for greywater treatment and 12 systems for combined treatment of black and greywater adapting several kinds of techniques. They used a contact oxidation system combined with physical and chemical treatment for greywater treatment. In the treatment

of mixed wastewater, contact oxidation plus physical and chemical treatment and submerged membrane bioreactor plus physical and chemical treatment were used. In Netherlands and Sweden different treatment and reuse technologies such as sedimentation, trickling filter, and surface-flow constructed wetlands were used in wastewater treatment (Mels et al., 2007). In Palestine, an anaerobic pre-treatment step followed by an aerobic multi-layer filter (sand, coal, gravel) in wastewater treatment. The effluent was collected in a storage tank from where it is discharged into the irrigation network of the house garden (Mahmoud et al., 2003). In Beijing, activated sludge, contact oxidation (a type of moving bed reactor) and aerated ceramic filter (a fixed biofilm process) used for wastewater treatment (Guo et al., 2003). Dillon (2000) used many treatment and reuse technologies including air flotation, microfiltration, activated carbon, reverse osmosis and biological nutrient removal. The combined effect of these factors has resulted in an exponential growth in the availability of higher quality reclaimed water and opportunities for water reuse.

2.2.4.2. Disinfection of Wastewater. Every pollutant has significance in wastewater treatment. Bacterial contamination is one of the most important parameter of water reuse and can be reduced either a removal or an inactivation process. Inactivation of bacteria, which preferred in conventional systems, refers to the destruction of bacteria cells using a chemical or energy agent. Such inactivation is called as disinfection. Many techniques have been used for disinfection of the treated wastewater (US EPA, 2004; WPCR of Turkey, NTM, 2010; Mels et al., 2007; Tarasenko, 2009). The most common disinfectants used in wastewater treatment are free chlorine, sodium hypochlorite, chloramines, ultraviolet (UV) light and ozone. A previous study (Marc et al., 2004) performed in a hotel to reuse greywater for toilet flushing was based on filtration and sedimentation. Disinfection of the greywater was carried out using sodium hypochlorite as the disinfecting agent. As a result of the experiment, satisfactory results are achieved and quality requirements were fulfilled. Nolde et al. (1999) disinfected treated wastewater with sufficient ultraviolet doses. However, chemical disinfectants and UV method have some drawbacks. Contact of Cl_2 with organic matter causes toxic effect producing by products because it is a potent toxic substance and produce odor. TSS concentration of wastewater is also a disadvantage for UV systems reducing passage of UV light. Alternative technologies like membrane filtration also provide satisfactory results without any chemical addition or UV based applications. The removal process involves the physical separation of the bacteria from the wastewater through sedimentation and/or filtration. According to the WPCR NTM of Turkey, filtration process is capable to remove bacteria and viruses beside suspended solid, colloidal and particulate matter removal performance (see Table 2.6) (US EPA, 2004; WPCR of Turkey, NTM, 2010; Mels et al., 2007; Tarasenko, 2009).

Among many filtration alternatives ultrafiltration membranes have become popular in water reuse application offering a permanent barrier to suspended particles and bacteria greater than the size of membrane pore size, capacity of treating wide range of influent and producing high-quality water (Jefferson et al., 1999; Nghiem et al., 2006; Chang et al., 2002). Ultrafiltration provides economical opportunities for wastewater disinfection without any chemical addition and side-effect (Marrot et al., 2004; Jefferson et al., 2000; Jefferson et al., 2001; Bixio et al., 2006).

2.3. Membrane Bioreactor

2.3.1. Membrane Technology

Membrane, described as a material which is permeable to some substances while serving a selective barrier for some of substances including bacteria by filtration process (Jefferson et al., 2000). Membranes can be found in different physical forms as flat films, hollow fibers, tubules, and tubes. Membrane processes can be classified according to their material, driving force, separation mechanism, pore size etc. (Kamalesh et al., 1999).

Despite membranes can be produced from different organic or inorganic materials organic materials often used in wastewater treatment. Widely used types of membrane materials are polypropylene, cellulose acetate, polyacrilonitrile (PAN), polyethersulfone (PES), aromatic polyamides and thin-film composite. Membrane material is selected taking into consideration factors such as clogging and deterioration (Metcalf&Eddy, 2003; Kamalesh et al., 1999; Ramon et al., 2004).

Depending on their pore size membrane processes are classified as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO) etc. General characteristics of membrane process are presented in Table 2.7. In NF and RO, ions and small particles are also rejected by absorbed water layer on the membrane surface. Separation of the particles in UF and MF processes takes place mainly through filtration process (Stephenson et al., 2000; Metcalf&Eddy, 2003; Kamalesh et al., 1999)**.**

Table 2.7. General characterization of membrane process (Metcalf&Eddy, 2003)

Membrane Process	**Membrane Driving Force**	**Typical Separation Mechanism**	**Typical Operation Range, µm**	**Permeate Description**	**Typical Constituents Removed**
Microfiltration	Hydrostatic pressure or vacuum in open vessels	Sieve	0.08-2.0	Water and dissolved solutes	TSS, turbidity, protozoan oocysts and cysts, some bacteria and viruses
Ultrafiltration	Hydrostatic pressure difference	Sieve	0.005-0.2	Water and small molecules	Macromolecules, colloids, most bacteria, some viruses, proteins
Nanofiltration	Hydrostatic pressure difference	Sieve+ solution/diffusion+exclusion	0.001-0.01	Water and very small molecules, ionic solutes	Small molecules, some hardness, viruses
Reverse osmosis	Hydrostatic pressure difference	Solution/diffusion+exclusion	0.0001-0.001	Water, very small molecules, ionic solutes	Very small molecules, color, hardness, sulfates, nitrate, sodium, other ions

UF or MF membranes have a pore size of 2 µm or less. Depending on their low pore size, all the bacteria and even most of the viruses are retained within the UF or MF. Hydraulic pressure is usually used as the driving force to achieve the desired result of separation in membrane. However, in some cases that membrane is submerged into a tank applying to vacuum is necessary to draw water (Rosenberger et al., 2002; Ciardelli et al., 2000; Metcalf&Eddy, 2003).

2.3.2. Operation Principle of Membrane Bioreactors

MBRs are simply the combination of a membrane filter and a bioreactor. The operation of membrane is basically creating pressure on a liquid (e.g. wastewater) to send it through the membrane module or applying vacuum force on the liquid to suck permeate from the membrane (Metcalf&Eddy, 2003; Le-Clech et al., 2006). While wastewater is biologically treated in reactor by microorganism, separation of the particulate matter, suspended solid, bacteria and viruses is performed by membrane filter (Brindle et al., 1996; Marrot et al., 2004; Merz et al., 2007; Kitis et al., 2005; Shao-yuan et al., 2002). Aeration or oxygen for the biological treatment is provided by diffusers and air pumps. Situated air diffusers at the bottom of the reactor create air bubbles Air bubbles rise from the bottom to the surface of the water, scouring and cleaning the surface of the membrane (Jefferson et al., 1999).

2.3.2.1 Configuration. Membrane can be installed in two different ways (see Figure 2.4). Membranes submerged into either the bioreactor or positioned outside of the bioreactor sending the mixed liquor through the filter module (Chang et al., 2002; Leiknes et al., 2007; Metcalf&Eddy, 2003; Jefferson et al., 2000; Ramon et al., 2004; Stephenson et al., 2006).

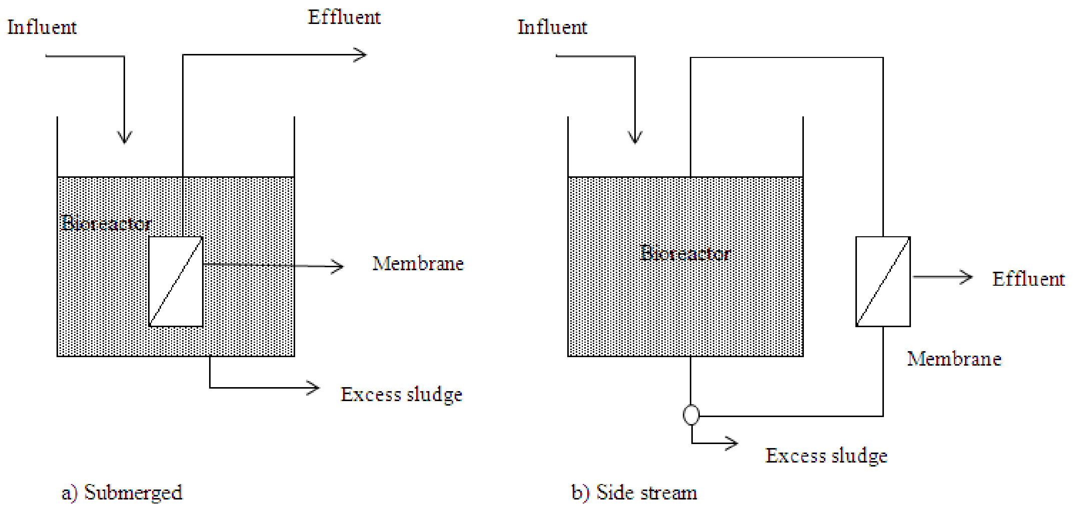


Figure 2.4. Picture of submerged and side stream MBR (WPCR NMT, 2010; Brindle et al., 1996)

2.3.3. Advantages and Disadvantages of Membrane Bioreactors

2.3.3.1. Advantages of Membrane Bioreactors. MBRs have gained popularity in wastewater treatment and reuse applications since MBRs have many advantages over conventional wastewater treatment processes (Merz et al., 2007; Le-Clech et al., 2006).

MBR process provides high-quality effluent in terms of turbidity, TSS, nutrient and COD. MBRs also offer disinfection by using UF and MF depending on their low pore size ranging from 0.005 to 2 µm (Dijk et al., 1997 Le-Clech et al., 2006).

MBRs can be operated at longer SRT and higher biomass concentration up to 20000 mg/L resulting in less sludge production and higher rate of BOD and COD removal. It also brings financial benefits because excess sludge and its treatment and disposal represent 50% of total treatment cost (Defrance et al., 1999). Higher volumetric loading rates, thus shorter HRT results in a reduction of the overall operating costs. As a result of membrane separation, solids retention time independent of HRT. Operation of MBR at low dissolved oxygen concentrations with potential for simultaneous nitrification-denitrification in long SRT designs (Marrot, 2004; Stephenson et al., 2000; Merz et al., 2007; Brindle et al., 1996; Le-Clech et al., 2006; Jefferson et al., 1999; Dijk et al., 1997). Moreover, membrane bioreactors eliminate several treatment units such as sedimentation, aeration and disinfection tanks used in conventional treatment systems due to its special design that MBRs treat the wastewater both biologically and physically at same treatment unit which makes them desirable e.g. for buildings and ships (Rosenberger et al., 2002; Kitis et al., 2005; Karakulski et al., 1998; Gryta et al., 2001).

