

**DOKUZ EYLÜL UNIVERSITY**  
**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

**TREATMENT OF DOMESTIC/MUNICIPAL  
WASTEWATERS BY USING DYNAMIC  
MEMBRANE BIOREACTOR SYSTEM FOR  
IRRIGATION PURPOSE**

**by**

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**İZMİR**

# **TREATMENT OF DOMESTIC/MUNICIPAL WASTEWATERS BY USING DYNAMIC MEMBRANE BIOREACTOR SYSTEM FOR IRRIGATION PURPOSE**

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**by  
Yaşar Onur DEMİRAL**

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## M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**TREATMENT OF DOMESTIC/MUNICIPAL WASTEWATERS BY USING DYNAMIC MEMBRANE BIOREACTOR SYSTEM FOR IRRIGATION PURPOSE**” completed by **YAŞAR ONUR DEMİRAL** under supervision of **PROF. DR. AZİZE AYOL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Yaşar Onur DEMİRAL

**TREATMENT OF DOMESTIC/MUNICIPAL WASTEWASTERS BY USING  
DYNAMIC MEMBRANE BIOREACTOR SYSTEM FOR IRRIGATION  
PURPOSE**

**ABSTRACT**

The world water reserves are consumed rapidly due to the increasing population, industrialization and agricultural activities in recent years. Especially, since approximately three-quarters of the water consumption in the world is formed as a result of agricultural irrigation activities, meeting water need of agricultural sector with sustainable and efficient treatment of wastewaters will create water recycle and reduce the use of clean water resources.

Membrane bioreactor systems (MBR) are effective treatment systems in which both biological treatment and physical treatment take place together in wastewater treatment. However, high membrane costs and clogging problem restricting the sustainability of these systems have caused development of textile filter materials for MBR systems as a new research subject.

Dynamic membrane bioreactor (DMBR) systems are modified MBR systems where various membrane support materials are used instead of polymeric membranes. Many researchers have reported that DMBR systems reduce the clogging problem encountered in MBR systems and thus operation with high flux is obtained.

In this thesis, effective treatment of domestic/municipal wastewater by using different textile membrane support materials with DMBR systems was investigated. Synthetic wastewater and different municipal wastewaters were treated with the use of various membrane and textile membrane support materials. It was determined that DMBR systems equipped with textile membrane support materials achieved good removal efficiencies as high as MBR systems. In addition, it was stated whether the

treated water was suitable for various parameters specified in the irrigation water criteria.

**Keywords:** Dynamic membrane bioreactor, wastewater treatment, reuse of wastewaters, irrigation water



# **EVSEL/KENTSEL ATIKSULARIN SULAMA SUYU AMACIYLA DİNAMİK MEMBRANBİYOREAKTÖR SİSTEMİ İLE ARITIMI**

## **ÖZ**

Son yıllarda artan nüfus, endüstrileşme ve tarımsal faaliyetlerden dolayı dünya su rezervleri hızlı bir şekilde tüketilmektedir. Özellikle dünyadaki su tüketiminin yaklaşık dörtte üçünün tarımsal sulama faaliyetleri sonucunda oluşması sebebiyle tarım sektörünün sulama suyu ihtiyacının atıksuların sürdürülebilir ve verimli arıtımı ile karşılanması hem su geri döngüsü oluşturacak hem de temiz su kaynaklarının kullanımını azaltacaktır.

Membran biyoreaktör sistemleri (MBR) atıksu arıtımında hem biyolojik arıtımın hem de fiziksel arıtımın bir arada gerçekleştiği etkili arıtma sistemleridir. Fakat yüksek membran maliyetlerinin ve tıkanma probleminin bu sistemlerin sürdürülebilirliğini kısıtlaması, MBR sistemleri için tekstil filtre malzemelerinin geliştirilmesinin yeni bir araştırma konusu olmasına etken olmuştur.

Dinamik membran biyoreaktör (DMBR) sistemleri polimerik membranların yerine çeşitli tekstil membran destek malzemelerinin kullanıldığı modifiye MBR sistemleridir. Birçok araştırmacı DMBR sistemlerinin MBR sistemlerinde karşılaşılan tıkanma problemini azalttığını ve dolayısıyla yüksek akıda işletim elde edildiğini ortaya koymuştur.

Bu tez çalışmasında, DMBR sistemleri ile evsel/kentsel atıksuların farklı tekstil membran destek malzemeleri kullanarak etkin arıtımı araştırılmıştır. Çeşitli membran ve tekstil membran destek malzemelerinin kullanımı ile farklı kentsel ve sentetik atıksuların arıtımı gerçekleştirilmiştir. Tekstil membran destek malzemesi ile donatılan DMBR sistemlerinin MBR sistemleri kadar yüksek giderim verimleri elde ettiği tespit edilmiştir. Ayrıca arıtılan süzüntü suyunun sulama suyu kriterlerinde belirtilen çeşitli parametreler için uygun olup olmadığı belirtilmiştir.

**Anahtar kelimeler:** Dinamik membran biyoreaktör, atıksu arıtımı, atıksuların tekrar kullanımı, sulama suyu



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# **CHAPTER ONE**

## **INTRODUCTION**

### **1.1 Introduction**

Fresh water resources have been consumed rapidly due to industrialization, agricultural irrigation, increasing population growth and shifting consumption patterns in recent years and water use still goes on growing consistently at a rate of 1% per year (UNESCO, 2020). Thus, protection of existing water resources and development of alternative water resources has come into prominence. It is well-known that three quarters of the World's water consumption stems from agricultural sector. World's population is expected to increase to 10 billion by 2050 and the demand for water resources will inevitably increase due to drinking water consumptions, agricultural and industrial activities in the future (The World Bank, 2020). Beyond this, the negative effects of climate change -induced rainfall reduction, uneven distribution of the rainfall, and soil degradation on natural resources- create a great stress on the water resources. It also brings some important risks like food security and accessing of clean water resources in the content of food-water nexus. Therefore, meeting irrigation water needs of agricultural sector with alternative water resources is important for protection of clean water resources and allowing them available for other use purposes. Wastewater, which is constantly available year-round, is considered as an alternative water resource in that purpose. Moreover, the use of treated wastewater in agriculture is regarded as a kind of nutrient and water recycling, as wastewater contains nutrients necessary for plant growth (World Health Organization, 2006). Additionally, utilizing treated wastewater for irrigation purpose can also contribute to promotion of circular economy by regaining nutrients from treated water and applying them for crop harvesting (European Commission, 2020). In this context, the development of treatment systems that are sustainable, reliable and able to provide irrigation water standards has currently been an important research topic. Studies carried out in recent years reveal that wastewaters can be reused by applying advanced treatment

techniques. These techniques provide the reductions in consumption of fresh water resources and the environmental impacts of discharged waters.

Membrane bioreactor process (MBR) that separates solid and liquid in a bioreactor system has drawn attention for effective wastewater treatment with their advantages such as small space requirement and high removal efficiencies compared to conventional systems. In membrane filtration, substances smaller than the membrane pore size pass through the membrane surface, while substances larger than the membrane pore size cannot penetrate the membrane surface. This mechanism is provided by driving forces in general with pressure. Therefore, concentrated and filtrate parts are formed on both sides of the membrane surface. Moreover, it is possible to disinfect wastewater by removing colloids, pathogens, particles and macromolecules from wastewater with membrane bioreactors. Therefore, MBRs enable discharge of treated water into sensitive receiving environment (Judd, 2011). However, as an important drawback of MBRs, some particles accumulate on membrane surface and this accumulation consequently leads to membrane fouling during membrane filtration. Membrane fouling hinders continuous operation of filtration process. Most of the researches have focused on the fouling phenomena in MBR systems for decades (Santos et al., 2011). Some methods such as coagulant addition, adsorbent addition, use of granular biomass, and quorum quenching have been developed to solve the fouling problem. (Iorhemen et al., 2016) However, as fouling, cleaning, maintenance and operating and membrane costs limit the widespread use of conventional membrane bioreactors. So, cheap and sustainable technologies still need to be developed to enhance the operational stability of membrane bioreactors.

Dynamic membrane bioreactors (DMBR) are defined as novel modified membrane bioreactor systems as they use different membrane support materials instead of conventional polymeric membranes as filter material like mesh, non-woven fabric, woven filter cloth, and stainless-steel mesh. Dynamic membrane (DM) systems can be classified as pre-coated and self-forming systems. While the pre-coated DM is formed on the support material during the filtration, the self-forming

one is formed by the substances existing in the filtered liquor, such as suspended solids in wastewater (Li et al., 2018). One of the major benefits of these systems is that the membrane itself is no longer needed. A cake layer is formed by accumulation of solid particles on the membrane support material and this layer called the dynamic membrane (DM) provides a high rate of solid rejection by acting as a secondary membrane. Thus, microbial cells and flocks that normally cause membrane clogging will contribute to the formation of dynamic membrane. The dynamic membrane will delay membrane clogging by acting as a barrier in front of the membrane support material after its formation (Ersahin et al., 2012). A wide variety of inexpensive membrane support materials such as stainless steel mesh, woven fabric and non-woven fabric can be used instead of conventional microfiltration and ultrafiltration membranes. Utilizing cheap support materials thereby procures continuous high flux and lower transmembrane pressure in a cost effective way. Although DMBR provides significant benefits in the field of wastewater treatment, it has not received the necessary attention because it is in the development stage (Li et al., 2018).

## **1.2 Aim of the Thesis**

Overall aim of the study is to investigate the treatability of domestic/ municipal wastewater with a dynamic membrane bioreactor (DMBR) system to reuse the wastewaters for irrigation purpose. It is also aimed to make contribution to the development of DMBR systems regarding the information gaps in the literature. The objectives of the thesis are therefore:

- To investigate the treatability of domestic/municipal wastewaters by dynamic membrane bioreactors and identification of appropriate operating conditions,
- To determine the most suitable support material to ensure the continuity of the system by applying different membrane support materials,
- To assess the effluent water quality based on the Turkish legislation on the irrigation water criteria,

- To reveal the properties of treatment sludge formed in the system including the rheological properties of the mixed liquid and the formed sludge in the system,
- To determine the biokinetic modeling of the system,
- To analyze of the active microbial population involving the treatment process.

All pursuits from the thesis study will shed light on full-scale treatment applications.



## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 Membrane Technology

Membrane technology based on the principle of separating two phases on a selectively permeable surface has a very important role in the separation industry. Removal and extent to which of pollutants available in water/wastewaters like dissolved solids, organic materials, microorganisms, and turbidity depend on the pore size of the membranes used in treatment. While the substances having larger size than the pores in the membranes are completely removed, other substances having smaller sizes are partially removed, depending on the construction of a refuse layer on the membrane (Judd, 2011). The particle movement in membrane separation takes place with the formation of different driving forces (Ezugbe & Rathilal, 2020). In membrane applications, there are different processes like equilibrium and non-equilibrium processes, and pressure driven and non-pressure driven processes as depicted in Figure 2.1. Among them, the pressure driven processes are the most widely used in wastewater treatment.

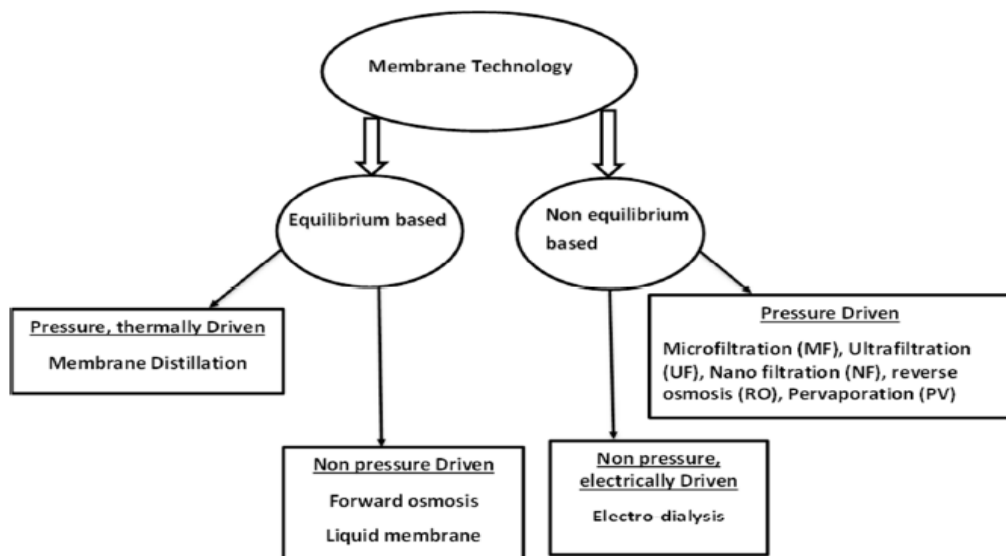


Figure 2.1 Schematic representation of some membrane processes (Ezugbe & Rathilal, 2020)

### 2.1.1 Pressure Driven Membrane Processes

Pressure driven membrane processes requiring pressure for separation have four main types as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. These systems differ in their pore sizes as well as the pressure they need (Ezugbe & Rathilal, 2020). Table 2.1 shows the classification of the processes regarding the pore size, driving force, and permeability.

Table 2.1 Classification of pressure driven membrane processes (Hankins & Singh, 2016)

| Process         | Pore Size     | Driving Force | Average Permeability (L/m <sup>2</sup> h) |
|-----------------|---------------|---------------|-------------------------------------------|
| Microfiltration | 0.05-10 µm    | 1-3 bar       | 500                                       |
| Ultrafiltration | 0.001-0.05 µm | 2-5 bar       | 150                                       |
| Nanofiltration  | <2 nm         | 5-15 bar      | 10-20                                     |
| Reverse Osmosis | ~0.5 nm       | 15-75 bar     | 5-10                                      |

Membranes with pore sizes between 0.05 µm and 10 µm are classified as microfiltration membranes, which may remove all bacteria in wastewater. Although viruses are smaller than pore size of a microfiltration membrane, viral contamination may be reduced partially as viruses can attach themselves to bacterial biofilm (Wenten & Khoiruddin, 2016).

Microfiltration (MF) may be used in various water treatment processes to remove particles with particle size larger than 10 µm. Examples of microfiltration applications are:

- Separation of oil/ water emulsions,
- Separation of bacteria from wastewater
- Cold sterilization of beverages and pharmaceuticals
- Effluent treatment

- Pre-treatment of water for nanofiltration and reverse osmosis
- Clearing of fruit juice, wines and beer

Ultrafiltration (UF) membranes include membranes with a pore size ranging from 0.001  $\mu\text{m}$  to 0.05  $\mu\text{m}$ . UF membranes have an asymmetric structure with a much denser skin layer that produces higher hydrodynamic resistance. Compared to MF membranes, ultrafiltration membranes can achieve complete removal of viruses (Singh, 2005). Example of ultrafiltration process applications are:

- Sugar refining – removal of polysaccharides, proteins, colloids.
- Lignin removal in pulp and paper processes.
- High purify water
- Potable water – removal of bacteria and viruses
- Reverse osmosis pre-treatment

Nanofiltration (NF) uses more fine membranes; therefore, the feed pressure of the nanofiltration system is generally higher compared to microfiltration and ultrafiltration membranes. NF membranes can be applied for the removal of two valued ions and larger mono valued ions such as heavy metals (Hankins & Singh, 2016). Specific applications of NF membranes are as follows:

- Selective salt rejection
- Treatment of effluents containing heavy metals
- Cleaning of contaminated groundwater
- Water softening

Reverse osmosis (RO) systems, which the mass transfer occurs via diffusion through the membranes, are known as diffusion- controlled processes. As RO membranes are hydrophilic, water easily diffuse through membrane polymer structure (Wenten & Khoiruddin, 2016). Example of RO applications are:

- Seawater desalination
- Water softening

- Ultrapure water production
- Mining effluent treatment

### 2.1.2 Membrane Materials

Although the number of materials used for membrane production is more than a hundred, this number is very low in water and wastewater treatment applications as high acidic, basic, chemical and mechanical durability is needed (Park et al., 2015). There are generally two types of membrane materials for treatment processes: polymeric and ceramic membranes. The polymeric materials used commonly are polysulfone (PSF), polytetrafluoroethylene (PTFE), cellulose acetat (CA), polyvinylidene fluoride (PVDF), polyvinyl chloride (PVC), polyethylene (PE) and polypropylene (PP) with mechanical strength, chemical resistance, and biological stability. Additionally, polyether sulfone (PES) membranes are very popular for ultrafiltration process (Huang et al., 2010). Figure 2.2 shows the molecular structure of the most commonly used polymers for membranes. The membrane materials have advantages and disadvantages according to their intended use or advantages over each other as summarized in Table 2.2.

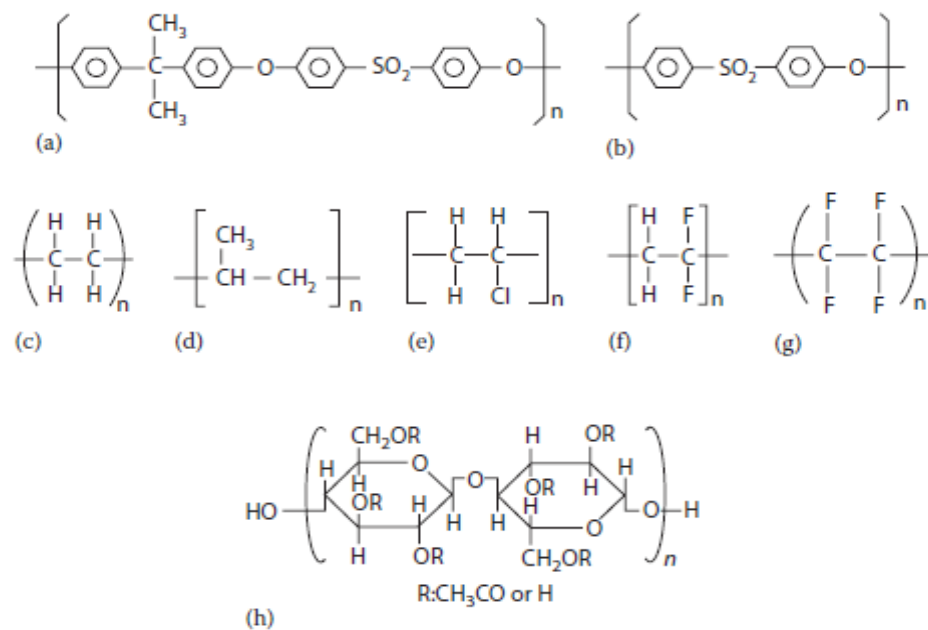


Figure 2.2 Molecular structure of most commonly used polymers for membranes: (a) PSF, (b) PES, (c) PE, (d) PP, (e) PVC, (f) PVDF, (g) PTFE, and (h) CA (Park et al., 2015)

Table 2.2 Advantages and disadvantages of membrane materials (Park et al., 2015)

| Polymer | Advantage                                                                                                                                        | Disadvantage                                                                                                        |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|
| PSF     | <ul style="list-style-type: none"> <li>✓ Easy to structure</li> <li>✓ Safe from leaching</li> <li>✓ High mechanical strength</li> </ul>          | <ul style="list-style-type: none"> <li>✓ Rigid/ brittle</li> <li>✓ Low chemical durability</li> </ul>               |
| PES     | <ul style="list-style-type: none"> <li>✓ Easy to form structure</li> <li>✓ Safe from leaching</li> <li>✓ High mechanical strength</li> </ul>     | <ul style="list-style-type: none"> <li>✓ Rigid/ brittle</li> <li>✓ Low chemical durability</li> </ul>               |
| PE      | <ul style="list-style-type: none"> <li>✓ Low material cost</li> <li>✓ High elongation</li> </ul>                                                 | <ul style="list-style-type: none"> <li>✓ Wide pore size distribution</li> </ul>                                     |
| PP      | <ul style="list-style-type: none"> <li>✓ Low material cost</li> <li>✓ High elongation</li> </ul>                                                 | <ul style="list-style-type: none"> <li>✓ Wide pore size distribution</li> </ul>                                     |
| PVC     | <ul style="list-style-type: none"> <li>✓ Low material cost</li> <li>✓ High elongation</li> </ul>                                                 | <ul style="list-style-type: none"> <li>✓ Wide pore size distribution</li> <li>✓ Side effect by additives</li> </ul> |
| PVDF    | <ul style="list-style-type: none"> <li>✓ Narrow pore size distribution</li> <li>✓ High chemical durability</li> </ul>                            | <ul style="list-style-type: none"> <li>✓ Not easy to form structure</li> <li>✓ Weak to basic conditions</li> </ul>  |
| PTFE    | <ul style="list-style-type: none"> <li>✓ High water permeability</li> <li>✓ High chemical durability</li> <li>✓ Low fouling potential</li> </ul> | <ul style="list-style-type: none"> <li>✓ Difficult module fabrication</li> <li>✓ High material cost</li> </ul>      |
| CA      | <ul style="list-style-type: none"> <li>✓ Hydrophilic (easily wet)</li> <li>✓ Easy to form structure</li> </ul>                                   | <ul style="list-style-type: none"> <li>✓ Low acid/base durability</li> <li>✓ Low chemical durability</li> </ul>     |

### 2.1.3 Membrane Configuration

The configuration or geometric shape of membrane indicates how the membranes will allow fluid flow. Membrane configuration as an important factor on the process performance are fall into four main configurations as flat sheet (FS) or flat plate (FP), spiral wound (SW), hollow fiber (HF), and multi tubular (MT) in treatment processes. While the membrane geometry is planar for FS and SW, it is cylindrical for HF and MT as shown in Figure 2.3. The compactness, high degree of turbulence at the retentate side, uniform velocity distribution, easy cleaning and maintenance, and low cost are the most sought-after features in membrane configuration (Judd, 2011).

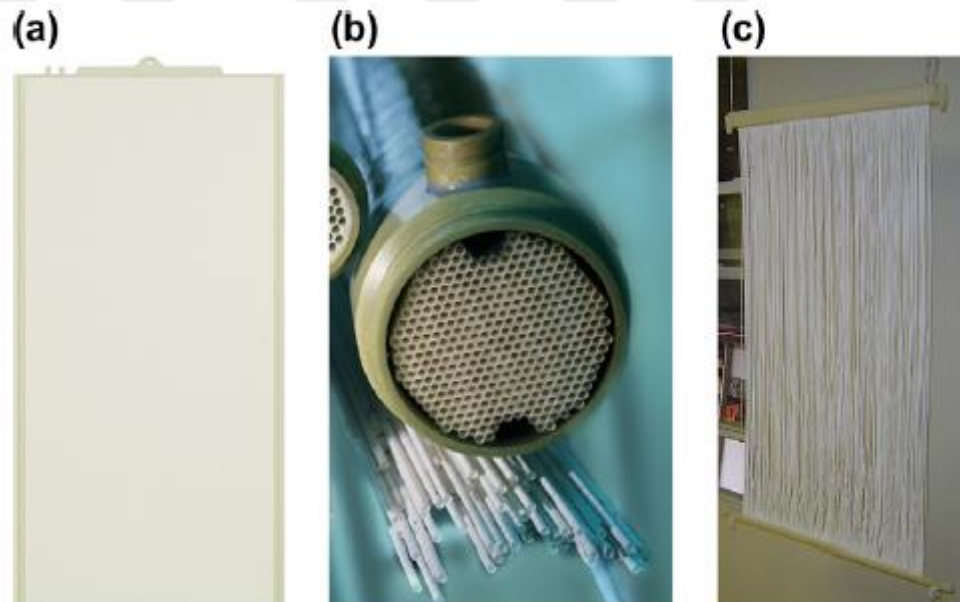


Figure 2.3 Membrane configurations: (a) FS, (b) MT, (c) HF modules (Judd, 2011)

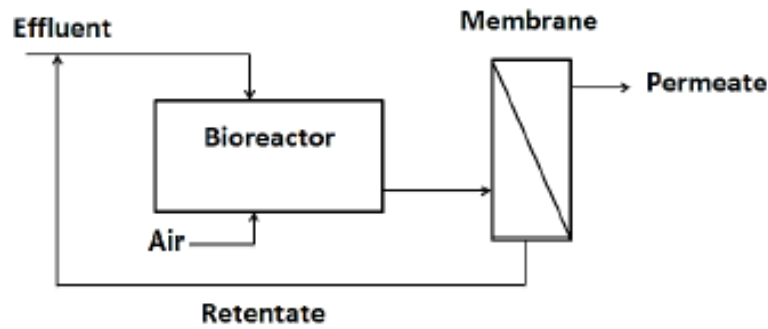
As the most commonly applied membrane configuration, FS membranes generally having a rectangular shape arranged in vertical or horizontal stacks. FS modules can be limited to MF and UF processes since it cannot tolerate very high pressure. The surface area to volume ratio of flat sheet modules is not high. Since the hollow fiber module's small diameter conveys to the tubes necessary mechanical strength, an external rigid support is not necessary. Lots of HF may be placed on module efficiently. Therefore, compactness is the significant advantage of hollow fiber modules (Judd, 2011).

## **2.2 Membrane Bioreactor**

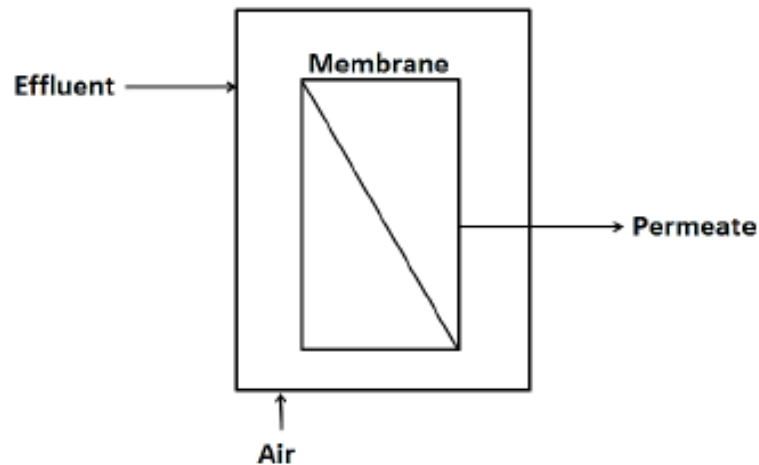
### ***2.2.1 Principles of Membrane Bioreactor***

Membrane bioreactor (MBR) is considered as a hybrid process including biological- secondary and tertiary treatment in the same tank. The MBR process provides a solid free effluent, nutrient removal and disinfected effluent that can be discharged to sensitive environment (Katz et al., 2017). MBRs that separate permeate biomass physically thanks to membrane equipment are biological processes operating in suspension growth mode. It is possible to operate MBRs with high MLSS concentration by reducing the reactor volume to achieve a high organic loading rate. Moreover, MBR systems withhold all biomass and suspended solids in reactor and guarantee effluent without turbidity.

Two types of MBR configuration are currently in use, namely internal/submerged MBR and external/side stream MBR as shown in Figure 2.4. The membrane is placed outside the bioreactor in external MBR configuration. The mixed liquid is transported to the membrane through pump for filtration. Therefore, external MBRs require more energy use and application of external MBRs are very limited, whereas the membrane module is placed into bioreactor in submerged MBR configuration and this configuration has been applied widespread due to its simplicity and lower energy consumption. Nevertheless, it has its own disadvantages due to difficulties in membrane cleaning as it is submerged in bioreactor (Ezugbe & Rathilal, 2020).



**A. Side stream MBR**



**B. Submerged MBR**

Figure 2.4 Types of MBR configuration (Ezugbe & Rathilal, 2020)

### 2.2.2 Development of MBRs

First MBR technology in the literature was introduced by Dorr-Oliver research program. They develop an alternative wastewater treatment process without settlement tank to separate treated water and sludge with an ultrafiltration membrane (Park et al., 2015). Historically, the first MBR systems were used for small-scale water treatment in hotels, amusement parks and watercrafts due to its cost and small space requirements. With the development of MBR technology in 1990s, a full-scale domestic wastewater treatment plant equipped with MBR was installed in the UK with a capacity of 1.9 mega gallon per day (MGD) (Le-Clech, 2010). MBRs have been also used for industrial wastewater treatment such as pharmaceutical, paper and pulp, landfill, and textile industries. Table 2.3 summarizes the historical development of MBR technology.

Table 2.3 Historical development of MBR technology (Buer & Cumin, 2010)

| Time        | Event                                                                            | Technology                         |
|-------------|----------------------------------------------------------------------------------|------------------------------------|
| Late 60s    | Dorr Oliver develops first MBR                                                   | Pressurized flat-sheet             |
| Early 70s   | Thetford-Systems (ZENON) commercializes Cyle-Let for water reuse in Japan        | Pressurized flat-sheet             |
| Mid 80s     | Nitto-Denko files a Japanese patent on a immersed MBR                            | Immersed flat-sheet                |
|             | University of Tokyo experiments with hollow fiber MBR                            | Immersed hollow fiber              |
| Early 90s   | Kubota commercializes an MBR in Japan                                            | Immersed flat-sheet                |
|             | Mitsubishi Rayon commercializes an MBR in Japan                                  | Immersed unsupported hollow fibers |
| Early 2000s | USF commercializes Memjet                                                        | Immersed unsupported hollow fibers |
|             | Toray introduces a copy-like version of Kubota module                            | Immersed flat-sheet                |
|             | Mitsubishi Rayon replaces their fine hollow fiber with a braid based HF membrane | Immersed reinforced hollow fiber   |

### 2.2.3 Advantages and Drawbacks of MBRs

Researchers are working on advanced treatment systems that will reduce the investment and operating costs by developing conventional sludge systems. MBR systems have several advantageous features when compared to conventional activated sludge systems. MBR systems have attracted attention not only with operating parameters such as high biomass, low sludge production, but also with low treatment, low energy consumption, and low manpower requirement (Kizilet et al., 2017). Additionally, hydraulic retention time (HRT) and sludge retention time (SRT) value ranges are wide in these systems permitting a flexible control of operational parameters. A MBR is able to process significantly higher sludge concentrations in lower reactor volumes, which allows efficient treatment of strength wastewaters. As membranes withhold bacteria and viruses especially UF applications, a MBR provides removal of pathogens (Melin et al., 2006). General advantages can be listed as follows (Kootenaei & Aminirad, 2014):

- Extremely good quality filtered effluent,
- High solids concentrations and eliminating sludge bulking, sludge rising problems,
- Modular construction possibility,
- Low energy consumption,
- High removal efficiency of total coliform,
- No chemical requirement,
- Reusability of effluent water,
- Higher rate of nitrification and denitrification,
- Degradation of slowly biodegradable contaminants,
- Constant effluent quality regardless of influent.

Some important drawbacks of MBR systems can be given as follows:

- Partial investment and operation cost,
- Membrane lifetime and replacement,
- Membrane fouling problem.

#### ***2.2.4 MBR Applications in Municipal Wastewater Treatment***

MBR systems are currently used in many parts of the World for treatment of municipal wastewaters. Many studies in the literature reported that MBRs give better treatment efficiencies compared to conventional biological wastewater treatment processes.

Removal efficiencies of organic matters from wastewaters are remarkably high in MBR applications based on BOD, COD, TOC and DOC parameters. COD removal efficiency varies from 90% to 99% for domestic, municipal, and synthetic wastewaters. Most of the removal efficiencies almost 80-90% takes place inside the bioreactor due to biological degradation and the membrane contributes 10-20% COD removal due to rejection, plugging and adsorption properties. The membrane itself is not enough for effective nutrient removal. However, MBR units operated with

anaerobic and anoxic tanks can achieve high nutrient removal. Almost all of the studies showed that MBRs had suspended solids free effluent water. Additionally, MBRs have potential to increase total coliform below detection limits, less than 1 CFU/100 mL in the effluent (Jadhao & Dawande, 2012). Table 2.4 gives some removal efficiencies and effluent quality for municipal wastewaters obtained from the study done by Melin et al. (2006).

Table 2.4 Removal efficiencies and effluent quality (Melin et al., 2006)

| Parameter          | Unit       | Removal Efficiency (%) | Effluent Quality |
|--------------------|------------|------------------------|------------------|
| TSS                | mg/L       | >99                    | <2               |
| Turbidity          | NTU        | 98.8-100               | <1               |
| COD                | mg/L       | 89-98                  | 10-30            |
| BOD                | mg/L       | >97                    | <5               |
| DOC                | mg/L       |                        | 5-10             |
| NH <sub>3</sub> -N | mg/L       | 80-90                  | <5               |
| TN                 | mg/L       | 36-80                  | <27              |
| TP*                | mg/L       | 62-97                  | 0.3-2.8          |
| Total Coliform     | CFU/100 mL | 5-8 log                | <100             |
| Faecal Coliform    | CFU/100 mL |                        | <20              |

\*with a dosage of ferric

Shen et al. (2012) investigated treatment performance of full-scale domestic wastewater treatment plants (WWTPs) operated with MBR in China. All plants are operated by processes consisting of anaerobic, anoxic and aerobic tanks and have microfiltration membranes of different membrane suppliers. The technical information of WWTPs is given in Table 2.5. Each plant achieved a high degree of nutrient and organic matter removal. Those results reveal that membrane bioreactors operated with advanced treatment systems such as A<sup>2</sup>O and BardenPho have high nutrient removal as well as organic matter removal. Influent and effluent wastewater characteristics and other operating parameters are summarized in Table 2.6.

Table 2.5 Properties of wastewater treatment plants (Shen et al., 2012)

| WWTP <sup>a</sup> | Process <sup>b</sup> | Membrane Suppliers                      | Membrane Parameters (μm) | Capacity (m <sup>3</sup> /d) | Wastewater Type               | Date |
|-------------------|----------------------|-----------------------------------------|--------------------------|------------------------------|-------------------------------|------|
| B1                | A1-A2-O-MBR          | Siemes, Membcor, Germany                | PVDF, 0.04               | 60000                        | Domestic                      | 2007 |
| B2                | A1-A2-O-MBR          | Asahi Kasei, Microza MUNC-620A, Japan   | PVDF, 0.1                | 35000                        | 80% Domestic + 20% Industrial | 2007 |
| B3                | A1-A2-O-MBR          | Mitsubishi Rayon, Sterapore SADF, Japan | PVDF, 0.4                | 40000                        | 80% Domestic + 20% Industrial | 2010 |
| B4                | A1-A2-O-MBR          | Mitsubishi Rayon, Sterapore SADF, Japan | PVDF, 0.4                | 30000                        | Domestic                      | 2009 |
| W1                | A1-A2-O-MBR          | GE/Zenon, ZeeWeed 500d, USA             | PVDF, 0.04               | 30000                        | 40% Domestic + 60% Industrial | 2009 |
| W2                | A1-A2-O-MBR          | Siemes, Membcor, Germany                | PVDF, 0.04               | 20000                        | 40% Domestic + 60% Industrial | 2009 |
| W3                | A1-A2-O-A2-MBR       | Mitsubishi Rayon, Sterapore SADF, Japan | PVDF, 0.4                | 20000                        | 40% Domestic + 60% Industrial | 2009 |
| W4                | A1-A2-A2-O-MBR       | OriginWater, China                      | PVDF, 0.1                | 50000                        | 60% Domestic + 40% Industrial | 2010 |
| S1                | A1-A2-O-MBR          | OriginWater, China                      | PVDF, 0.1                | 110000                       | Domestic                      | 2009 |
| K1                | A1-A2-O-A2-MBR       | OriginWater, China                      | PVDF, 0.1                | 60000                        | Domestic                      | 2010 |

<sup>a</sup> WWTP: wastewater treatment plant<sup>b</sup> A1: anaerobic, A2: anoxic, O: oxic

Table 2.6 Treatment efficiencies of wastewater treatment plants (Shen et al., 2012)

| WWTP | HRT (h) | SRT (g) | MLSS (g/L) | Influent Concentration (mg/L) |        |          | Effluent Concentration (mg/L) |           |           |
|------|---------|---------|------------|-------------------------------|--------|----------|-------------------------------|-----------|-----------|
|      |         |         |            | COD                           | TN     | TP       | COD                           | TN        | TP        |
| B1   | 17.3    | 20      | 7.0-8.5    | 550-700                       | 60-80  | 7-9      | 15-20                         | 15-25     | 0.30-0.50 |
| B2   | 40.6    | 25-30   | 3.4-12.1   | 260-1100                      | 40-130 | 3.5-15.0 | 11-56                         | 6.7-11.2  | 0.03-2.65 |
| B3   | 30.2    | 30      | 2.6-7.8    | 70-556                        | 35-78  | 1.2-7.8  | 15-45                         | 12.0-48.0 | 0.04-0.70 |
| B4   | 16-17   | 24-28   | 3.5-4.2    | 137-1400                      |        |          | 12-58                         |           |           |
| W1   | 10.9    | 20-30   | 5.6-16.5   | 86-867                        | 23-162 | 1.0-34.1 | 2-61                          | 3.6-24.7  | 0.04-0.40 |
| W2   | 10-14   | 14      | 3.2-12.0   | 165-1404                      | 30-81  | 2.5-22.4 | 8-91                          | 3.4-18.6  | 0.05-0.89 |
| W3   | 33-38   | 27-37   | 7.0-11.5   | 159-781                       | 22-67  | 1.4-5.4  | 3-36                          | 3.0-13.1  | 0.03-0.67 |
| W4   | 12-13   | 25-32   | 5.6- 10.4  | 140-1250                      | 15-165 | 1.6-48.0 | 8-53                          | 4.2-22.7  | 0.03-1.45 |
| S1   | 16.4    | 24      | 1.9-3.0    | 178-268                       |        | 1.1-2.6  | 6-30                          |           | 0.03-1.87 |
| K1   | 16-17   | 24-25   | 5.6-9.6    | 98-393                        | 21-38  | 2.0-6.1  | 15-25                         | 8.8-14.6  | 0.08-0.23 |

## 2.2.5 Specific Parameters of MBRs

### 2.2.5.1 Flux

Flux is the amount of water flowing through the simple unit membrane area per unit time. Flux ( $J$ ) is given in  $L/m^2/h$  (LMH) in MBRs. According to Darcy's Law, flux is a function of the transmembrane pressure (TMP), the permeate viscosity ( $\eta$ ) and the total resistance ( $R_T$ ) (Judd, 2011).

$$J = \frac{TMP}{\eta \cdot R_T} \quad (2.1)$$

### 2.2.5.2 Critical Flux

Critical flux determines the level at which the sharp increase in TMP begins. The step-wise method is frequently used in the determination of critical flux as plotted in Figure 2.5. In this method, the flux is gradually increased and the sharp rise in TMP is detected. Thus, control of the material storage becomes easier and early clogging can be prevented (Le et al., 2003).

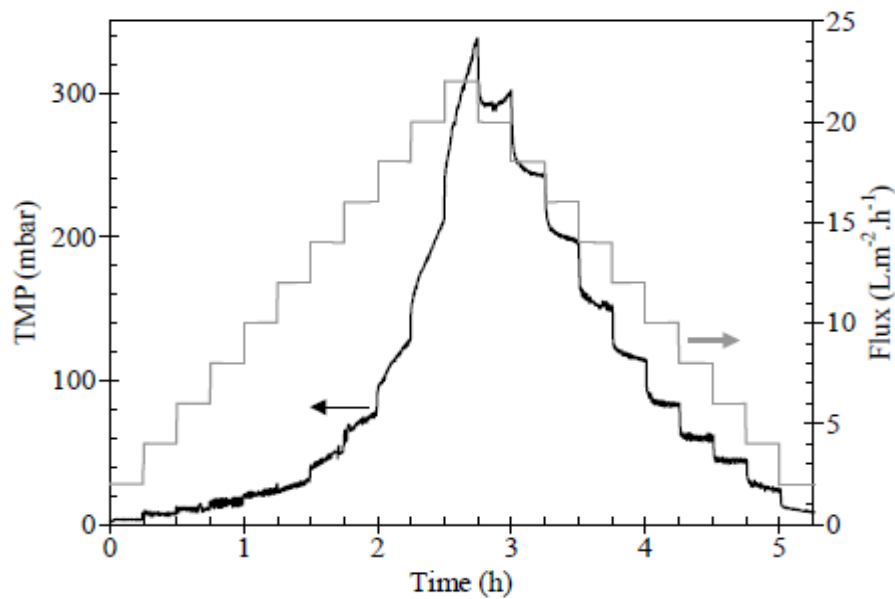


Figure 2.5 Critical flux determination (Le et al., 2003)

### 2.2.5.3 Membrane Resistance

The total membrane resistance may be divided in four different partial resistances (Mulder, 1996) as shown in Eq. 2.2. The resistance component during membrane process is also depicted in Figure 2.6.

$$R_T = R_M + R_C + R_F + R_{CP} \quad (2.2)$$

$R_T$ : Membrane resistance,

$R_C$ : Resistance due to cake layer formation on the membrane,

$R_F$ : Resistance due to membrane fouling linked to adsorption and pore blocking,

$R_{CP}$ : Resistance originated from the formation of condensation polarization layer.

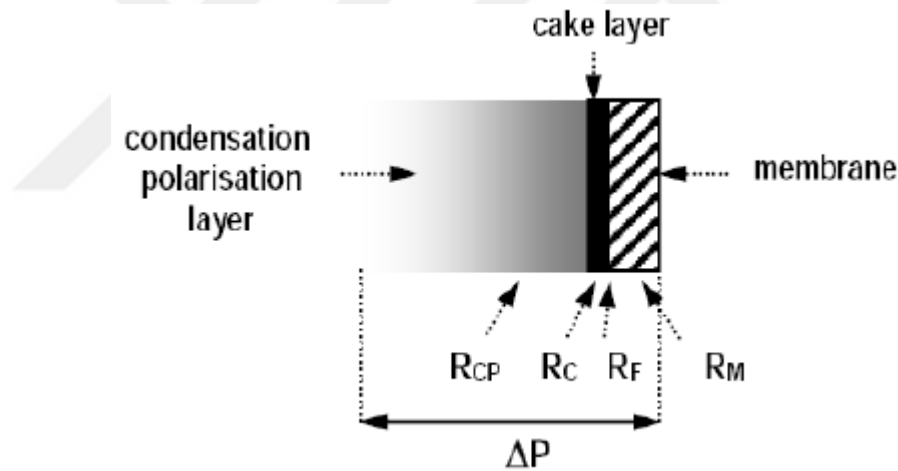


Figure 2.6 Resistance components during membrane process (Jeison, 2007)

## 2.3 Membrane Fouling

The clogging problem occurring when substances such as microorganisms, colloids, suspended solids accumulate on the membrane surface or inside its pores is the most important factor affecting membrane operation. International Union of Pure and Applied Chemistry (IUPAC) working group on membrane nomenclature explains membrane fouling as follows: “*process resulting in loss of performance of a membrane due to the deposition of suspended or dissolved substances on its external*

surfaces, at its pore openings, or within its pores” (Koros et al., 1996). If foulants are deposited in the pores of membrane, fouling is described as irreversible. Whereas, if foulants are deposited only on the membrane surface and form a cake layer thus prevent permeability, fouling is described as reversible (Ezugbe & Rathilal, 2020). Fouling in MBR systems occurs by three different processes, which are pore narrowing, pore clogging, and cake formation respectively. Consequently, formed sludge cake increases membrane resistance and decreases filterability. Membrane foulants may be classified into three groups, which are biofoulants, organic foulants and inorganic foulants. Biofoulants usually consist of bacteria and flocks. Organic foulants arise from biopolymers such as polysaccharides and proteins. Soluble microbial products (SMPs) are also an important component of organic foulants. Inorganic foulants, on the other hand, consist of anions and cations such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$ ,  $\text{SO}_4^{2-}$ ,  $\text{PO}_4^{3-}$ ,  $\text{CO}_3^{2-}$  accumulating on the surface or inside the pores (Iorhemen et al., 2016). Figure 2.7 shows the fouling processes in MBRs.

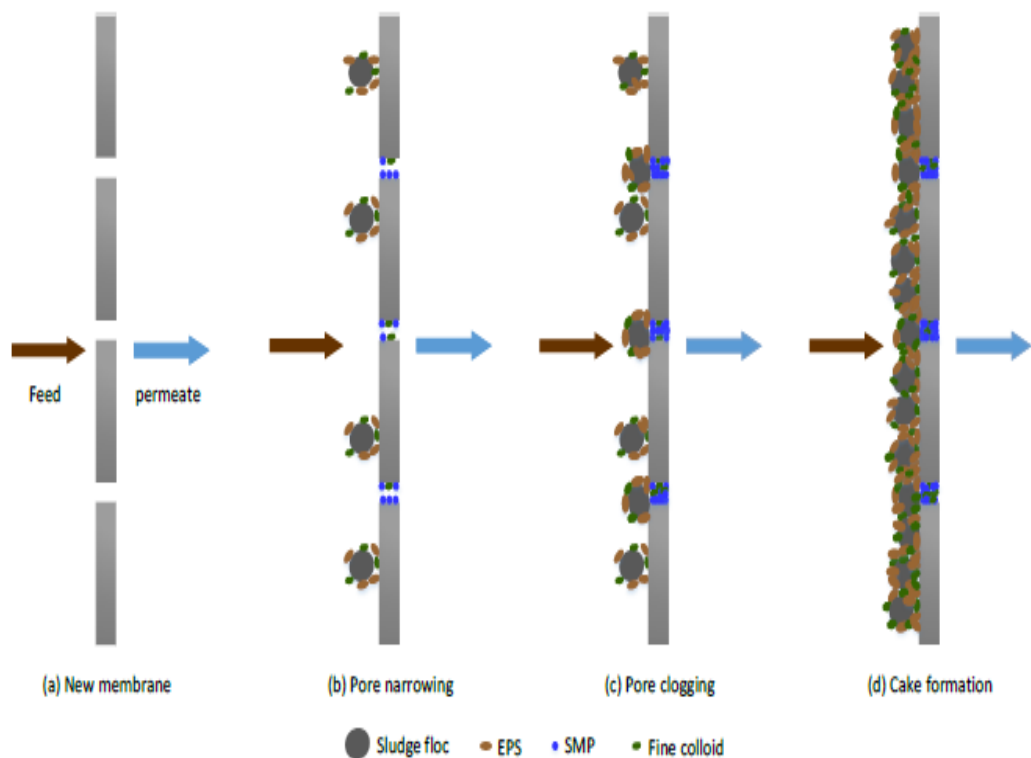


Figure 2.7 Fouling processes in MBRs (Iorheman et al., 2016)

Other main factors affecting membrane fouling can be divided into three as membrane characteristic, operational conditions, and feed and biomass characteristics. All factors are schematized in Figure 2.8.