2.3.3.2. Disadvantages of Membrane Bioreactors. The most significant disadvantage is operation and maintenance cost of MBR process due to its high energy requirement for aeration and mixing and periodic membrane filter cleaning and replacement. Furthermore, if flux can not be increased to sufficient levels with respect to membrane area, MBR can not be operated at its full capacity increasing the cost based on the wasted energy. Another problem is membrane fouling which is the accumulation of the constituents on the surface of the membrane over time causing reduced flux and affecting filtration performance and effluent water quality (Metcalf&Eddy, 2003; Stephenson et al., 2000; Marrot, 2004; Merz et al, 2007). In this case, the membrane should be cleaned by backwashing, or chemical addition. Eventually, fouling is a significant problem in terms of design and operation of membrane bioreactors because it causes cleaning requirements and extra cost, affecting operational conditions and performance of the membrane (Jefferson et al., 2000; Tomaszewska et al., 2005)

2.3.4. Operational Parameters of MBR

Significant operational parameters for MBR are MLSS-MLVSS, flux, Sludge Residence Time (SRT) and Hydraulic Retention Time (HRT) (Stephenson et al., 2000). Table 2.8 shows typical operational conditions of MBR and Conventional Activated Sludge Processes.

Table 2.8. Typical operational conditions for membrane bioreactors and conventional activated sludge processes

Operational Parameter	**MBR** (Metcalf&Eddy, 2003)	Conventional Activated Sludge	
		Extended Aeration Activated Sludge System (WPCR NTM of Turkey, 2010)	**Sequencing Batch Reactor** (Metcalf&Eddy, 2003)
COD Loading, $kg/m^3.d$	1.2-3.2	-	-
MLSS, mg/L	5000-20000	2000-6000	2000-5000
F/M, g COD/g MLVSS.d	0.1-0.4	0.05-0.10	0.04-0.10
SRT, d	5-20	20-100	10-30
HRT, h	4-6	48-120	15-40
Flux, $L/m^2.h$	25-45	-	-
Applied vacuum, kPa	4-35	-	-
DO, mg/L	0.5-1	> 2	-

<u>2.3.4.1. MLSS Concentration.</u>. MBR can be operated at higher MLSS concentrations than conventional active sludge treatment process. Metcalf&Eddy, (2003) reported that MBRs allows a MLSS concentration range between 5000 mg/L to 20000 mg/L while this value is

between 2000 and 6000 mg/L in conventional wastewater treatment systems (see Table 2.8). Jefferson et al. (2000) operated the MBR in a range between 400 and 8000 mg/L, remaining below 2000 mg/L for 80% of the operational run in greywater treatment. Atasoy et al. (2007) used a start up MLSS concentrations which were 1500 mg/L and 3000 mg/L for greywater and blackwater, respectively that increased to 3000 mg/L and 12000 mg/L at the end of the study. Defrance et al. (1999) used a 10000 mg/L of MLSS concentration for wastewater treatment. When all conditions are taken into consideration, 8000-10000 mg/L MLSS concentrations have been reported as the most cost-effective range (Metcalf&Eddy 2003).

<u>2.3.4.2. Flux.</u> Flux, described as the volume of water passing through a unit area of membrane surface per unit time (Stephenson et al., 2000), is an important parameter in operation and design of the MBR because it affects the process economics. For economic reasons, increase of the flux is highly desirable because improved flux diminishes the operational costs (Defrance et al., 1999). Melcalf&Eddy (2003) gives typical flux values in a range between 25 and 45 $L/m^2.h$ (see Table 2.8). In the literature, flux rates generally range between 8 and 40 $L/m^2.h$ (see Table 2.9). Atasoy et al. (2007) operated a MBR at higher flux ranges between 26 and 36 $L/m^2.h$ for greywater and 30 and 40 $L/m^2.h$ for blackwater while Merz et al. (2007) used a lower value of 8 $L/m^2.h$ in average for greywater treatment.

<u>2.3.4.3. Solid Retention Time (SRT) and Hydraulic Retention Time (HRT).</u> SRT which ultimately controls biomass characteristics and HRT are significant parameters of biological treatment. SRT can be extended regardless of the HRT which make MBR attractive than conventional activated sludge systems. Apart from the conventional activated sludge process, the MBR completely retain the biomass inside the bioreactor and can be operated in longer SRTs. Longer SRT allows the increase of MLSS concentration, supporting biological treatment since the long sludge age provides a adaptation period for biomass to treat the hard to degrade fractions of the greywater. However, extended SRT may cause occurance of anaerobic conditions resulting in the generation of organic components which are less readily rejected by the membrane. The other difficulty with high SRT is the raised viscosity that could attenuate the effect of bubbles. Extended SRT increases MLSS concentration that result in higher fouling tendency even with the aeration

raised significantly (Marrot et al., 2004; Jefferson et al., 2000). Operating MBR at higher SRT leads inevitably to increase of MLSS concentration and fouling. However, low SRT also lead fouling. Extremely low SRTs (down to 2 days) have been tested to assess fouling propensity. The reasons suggested for the increased fouling rate at very low SRT include the increased levels of EPS production. SRT also affects directly the F/M ratio which is recommended to be maintained below 0.5. In many studies, MBRs were run at very long or infinite SRTs to minimize development of excess sludge. Jefferson et al. (2000) (Greywater), Merz et al. (2007) (Greywater), Atasoy et al. (2007) (Greywater) and Atasoy et al. (2007) (Blackwater) operated MBR at infinite SRT. However, if wastewater is treated at infinite SRT, it should be prefiltered taking into consideration the accumulation of inert material like hair and lint in the tank which leads to clogging of the membrane module (Le-Clech et al., 2006). Lesjean et al. (2006) used 20 days, 9 days, 6 days and 4 days of SRT for greywater treatment. Ueda et al. (1998), Defrance et al. (1999) and Sarioglu et al. (2007) operated MBR at extended SRTs as 72, 60 and 38 days for wastewater treatment, respectively (see Table 2.9).

In MBR operation, lower HRT is preferred due to economical reasons. Typical HRT is reported as in a range between 4-6 hours (Marrot et al., 2004; Metcalf&Eddy, 2003; Jefferson et al., 1999). In the literature, SRT is given in a range between 2 and 18 hours for greywater and 8 and 36 hours for wastewater and blackwater treatment (see Table 2.9). Atasoy et al. (2007) used HRT values of 18 h and 36 h for grey and blackwater, respectively. MBR was operated at 13 h of HRT in another study (Merz et al., 2007) which remarkably lower than activated sludge process and Defrance et al. (1999) operated a MBR at 24 h.

<u>2.3.4.4. Aeration.</u> Aeration used in MBR systems has three major roles: providing oxygen to the biomass, maintaining the activated sludge in suspension and eliminating fouling by constant scouring of the membrane surface. The aim of the air bubbles are producing shear stress on the membrane surface and providing flow circulation. The shear stress prevents large particle deposition on the membrane surface. The effect of tangential shear is a function of particle diameter, with lower shear induced diffusion and lateral migration velocity for smaller particles, leading to more severe membrane fouling by fine materials (Le-Clech et al., 2006).

2.6. Literature Review

2.6.1. Greywater and Wastewater Treatment by Membrane Bioreactor

Recent investigations have pointed out the benefits and the potential of MBR providing high effluent quality in both wastewater and greywater treatment and reuse resulting in acceptable levels of pollutant and fecal bacteria concentrations in permeate. Table 2.9 summarizes the reported greywater and wastewater treatment studies by MBR in the literature.

Jefferson et al. (2000) evaluated the potential of MBR for greywater recycling. The MLSS concentration of the MBR ranged from 400 to 8000 mg/L, remaining below 2000 mg/L for 80% of the operational run. MBR was operated at 12 h of HRT without any sludge waste. They achieved 100% turbidity (<2 NTU in permeate), 100% total coliforms removal in greywater treatment by a MBR with a mean pore size of 0.4 μm membrane filter.

Merz et al. (2007) had an experiment on greywater treatment by a lab-scale MBR with a pore size of 0.1 μm hollow fiber membrane. MBR was operated at 13 h of HRT, 8 L/m^2.h of flux in average. After continuous operation of 137 days, permeate was found as acceptable quality and complied with standards for domestic reuse, except bacterial contamination. Permeate quality of treated greywater was found to be 15 mg/L, 3.3 mg/L, 0.5 NTU for COD, ammonium and turbidity, respectively. 99% of fecal bacteria removal was also achieved as 68 CFU/100 mL in permeate.

Another reported study was carried out in a pilot plant. An MBR treated greywater coming from bathrooms and kitchens. MBR was operated at 20 d, 9 d, 6 d and 4 d sludge age and at a very low HRT (2 hours). COD removal efficiency was higher 85% and phosphorous removal efficiency was around %50 in all sludge age. SS, COD, NH_4^+-N and P concentrations in permeate were found to be <1 mg/L, 24 mg/L, <0.2 mg/L and 3.5 mg/L, respectively (Lesjean et al., 2006).

Table 2.9. Summary of the MBR studies reported in the literature

Parameters	**Greywater** (Jefferson et al., 2000)	**Greywater** (Merz et al., 2007)	**Greywater** (Lesjean et al., 2006)	**Greywater** (Atasoy et al., 2007)	**Blackwater** (Atasoy et al., 2007)	**Wastewater** (Sarioglu et al., 2007)	**Wastewater** (Ueda et al., 1998)
MLSS, mg/L	400-8000 remaining below 2000	1300	-	1500	3000	13000-16000	12930
Pore size, µm	0.4	0.1	-	0.4	0.4	0.4	0.4
HRT, hours	12	13	2	18	36	8.4	13.4
SRT, days	infinite	infinite	20, 9, 6 and 4	infinite	infinite	38	72
Flux, $m^3/m^2.h$	28	8	-	26-36	30-40	20.8	19.6
COD, mg/L	-	15 (85% removal)	24 (>85% removal)	13 (95% removal)	42 (96% removal)	95-99% removal	-
NH_4^+-N, mg/L	-	3.3 (72% removal)	<0.2 (96% removal)	0.23 (82% removal)	11 (92% removal)	-	0.3
TP, mg/L	-	1.3 (19% removal)	3.5 (%50 removal)	-	-	-	1 (74% removal)
TN, mg/L	-	-	10 (52% removal)	-	-	(50%, 60%, 99% removal)	7.1 (79% removal)
Turbidity, NTU	<2, (100% removal)	0.5 (98% removal)	-	-	-	-	-
TOC, mg/L	-	-	-	-	-	-	3.7 (93% removal)
Total Coliform/100 mL	0	-	-	0	0	-	-
Fecal Coliform/100 mL	0	68 (99% removal)	-	-	-	-	3.8 (99.99% removal)

Atasoy et al. (2007) operated two different MBRs to treat greywater and blackwater generated from lodging houses of the TUBITAK MRC Campus. In the study, a MBR having pore size of 0.4 µm was used for both greywater and blackwater treatment. Flux was in a range between 26 and 36 $m^3/m^2.h$ for greywater and 30 and 40 $m^3/m^2.h$ for blackwater. MBR was operated at 1500 mg/L of MLSS and 18 hours of HRT for greywater and 3000 mg/L of MLSS and 36 hours of HRT for blackwater treatment. Excess sludge was not removed from reactors (infinite SRT). After 50 days of operation time, 96% of COD, 92% of NH_4^+-N and 100% total coliform for blackwater average removal efficiencies were achieved for blackwater. Treatment efficiencies of MBR were 95% of COD, 82% of NH_4^+-N and 100% of total coliform for greywater samples.

Sarıoğlu et al. (2007) set up a pilot scale MBR having a pore size of 0.4 µm. MBR was located in the beginning of a wastewater treatment plant and operated at a 20.8 $L/m^2.h$ of flux, 8.4 hours of HRT, 38 days of SRT and a higher MLSS concentrations range between 13000 and 16000 mg/L. Average COD removal efficiency was found as 95 % and achieved up to 99 %. Total nitrogen removal was almost 99% while this ratio decreased in a range between 50 % and 60 % increasing oxygen concentration.

Ueda et al. (1998) examined practical performance of a submerged membrane bioreactor with gravitational filtration, using a pilot-scale plant raw domestic wastewater. Flat microfiltration membrane polyethylene modules having a pore size of 0.4 µm were used as solid/liquid separation apparatus. A combined aerobic/anaerobic (single-sludge) system was used to enhance nitrogen removal. Operation was continued for 491 days. Average removal ratios of BOD, TOC, SS, total nitrogen, total phosphorous and coliform bacteria were 99, 93, 100, 79, 74 and 99.99 % units, respectively. Permeate quality of treated wastewater were 1.3 mg/L for BOD_5, 3.7 mg/L for TOC, 0.03 mg/L for SS, 7.1 mg/L for TN, 0.3 mg/L for NH_4^+-N, 1 mg/L for TP and 6 CFU/100 mL for coliform bacteria.

2.6.2. Greywater and Wastewater Treatment by Membrane Filter

Apart from performance of MBR, the filtration performance of membranes alone also evaluated in various investigations (see Table 2.10).

Smith et al. (2000) collected greywater from the hand wash-basins and investigate the performance of a pilot scale Biological Aerated Filter (BAF), followed by a variety of membranes, was investigated using synthetic greywater. It was operated in batch mode with a variety of UF, NF and RO membranes. BAF was capable of achieving a total BOD of between 20 and 25 mg/L. In terms of BOD removal, the permeate quality after treatment of UF membranes were 10.6, 5.1 and 6.3 mg/L for MWCO 200 kDa, 6 kDa and 4 kDa, respectively.

Another study (Ramon et al., 2004) aimed to observe the effluent quality produced by three different UF direct membranes with three different Molecular Weight Cut Off (MWCO). Flat-sheet UF membranes with a MWCO of 400 kDa, 200 kDa and 30 kDa were tested in low strength greywater treatment. An increase of permeate quality with the decrease of the MWCO was observed. COD removal ratios are reported as 45 %, 50 % and 70% for the MWCO values of 400 kDa, 200 kDa and 30 kDa, respectively. Turbidity reduction is also presented as 69%, 92% and 97% according to the decrease of MWCO.

Table 2.10. Performance of membrane filters reported in the literature

Parameters	**Greywater** (Ramon et al., 2004)			**Greywater** (Smith et al., 2000)		
Method	Direct Ultrafiltration			UF after BAF treatment		
MWCO, kDa	30 kDa	200 kDa	400 kDa	200 kDa	6 kDa	4 kDa
BOD_5, mg/L	-	-	-	10.6	5.1	6.3
COD, mg/L	50.6 (69.3% removal)	74.3 (49.1% removal)	80 (45.2% removal)	-	-	-
Turbidity, NTU	0.8 (96.6% removal)	1 (94.2% removal)	1.4 (92.3% removal)	-	-	-

3. MATERIAL AND METHODS

In this study, MicroClear Filter ® was used for the filtration of both low-load greywater and municipal wastewater. MicroClear Filter®, made of Polypropylene (PP), is a plate type of ultrafiltration membrane with a molecular cut-off of 150 kDalton that equals approximately to a pore size of 0.05 µm (see Figure 3.1). The 0.05 µm pore size is supposed to provide safe separation of bacteria and parasites having size of 1-2 µm and 5-50 µm, respectively (MicroClear Filter ® MBR Guide, 2009).

Figure 3.1. MicroClear® Filter Module

3.1. Greywater Collection, Treatment and Operational Conditions

Low-load greywater was collected from the hand basins in the toilets of Boğaziçi University, Institute of Environmental Sciences which serves to approximately to 10-15 people per day. Greywater samples were stored at + 4 ^{o}C for maximum 48 hours. A 200 L real-scale MBR, operating as a semi-batch reactor, was used for the greywater treatment (see Figure 3.2) During 2 months of operation time 60 L/day of fresh greywater was fed into the reactor while equal amount of permeate was sucked from the membrane filter to keep reactor volume constant. The submerged plate type filter module consists of 24 parallel membrane plates with a total area of 3.5 m². An air blower was used to supply air for the system. Oxygen concentration was measured at different intervals to prevent formation of aerobic conditions.

Figure 3.2. MicroClear® MBR for Greywater Treatment

In this system aeration and short pauses were used to prevent fouling of the membrane. The exact bubble size matching to the spacing between filter plates removed fouling problem by the scouring effect of the aeration (MicroClear Filter ® MBR Guide, 2009). Operation was carried out at three different conditions <10 mg/L (I. condition), 350-500 mg/L (II. condition) and 1000-1200 mg/L (III. condition) MLSS concentrations. Other operational conditions were constant for greywater treatment (Table 3.1).

3.1.1. Greywater Treatment Process

A schematic illustration of MBR set-up is shown in Figure 3.3. MBR processes basically occurred as in the following explanations. Raw greywater was fed into the reactor in a pipe (1), aerated by an air pump (3) and biologically treated in reactor. After biological treatment, permeate pump (4) sucked and run greywater to the filter module (2). While greywater pass through the filter plates, it was also physically treated. At last clean water was collected in permeate box (5) and pumped out of to the reactor (6).

Table 3.1. Operational conditions of the MBR in the greywater and wastewater treatment

Operational Conditions	Greywater Treatment			Wastewater Treatment
	(I)	(II)	(III)	
Reactor Volume (L)	200	200	200	30
MLSS (mg/L)	0 (<10)	350-500	1000-1200	5500-6500
MLVSS (mg/L)	0 (<10)	250-400	800-950	4000-5500
HRT (day)	3.3	3.3	3.3	6
SRT (day)	infinite	infinite	Infinite	30
Flux ($L/m^2.h$)	0.7	0.7	0.7	1.2
Dissolved Oxygen (mg/L)	> 4	> 4	> 4	> 4
Operation Time (day)	60 for total operation period			30

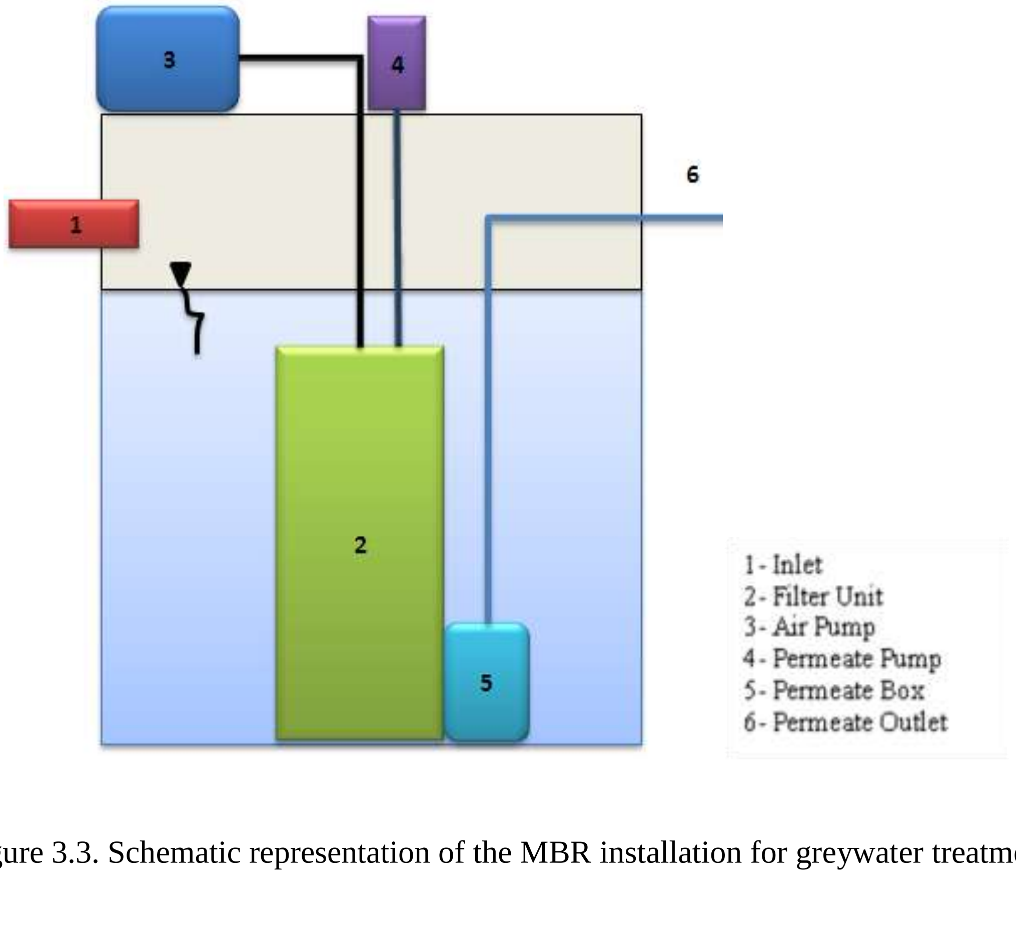


Figure 3.3. Schematic representation of the MBR installation for greywater treatment

3.2. Wastewater Collection, Treatment and Operational Conditions

Wastewater samples were supplied from Paşaköy Advanced Biological Wastewater Treatment Plant and stored at + 4 ^{o}C. MicroClear® MBR was mimicked and a 30 L of lab-scale MBR was set up for domestic wastewater treatment (see Figure 3.4). A plastic perforated pipe was located both at the bottom of the reactor to provide aeration and bottom edges of the membrane plate to clean the surface of the membrane. The reactor was operated as a semi-batch reactor. A single filter plate having 0.14 m^2 surface area was submerged into the reactor. The reactor was fed with 4 L wastewater per day while the equal amount of permeate was sucked from the filter. Aeration of the system was supplied by using a stationary compressor. The MBR was operated at a MLSS range between 5500-6500 mg/L. The excess sludge was taken from the reactor to keep the MLSS concentration constant. Other operational conditions of MBR for wastewater treatment are presented at Table 3.1.

Figure 3.4. Picture of MBR set-up for domestic wastewater treatment

3.2.1 Wastewater Treatment Process

A schematic illustration of MBR set-up is shown in Figure 3.5. Treatment processes basically occurred as in the following explanations. Wastewater was manually fed into the reactor. Air was supplied from a stationary air pump through a plastic perforated pipe (2). After biological treatment, a stationary vacuum pump (5) sucked and run wastewater to the filter plate (1). When wastewater passes through the filter plate it was physically treated. At last, clean water was collected in a Nutsche flask (4).