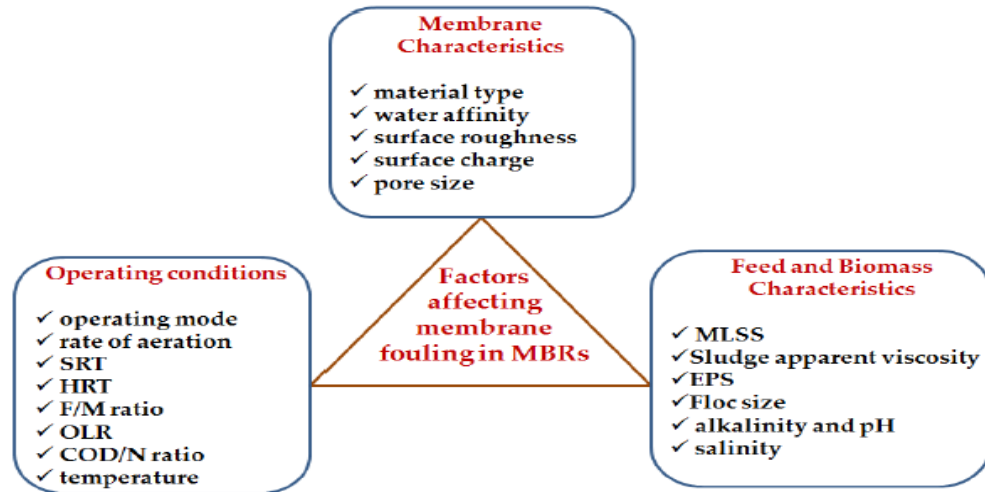


Figure 2.8 Factors affecting fouling in MBRs (Iorhemen et al., 2016)

Since membrane fouling is the most important operational problem in MBRs, many researchers have done research especially on this subject. In these studies, main aim is to determine the factors that cause fouling and to minimize the problems in MBR operation by eliminating these factors. Santos et al. (2011) reviewed publications on MBRs as summarized in Figure 2.9 and found that MBR researches were mostly on the problem of fouling with a focus on EPSs and SMPs.

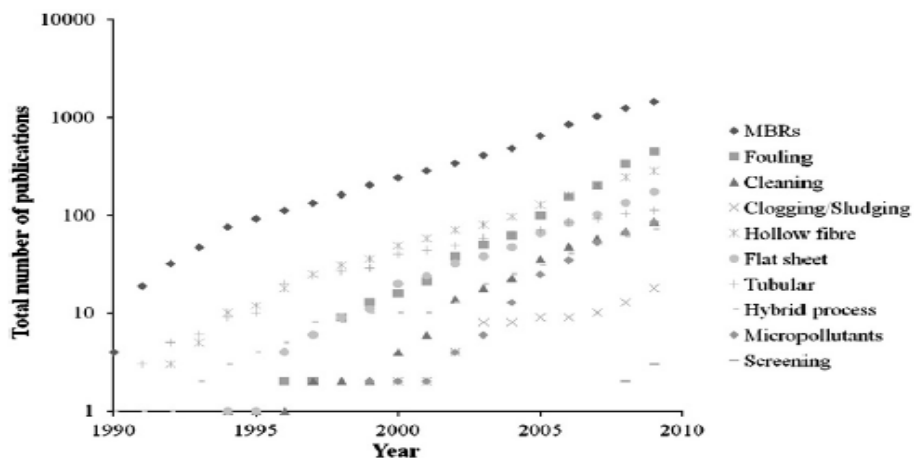


Figure 2.9 Research trends in MBRs (Santos et al., 2011)

### ***2.3.1 Control Methods of Membrane Fouling***

Membrane fouling can be removed and operation flux can be adjusted again by utilizing membrane cleaning methods. Membrane cleaning methods are classified as physical cleaning (back flushing and pneumatic cleaning), chemical cleaning, and electric cleaning (Du et al., 2020).

**Back Flushing:** This method is based on the mechanical removal of foulants from membrane surface. Foulants are removed by applying pressure in the opposite direction. However, this method is not efficient to remove irreversible fouling caused by colloidal and dissolved particles (Yigit et al., 2009).

**Pneumatic Cleaning:** This method includes air lifting, air sparging and air scouring. The air causes shear force on the membrane surface and distributes the pollutants on the surface. This method is advantageous as no chemicals are used, but it requires a large amount of air pumping (An et al., 2010).

**Chemical Cleaning:** Chemical cleaning is used for irreversible fouling. Choosing the right chemical is an important issue for this method. Because, chemicals should dissolve foulants and not damage the structure of the membrane. Generally acids, alkalis/bases, surfactants and disinfectants are used as cleaning detergent (Ezugbe & Rathilal, 2020).

**Electric Cleaning:** In this method, an electric field is used to make foulants move from the film surface in the direction of the electric field and therefore membrane surface is cleaned (Iorhemen et al., 2016).

## 2.4 Dynamic Membrane Bioreactor

The high membrane material cost, energy requirement and fouling problem of membrane bioreactors restrict the widespread use of these systems. Therefore, dynamic membrane bioreactors have been introduced as an alternative and novel technology due to their low support material cost, high flux and easy backwashing (Hu et al., 2016). A dynamic membrane (DM) is formed by the accumulation of suspended solids and colloids on a support material in a bioreactor. DM acts as a secondary membrane from the moment it is formed on (Li et al., 2018). IUPAC's working group on membrane nomenclature explains dynamic membrane (DM) formation as follows: *“process in which an active layer is formed on the membrane surface by the deposition of substances contained in the fluid being treated”* (Koros et al., 1996). These systems based on the formation of a dynamic cake layer on the support material are called dynamic membrane bioreactor (DMBR). The comparison of MBR and DMBR systems done by Cinar et al. (2016) is given in Table 2.7.

The first dynamic membrane application was applied in 1966 for salt rejection in a reverse osmosis process. In the 1980s, dynamic membrane applications were used UF process for wastewater treatment, dye and protein removal. Dynamic membrane applications have been studied in the field of wastewater treatment since the 1990s. The dynamic membrane process, which is operated both anaerobically and aerobically, attracts the attention of researchers due to low investment cost and convenience of operation. Many researchers have determined that dynamic membranes provide treatment close to conventional UF/MF membranes (Ersahin et al., 2012).

DMs are classified into two main groups, self-forming and pre-coated. Pre-coated DMs are formed by passing additional materials such as powdered activated carbon, kaolite and bio-diatomite over the surface of support material. Self-forming dynamic membranes (SFDM) draw more attention than pre-coated dynamic membrane. A SFDM formed by the deposition of filtered materials, namely cake layer, in mixed liquid suspended solids. Colloids and flocks are important factors in the formation of

SFDM (Fan & Huang, 2002). Additionally, it is reported that electrostatic interaction, van der Waals interactions, hydrophobic interactions and steric interactions are important mechanisms playing significant role in DM formation (Li et al., 2018). From formation of the cake layer on, DM retains suspended solids as a secondary membrane and prevents the support material from fouling (Veral et al., 2017). Figure 2.10 illustrates the formation of dynamic membrane layer.

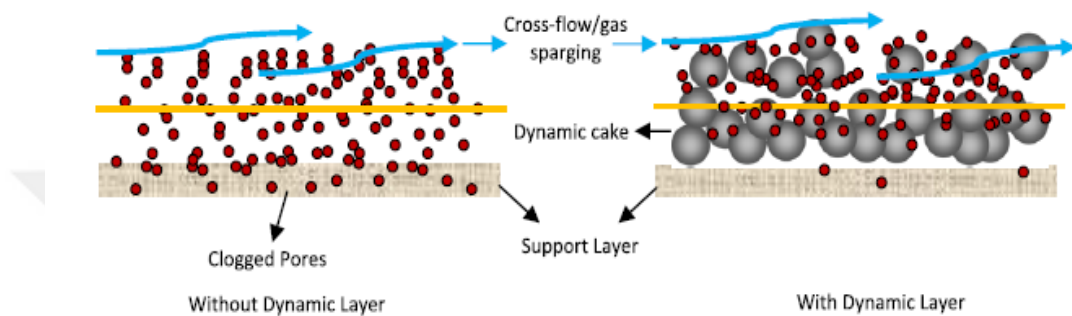


Figure 2.10 Illustration of dynamic membrane layer (Ersahin et al., 2012)

The major benefit of DMBR is that polymeric membranes are no longer required. Support materials are utilized to form the dynamic membrane layer. There are many materials used as dynamic membrane support materials. Ersahin et al. (2012) investigated the support materials in the literature and stated that nylon mesh, dacron mesh, fabric filter, non-woven, woven nylon fabric, filter cloth, terylene filter cloth, ceramic, nylon mesh, stainless steel mesh and silk have been used as support material. However, mesh, woven and non-woven fabrics have been the most popular materials in DMBR applications (Cinar et al., 2016).

Dynamic membrane support materials pore sizes are generally higher compared to those of conventional polymeric microfiltration and ultrafiltration membranes. Support material pore sizes vary between  $1\mu\text{m}$  and  $150\mu\text{m}$  in different dynamic membrane applications. As the pore size increases, the membrane permeability correspondingly increases (Cai et al., 2018). It is obvious that high pore size provides a desired operation with long filtration time and high flux. Nonetheless, large pore size prolongs formation time of the dynamic layer as small particles and colloids can more difficultly hold on support material (Li et al., 2018).

Cake layer formation in DMBRs is a complex mechanism involving biological and hydrodynamic processes. Since the support material with large pore size provides high permeability under pressure, small particles cannot hold onto the support material in the first phase. Turbidity of effluent water is high at this stage. Then, the cake layer begins to form and turbidity and flux start to reduce by holding flocks on the support material. Dynamic layer formation is completed when the effluent turbidity drops below 5 NTU. Duration of this process depends on particle size of sludge and pore size of support material. After dynamic layer formation, the cake layer resistance constitutes 90% of the total resistance (Zhu et al., 2019). The second part is maturation phase. Surface of support material is completely covered with flocks and the continuous flow lasts for a long time compared to polymeric membranes (Mohan & Nagalakshmi, 2020).

Fouling problem in DMBRs is more easily manageable than conventional MBRs. Irreversible membrane fouling is prevented because the dynamic layer restricts direct contact of foulants with support material. Although accumulation and deposition of particles is important for dynamic membrane layer, undesired accumulation of particles on support material, which causes filtration resistance and reduces flux, can cause membrane fouling. As porous structure of dynamic membrane cannot remain stable, the particle density in dynamic membrane will be prone to fouling. As the operating day increases, compression of cake layer increases and thus flux diminishes (Yang et al., 2019). Stable and long-term operation is an important consideration for DMBRs to avoid loss of biomass. Fouling control and membrane cleaning frequency must be regulated. This can be achieved by optimization of operating conditions, sludge characteristics, and reactor modification (Mohan & Nagalakshmi, 2020).

In case of fouling, sludge particles, cells and biopolymers accumulated on support material can be easily removed from surface with cleaning. A number of membrane cleaning strategies have been developed in accordance with dynamic membrane filtration. The most common methods are surface brushing, water backwashing and air backwashing (Li et al., 2018).

Table 2.7 Comparison of MBR and DMBR Systems (Cinar et al., 2016)

| MBR                                         |                                     | DMBR                                       |                                                                        |
|---------------------------------------------|-------------------------------------|--------------------------------------------|------------------------------------------------------------------------|
| Advantages                                  | Disadvantages                       | Advantages                                 | Disadvantages                                                          |
| High MLSS                                   | --                                  | High MLSS                                  | --                                                                     |
| Low footprint                               | --                                  | Low footprint                              | --                                                                     |
| Higher volumetric loading                   | --                                  | Higher volumetric loading                  | --                                                                     |
| Fine control of SRT                         | --                                  | Fine control of SRT                        | --                                                                     |
| Greater operational and process complexity  | --                                  | Greater operational and process complexity | --                                                                     |
| Lower sludge production                     | --                                  | Lower sludge production                    | --                                                                     |
| --                                          | Higher capital low operational cost | Low capital, Low operational cost          | --                                                                     |
| --                                          | Greater foaming propensity          | --                                         | Greater foaming propensity                                             |
| Treated water that reusable                 | --                                  | Treated water that reusable                | --                                                                     |
| Unlimited by settling due to gravity        | --                                  | Unlimited by settling due to gravity       | --                                                                     |
| --                                          | High module cost                    | Low module cost                            | --                                                                     |
| Simple TMP control based on constant flow   | --                                  | --                                         | Complex TMP control based on constant flow                             |
| Simple fouling control                      | --                                  | --                                         | Complex fouling control                                                |
| Chemical wash easier applied                | --                                  | --                                         | Chemical wash not easily applied by taking into account microorganisms |
| Very high physical disinfection performance | --                                  | Normal physical disinfection performance   | --                                                                     |
| Affected indirectly by bulking problem      | --                                  | Affected indirectly by bulking problem     | --                                                                     |

#### ***2.4.1 Different Dynamic Membrane Bioreactor Studies in Literature***

Many researches are interested in dynamic membrane bioreactor systems. Municipal and industrial wastewater treatment studies have been carried out using various membrane support materials with different pore sizes. Some of these studies are summarized in this section.

Veral et al. (2020) compared to membrane bioreactor and dynamic membrane bioreactor under the same conditions. They used non-woven flat-sheet polyethersulfone with  $\sim 250\text{ }\mu\text{m}$  pore size and  $0.45\text{ }\mu\text{m}$  conventional membrane in different modules in the same bioreactor to treat synthetic wastewater containing  $500\text{ mg/L}$  COD. No sludge was withdrawn from reactor and thus reactor operated with infinite SRT. Operation was divided into three periods depending on the flux  $10\text{ LMH}$ ,  $15\text{ LMH}$ ,  $20\text{ LMH}$ , respectively. In the first period ( $10\text{ LMH}$ ), conventional membrane and dynamic membrane received  $99.47\%$  and  $97.02\%$  COD removal, respectively. In other periods ( $15$  and  $20\text{ LMH}$ ) increased flux did not cause a decrease in removal performance ( $96.05\%$  and  $95\%$ ) for conventional membrane but increased flux reduced the removal performance of dynamic membrane to some extent ( $82.89\%$  and  $79\%$ ). This comparative study shows that the dynamic membrane operated at low flux achieves approximately similar removal efficiencies compared to conventional membranes.

Isik et al. (2019) operated dynamic membrane and conventional ultrafiltration membrane in the same bioreactor in hollow fiber configuration for municipal wastewater treatment. They used polyester fabric with  $0.39\text{ }\mu\text{m}$  pore size for dynamic membrane support material and PVDF membrane with  $0.05\text{ }\mu\text{m}$  pore size for UF membrane. They stated that both membranes show almost the same TS, COD, TN and TP removal efficiencies and permeate turbidity values. It was also expressed that after formation of dynamic layer average TMP and filtration resistance of dynamic membrane higher than those of UF membrane at averagely  $4.7\text{ LMH}$  constant flux for both.

Wang et al. (2012) investigated dynamic membrane bioreactor using mesh filter for treating low-strength municipal wastewater. Their system was operated with 0.6 m<sup>3</sup>/h inflow rate and 5h HRT. The initial MLSS in reactor was 3.89 g/L and as no sludge was withdrawn during the experimental period, prolonged SRT was achieved. Nylon mesh with an average pore size of 80 µm was used as a membrane support material. They stated that after support material settled the effluent turbidity value decreased from 52.3 to 1.8 NTU within 3 days and remained almost same after that. It reveals that dynamic cake layer forms properly in partially short time. It was also emphasized that backwashing was required only once in the fiftieth day in the ninety days operation period. It is an important result showing that dynamic membrane bioreactor may be operated under low transmembrane pressure and high flux values. Average removal efficiencies of COD, NH<sub>4</sub><sup>+</sup>-N, TN and TP are 83.3%, 98.1%, 15.7% and 53.5%, respectively.

Li et al. (2018) researched micro-particle removal performance of dynamic membrane and influencing factors in wastewater treatment. A 90 µm mesh was used as a support material and they focused on removing of micro-particles with dimensions between 1x10<sup>-7</sup> and 1x10<sup>-4</sup> m in synthetic wastewater. The initial turbidity was 195 NTU and it decreased less than 1 NTU after 20 minutes of filtration. They pointed out that although more than 90% of the particles in influent wastewater were smaller than 90 µm, the dynamic membrane layer was able to hold micro-particles. They also reported that wastewaters with higher particle concentration contributes to formation of dynamic layer and shorten duration of formation, however once dynamic layer formed, effluent turbidity were almost equal regardless of influent particle concentration.

Cai et al. (2018) did research on effect of material pore size on the filtration behavior of dynamic membrane bioreactor. They compared filtration behavior mesh filter with different pore sizes 1, 5, 10, 25 and 50 µm. System was operated with 3 g/L MLSS concentration and SRT controlled at 40 days by discharging biomass daily for each. After screening test, they chose 5, 10 and 25 µm mesh filters because initial turbidity of 50 µm filter was too high and flux for 1 µm filter was too low.

Long-term result of filters showed that effluent COD concentrations ( $\sim 20$  mg/L) and turbidity ( $\sim 0.3$  NTU) values are approximately the same for each pore size. However, 25  $\mu\text{m}$  filter mesh maintained higher than 5 and 10  $\mu\text{m}$  mesh filters for long-term operation. Thus, 25  $\mu\text{m}$  filter mesh exhibits stable high flux and low TMP for two months without backwash or cleaning. This study exhibits that pore size of dynamic membrane support material is significant factor to achieve high removal efficiencies and filtration stability.

Ren et al. (2010) investigated a novel membrane bioreactor equipped with non-woven fabric filter bag with 100  $\mu\text{m}$  pore size to treat raw household wastewater. They installed the bioreactor with initial 5 g/L MLSS and no excess sludge was discharged from the system during entire period of 167 days. The system was operated there different HRT 12, 10 and 8h. It was pointed out that dynamic cake layer was formed within 2 hours because turbidity value and suspended solids concentration dropped under 5 NTU and 5 mg/L, respectively. Long-term of the system in terms of removal efficiencies of COD, BOD,  $\text{NH}_3$ , TP, TN and SS are 85.5-89.3%, 96.7-97.9%, 91.9-99.4%, 33.6-37.8%, 18.3-32.3%, 93.3-95.7%. It was also stated as flux was enhanced, membrane resistance was decreased depending on increasing HRT.

## CHAPTER THREE

### MATERIAL AND METHODS

#### 3.1 Materials

##### 3.1.1 Support Materials and Membrane Module

The membrane modules having an effective filtration area of 0.056 m<sup>2</sup> was constructed from delrin material as a flat plate configuration. The dimensions of the membrane module (length- wide- thickness) are 18 cm x 24 cm x 2.5 cm. Microfiltration or ultrafiltration membranes were connected to membrane cassette. As support layer materials, the textile fabrics as cotton textile fabric (TF) and metal braided one (MBTF) - 50% cotton and 50% polyester- were supplied from a textile factory located in Izmir, Turkey. For the first time, the availability of the usage of the fabrics in wastewater treatment field was tested in this study. The properties of support material and membranes (MF or UF) used in the experimental trials are given in Table 3.1. The photographs of the membrane module -alone and prepared one- are also shown in Figure 3.1.