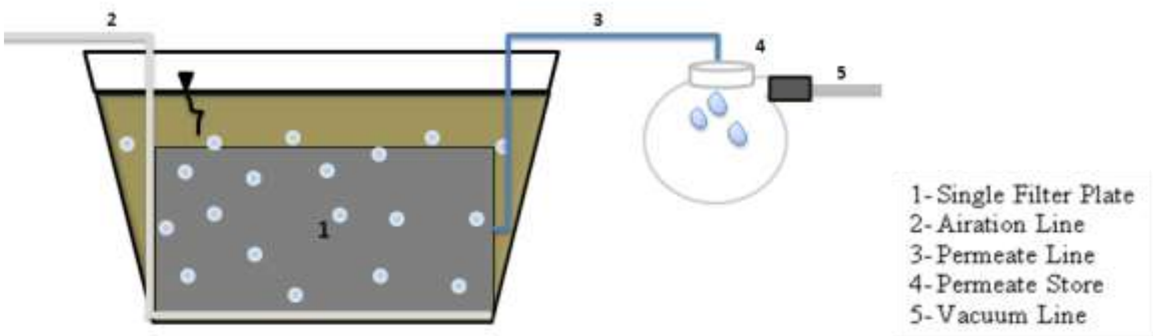


Figure 3.5. Schematic representation of the MBR installation for domestic wastewater treatment

3.3. Analytical Methods

3.3.1. Sample Preparation

Raw wastewater samples were centrifuged for 15 minutes at 5000 rpm before the analysis. Raw greywater samples were not centrifuged or filtered because of not having suspended materials. Treated greywater and wastewater samples were analyzed without being filtered or centrifuged since they were filtered through low pore size (≈0.05 µm) of the membrane. Before TOC analysis samples were filtered through a milipore filter which had a pore size of 0.45 µm. Samples were analyzed in maximum 6 hours for coliform detection.

3.3.2. Experimental Procedure

All analyses were performed in accordance with the Standard Methods (20th Edition). Methodologies for raw sample and permeate analysis are shown in Table 3.2.

Table 3.2. Methodology for Analysis

Parameter	Analytical Method	Instrumental Equipment
COD	Closed Reflux, Colorimetric Method: Ignition to 150 ^oC followed by monitoring of the absorbance at 600 nm for high range COD and 420 nm for low range COD.	Hach COD Reactor (heater), Hach DR/2010 Spectrophotometer
TOC	All samples were measured for three times by TOC Analyzer	Shimadzu TOC-V CSH Analyzer.
NO_2^--N	Hach Method, 8153, Ferrous Sulfate Method: Dissolution of Nitriver 2 and monitoring of the absorbance at 585 nm.	Nitriver 2 Reagent Powder Pillows, Hach DR/2010 Spectrophotometer
NH_4^+-N	Nesslerization Method and monitoring of the absorbance at 425 nm	Hach DR/2010 Spectrophotometer
PO_4^{-3}-P	Hach Method, 8048, PhosVer 3 Method, Test'N Tube Procedure: Filtration of samples through 0.45 µm-membrane filters, Dissolution of PhosVer 3 and direct monitoring of the absorbance at 890 nm.	PhosVer 3 Reagent Powder Pillows, Hach DR/2010 Spectrophotometer
MLSS	Filtration, drying at 103–105 ^oC for 1 hours and gravimetry	Oven, Whatman Grade GF/C glass microfiber filter paper (1.2 µm particle retention capacity)
MLVSS	Filtration, incineration at 550 ^oC and gravimetry	Muffled Furnace
Fe, Al, Mn	-	Perkin Elmer Optima 2100 DV ICP Emission Spectrometer
pH	-	WTW InoLab Benchtop Level 2 pH/mV meter
O_2	-	Hach HQ30d Field case Oxygen meter
Fecal Coliform	Membrane Filtration and incubation at 37 ^oC in 24 hours	Sartorius Endo NKS filter (0.45 µm), Sartorius Endo NKS ready-to-use culture medium and Agar plates, incubator
Total Coliform	Membrane Filtration and incubation at 37 ^oC in 48 hours	Sartorius Endo NKS filter (0.45 µm), Sartorius Endo NKS ready-to-use culture medium and Agar plates, incubator

4. RESULTS AND DISCUSSION

This study investigates the efficiency of Membrane Bioreactors (MBRs) having a plate type membrane filter module in the treatment of the low-load greywater and the municipal wastewater. MicroClear Filter ® MBR was used for the treatment of both low-load greywater and municipal wastewater.

4.1. Greywater Treatment

4.1.1 Characteristics of Low-load Greywater

Greywater samples, collected from the hand basins in the toilets of Bogazici University, Institute of Environmental Sciences, were analyzed for a 60-day period. Table 4.1 summarizes the characteristics of the low-load greywater used in this study.

Table 4.1. Characteristics of the greywater

Parameters	**Average**	**Max.**	**Min.**
COD, mg/L	248	428	57
NH_4^+-N, mg/L	0.45	0.60	0.30
NO_2^- -N, mg/L	0.04	0.08	0.02
PO_4^{-3}-P, mg/L	0.04	0.10	0.01
TSS, mg/L	<10	-	-
Al, µg/L	700	1800	100
Fe, µg/L	400	600	300
Mn, µg/L	50	200	20
Turbidity , NTU	12	17	7
pH	7.4	7.9	7.2

4.1.1.1. Chemical Oxygen Demand. Greywater had an average COD concentration of 248 mg/L. This value is compatible with the average COD values of low-load greywater which generated from hand basin reported as average 244 mg/L and in a range between 171 and 298 mg/L (March et al., 2004; Jefferson et al., 1999; Almeida et al., 1999). COD and sCOD concentrations of greywater samples were almost equal indicating that great part of the COD in greywater was soluble (see Table 4.2).

Table 4.2. Total and soluble COD of greywater

Number of Sample	sCOD (mg/L)	COD (mg/L)
1	60	69
2	101	118
3	77	87
4	54	58
5	54	57

4.1.1.2. Nitrogen Content. 0.45 mg/L of average NH_4^+-N concentration was relatively lower than the some other studies in which samples were collected from showers or baths and contained higher concentration of ammonium in a range between 6.7 and 11.8 mg/L (Lamine et al., 2007; Merz et al., 2007; Ramon et al., 2004; Nolde et al., 1999; Atasoy et al., 2007; Almeida et al., 1999). Higher ammonium concentration is explained with the presence of urine, the main source of nitrogen. Other sources of nitrogen, like household cleaning products and shampoos (Schafer et al., 2006), were also missing in the low-load greywater used this study.

4.1.1.3. Phosphorous Content. The phosphorus content of greywater samples was in a range between 0.01 and 0.1 mg/L. This indicated that hand soap, the most observed chemical in the subject greywater, has lower phosphorus content than the detergents which are the main sources of phosphorus in the domestic wastewaters (Schafer et al., 2006). Almeida et al. (1999) found average phosphorus concentration of greywater collected from washing machines as 21 mg/L. Kitchen based greywaters also found to be containing higher concentrations of phosphorus (7.4-26 mg/L) due to the presence of organic component and the cleaning chemicals (Lesjean et al., 2006; Almeida et al., 1999).

4.1.1.4 Turbidity. An average 12 NTU turbidity content was detected in the study. Turbidity values of greywater samples were almost compatible with the experiments. 20 NTU of turbidity was reported in older studies which carried out on hand basin based greywater (see Table 2.1). However, a range between 23 and 29 NTU were given in the previous studies (Lamine et al., 2007; March et al., 2004; Jefferson et al., 1999) for low-load greywater (see Table 2.1) sourced from bath and shower. This indicates that the greywater samples collected from hand basins include lower TSS values than the greywaters collected from shower and baths. Hair and fibres from laundry can lead to high solid contents and so the turbidity in greywater (Sandec, 2006).

4.1.1.5. Total Suspended Solid Concentration. Total suspended solid concentrations of all greywater samples were found to be less than 10 mg/L supporting that the great part of the pollutants were dissolved in the greywater.

4.1.1.6. Biodegradability. COD:NH_4^+-N:P ratio of greywater was measured as 100:0.4:0.05. Compared to common values for domestic wastewater (100:5:1) (Jefferson et al., 2000), COD to nutrient ratio of subject greywater was found to be unfavorable for biological treatment. Similarly, Jefferson et al., 1999 found the COD to nutrient ratio for mixed greywater as unfavorable (C:NH_3-N:P, 1030:2.7:1). However, Merz et al. (2007) reported this ratio as 100:14:1.5 (C:NH_3-N:P) that promotes biological activity measuring greywater coming from showers.

4.1.2. Operational Conditions of MBR in Greywater Treatment

MBR was operated at three different MLSS concentrations of 0 mg/L less than 10 mg/L), 350-500 mg/L and 1000-1200 mg/L. The operational conditions of MBR are given in Table 3.1 (Section 3.1).

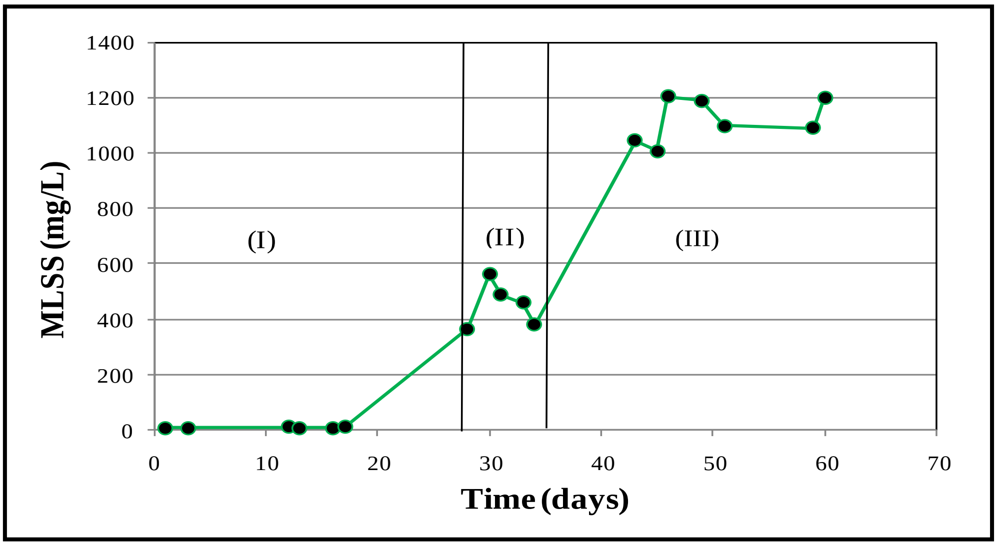
4.1.2.1. HRT and Flux. In all conditions, high HRT values were used (3.3 days). In previous studies, HRT was selected in a range of 2 to 18 hours for greywater treatment

(Jefferson et al., 2000; Merz et al., 2007; Atasoy et al., 2007; Lesjean et al., 2006). The typical HRT range is given as 4-6 hours in Metcalf&Eddy (2003).

In this study, considerably lower flux value of 0.7 L/m^2.h was used due to the limited greywater supply. The suggested flux range given in Metcalf&Eddy, (2003) is 25-45 L/m^2.h. Although the membrane had high surface area of 3.5 m^2, the low greywater supply (60 L/d) lead to operate MBR at lower flux.

4.1.2.2. SRT. Sludge production in the reactor was negligible due to the low TSS concentration (less than 10 mg/L) of influent. Therefore, the SRT of the reactor was selected to be infinite, without wasting any excess sludge from the system. Operating MBR without remove excess sludge did not cause any operational drawback during 60 days of operation time. However, a precise comment about effectiveness of infinite SRT can not be made because infinite SRT may cause accumulation of inert materials like hair in the reactor in the long turn.

4.1.2.3. MLSS. The effect of MLSS on the treatment of greywater by MBR was investigated operating the reactor at three conditions having different MLSS content (see Figure 4.1).



4.1. MLSS concentrations of greywater at condition I, II and III

First Condition (From 1st to 27th days): In the first part of the greywater experiments, MBR was operated without seeding to observe the filtration efficiency of membrane filter itself in the absence of microbial activity. The MLSS concentration in the reactor was accepted as 0 mg/L because of low TSS concentration (<10 mg/L) of the greywater. O_2 concentration of the effluent in this stage was very high (near saturated) indicating low bacterial activity in the system. COD:NH_4^+-N:P was 100:0.4:0.05 for this section.

Second Condition (From 28th to 35th days): Results of greywater characterization showed that the nutrient (N and P) content of greywater was very low for sufficient microbiological activity and the organic removal, as well. In the second part of the study, some amount of wastewater and waste activated sludge were added into the reactor to increase the nutrient content and the microorganism concentration in the reactor, respectively. As a result of microbial seeding, MLSS concentration increased to a range between 350 and 500 mg/L. Phosphorus concentration of mixed liquor increased to 1.17 from 0.03 mg/L (see Figure 4.2). NH_4^+-N concentration was also enhanced to 0.54 mg/L from 0.35 mg/L (see Figure 4.3). COD:NH_4^+-N:P was 100:0.2:0.2 for this section.

Third Condition (From 36th to 60th days): In the last section of the study, MLSS concentration was raised to 1000-1200 mg/L with the addition of extra waste activated sludge. Phosphorus concentration of mixed liquor increased to 5.04 from 1.23 mg/L (see Figure 4.2) and NH_4^+-N concentration or the reactor slightly increased to 0.59 from 0.54 mg/L (see Figure 4.3) with the addition of more wastewater into the reactor, too. COD:NH_4^+-N:P was 100:0.2:2 for this section.

Although the addition of wastewater increased the nutrient content of mixed liquor in the reactor from 100:0.4:0.05 to about 100:0.2:2, the desired C:N:P level of 100:5:1 for biodegradability could not be reached.

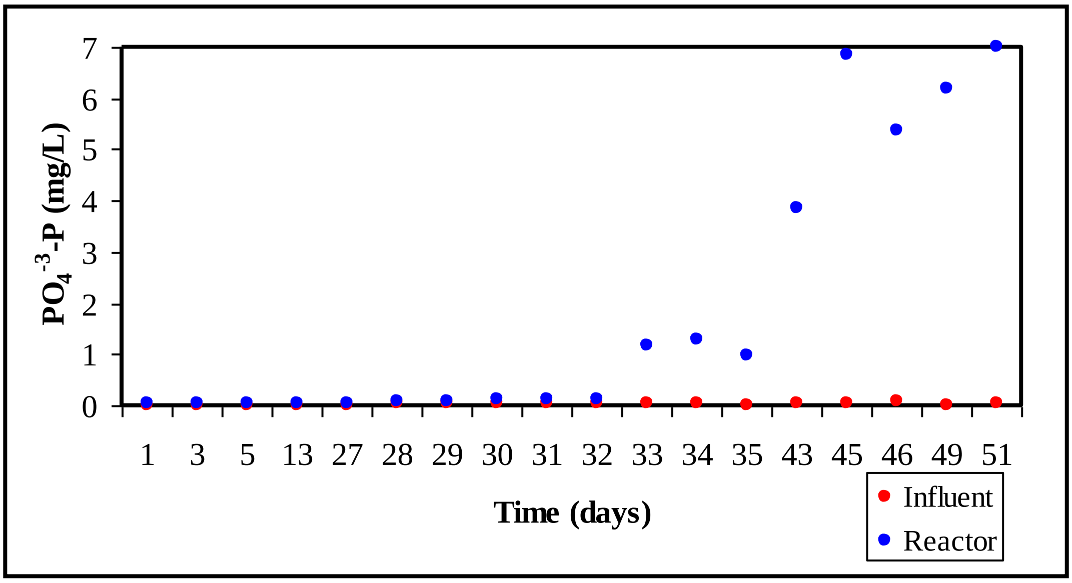


Figure 4.2. Increase of PO_4^{-3}-P concentrations depending on rising MLSS ratio

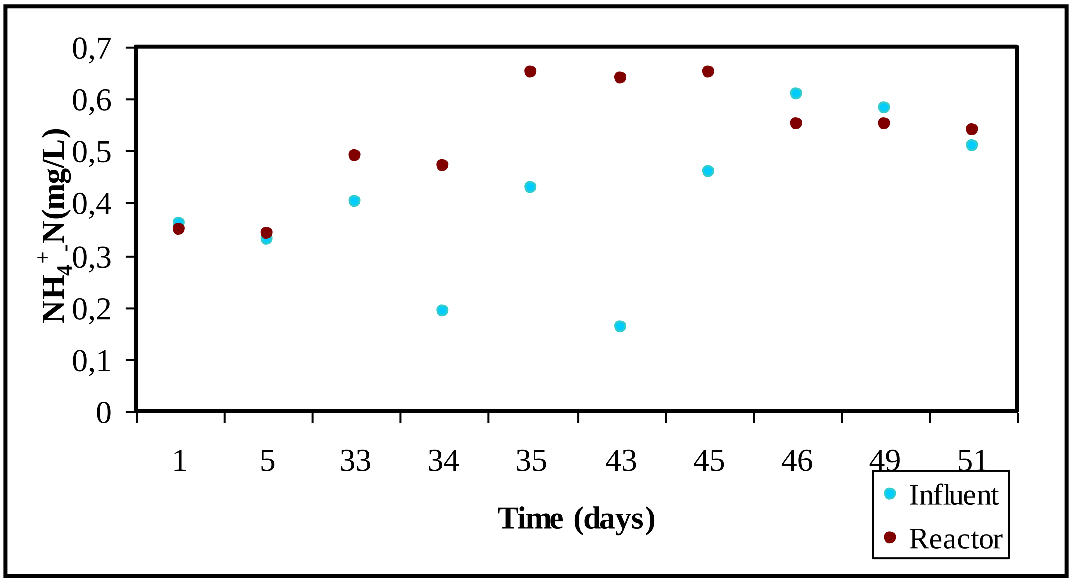


Figure 4.3. Increase of NH_4^+-N concentrations depending on rising MLSS ratio

In the first condition, foaming due to the soaps and detergents in the greywater became a serious problem during the aeration of the reactor because of non existing adaptation of the microorganism at the beginning of the operation. However, when the biomass was developed in the reactor (at second and third conditions) the foaming problem decreased due to the decomposition of soaps and detergents by the microorganisms (see Figure 4.4.)

Figure 4.4. Foaming in the Membrane Bioreactor

4.1.3. Treatment Efficiency of MBR in Greywater Treatment

Permeate quality was monitored continuously to determine removal efficiency of the MBR in terms of COD, ammonium, nitrite, phosphorus and turbidity (see Table 4.3). Influent and effluent concentrations for COD, ammonium, nitrite, phosphorus and turbidity at three MLSS concentrations and removal trends for these parameters are shown in Figure 4.5, 4.6, 4.7, 4.8 and 4.9, respectively.

Table 4.3. Greywater permeate quality and removal efficiencies at different MLSS concentrations

	0 (<10) (mg/L MLSS)		350-500 (mg/L MLSS)		1000-1200 (mg/L MLSS)	
Parameters	Effluent	Removal (%)	Effluent	Removal (%)	Effluent	Removal (%)
COD, mg/L	58±18	37±12	63±9.93	80±5	24±8	93±1.70
NH_4^{+-}N, mg/L	0.24±0.02	31±0.4	0.18±0.09	57±18	0.11±0.06	82±10
NO_2^--N, mg/L	0.03±0	58±6.64	0,01±0	76±8	0.01±0	80±2.40
Turbidity, NTU	1.6±0.60	85±9	1.90±1	85±8	0.60±0.02	95±0.50
TOC, mg/L	16±4	-	19±2.30	-	7±2.30	-
TSS, mg/L	0	-	0	-	0	-
Al, µg/L	117±30	-	320±200	-	90±50	-
Fe, µg/L	56±10	-	47±17	-	41±23	-
Mn, µg/L	24±10	-	40±20	-	35±14	-
pH	7.5±0.3					

4.1.3.1. COD Removal. Average COD removal efficiency of MBR was found to be 37% at first condition. This was another evidence of that the great part of organic material in the greywater was soluble with a relatively low molecular weight. MLSS concentration in the reactor was also almost zero mg/L eliminating the biological removal of organic matters. In the second condition where the MLSS concentration is between 350-500 mg/L, although COD removal efficiency increased considerably to 80%, permeate COD concentration increased slightly from 58 mg/L to 63 mg/L. This can be explained that wastewater addition to enhance microbial activity causes the increase and passage of low molecular weight particles through the membrane. COD:NH_4^+-N:P ratios of 100:0.4:0.05 and 100:0.2:0.2 for first and second conditions, respectively explain the low COD removal efficiencies for these conditions. Maximum efficiency was observed at last condition in which MLSS concentration in the range of 1000-1200 mg/L indicating the positive effect of increasing MLSS concentration on COD removal. The average COD concentration in the permeate was about 24 mg/L, which corresponds to an overall COD removal efficiency of 93%. COD:NH_4^+-N:P ratio was found to be 100:0.2:2 for this condition. It seems that permeate had some soluble non-biodegradable COD or limited Nitrogen concentration did not allow microorganisms to remove al of the organics. Influent and effluent COD concentrations and removal ratios for COD are presented in Figure 4.5.