Table 3.1 The properties of support materials and MF/UF membranes

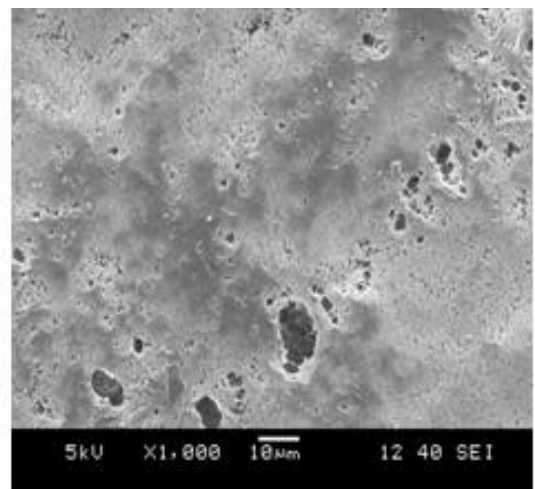
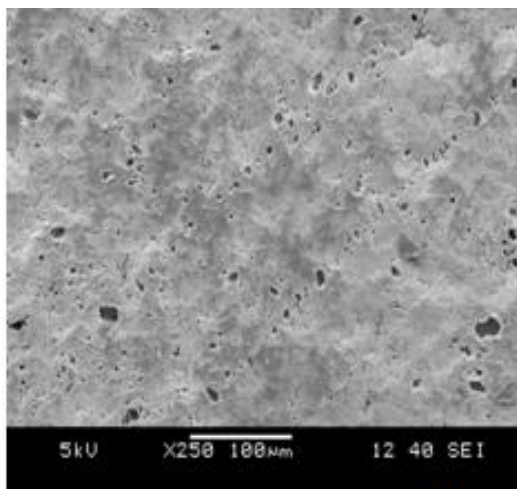
| Support Material                                             |                         |                                      |                                       |                          |
|--------------------------------------------------------------|-------------------------|--------------------------------------|---------------------------------------|--------------------------|
|                                                              | Fiber Thickness<br>(Ne) | Weft Wrap<br>Density<br>(wire/cm)    | Pore Size<br>( $\mu$ m)               |                          |
| Cotton Textile<br>Fabric (TF)                                | 30x30                   | 27x30                                | 20                                    |                          |
| Stainless Steel<br>Metal Braided<br>Textile Fabric<br>(MBTF) | 12 for cotton           | 50 mm for<br>stainless steel<br>wire | 30                                    |                          |
| Microfiltration Membranes                                    |                         |                                      |                                       |                          |
|                                                              | Membrane<br>Material    | Pore Size<br>( $\mu$ m)              | Flux Rate (LMH)<br>at 25 °C, 0.35 Mpa | Replacement<br>Reference |
| MF010                                                        | PVDF                    | 0.10                                 | > 500                                 | TORAY                    |
| MF022                                                        | PVDF                    | 0.22                                 | > 1000                                | KUBOTA                   |
| Ultrafiltration Membrane                                     |                         |                                      |                                       |                          |
|                                                              | Membrane<br>Material    | MWCO<br>(Dalton)                     | Flux Rate (LMH)<br>at 25 °C, 4 Mpa    | Replacement<br>Reference |
| UE001                                                        | PES                     | 1000                                 | 40                                    | MICRODYN                 |



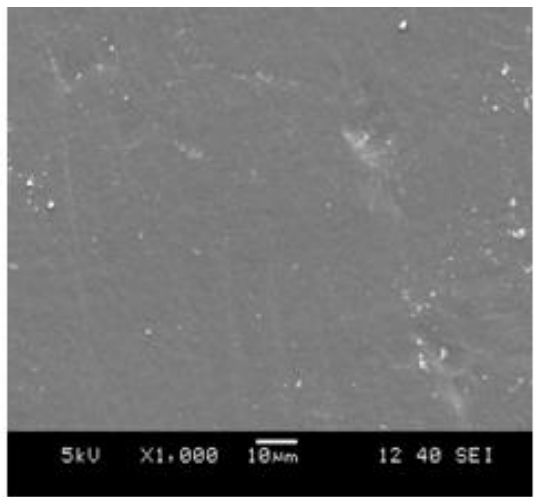
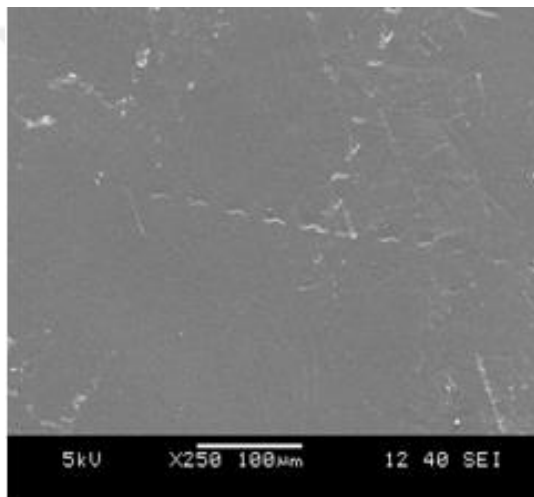
Figure 3.1 Photographs of the membrane module (Personal archive, 2019)

#### *3.1.1.1 SEM-EDS Analysis of Support Materials and MF/UF Membranes*

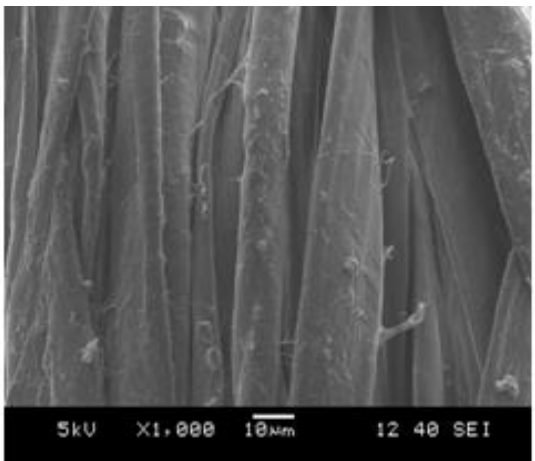
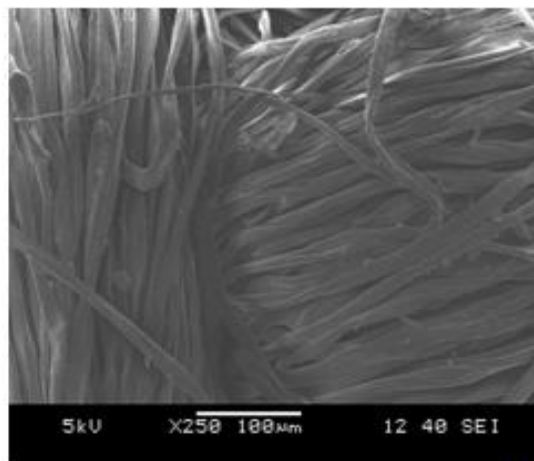
SEM-EDS analyzes of virgin PVDF, MF membrane representing MF022/ MF010 and UF membrane UE001 were performed at Department of Material Science Engineering in Dokuz Eylül University to make a comparison with their final state after operation. Both MF022 and MF010 membranes are PVDF membranes with the same polymeric composition. UF001 membrane has PES composition. SEM images and EDS results of the membrane materials and virgin MBTF are given in Figure 3.2 and Figure 3.3, respectively.



**MF 022 membrane**

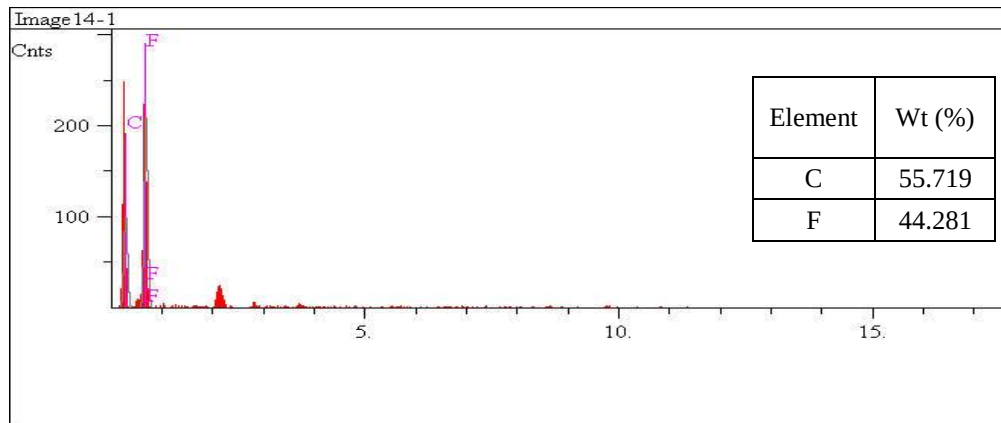


**UF 001 membrane**

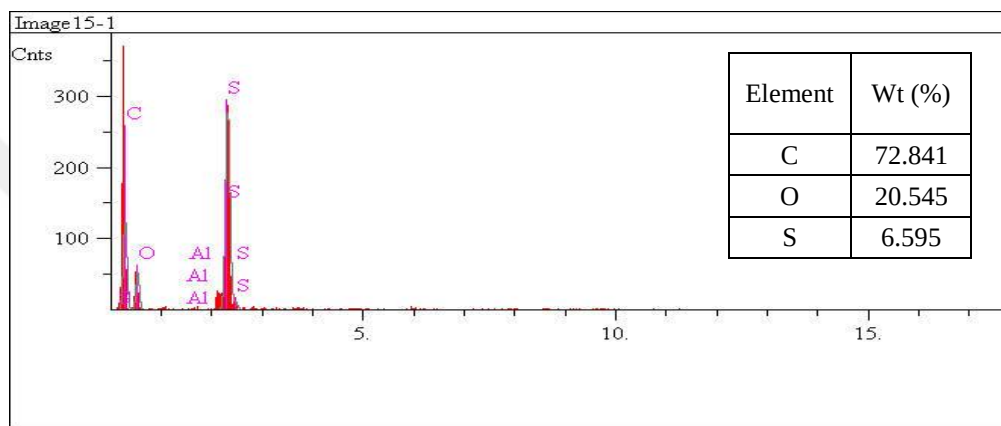


**MBTF**

Figure 3.2 SEM images of MF, UF membranes and MBTF textile



(a)



(b)

Figure 3.3 EDS analysis of membranes: (a) MF membrane, (b) UF membrane

### 3.1.2 DMBR Reactor Setup

Schematic diagram and general view of the laboratory-scale dynamic membrane bioreactor system used in this research are shown in Figure 3.3 and Figure 3.4, respectively. This system consists of feeding tank, aerobic tank, membrane module, and storage tank. Wastewater is supplied to the aeration tank with a submersible pump inside the feeding tank. The membrane module operated in submerged form was placed in the aerobic tank made of plexiglas material with a total volume of 15.4 L. The membrane modules immersed in the bioreactor and integrated into the peristaltic pump. Peristaltic pump was used for filtration purpose and vacuum gauge was installed to monitor the transmembrane pressure momentarily. Both influent and effluent pumps are equipped with flow meters that can be adjusted instantly and air pump was used to supply air to the aerobic tank with diffuse aeration materials. At

the start-up studies, activated sludge samples as an inoculum sludge, which was taken from a municipal wastewater treatment plant, was fed to the reactor system.

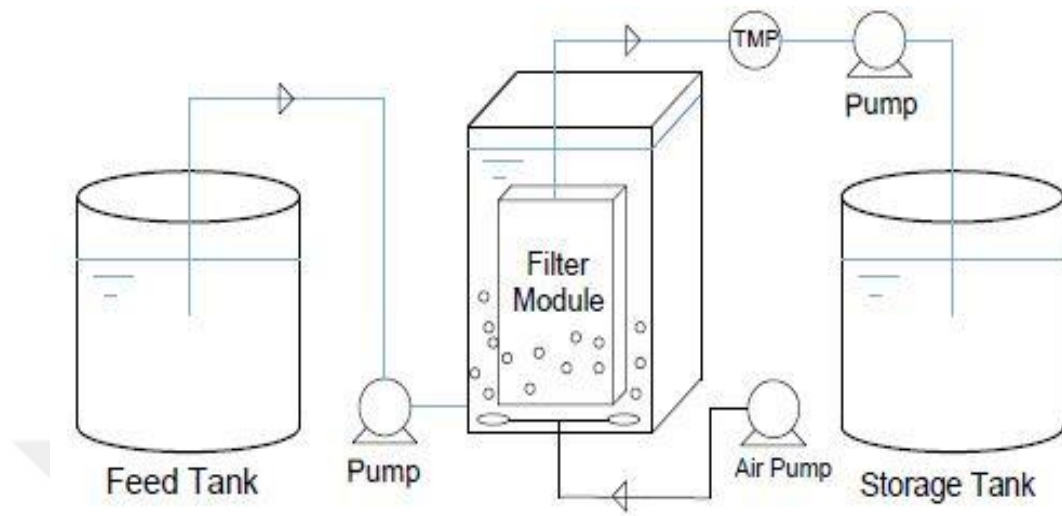


Figure 3.4 Schematic diagram of lab-scale DMBR



Figure 3.5 General view of the system (Personal archive, 2019)

### 3.2 Characterization Studies

DMBR system was operated by using synthetic and real wastewater taken from municipal and domestic wastewater treatment plants. Full characterization studies were done by using the synthetic and real wastewater samples and also inoculum sludge based on the parameters of suspended solids (SS), biological oxygen demand (BOD), chemical oxygen demand (COD), pH, Electrical Conductivity (EC), salinity, total dissolved solids (TDS), chloride ( $\text{Cl}^-$ ), Alkalinity, total Nitrogen (TN), ammonia ( $\text{NH}_4^+\text{-N}$ ), total phosphorus (TP), sulfate ( $\text{SO}_4^{2-}$ ). All analysis was done according to Standard Methods (APHA, 2005). Particle size distribution of the inoculum sludge was also analyzed by using Malvern Master Sizer 2000, Hydro QM unit. Capillary suction time (CST) analysis was also done by using Triton A 304 M type analyzer.

#### 3.2.1 Characterization of Inoculum Sludge

Activated sludge as an inoculum was taken from sludge recycling line of a municipal wastewater treatment plant located in Izmir, Turkey. The characteristic of the inoculum sludge is shown in Table 3.2. Particle size distribution of the inoculum sludge was depicted in Figure 3.5 and also shown in Table 3.3.

Table 3.2 The characteristics of inoculum activated sludge

| Parameter | Unit  | Value |
|-----------|-------|-------|
| SS        | mg/L  | 15760 |
| VSS       | mg/L  | 13655 |
| COD       | mg/L  | 540   |
| pH        | -     | 6.93  |
| EC        | mS/cm | 11.33 |
| Salinity  | ‰     | 6.1   |
| CST       | s     | 18.8  |

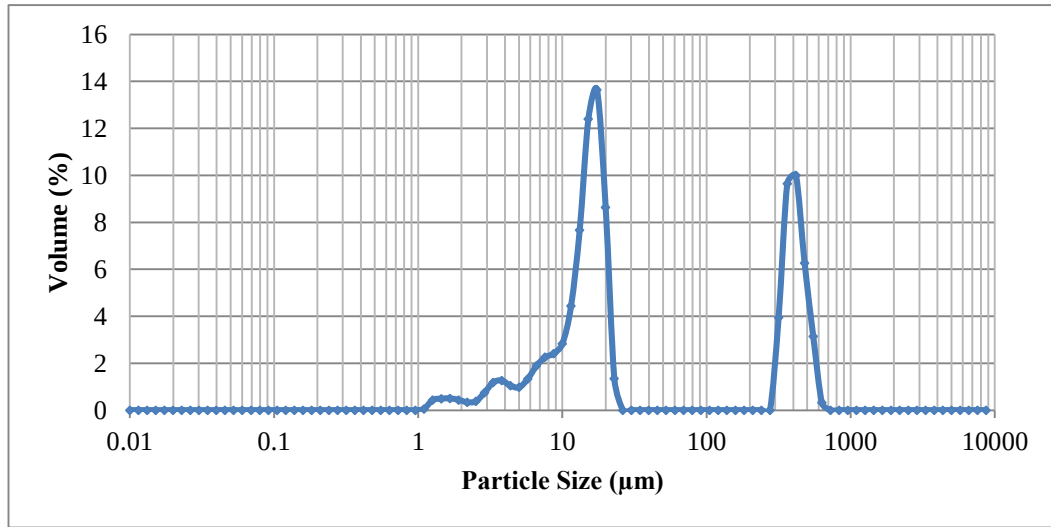


Figure 3.4 Particle size distribution of inoculum sludge

Table 3.3 Information about particle size distribution of inoculum sludge

| Sample                          | D [4, 3] -<br>Volume<br>weighted<br>mean (μm) | D [3, 2] -<br>Surface<br>weighted<br>mean (μm) | Specific<br>surface<br>area<br>(m <sup>2</sup> /g) | d(0.1)<br>(μm) | d(0.5)<br>(μm) | d(0.9)<br>(μm) |
|---------------------------------|-----------------------------------------------|------------------------------------------------|----------------------------------------------------|----------------|----------------|----------------|
| Inoculum<br>Activated<br>Sludge | 157.987                                       | 14.352                                         | 0.418                                              | 7.058          | 18.714         | 476.545        |

### 3.2.2 Characterization of Synthetic Wastewater

Synthetic wastewater simulating high-strength municipal wastewater was used to feed the bioreactor in this study. The synthetic wastewater was comprised of as follows: CH<sub>3</sub>COONa 1500 mg/L, NH<sub>4</sub>Cl 400 mg/L, K<sub>2</sub>HPO<sub>4</sub>·7H<sub>2</sub>O 21 mg/L, FeSO<sub>4</sub>·7H<sub>2</sub>O 10 mg/L, MgSO<sub>4</sub>·7H<sub>2</sub>O 12 mg/L, CaCl<sub>2</sub>·2H<sub>2</sub>O 14 mg/L and trace solution was: H<sub>3</sub>BO<sub>3</sub> 100 mg/L, CoCl<sub>2</sub>·6H<sub>2</sub>O 100 mg/L, CuSO<sub>4</sub>·5H<sub>2</sub>O 30mg/L, FeCl<sub>3</sub>·6H<sub>2</sub>O 1000 mg/L, MnCl<sub>2</sub>·2H<sub>2</sub>O 110 mg/L, Na<sub>2</sub>Mo<sub>7</sub>O<sub>24</sub>·2H<sub>2</sub>O 70 mg/L, ZnSO<sub>4</sub>·7H<sub>2</sub>O 100 mg/L, KI 30 mg/L, NiCl<sub>2</sub> 60 mg/L as given in Li et al. (2007). The characteristics of synthetic wastewater used in this study are given in Table 3.4.

Table 3.4 Characteristics of synthetic wastewater used in experimental studies

| Parameter          | Unit                   | Value |
|--------------------|------------------------|-------|
| BOD <sub>5</sub>   | mg/L                   | 690   |
| SS                 | mg/L                   | 55    |
| COD                | mg/L                   | 1021  |
| Alkalinity         | mgCaCO <sub>3</sub> /L | 386   |
| TN                 | mg/L                   | 108.5 |
| NH <sub>4</sub> -N | mg/L                   | 85.1  |
| TP                 | mg/L                   | 4.29  |
| SO <sub>4</sub>    | mg/L                   | 18.8  |
| TDS                | mg/L                   | 1518  |
| Cl <sup>-</sup>    | mg/L                   | 245   |
| pH                 |                        | 7.45  |
| Conductivity       | mS/cm                  | 2.56  |
| Salinity           | ‰                      | 1.14  |

### 3.2.3 Characterization of Municipal Wastewaters

Two different real wastewaters used in experimental studies were taken from a municipal WWTPs located in Izmir, Turkey denoted as WW1 and Manisa, Turkey denoted as WW2, respectively. The raw wastewaters were sampled after primary treatment units. The characteristic of municipal wastewaters is shown in Table 3.5.

Table 3.5 Characteristics of municipal wastewaters used in the experimental studies

| Parameter                       | Unit                   | Value       |              |
|---------------------------------|------------------------|-------------|--------------|
|                                 |                        | Izmir (WW1) | Manisa (WW2) |
| SS                              | mg/L                   | 165         | 150          |
| BOD <sub>5</sub>                | mg/L                   | 150         | 195          |
| COD                             | mg/L                   | 360         | 422          |
| pH                              | -                      | 7.8         | 7.82         |
| Conductivity                    | mS/cm                  | 9.53        | 1.51         |
| Salinity                        | ‰                      | 5.5         | 0.6          |
| Cl                              | mg/L                   | 2640        | 250          |
| Alkalinity                      | mgCaCO <sub>3</sub> /L | 342         | 406          |
| TN                              | mg/L                   | 27          | 50           |
| NH <sub>4</sub> <sup>+</sup> -N | mg/L                   | 21.8        | 44.4         |
| TP                              | mg/L                   | 3.75        | 6.5          |
| SO <sub>4</sub> <sup>=</sup>    | mg/L                   | 303         | 154          |

### 3.3 Methods

The analyses were done in Department of Environmental Engineering, Sludge Laboratory at Dokuz Eylül University according to Standard Methods (APHA, 2005). In the lack of any standard methodology, the most accepted protocols in the scientific studies were used. The experiments were repeated three times and results are given as average. Only some analyses as SEM-EDS, FTIR, and PCR-DGGE were obtained through service procurement. During the DMBR operation, samples taken, analysis parameters, applied standard methodology, and analysis frequency were summarized in Table 3.6 in detail.

Table 3.6 Analysis parameters, frequency and methods used in experimental studies

| Sample Name                     | Analysis Parameters                                                                    | Analysis Frequency | Method or Device and Equipment                                     |
|---------------------------------|----------------------------------------------------------------------------------------|--------------------|--------------------------------------------------------------------|
| Influent Wastewater             | BOD <sub>5</sub>                                                                       | Once a week        | SM 5210 B, Merck Test Kit No: 00687                                |
|                                 | COD                                                                                    | Once a week        | SM 5220B, Merck Test Kit No: 14541                                 |
|                                 | SS                                                                                     | Once a week        | SM 2540 D                                                          |
|                                 | VSS                                                                                    | Once a week        | SM 2540 E                                                          |
|                                 | pH, Salinity, Conductivity                                                             | Everyday           | WTW Multiparameter 304i                                            |
|                                 | Alkalinity                                                                             | Once a week        | SM 2320 B, Merck Test Kit No: 01758                                |
|                                 | TN                                                                                     | Once a week        | SM 4500 Norg B, Merck Test Kit No: 00613                           |
|                                 | TP                                                                                     | Once a week        | SM 4500-P B, Merck Test Kit No: 14543                              |
|                                 | Sulphate                                                                               | Once a week        | SM 4500- SO <sub>4</sub> <sup>2-</sup> C, Merck Test Kit No: 14548 |
| Mixed Liquid Sampled in Reactor | pH, Salinity, Conductivity, Oxidation Reduction Potential (ORP), Dissolved Oxygen (DO) | Everyday           | WTW Multiparameter 304i                                            |
|                                 | MLSS, MLVSS, SVI                                                                       | Twice a week       | SM 2540 D, SM 2540 E                                               |
|                                 | Capillary Suction Time (CST)                                                           | Once a week        | Triton Electronics 304M                                            |
|                                 | Specific Resistance to Filtration (SRF)                                                | Once a week        | Sorensen et al. (1995)                                             |
|                                 | Particle Size Distribution                                                             | Once a week        | Malvern Mastersizer 2000                                           |
|                                 | Rheological Properties (Viscosity, Shear Stress)                                       | Once a week        | ASTM D2196, Brookfield RVDV III type rheometer (Spindle No SC 27)  |
|                                 | Zeta Potential                                                                         | Once a week        | Zetameter 3+                                                       |

Table 3.6 continues

| Sample Name                      | Analysis Parameters                                                                          | Analysis Frequency          | Method or Device and Equipment                                                                                                             |
|----------------------------------|----------------------------------------------------------------------------------------------|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Effluent                         | COD                                                                                          | Three times a week          | SM 5220B, Merck Test Kit No: 14541                                                                                                         |
|                                  | BOD <sub>5</sub>                                                                             | Once a week                 | SM 5210 B, Merck Test Kit No: 00687                                                                                                        |
|                                  | pH, Salinity, Conductivity, ORP                                                              | Everyday                    | WTW Multiparameter 304i                                                                                                                    |
|                                  | Alkalinity                                                                                   | Twice a week                | SM 2320 B, Merck Test Kit No: 01758                                                                                                        |
|                                  | Sulphate                                                                                     | Once a week                 | SM 4500- SO <sub>4</sub> <sup>2-</sup> – C, Merck Tst Kit No: 14548                                                                        |
|                                  | EPS - Protein                                                                                | Once a week                 | Extraction for EPS analysis: Goodwin & Forster (1985). For protein analysis: Frolund et al. (1996) Procedure No. TP0300 Micro Lowry, Sigma |
|                                  | EPS - Polysaccharide                                                                         | Once a week                 | Extraction for EPS analysis: Goodwin & Forster (1985). For polysaccharide analysis: Dubois et al. (1956)                                   |
|                                  | TDS                                                                                          | Twice a week                | SM 2540 C                                                                                                                                  |
|                                  | SS                                                                                           | Twice a week                | SM 2540 D                                                                                                                                  |
|                                  | VSS                                                                                          | Twice a week                | SM 2540 E                                                                                                                                  |
|                                  | Residual Chlorine                                                                            | Once a week                 | SM 4500-Cl B, Merck Test Kit No: 14730                                                                                                     |
|                                  | Fluoride                                                                                     | Once a week                 | SM 4500-F B and D                                                                                                                          |
|                                  | Viscosity                                                                                    | Once a week                 | ASTM D2196, Brookfield RVDV III (Spindle No SC 27)                                                                                         |
|                                  | Particle Size Distribution                                                                   | Once a week                 | Malvern Mastersizer 2000, Hydro QM Unit                                                                                                    |
|                                  | NH <sub>4</sub> <sup>+</sup> -N, NO <sub>2</sub> <sup>-</sup> , NO <sub>3</sub> <sup>-</sup> | Once a week                 | SM 4500, : Merck Test Kit No: 14558, 00609, 14513                                                                                          |
|                                  | TN                                                                                           | Once a week                 | SM 4500 Norg B, Merck Test Kit No: 00613                                                                                                   |
|                                  | TP                                                                                           | Once a week                 | SM 4500-P B, Merck Test Kit                                                                                                                |
|                                  | Heavy Metals (Al, As, Be, B, Cd, Cr, Co, Cu, Ni, Zn, Fe, Pb, Mn, Mo, Se, Na, Ca)             | Once in each operating mode | ICP-QMS (Perkin Elmer- Optima 2100 DV)                                                                                                     |
| Sample taken on Support Material | E-Coli                                                                                       | Once in each operating mode | SM 9222 B                                                                                                                                  |
|                                  | PCR-DGGE                                                                                     | Once in each operating mode | Service Procurement                                                                                                                        |
|                                  | SEM-EDS                                                                                      | Once in each operating mode | Service Procurement                                                                                                                        |
|                                  | FTIR                                                                                         | Once in each operating mode | Service Procurement                                                                                                                        |

## CHAPTER FOUR

### RESULTS AND DISCUSSION

#### 4.1 Introduction

This chapter presents the research results of each experimental study on DMBR and evaluates the results comparing with previous findings in the literature.