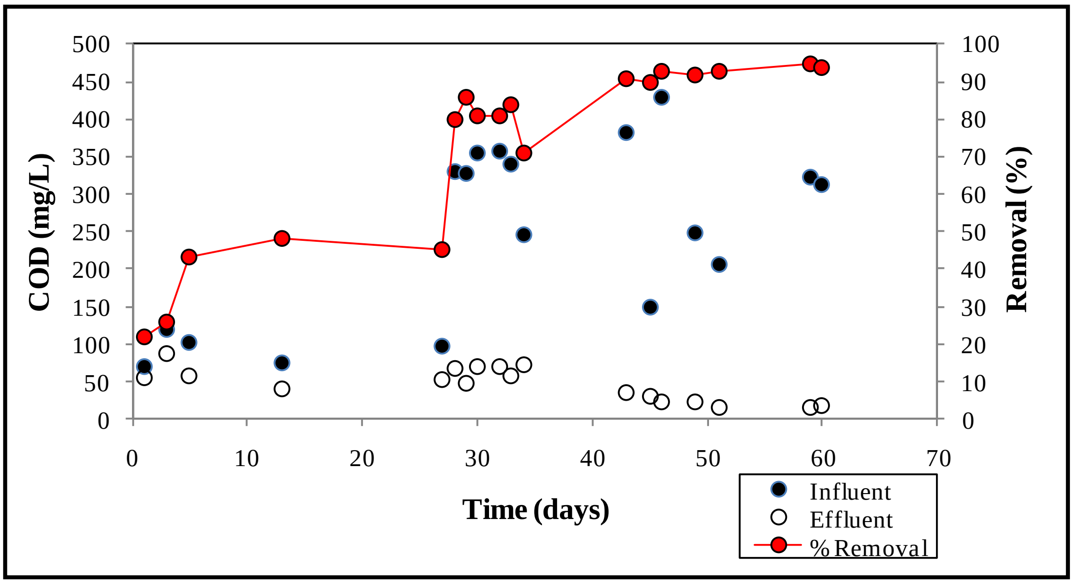


Figure 4.5. Influent and effluent COD concentrations and removal efficiency of MBR in greywater treatment at condition I, II and III

<u>4.1.3.2. Ammonium and Nitrite Removal.</u> Ammonium removal efficiencies were found to be as expected 31% and 57% for first and second conditions, respectively and Nitrite removal ratios were inconstant and ranged from 53% to 63% and 67% to 83 for first and second conditions, respectively. It might be possible that the low MLSS and low phosphorous concentrations limited the activity of nitrifying bacteria despite the reactor was continuously aerated (nearly saturated) expecting sufficient nitrification. At last section, increased phosphorus concentration supported ammonium removal. The best ammonium removal was achieved at COD:NH_4^+-N:P ratio of 100:0.2:2 of and the average ammonium removal efficiency of the MBR for ammonium increased considerably to 82% in this condition. At the last condition nitrite removal efficiency ranged from 80% and

81%. Quite lower difference between influent and effluent concentration of nitrite (max. 0.05 mg/L, min 0.01 mg/L) resulted in irregular MBR performances.

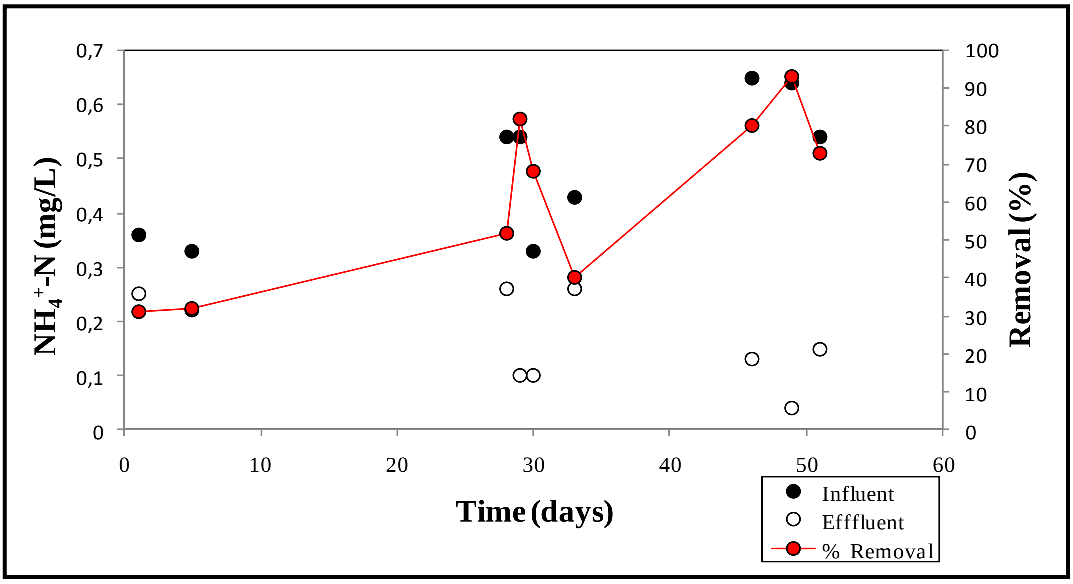


Figure 4.6. Influent and effluent NH_4^+-N concentrations and removal efficiency of MBR in greywater treatment at condition I, II and III

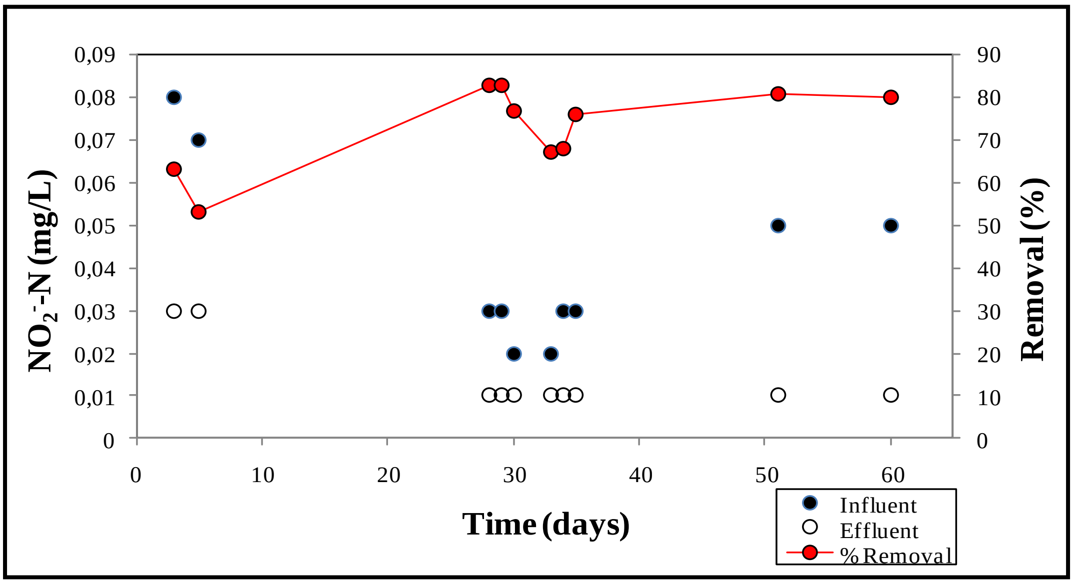


Figure 4.7. Influent and effluent NO_2^--N concentrations and removal efficiency of MBR greywater treatment at condition I, II and III

<u>4.1.3.3. Phosphorus Removal.</u> There was no phosphorous removal in the first section due to the absence of microbial activity. In the second condition waste activated sludge was added to enhance biomass growth in the reactor and also wastewater was added to increase nutrient concentrations. However, nitrogen was the limiting nutrient causing the accumulation of the phosphorus reactor (see Figure 4.8).

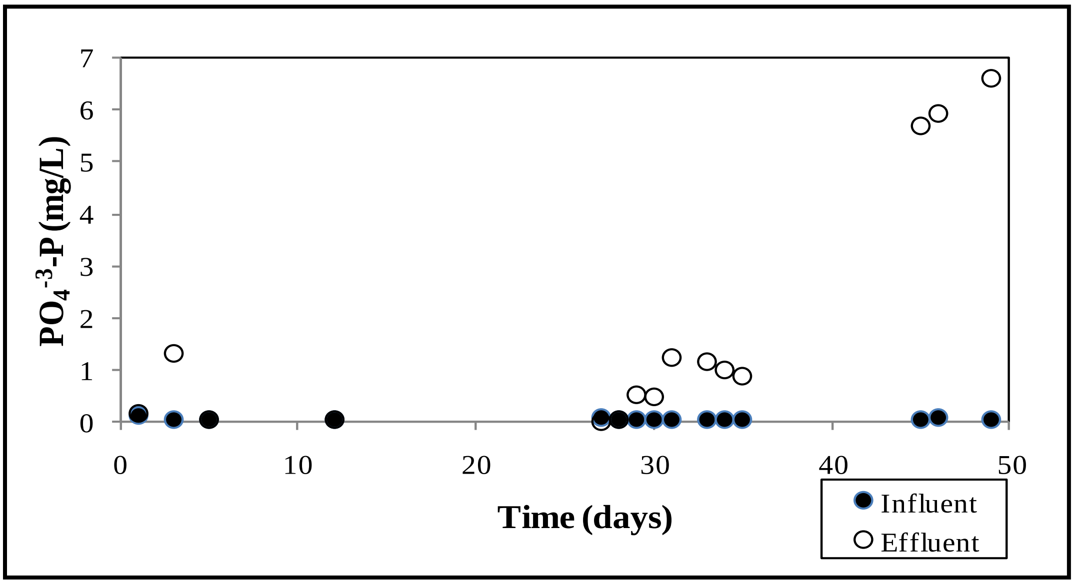


Figure 4.8. Influent and effluent PO_4^{-3}-P values for greywater treatment at condition I, II and III

<u>4.1.3.4. Turbidity Removal.</u> In the first section of the operation, turbidity was the single parameter that reasonably decreased to about 1.6 NTU and achieved 85% removal ratio in permeate due to filtration effect of the membrane itself. Ramon et al., 2004 observed that three different UF membrane filter with different MWCO of 400 kDa, 200 kDa and 30 kDa results in 1.4, 1, 0.8 NTU turbidity in permeate. At the following condition, turbidity removal ratio was almost same as in the first part of the study which was 85%. It can be explained that addition of the wastewater did not increase particles which have low molecular weight cut off. Despite constant turbidity removal efficiencies permeate turbidity a concentration was increased to about 1.9 NTU. The possible explanation is that microorganisms reduced the organic particles into the true colloids and dissolved solids decomposed by them. In the last section of the investment, removal ratio was 95% for

turbidity. Permeate quality of the greywater was also increased with a turbidity value of 0.6 NTU.