#### 4.2 Determination of Ideal Membrane Support Material

Dead-end filtration tests were performed to find the most suitable membrane support material. The filtration apparatus that have a dead-end filtration mechanism and the filter cloth- textile fabrics, membrane or the both- was set as either a filtration cloth or a support layer. The permeate sample was exposed to characterization studies in terms of COD, SS, particle size distribution parameters. The wastewater (WW) samples were used alone and as a mixture with waste sludge (WAS) to be used as inoculum sludge for lab scale reactor operation in the volume ratio as 1:1/1 and 1: ½ (WAS/WW) to determine the depth of the sludge cake formed on as a dynamic layer and treatment performance under different solid concentrations. Municipal wastewater samples (WW) were taken after the grit chamber units at the WWTP, Manisa-Turkey. Waste activated sludge (WAS) samples were also collected at the recycling sludge line in the plant. Both the samples were stored at 4° C prior to use to prevent the possible chemical reactions and microbial activity. Table 4.1 demonstrates the characterization results of WW and WAS.

Table 4.1 Characterization results of WW and WAS

| Parameter | Unit  | WW   | WAS  |
|-----------|-------|------|------|
| COD       | mg/L  | 400  | 540  |
| SS        | mg/L  | 180  | 7890 |
| pH        | -     | 7.93 | 7.40 |
| EC        | µS/cm | 1006 | 860  |

The textile fabrics as cotton textile fabric (TF) and metal braided one (MBTF) to be used as support layers were supplied from a textile factory located in Izmir, Turkey. TF having a 30x30 Ne fiber thickness and 27x30 weft warp density was produced from cotton while MBTF was produced from 50% cotton and 50% polyester and has a 20x20 Ne fiber thickness, 23x26 wire/cm weft warp density, and 12 Ne fiber thickness for cotton and 50 mm for stainless steel wire. Both of the woven fabrics were developed under long term R&D studies. For the first time, the availability of the usage of the fabrics in wastewater treatment field was tested in this study. Membrane used in the experimental studies was a PVDF ultrafiltration membrane.

COD and SS changes under different operational conditions are presented in Figure 4.1 and Figure 4.2, respectively. The both textile fabrics showed good COD and SS removal efficiencies. However, use of textile fabric with ultrafiltration membrane (M+TF, M+MBTF) was obviously better than fabrics used alone. Hu et al (2018) reported that widely used membrane support materials cannot effectively hold fine particles and colloids as dynamic layer will not be formed completely in short-term filtration. Therefore, effluent COD and SS were expected to be lower in long-term filtration process for textile fabric used alone.

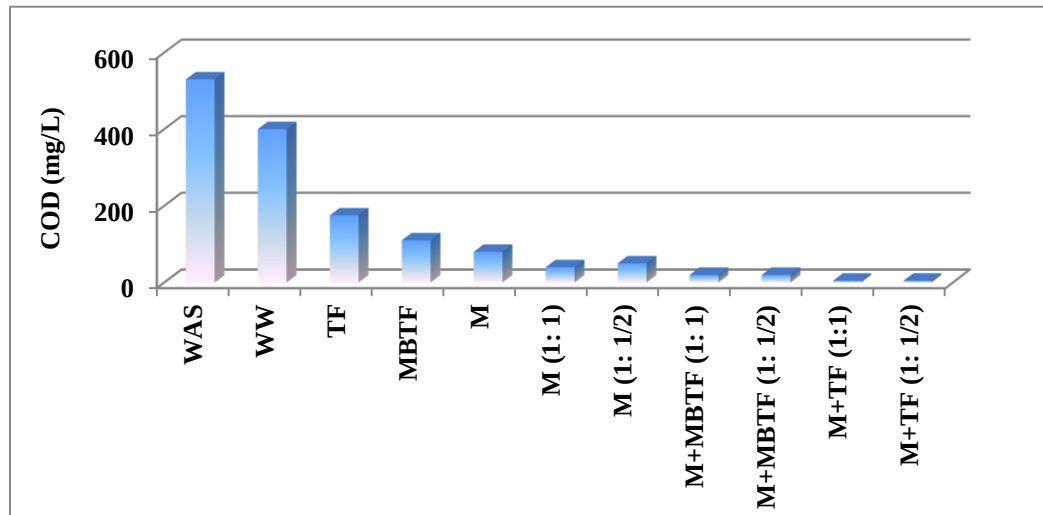


Figure 4.1 The change of COD values under different DM applications

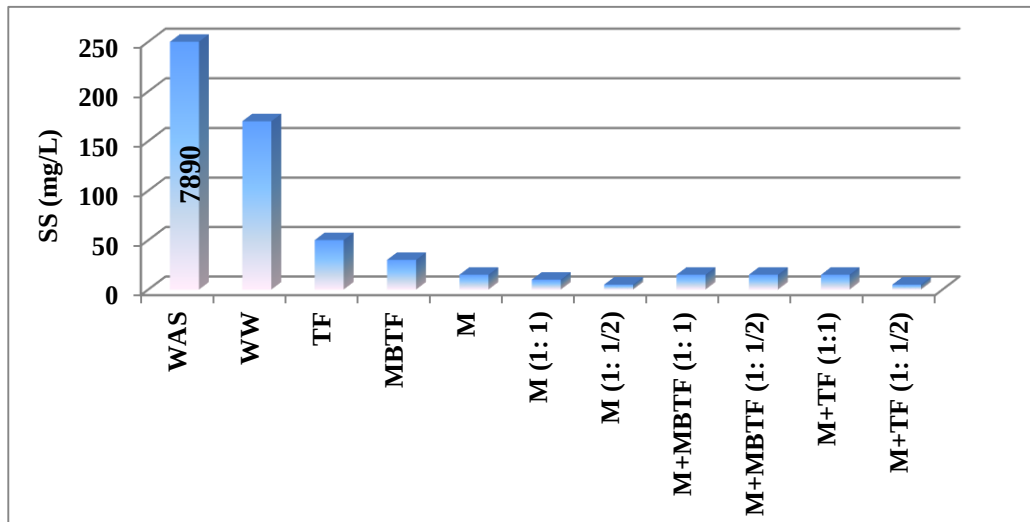


Figure 4.2 The change of SS values under different DM applications

Particle size of solids plays a vital role for formation of DM layer. Larger particles promote the formation of DM layer and contribute to accumulating biosolids on the supporting membrane with a shorter formation time. On the other hand, small particles may penetrate membrane support material in early formation stage resulting in high permeate concentration (Li et al., 2018). Particle size distribution of WW, WAS, and permeate is shown in Figure 4.3. While weighted mean  $D[4,3]$  and surface weighted mean  $D[3,2]$  of WW sample were analyzed as 94.943  $\mu\text{m}$  and 46.683  $\mu\text{m}$ ,  $D[4,3]$  and  $D[3,2]$  of WAS sample were found as 157.987  $\mu\text{m}$  and 14.352  $\mu\text{m}$ , respectively. The permeate results were found  $D[4,3]$  and  $D[3,2]$  as 14.016  $\mu\text{m}$  and 7.577  $\mu\text{m}$ , respectively for sample treated with M+TF (1:1), while the same application with MF+TF (1:1/2) were measured as 5.508  $\mu\text{m}$  and 3.865  $\mu\text{m}$ . Those results show that higher solid concentrations accelerated the formation of DM.

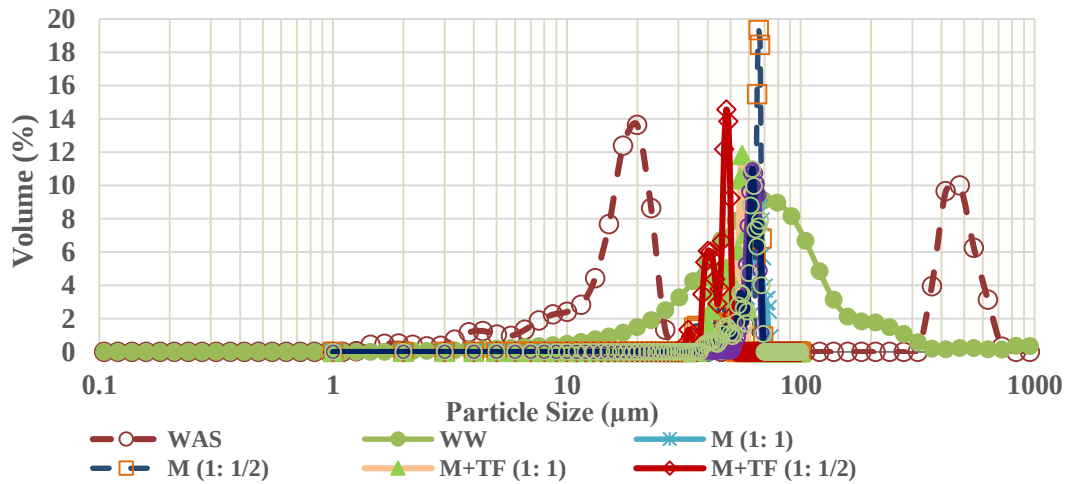


Figure 4.3 Particle size distribution of WAS, WW and permeate treated by different membranes

The results showed that all membrane applications enhanced the quality of the permeate samples; however, the membrane supported by textile fabrics led to better quality interims of particle availability in the effluents. M+TF was found the best application, which is also consistent with SS results. Very clear permeate samples were obtained in all membrane applications. As a result, since MBTF achieved better removal efficiency in terms of COD and SS removal in the use of textile material, it was decided to be used as a membrane support material in the dynamic membrane bioreactor system operation for further experimental trials.

#### 4.3 Performance of MF022+MBTF for Treatment of Synthetic Wastewater-First Experimental Study

MF022 microfiltration membrane and MBTF was selected to be used in membrane cassette. Synthetic wastewater (SWW) made ready according to the recipe given in Li et al. (2007) was daily prepared to feed to the DMBR system. The characterization of the synthetic wastewater was given in Table 3.4. Synthetic wastewater was transferred from influent tank to the DMBR system by a submersible pump according to the change in membrane flux.

The membrane module was operated as submerged configuration inside the aerobic tank by placing MBTF on the PVDF microfiltration membrane having 0.22

$\mu\text{m}$  pore size. The operation was carried out during 38 days. The operation flux was set at  $10.7 \text{ L/m}^2\text{h}$  (LMH) and was run in the same way until it dropped below 1 LMH. Initial hydraulic retention time (HRT) was 19 hours. Dissolved oxygen (DO) was supplied by aeration diffusers placed bottom of the aerobic DMBR and DO concentration was maintained higher than  $3 \text{ mg/L}$ . No excess feed sludge was inoculated into the system during entire experimental period and no sludge was withdrawn from the aerobic tank except for sampling purpose.

The changes in DO, pH, conductivity, and salinity were daily measured. DO concentration in the reactor was maintained higher than  $3 \text{ mg/L}$  during entire operation as shown in Figure 4.4. At the beginning of the operation, DO values were measured as very high, and then the air flow was adjusted to have lower DO values. pH, conductivity, and salinity values as a function of operation time is plotted in Figure 4.5. pH values ranged between 8.5 and 9 for MLSS and effluent stream. While conductivity value decreased in the reactor, effluent conductivity value had almost the same as the value in the reactor. However, they were lower than the influent wastewater. Xiao et al. (2014) stated that MBR having  $0.1 \mu\text{m}$  polymeric membrane was ineffective for removal of conductivity. This result is consistent with those obtained in this system. Likewise, salinity values were the same in the reactor and the effluent. Those results revealed that this membrane was partially efficient to decrease conductivity and salinity values.

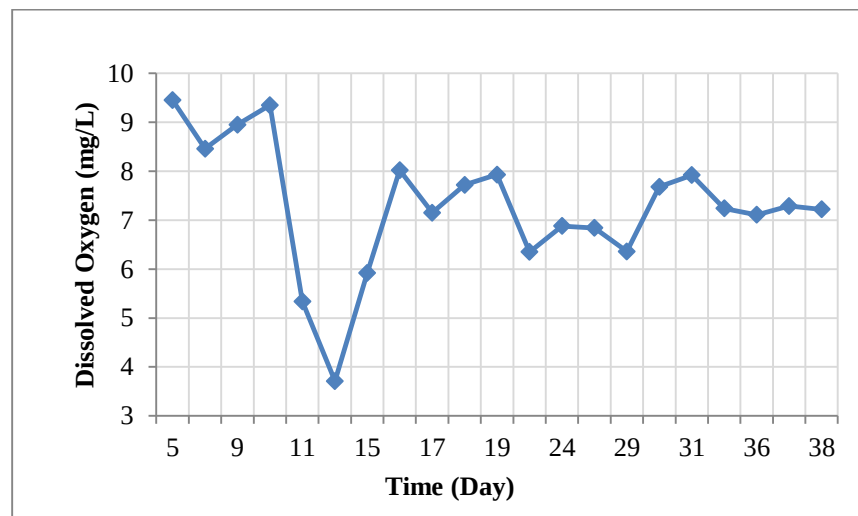


Figure 4.4 Daily changes in DO concentration in the reactor

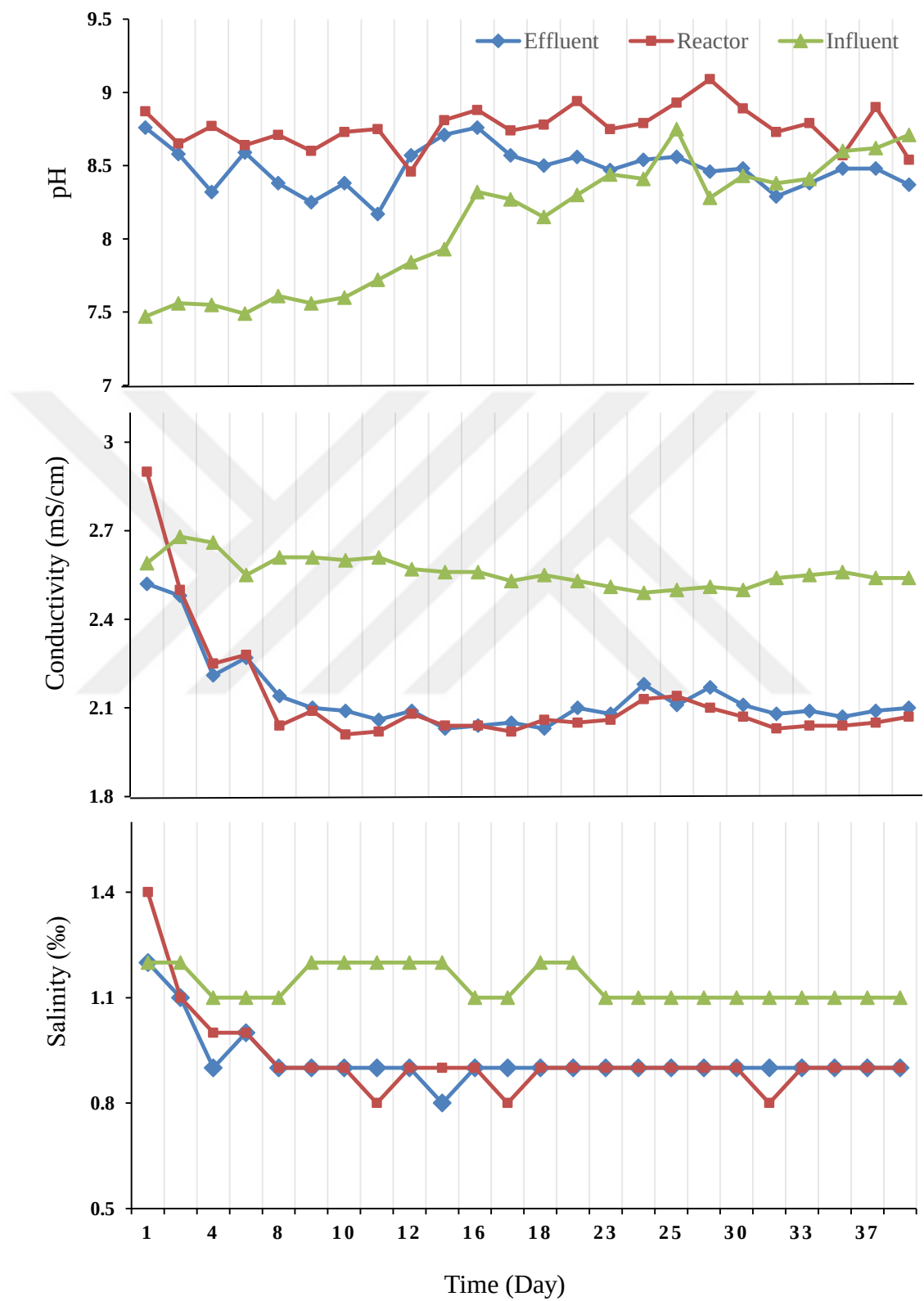


Figure 4.5 Daily changes in pH, conductivity and salinity

The graphical representations of the experimental results based on COD, BOD<sub>5</sub>, SS, NH<sub>4</sub><sup>+</sup>-N, TN, TP parameters were presented in Figure 4.6. The removal efficiencies of the system in terms of COD, BOD, SS and NH<sub>4</sub><sup>+</sup>-N were found remarkably high values as 98.6%, 98.5%, %100, and % 99.9, respectively. The system showed partial removal efficiencies for nutrients interims of TN and TP parameters. Average removal efficiencies of TN and TP were found as 29% and 24.4%, respectively. While average sulphate removal rate was reported as 44.6%, the residual chloride concentration was almost the same in the influent and effluent streams. Although proper nitrification took place in the reactor, alkalinity in the effluent flow was measured higher than the influent alkalinity value during entire period. It shows that the system has exceedingly adequate alkalinity.

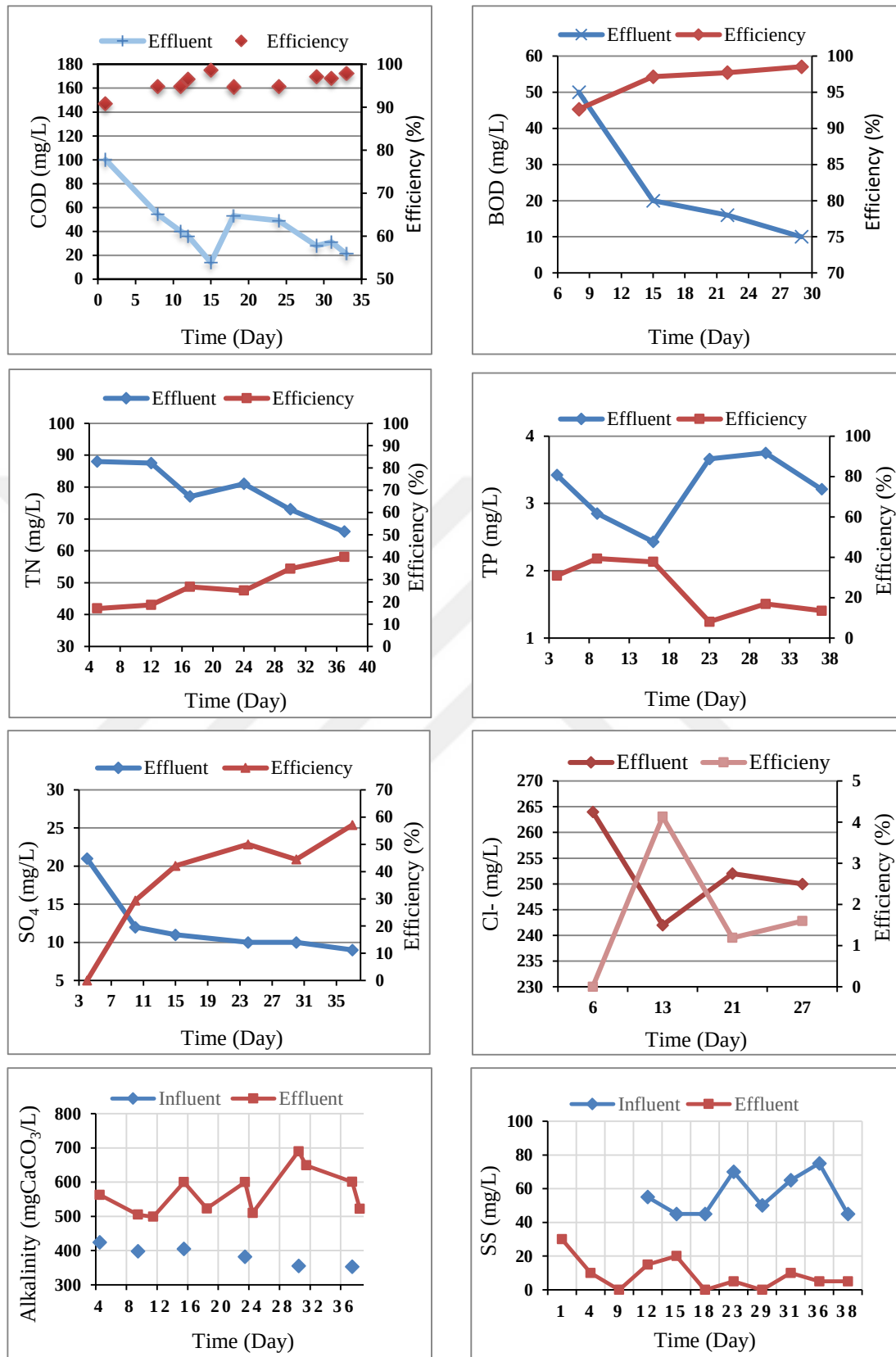


Figure 4.6 Graphical representation of results at the first experimental study

Changes in mixed liquor suspended solids were determined periodically as shown in Figure 4.7. MLSS concentration varied between 9320 mg/L and 6670 mg/L during operation. MLVSS/MLSS ratio was generally around 75%. Capillary suction time (CST) and sludge volume index (SVI) values increased slightly in the later days of operation. Therefore, the settling and dewatering properties of the sludge weakened. However, the flock formation was still good as evidenced by CST results. Isik et al. (2019) reported SVI and CST values in their DMBR as  $88.7 \pm 3.6$  mL/g and  $25.3 \pm 1.7$  s, respectively. Zeta potential measured to determine the adsorption tendency of the mixed liquid inside reactor varied between -41.3 mV and -34.8 mV. Although there was no continuous increase or decrease in zeta potential values, a partial change was observed. Yu et al. (2019) investigated change of three different sludge properties in DMBR application. They reported that zeta potential at 7.7 of pH varied between  $-25.81 \pm 1.17$  and  $-20.55 \pm 1.17$ , respectively.