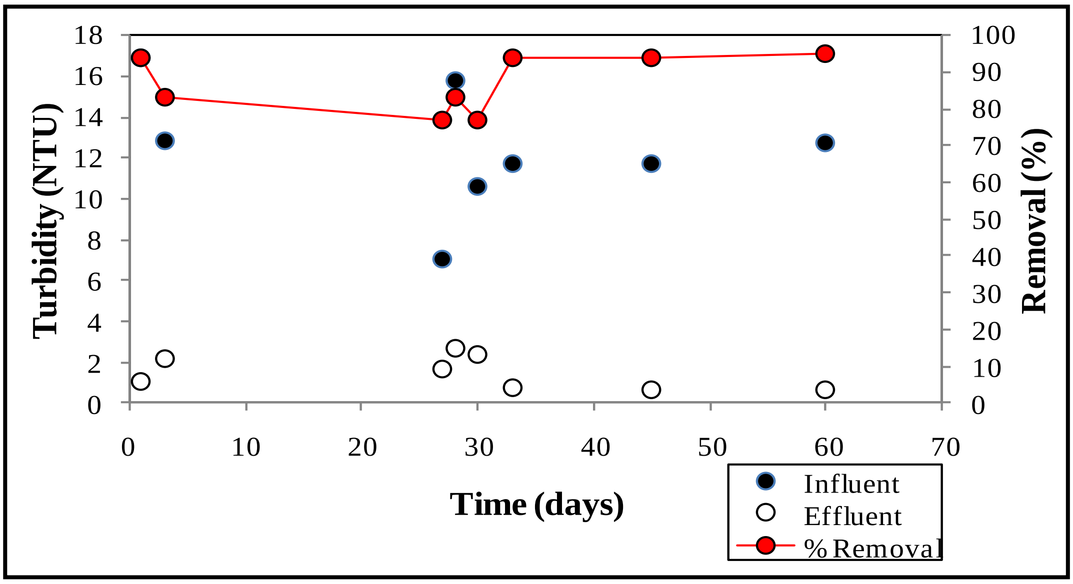


Figure 4.9. Influent and effluent turbidity concentrations and removal efficiency of MBR in greywater treatment at condition I, II and III

4.1.3.5. TSS Removal. TSS concentration of the greywater was measured as <10 mg/L. After the addition of wastewater to bioreactor TSS concentration increased but the low pore size of the membrane provided almost complete removal of TSS in all three conditions.

4.1.4. Comparison of the Permeate Quality with Regulations and Guidelines

Permeate quality of greywater was monitored by measuring TOC, ammonium, nitrite, aluminum, iron, manganese, turbidity and pH values to evaluate treated greywater with respect to “The Regulation Concerning Water Intended for Human Consumption of Turkey”, US EPA “Suggested Guidelines for Water Reuse”, “Water Pollution Control Regulation of Turkey; Notification of Technical Methods”.

When the obtained results were compared with respect to The Regulation Concerning Water Intended for Human Consumption limits (see Table 2.5), it was observed that satisfactory results were achieved in ammonium, nitrite, manganese, aluminum, iron content of permeate and pH value at all three conditions. Turbidity value also complied with the Regulation limit that found as 0.6 NTU at third condition. However, it was slightly above the limits at first and second conditions measured as 1.6 and 1.9 NTU, respectively. Another specified parameter, TOC, is limited as "No abnormal change" in the Regulation. TOC concentration was measured as 16, 19 and 7 mg/L in permeate. Average TOC concentration of tap water sampled from institute's handbasin taps was measured as 2.81 mg/L. Despite TOC concentration of permeate was found to be higher than TOC concentration of tap water, it was found to be safe for reuse in human consumption due to low value of TOC.

The internationally applied and suggested water reuse standards are given in Table 2.4. The result of this study showed that the effluent quality of the treated greywater complied with the reuse criteria for different purposes except "*urban reuse"* and *"irrigation of food crops not commercially processed"* at all three conditions. "Not detectable" coliform and ≤10 mg/L BOD concentrations are required for safe reuse of reclaimed water for these purposes. BOD_5 concentrations of the samples were not measured. Therefore, an accurate comment can not be made. However, Jefferson et al. (2004) and Aizenchtadt et al. (2009) showed that COD:BOD ratios were generally in a range between 3 and 3.6 for low-load greywater coming from hand basins while Jefferson at al. (2004) reported a COD/BOD_5 value to be 2.4. Based on the literature and considering that more organics can be oxidized chemically then microbiologically the COD/BOD_5 ratio of the greywater used in this study was accepted as 3. Therefore, effluent BOD_5 concentrations were estimated as 19 mg/L, 21 mg/L, and 8 mg/L for first, second and third conditions, respectively. Thus, the limits were not accomplished with BOD_5 concentrations of first and second conditions. Cl_2 concentrations of effluent were not measured because of not using Cl_2 for disinfection.

4.1.5. Disinfection Capacity

In all three conditions, bacterial analyses showed that permeate had trace amount of fecal and total coliforms although the pore size of membrane filter (0.05 μm) was smaller than the size of the coliforms (see Table 4.4). Membrane filter was supposed to retain all bacteria from the greywater. The contamination of fecal coliform into the greywater can be explained with the presence of a torn on the surface of the membrane which might develop during montage of the MBR. Based on the results, bacteriologic removal efficiency of the MBR found to be 99% for Total and Fecal coliforms indicating the necessity of disinfection process to provide hygienic conditions prior to the reuse of water and to meet the 100% removal requirement of The Regulation Concerning Water Intended for Human Consumption, US EPA Suggested Guidelines for Water Reuse (*"Urban reuse"* and *"Irrigation of food crops not commercially processed"*) (see Table 2.4).

Table 4.4. Microbial removal efficiency of MBR with permeate quality

Microbiological Parameters	Unit	Influent	Effluent	% Removal
Escherichia coli (E. Coli)	CFU/100 mL	5200	50	99
Total Coliform	CFU/100 mL	16000	120	99

4.2. Wastewater Treatment

4.2.1 Characteristics of Wastewater

Wastewater samples were analyzed for 30 days of operating time. Table 4.5 summarizes the characteristics of the wastewater. Pollutant concentrations were found to be compatible with the wastewater characterization given in the literature (see Table 2.3). COD:NH_4^+-N:P was measured as 100:9.5:1.8. P and N concentration of raw wastewater was found slightly above the desired limits (100:5:1 for C:N:P).

Table 4.5. Characteristics of the wastewater

Parameter	**Unit**	**Study Average**	**Max**	**Min**
COD	mg/L	358	406	236
NH_4^+-N	mg/L	34	45	20
NO_2^--N	mg/L	0.37	0.6	0.2
PO_4^{-3}-P	mg/L	6.5	7	5

4.2.2. Operational Conditions of MBR in Wastewater Treatment

Operational conditions of MBR in wastewater treatment were given in Table 3.1.

4.2.2.1. HRT and Flux. HRT was found quite higher (6 days) while the flux (1.2 $L/m^2.h$) was lower than the reported values in the literature. A study carried out by Cote et al. (2004) noted the optimum HRT and flux values were 3.6-6.5 h and 20 $L/m^2.h$. Merz et al. (2007) used a flux value between 8-10 $L/m^2.h$ in their study. The typical HRT and flux values were stated as 4-6 h and 25-46 $L/m^{2}\cdot h$ (Metcalf&Eddy, 2003). High HRT and low flux in wastewater treatment were the results of the limited wastewater supply and large surface area (0.14 m^2) of the membrane plate.

4.2.2.2. SRT. SRT was selected as 30 days close to reported values in previous studies on wastewater treatment by MBR (see Table 2.9).

4.2.2.3. MLSS Concentration. The MBR was operated at a MLSS concentration between 5500 and 6500 mg/L (see Figure 4.10). The excess sludge was taken from the reactor to keep the MLSS concentration constant. Compared to literature, this range was evaluated as average. Atasoy et al. (2007) operated a MBR at a start up MLSS concentrations of 3000 mg/L for blackwater treatment.

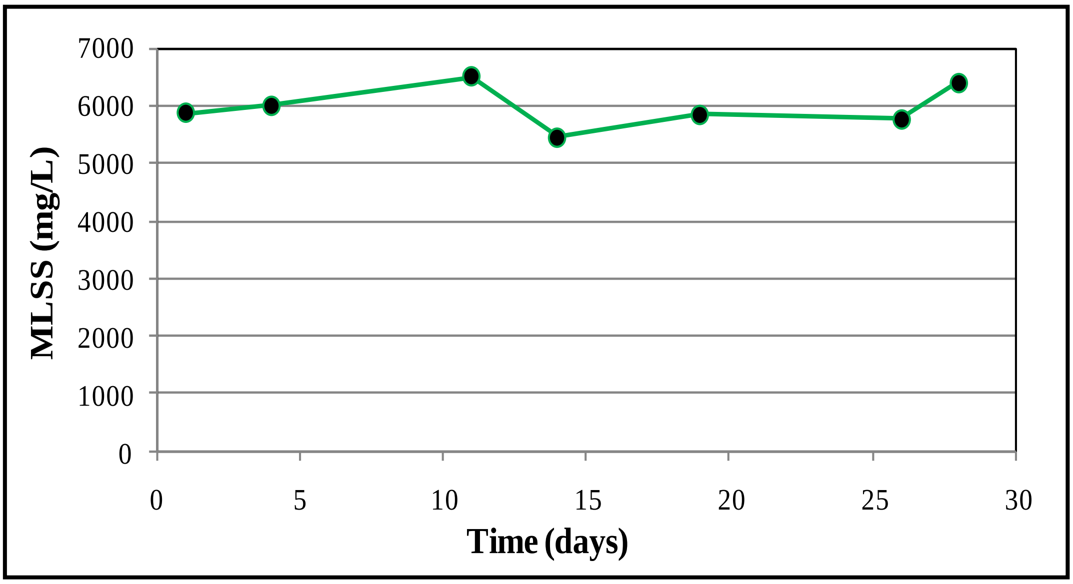


Figure 4.10. MLSS concentrations of wastewater

Ueda et al. (1998) measured an average MLSS concentration of 12930 mg/L and Sarioglu at al. (2007) operated a MBR in a MLSS range between 13000 and 16000 mg/L for wastewater treatment.

4.2.3. Treatment efficiency of MBR and permeate quality in domestic wastewater treatment

Permeate quality was monitored continuously to determine treatment efficiency of the MBR (see Table 4.6). Influent and effluent values for COD, ammonium, nitrite and phosphorus and removal efficiencies of for these parameters are shown in Figure 4.11, 4.12, 4.13, and 4.14, respectively.

Table 4.6. Permeate quality and removal efficiencies of MBR in wastewater treatment

Parameters	Unit	Effluent	Removal (%)
COD	mg/L	28±4	93±0.80
NH_4^+-N	mg/L	0.22±0.05	99±0
Nitrite	mg/L	0.02±0.01	94±3.10
PO_4^{-3}-P	mg/L	4.80±1.70	27±29

<u>4.2.3.1 COD Removal.</u> The average COD, removal efficiencies of MBR were found to be 93%, which corresponds to an average concentration of 28 mg/L in permeate. Nutrient and oxygen concentrations of wastewater were quite enough to support microbial activity, thus organic removal. 93% of COD removal efficiency was evaluated as an evidence of the presences of non-biodegradable soluble COD in permeate (see Figure 4.11).