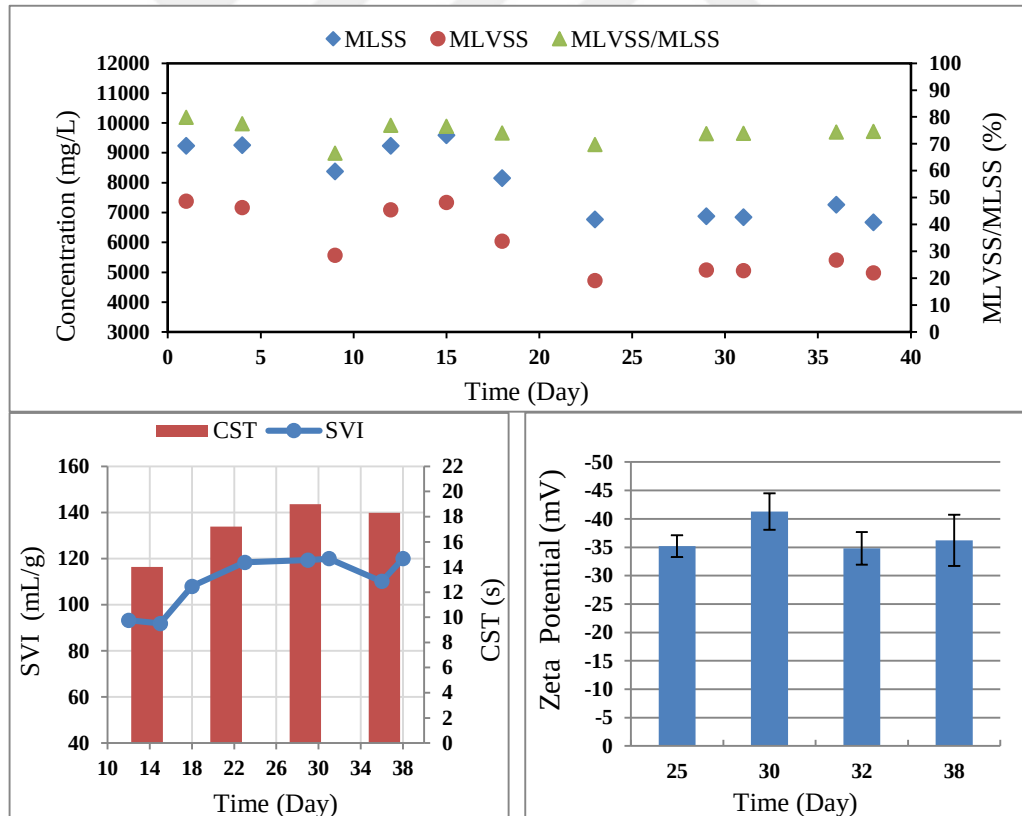


Figure 4.7 Changes in sludge characterization in first experimental study – MLSS and MLVSS values and the MLSS/MLVSS ratio; Variation in SVI and CST values; Zeta potential values

Particle size distribution results of MLSS and the treated wastewater in the effluent at regular intervals during experimental period were given in Figure 4.8 and 4.9, respectively. The results were also reported in Table 4.2 and Table 4.3. The volume weighted mean of sludge was 60.837 $\mu\text{m}$  in the first analysis. There were partial changes in particle size distribution on the following days. The particle size distribution of effluent remained quite stable during the entire operational period. However, the average particle size values were found higher values when considering the membrane pore size. It could be that the components like Ca, Mg, K which were not rejected during the treatment were available in the effluent and led to somewhat coagulation.

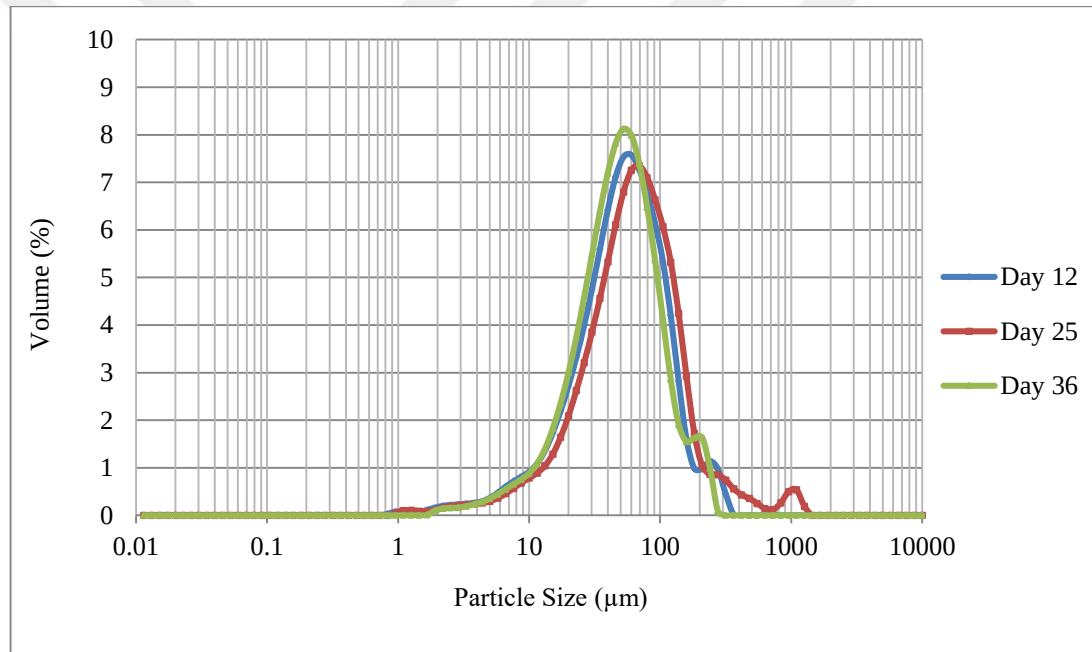


Figure 4.8 Particle size distribution of sludge at different days

Table 4.2 Detailed information on particle size distribution of sludge in the reactor

|                                                    | Day 12  | Day 25  | Day 36  |
|----------------------------------------------------|---------|---------|---------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 60.837  | 77.018  | 56.542  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 26.033  | 25.865  | 31.700  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.231   | 0.232   | 0.199   |
| d(0.1) ( $\mu\text{m}$ )                           | 15.053  | 15.299  | 18.249  |
| d(0.5) ( $\mu\text{m}$ )                           | 49.130  | 50.809  | 50.117  |
| d(0.9) ( $\mu\text{m}$ )                           | 115.700 | 128.249 | 101.592 |

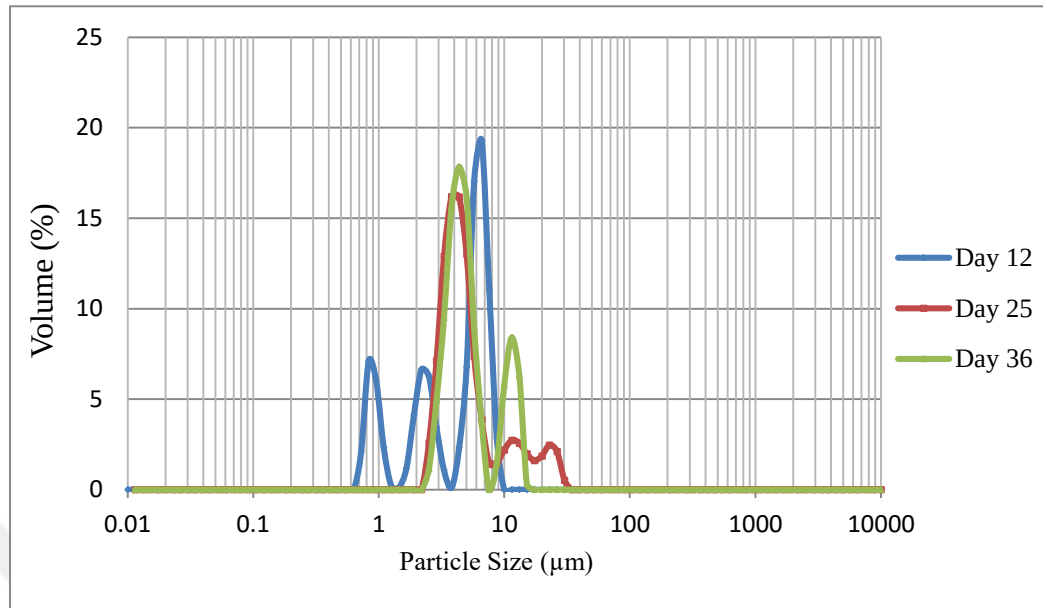


Figure 4.9 Particle size distribution of effluent stream

Table 4.3 Detailed information on particle size distribution of effluent

|                                                    | Day 12 | Day 25 | Day 36 |
|----------------------------------------------------|--------|--------|--------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 4.806  | 6.225  | 5.569  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 2.711  | 4.377  | 4.546  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 2.21   | 1.37   | 1.32   |
| $d(0.1)$ ( $\mu\text{m}$ )                         | 0.970  | 2.896  | 3.097  |
| $d(0.5)$ ( $\mu\text{m}$ )                         | 5.771  | 4.177  | 4.398  |
| $d(0.9)$ ( $\mu\text{m}$ )                         | 7.853  | 13.610 | 10.869 |

Rheological properties of sludge in the DMBR system were also analyzed periodically. Rheological properties as viscosity and shear stress as a function of shear rate were shown in Figure 4.10 and in Figure 4.11, respectively. It is clear that the sludge samples exhibited non-Newtonian flow behavior. Rheological parameters showed that sludge had shear thinning properties. Clouzot et al. (2011) and Azami et al. (2011) obtained the similar results that were consistent with this study. Azami et al. (2011) stated that the increasing MLSS concentration resulted in an increase in viscosity of the sludge. Furthermore, oxygen transfer rate and dissolved oxygen concentration decreased in highly viscous sludge. There was no remarkable change

in viscosity of sludge. Partial change was observed because of fluctuation of MLSS concentration.

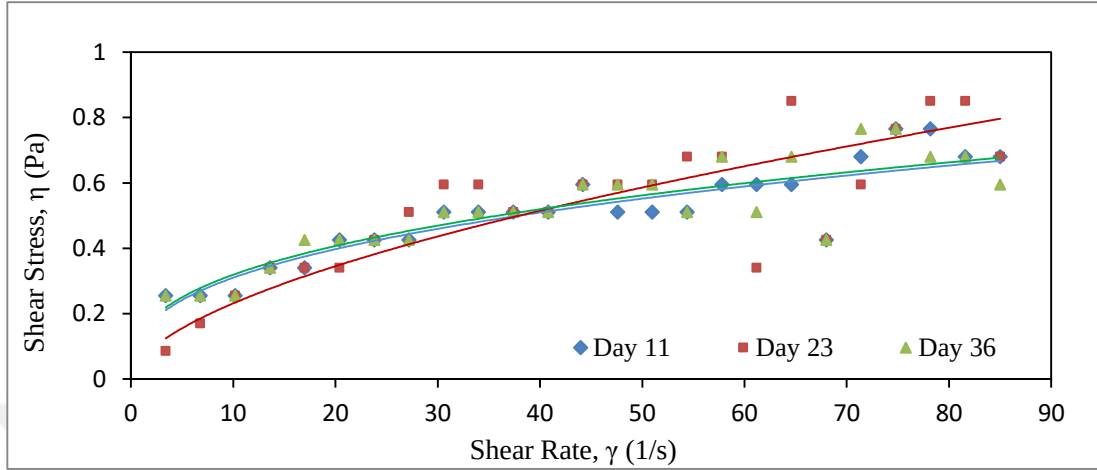


Figure 4.10 Viscosity of sludge as a function of shear rate

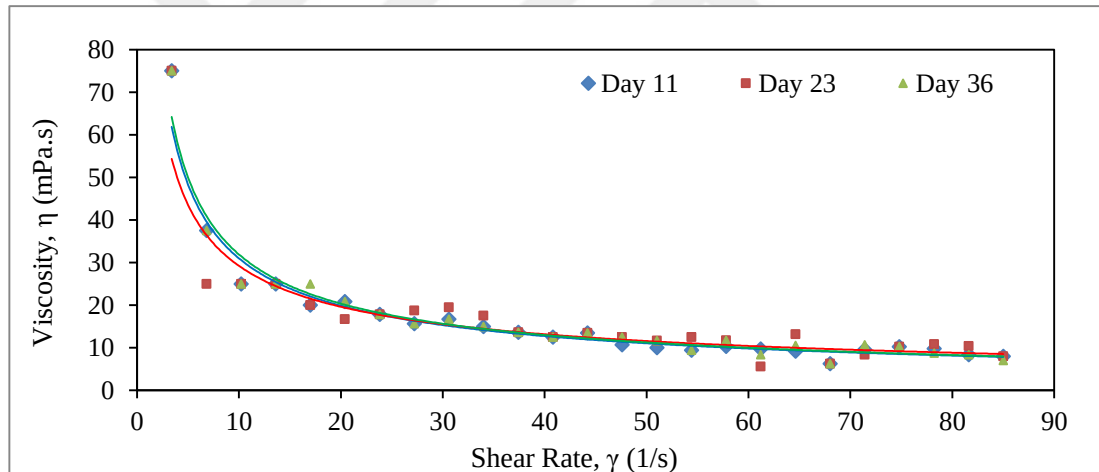


Figure 4.11 Shear stress of sludge as a function of shear rate

SEM-EDS analysis of MF022 and MBTF were done. The results were given in Figure 4.12 and Figure 4.13. The presence of inorganic substances in the mixed liquor such as Na, Mg, Al, Si, P, S, Cl, K was found on the MBTF support material used. However, only Si and Cl were detected on the MF022 membrane. Sludge accumulated on MBTF and formed dynamic layer and therefore no accumulation occurred on MF022 membrane. Consequently, the concentration of inorganic substances on the MF022 membrane remained at a very low level. Iorhemen et al.

(2016) indicated that inorganic foulants such as Ca, Mg, Al, and SO<sub>4</sub> resulted in membrane fouling as inorganic foulants precipitate onto the membrane surface or into the membrane pores. It is obvious that the formed dynamic layer prevented inorganic foulants from accumulating on the surface of MF022 membrane.

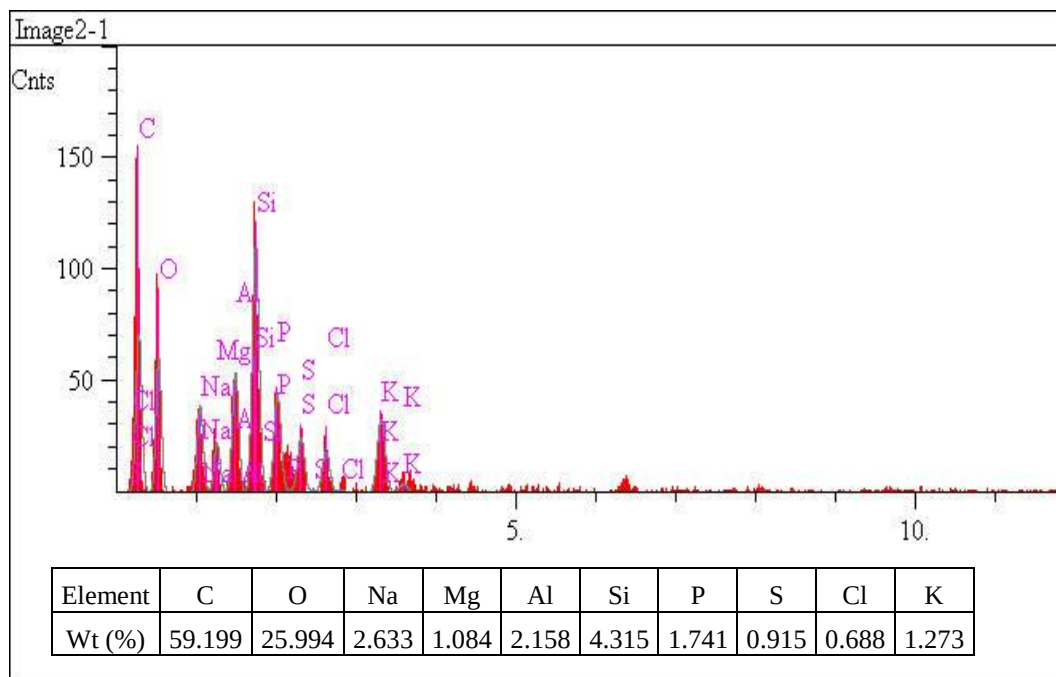
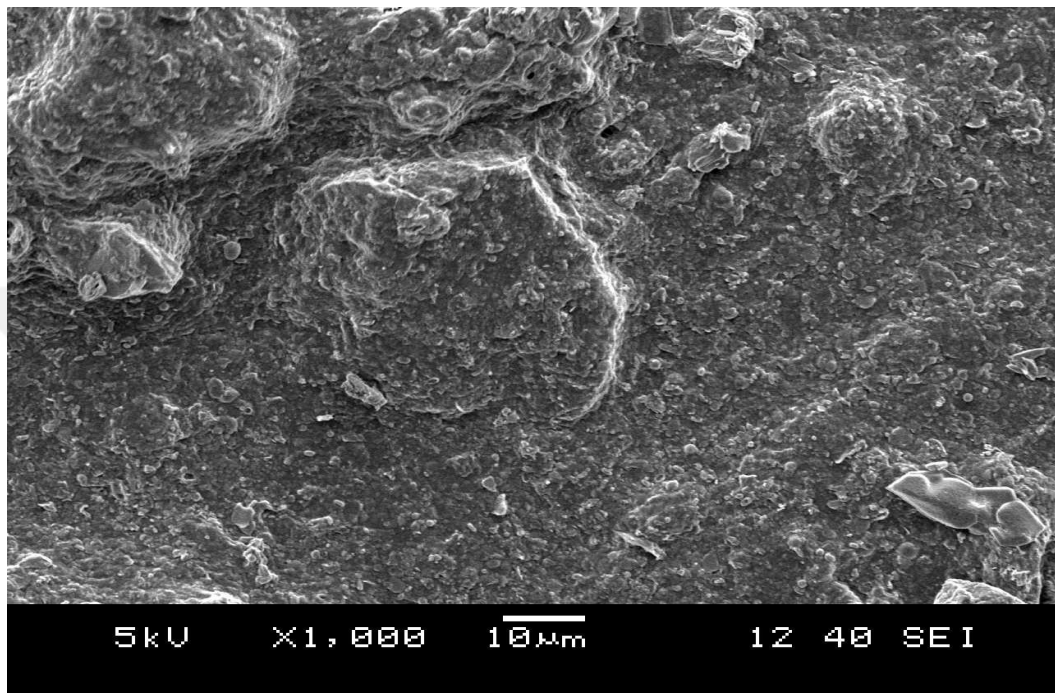


Figure 4.12 SEM image and EDS analysis result of dynamic layer on MBTF

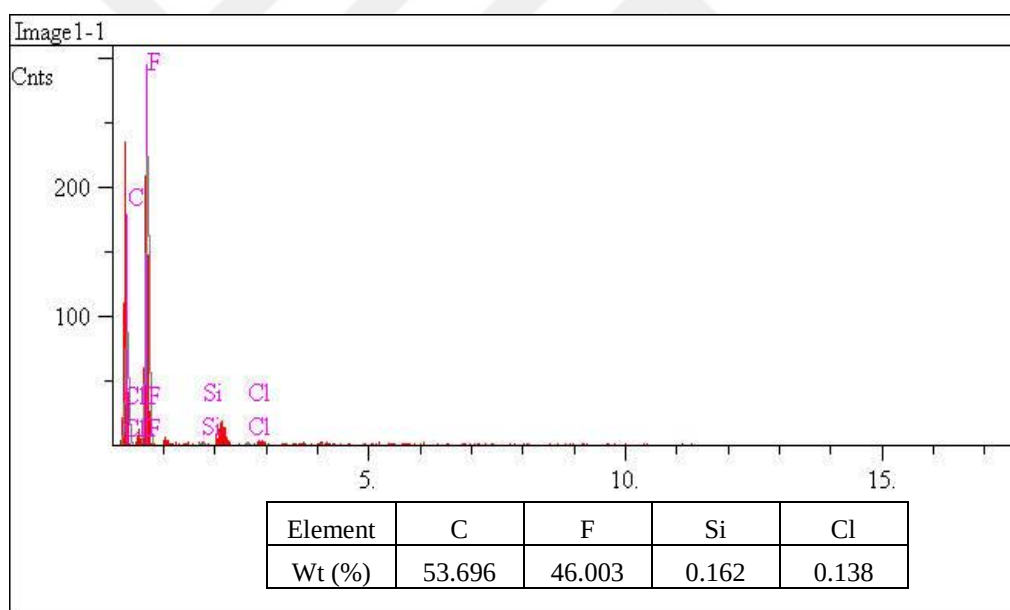
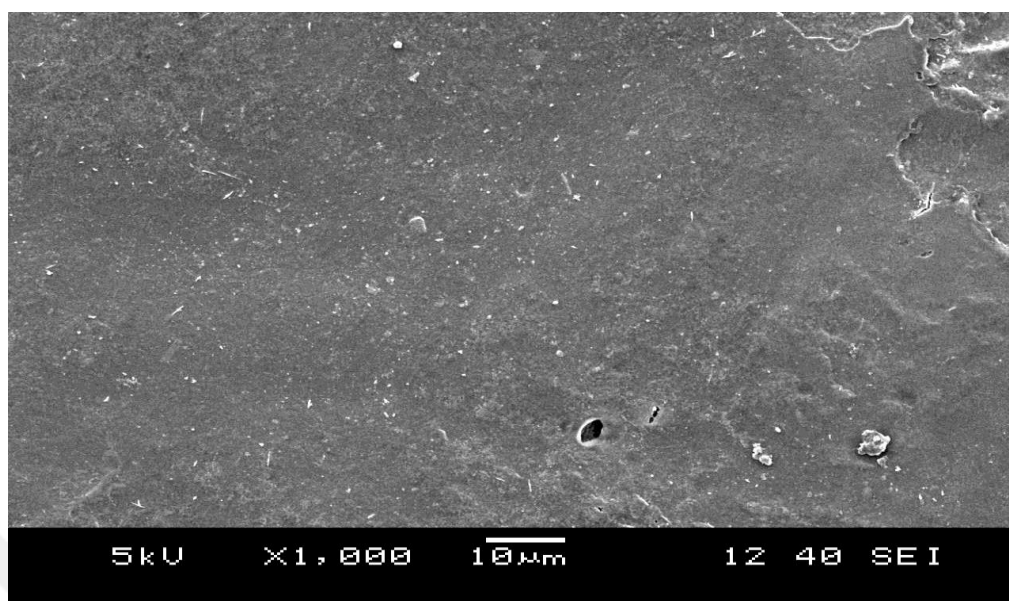


Figure 4.13 SEM image and EDS analysis result of MF022

The filterability property of the membrane was regularly determined. 10.74 LMH of the initial flux decreased sharply to 1.12 LMH after 34 days of the operation time. Consequently, TMP increased continuously during operation period. Figure 4.14 showed the relationship between flux and TMP.

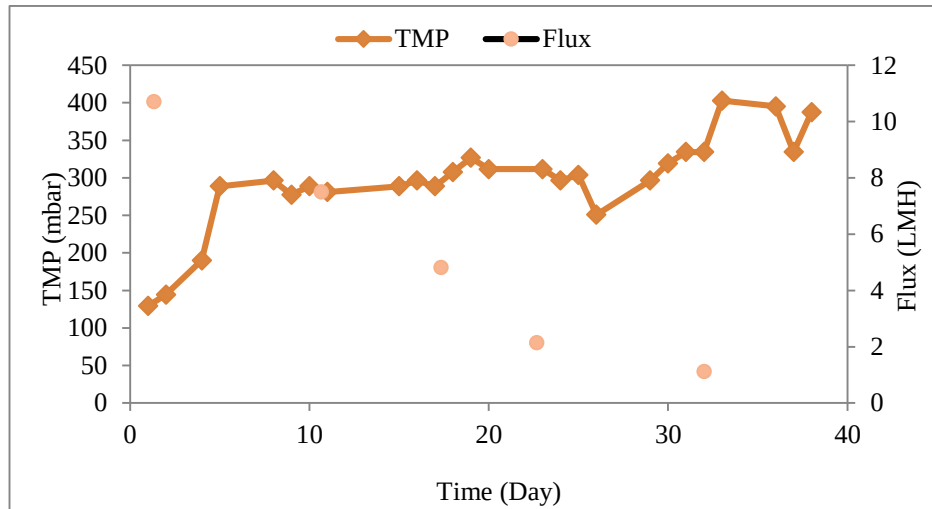


Figure 4.14 Changes in flux and TMP during operation

After 38 days of operation, the membrane support material and membrane were removed from system. Dynamic layer with a depth of 6 mm was observed on the MBTF. It was also determined that there was no excessive contamination on the surface of MF022 microfiltration membrane. Photographs of dynamic layer formed on MBTF and MF022 microfiltration membrane were shown in Figure 4.15.

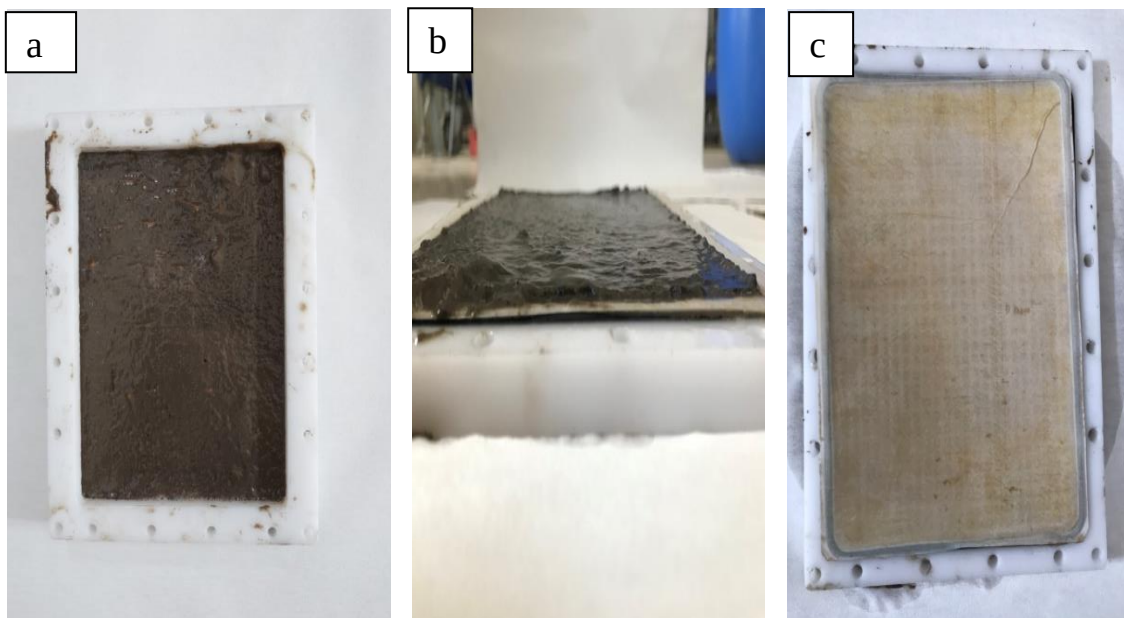


Figure 4.15 Images of surface of materials: (a), (b): MBTF, (c): MF022 (Personal archive, 2019)

#### **4.4 Performance of MF010+MBTF for Treatment of Synthetic Wastewater- Second Experimental Trial**

After the first experimental study, the MBTF and MF010 microfiltration membrane selected for second experimental study were placed in the cassette and immersed in the bioreactor. Synthetic wastewater was prepared every other day to feed the system as in the first experimental study. Synthetic wastewater was transferred from influent tank to the DMBR system by a submersible pump according to the change in membrane flux.

The membrane module was operated as a submerged configuration inside the aerobic tank by placing MBTF on the PVDF microfiltration membrane having 0.10  $\mu\text{m}$  pore size. The operation carried out during 27 days. The operation flux was set at 10.7 LMH and was run in the same way until it dropped below 1 LMH. Initial hydraulic retention time was 19 hours. Dissolved oxygen was supplied by aeration diffusers placed bottom of the aerobic DMBR and DO concentration was maintained higher than 1 mg/L. No excess feed sludge was inoculated into the system during the experimental period and sludge was only withdrawn from aerobic tank for sampling purpose.

The changes in DO, pH, conductivity, and salinity were daily measured. DO concentration in the reactor was maintained higher than 3 mg/L during entire operation as shown in Figure 4.16. Concentration of dissolved oxygen in the reactor did not fall below 1 mg/L during the entire period and reactor temperature varied between 12 °C and 15 °C. pH, conductivity, and salinity values as a function of operation time is plotted in Figure 4.17. pH values ranged between 8.5 and 9 for all samples. While conductivity value decreased in the reactor, effluent conductivity value had almost the same as the value in the reactor. However, they were lower than the influent wastewater. Those results pointed out that this membrane having 0.10  $\mu\text{m}$  pore size was not very effective to decrease conductivity and salinity values as in 0.22  $\mu\text{m}$  membrane in previous experimental study.

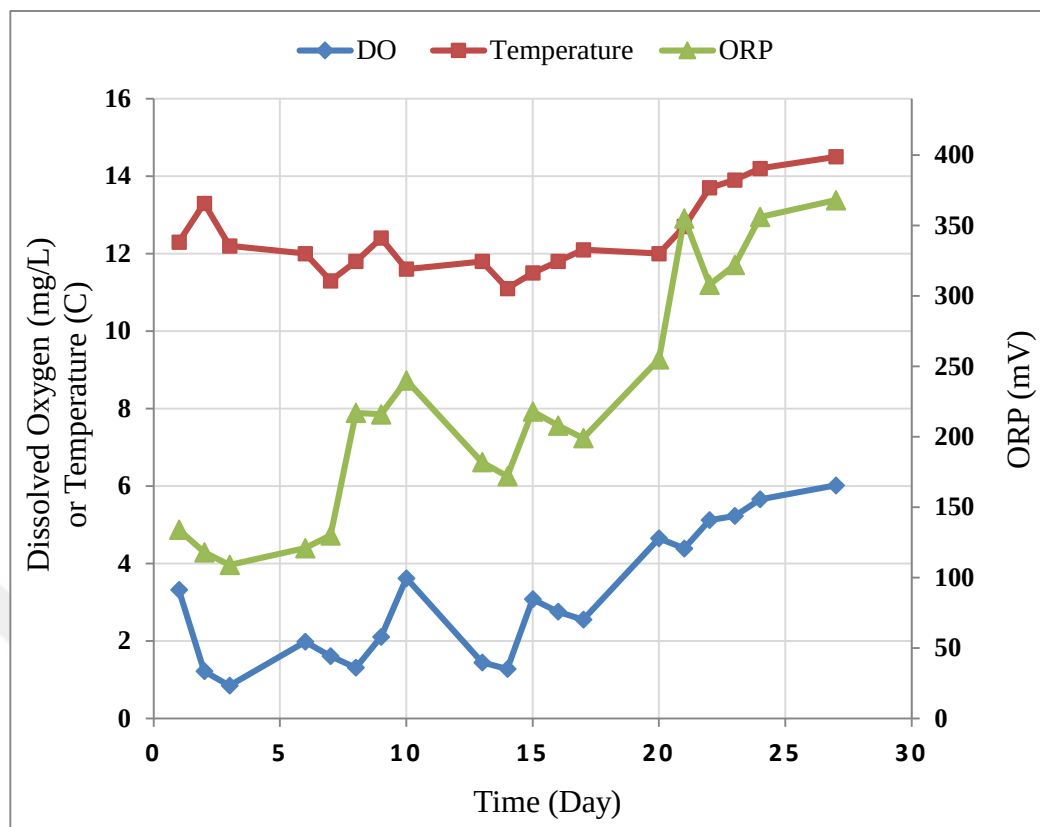


Figure 4.16 Daily changes in DO, temperature and ORP in the reactor of second experimental trial

The graphical representations of the experimental results based on COD, BOD<sub>5</sub>, SS, NH<sub>4</sub><sup>+</sup>-N, TN, TP parameters were presented in Figure 4.18. The removal efficiencies of the system in terms of COD, BOD, SS and NH<sub>4</sub><sup>+</sup>-N were found remarkably high values as 99%, 99.3%, %100, and % 99.7, respectively. A partial nutrient removal was obtained in the system similar to the first experimental study. Average removal efficiencies of TN and TP were found as 33% and 14.4%, respectively. While average sulphate removal rate was reported as 70.3% that was significantly higher than the average removal in first experimental study. Nevertheless, residual chloride concentration remained the same at influent and effluent. Effluent alkalinity concentration was generally higher than influent alkalinity concentration in this experimental study as well.

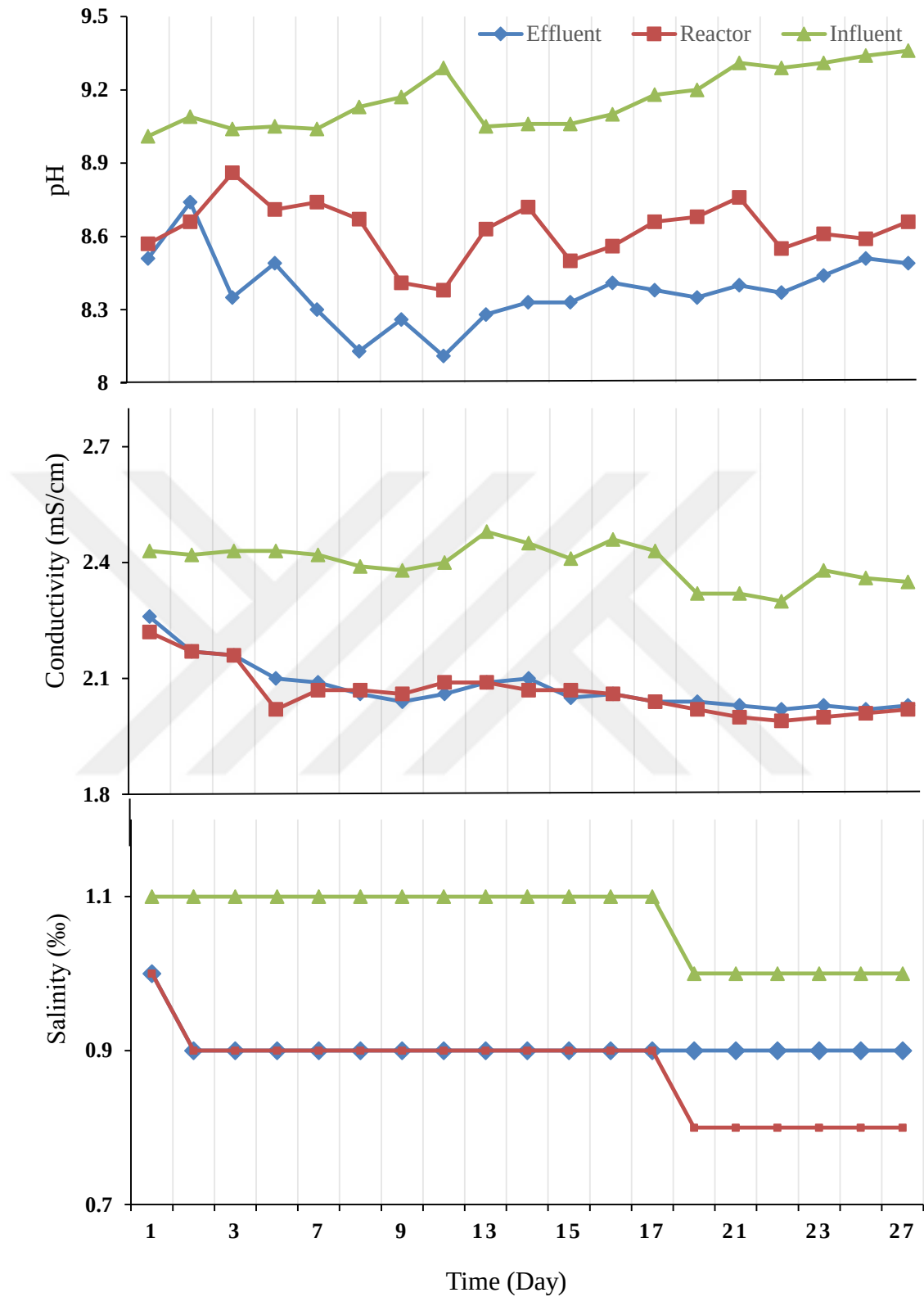


Figure 4.17 Daily changes in pH conductivity and salinity values of second experimental

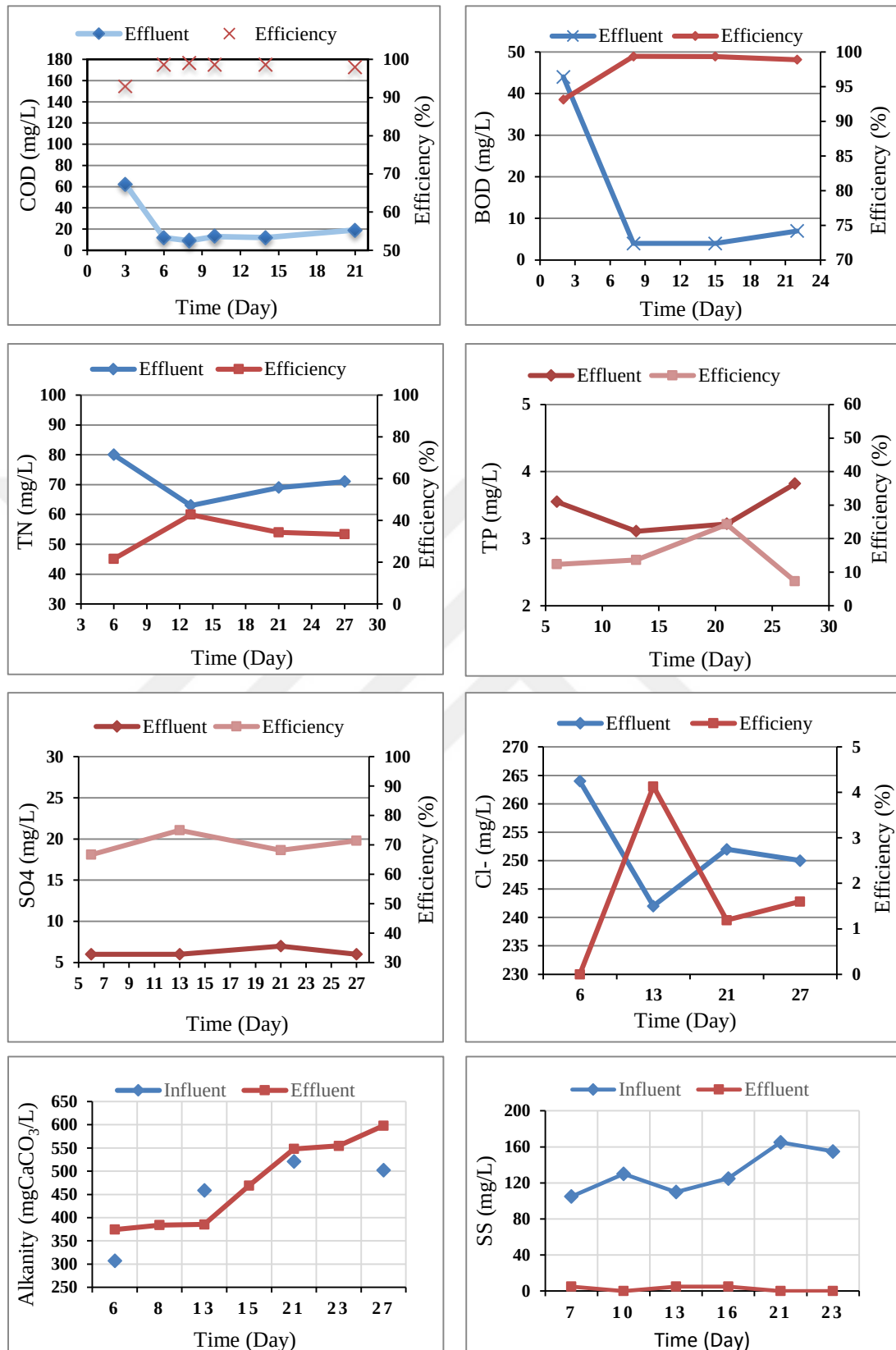


Figure 4.18 Graphical representations of results at the second experimental study

Changes in sludge characterization were analyzed periodically as depicted in Figure 19. MLSS concentration varied between 8050 mg/L and 6745 mg/L during operation. Average MLVSS/MLSS ratio was about 70%. CST and SVI values increased to certain extent in the later days of operation. Zeta potential declined from -43.2 mV to -51.1 mV at the end of the operation that indicates a decrease in adsorption capacity of the sludge.

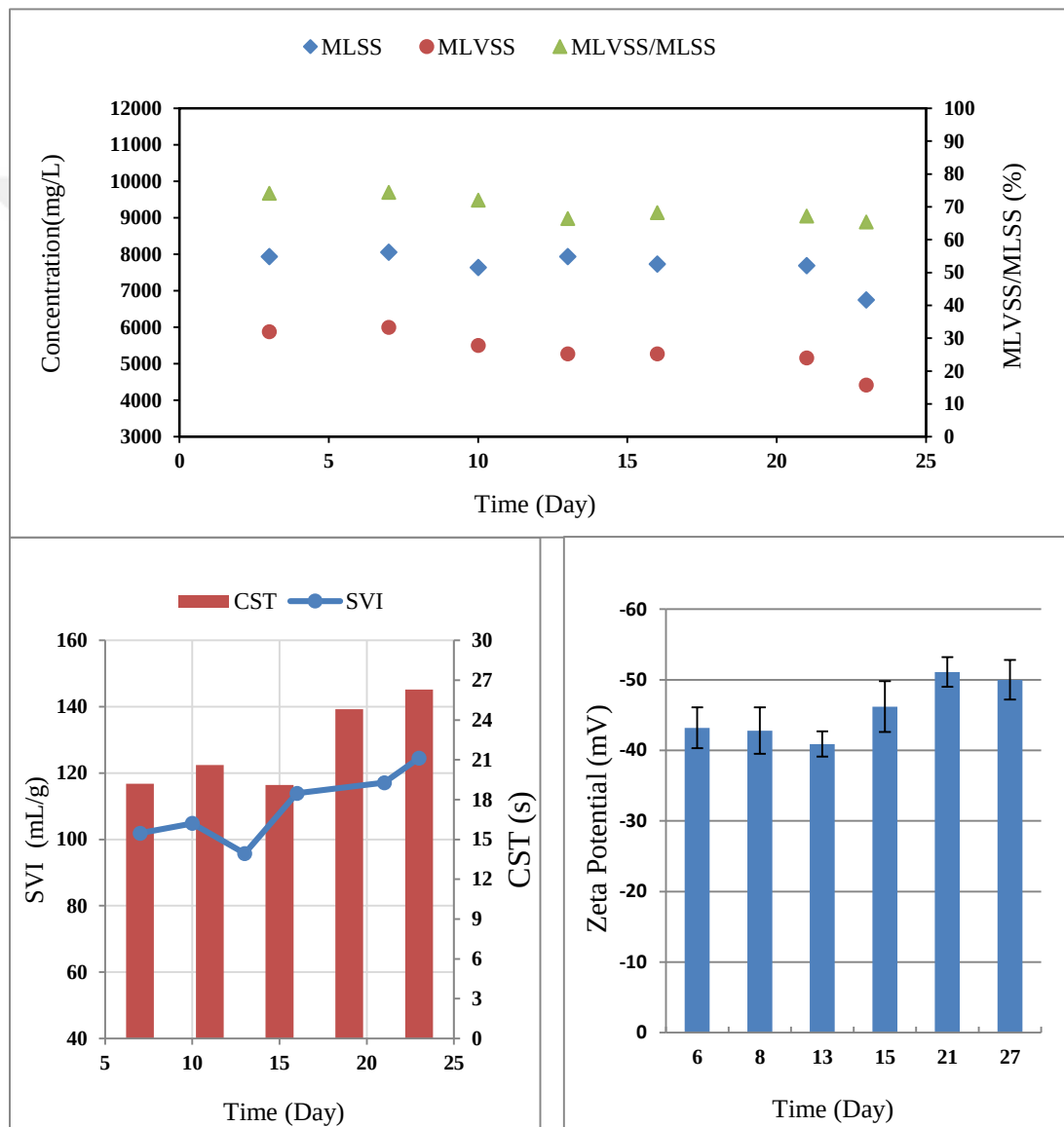


Figure 4.19 Changes in sludge characterization in first experimental study- MLSS and MLVSS values and the MLSS/MLVSS ratio; Variation in SVI and CST values; Zeta potential values

Particle size distributions of the sludge in the reactor and the treated wastewater in the effluent were analyzed at regular intervals during experimental period as given in Figure 4.20 and 4.21, respectively. The results were also reported in Table 4.4 and Table 4.5. The volume weighted mean of sludge was 77.018 $\mu\text{m}$ . However, this value decreased a little on following days. Beyond this, the average particle size values of the effluent samples were found higher values when considering the membrane pore size. It could be that the components like Ca, Mg, K which were not rejected during the treatment were available in the effluent and led to somewhat coagulation.