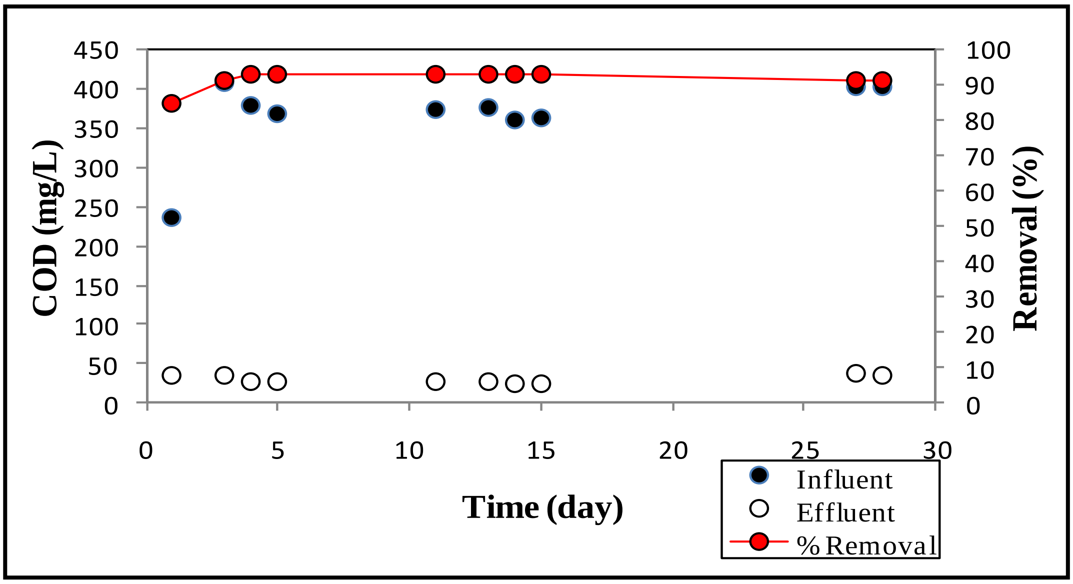


Figure 4.11. Influent and effluent COD concentrations and removal efficiency of MBR in wastewater treatment

4.2.3.2. Ammonium and Nitrite Removal. The average ammonium and nitrite removal efficiencies of MBR were found to be 99% and 94% revealing high-level nitrification capacity of MBR in wastewater treatment (see Figure 4.12 and Figure 4.13).

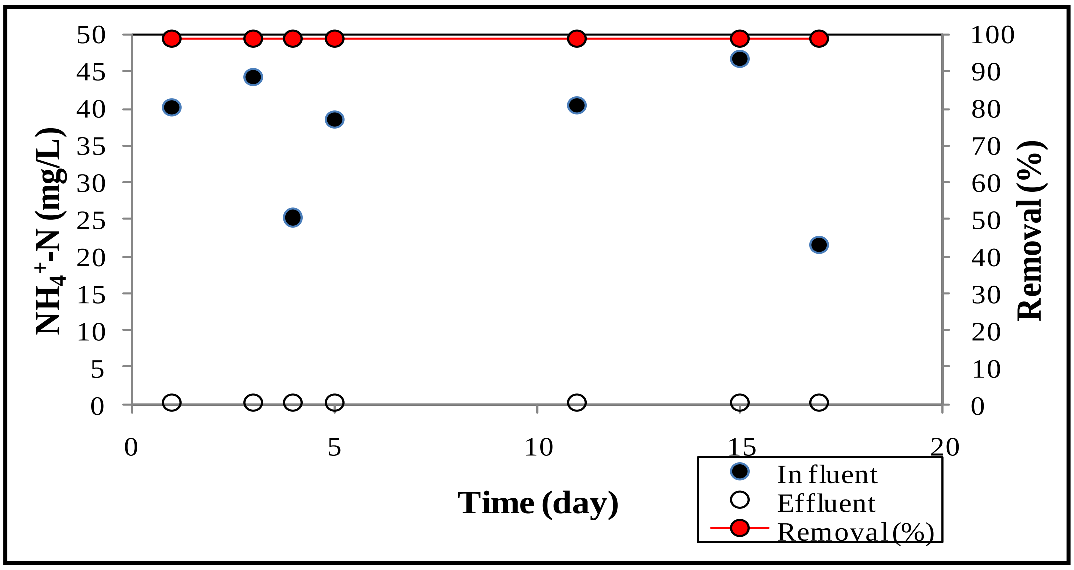


Figure 4.12. Influent and effluent NH_4^+-N concentrations and removal efficiency of MBR in wastewater treatment

Due to high removal efficiency achieved, it was concluded that the soluble biodegradable ammonium and nitrite content is negligible in the effluent.

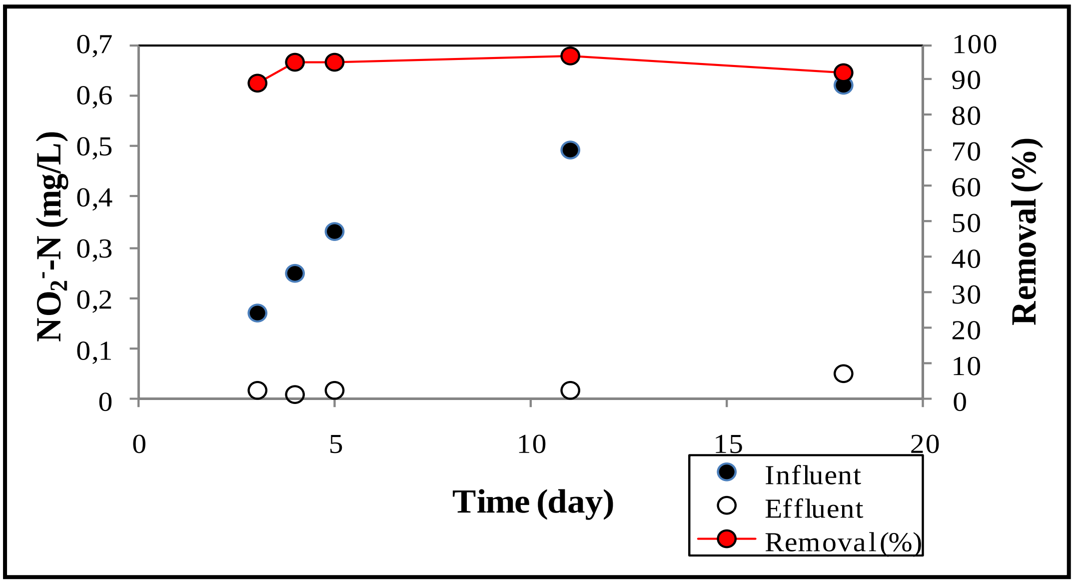


Figure 4.13. Influent and effluent NO_2^--N concentrations and removal efficiency of MBR in wastewater treatment

<u>4.2.3.3. Phosphorus Removal.</u> The reactor was not optimized for phosphorus destruction and overall removal was low. PO_4^{-3}-P removal efficiencies of MBR were found to be 27%. The negative PO_4^{-3}-P removal efficiencies were obtained certain days of the study. Possible explanations are the accumulation of P in the system (Huett et al., 2005) and high HRT causing the hydrolysis of particulate P and affecting permeate quality (Elmitwalli et al., 2007).

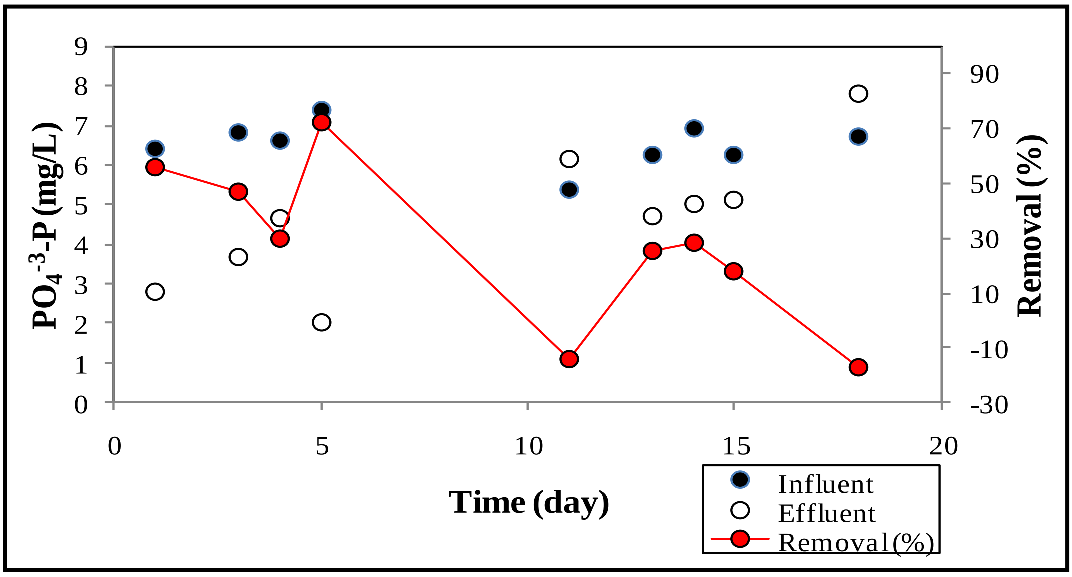


Figure 4.14. Influent and effluent PO_4^{-3}-P concentrations and removal efficiency of MBR in wastewater treatment

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

This study investigated the efficiency of a specific MBR in the treatment of greywater and domestic wastewaters in different MLSS concentrations. Study revealed that MBR provides acceptable results in domestic wastewater treatment. However, feasibility studies and pilot studies should be carried out to determine optimum conditions for efficient treatment. Based on the results of this study following conclusions can be drawn:

- In the treatment of greywater, the highest treatment efficiency of 93% for COD, 82% for NH_4^+-N, 80% for NO_2^--N and 95% for turbidity were achieved at a MLSS concentration of 1000-1200 mg/L.

- Greywater permeate was excellent aesthetic quality and free from odours, which is very important in public acceptance of water reuse.

- The wastewater treatment was realized at a range from 5500 to 6500 mg/L MLSS concentrations. COD, NH_4^{+}-N, nitrite and PO_4^{-3}-P removal efficiencies were found as 93%, 99%, 94% and 27%, respectively.

- In the treatment of greywater, ***"****The Regulation Concerning Water Intended for Human Consumption"* requirements were fulfilled in terms of TOC, ammonium, turbidity, manganese, aluminum, iron and nitrite content of permeate and pH value of effluent. Only bacteria concentrations of the treated greywater were slightly higher than the Regulation limits.

- *US EPA "Suggested Guidelines for Water Reuse"* and "*Water Pollution Control Regulation of Turkey; Notification of Technical Methods"* requirements were complied with except "*urban reuse"* and "*irrigation of food crops not commercially processed"* limits in greywater treatment. Presence of fecal coliform in the effluent made treated greywater unsafe for these purposes.

- Despite 99% removal efficiencies both *e.coli* and total coliform removal, greywater effluent quality was not satisfactory since the *e.coli* and total coliform concentration of >0 CFU/100 mL. The possible reasons were the presence of a torn on the surface of the membrane which might develop during montage of the MBR or contamination of permeate box and/or permeate pipe due to certain reasons during the operation. It is apparent that the MBR requires further disinfection against operational diversities when it is used for human-contact purposes.

- High HRT and low flux affected the quality of permeate negatively that in the negative phosphorus removal was obtained at certain days of the study. Operational conditions especially HRT and flux should be feasibly selected to operate MBR process economically and to achieve satisfactory permeate results because operating a MBR at a low flux and/or high HRT means that the MBR does not operate with its full capacity.

Recommendations for future works:

- Further investigations are needed about nitrification-denitrification processes to achieve reasonable results for nitrogen removal.

- Fouling of the MBR is one of the most significant problems of the MBR process that should be observed and investigated.

- In further investigations, subject MBR should be operated without removal of excess sludge to determine MBR performance in increased MLSS and observe excess sludge production.

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