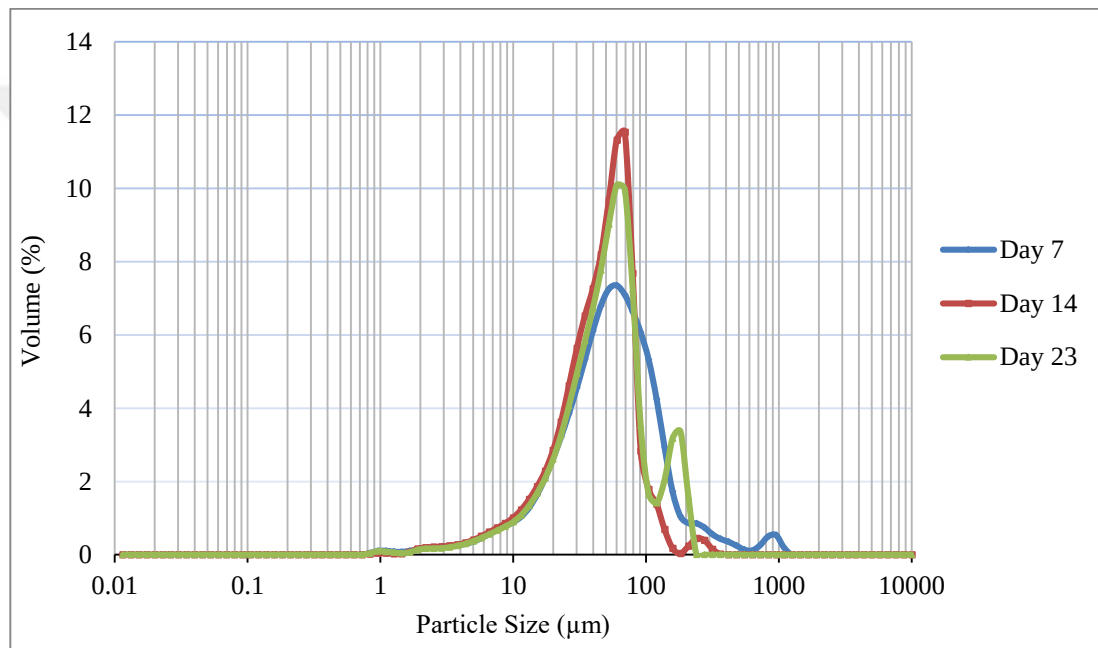


Figure 4.20 Particle size distribution of sludge at different days

Table 4.4 Detailed information on particle size distribution of sludge in the reactor

|                                                    | Day 7   | Day 14 | Day 23  |
|----------------------------------------------------|---------|--------|---------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 77.018  | 47.807 | 56.652  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 25.865  | 25.147 | 26.254  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.232   | 0.239  | 0.229   |
| d(0.1) ( $\mu\text{m}$ )                           | 15.299  | 14.492 | 15.554  |
| d(0.5) ( $\mu\text{m}$ )                           | 50.809  | 44.548 | 48.017  |
| d(0.9) ( $\mu\text{m}$ )                           | 128.249 | 76.017 | 121.874 |

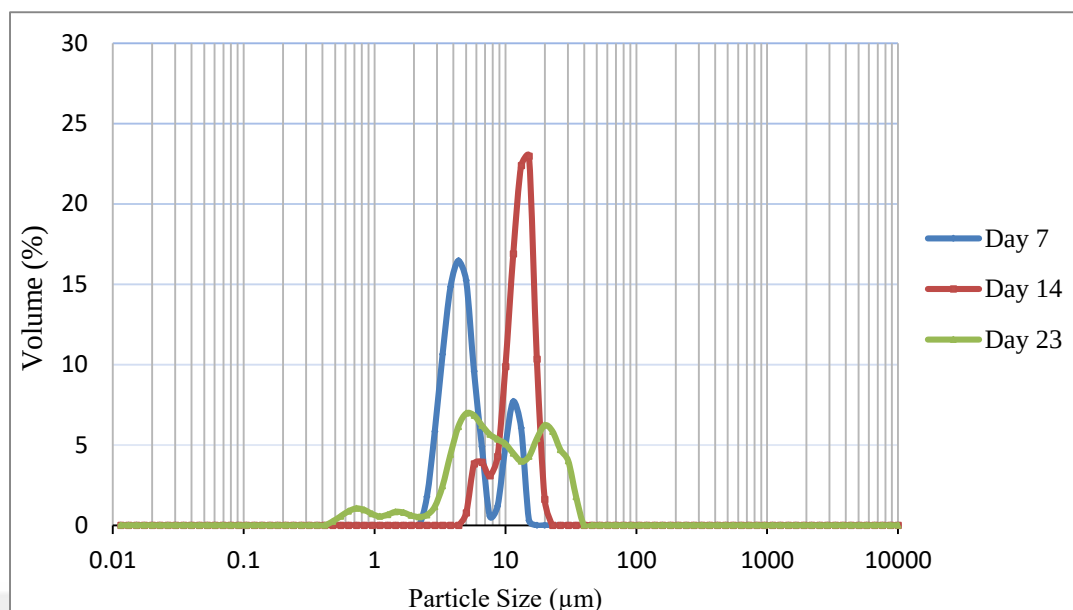


Figure 4.21 Particle size distributions of effluent stream at different days

Table 4.5 Detailed information on particle size distribution of effluent

|                                                    | Day 7  | Day 14 | Day 23 |
|----------------------------------------------------|--------|--------|--------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 5.463  | 11.760 | 10.717 |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 4.461  | 10.771 | 4.555  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 1.34   | 0.557  | 1.32   |
| $d(0.1)$ ( $\mu\text{m}$ )                         | 2.994  | 7.033  | 4.555  |
| $d(0.5)$ ( $\mu\text{m}$ )                         | 4.382  | 12.049 | 7.804  |
| $d(0.9)$ ( $\mu\text{m}$ )                         | 10.780 | 15.385 | 23.202 |

Rheological properties of sludge in the DMBR system were also analyzed periodically. Rheological properties as viscosity and shear stress as a function of shear rate was shown in Figure 4.22 and in Figure 4.23, respectively. The sludge samples exhibited non-Newtonian flow behavior. Rheological analysis showed that sludge had shear thinning properties. Significant change in viscosity of the sludge was not observed. Partial change was observed because of fluctuation of MLSS concentration.

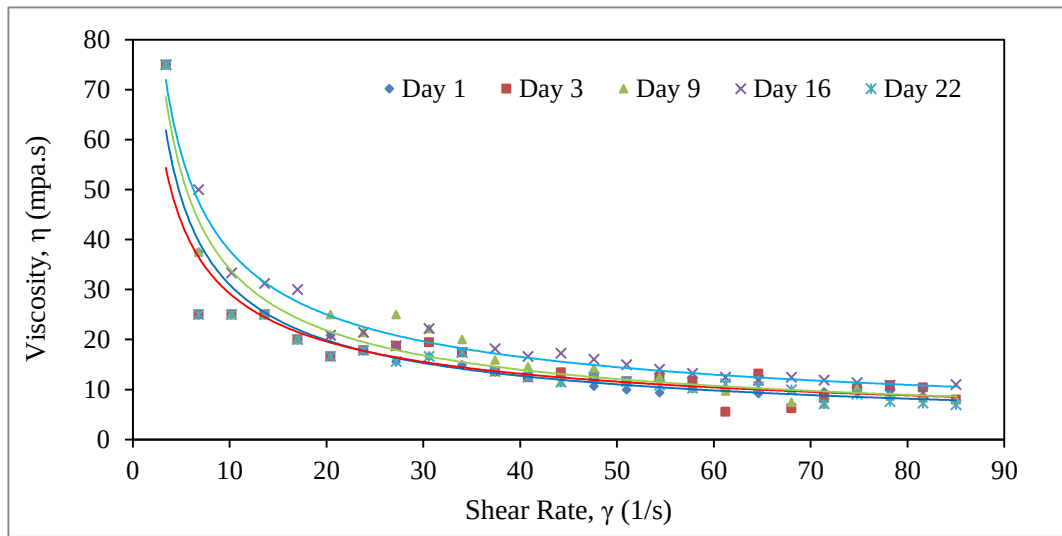


Figure 4.22 Viscosity of sludge as a function of shear rate

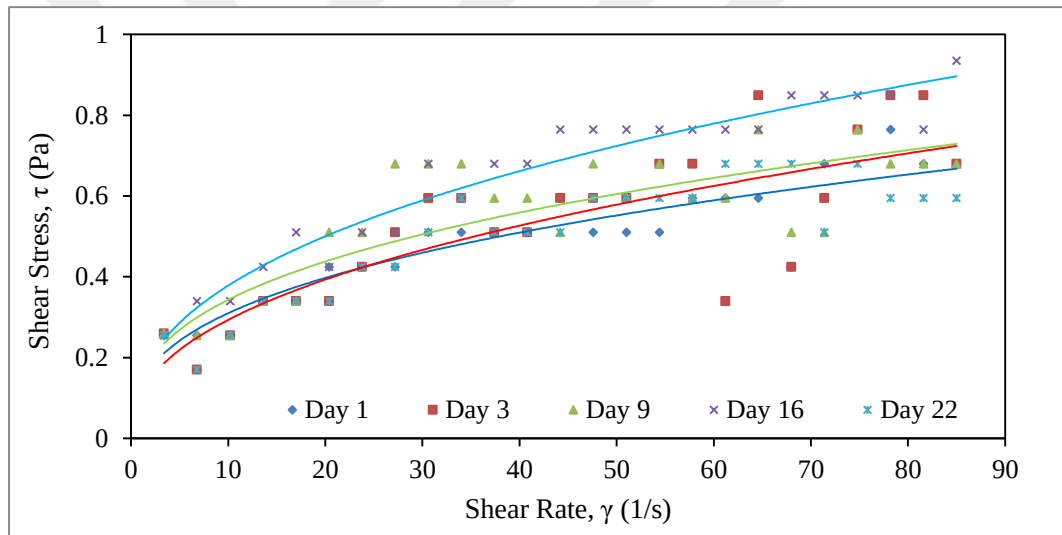


Figure 4.23 Shear stress of sludge as a function of shear rate

SEM-EDS analysis of MF010 and MBTF were done. The results were given in Figure 4.24 and Figure 4.25. It is obvious that the dynamic layer was formed on the membrane support material according to SEM image of MBTF. EDS analyze of MBTF revealed that inorganic substances such as Na, Mg, Al, Si, P, S, Cl, K and Ca accumulated in the dynamic layer formed on MTBF. In contrast to MBTF, less inorganic material accumulation was found on the MF010 membrane. It is obvious that the formed dynamic layer prevented inorganic foulants from accumulating on the surface of MF010 membrane.

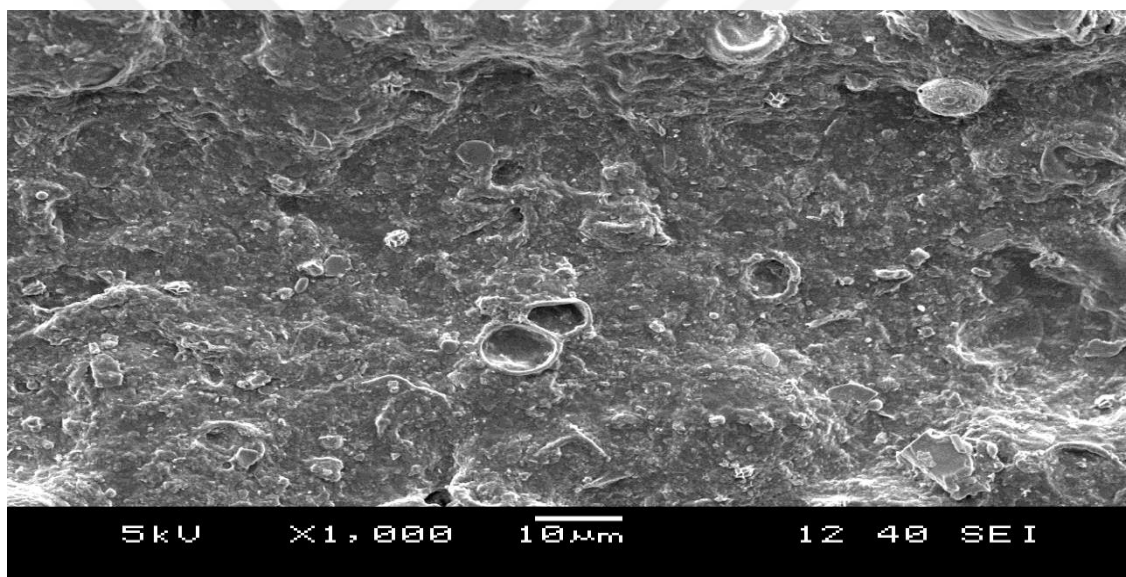
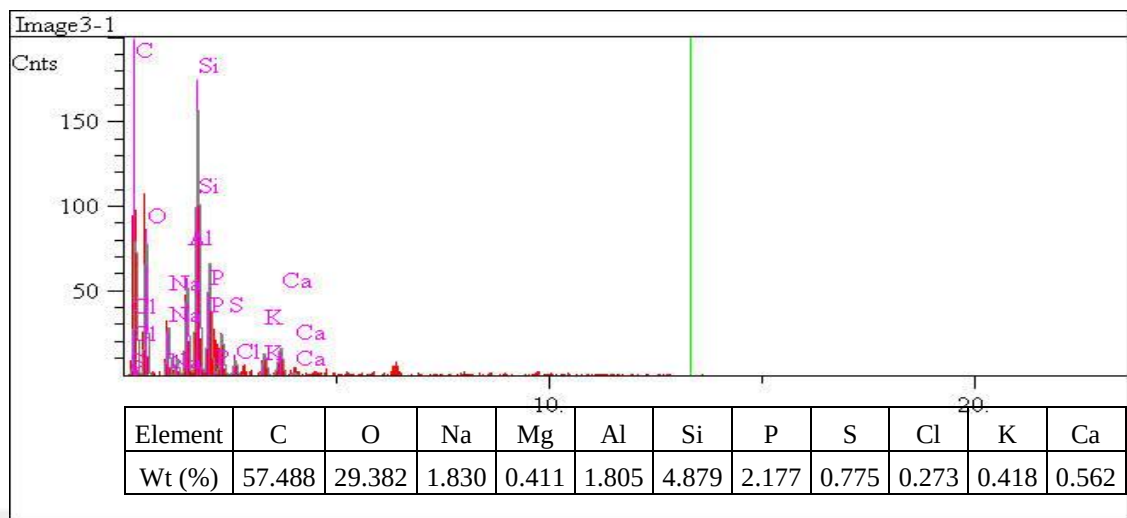


Figure 4.24 SEM photograph and EDS analysis of dynamic layer on MBTF

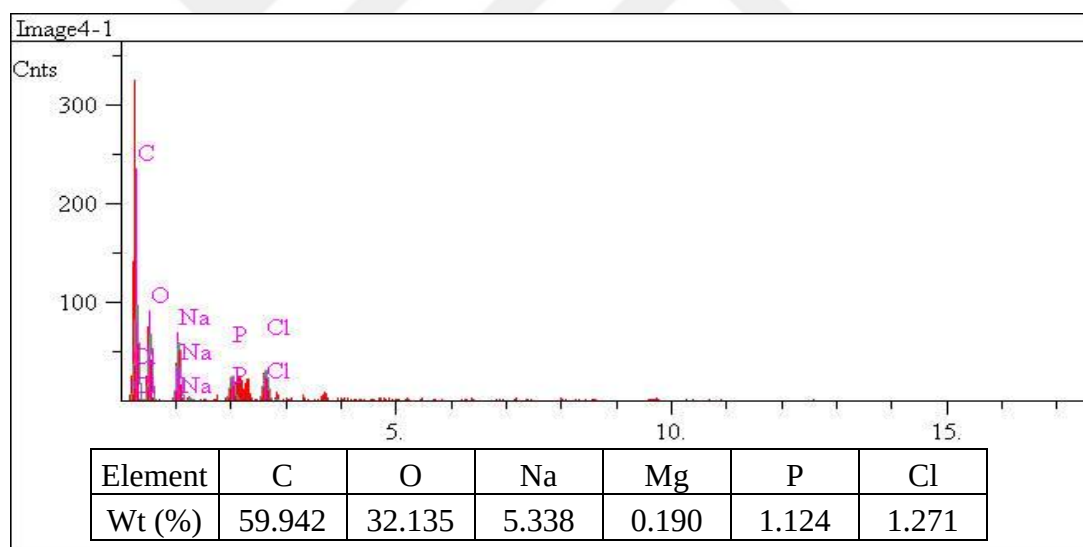
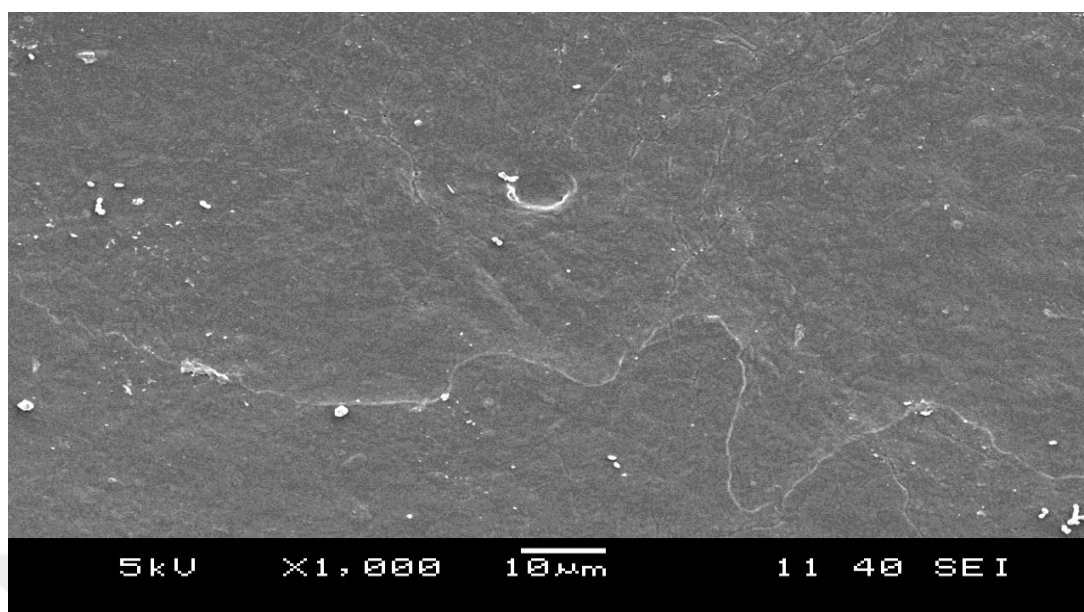


Figure 4.25 SEM photograph and EDS analysis of MF010

The filterability of the membrane was measured regularly. 10.74 LMH initial flux dropped regularly until 1.07 LMH after 27 days of operation time. TMP accordingly increased continuously during operation period. Figure 4.26 showed the relationship between flux and TMP.

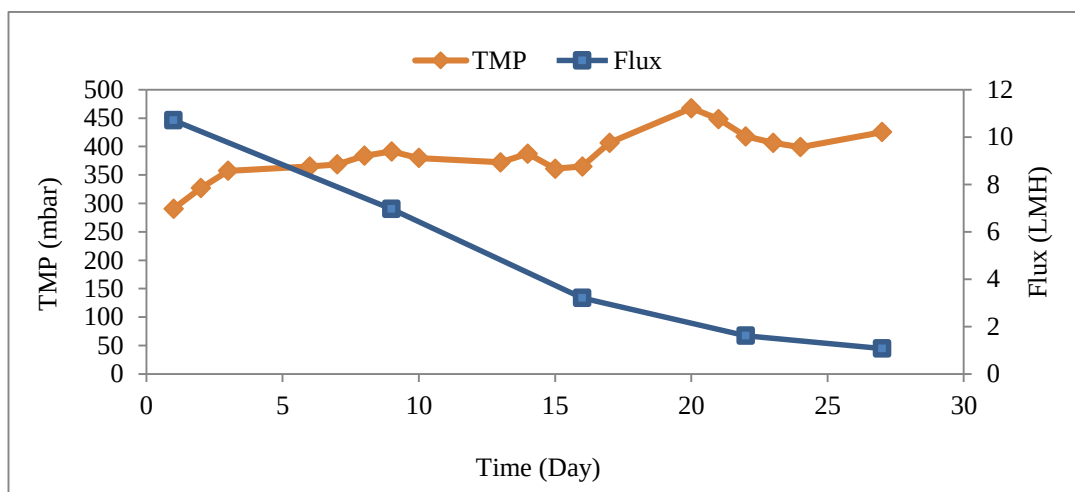


Figure 4.26 Changes in flux and TMP during operation in second experimental study

After 27 days of operation, the membrane support material and membrane were removed from system. It was observed that proper dynamic layer formed on the MBTF. In contrast to first experimental study, it was noticed that there was a gel-like fouling on the MF010 microfiltration membrane. Images of dynamic layer formed on MBTF and MF010 microfiltration membrane was shown in Figure 4.27.

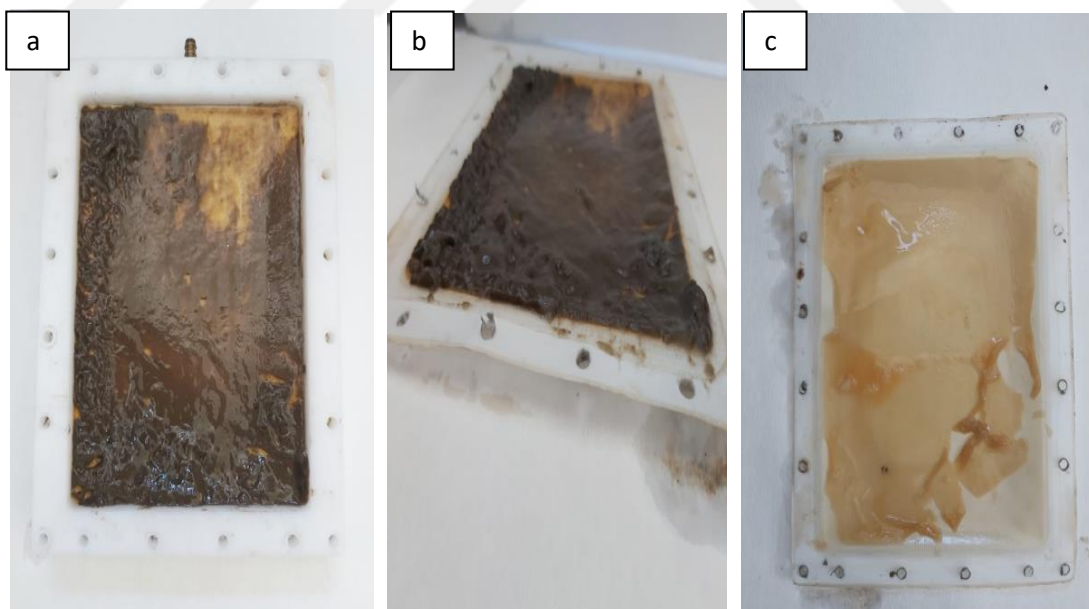


Figure 4.27 Images of surface of materials: (a), (b): MBTF, (c): MF010 (Personal archive, 2019)

#### **4.5 Performance of Double Layer MBTF for Treatment of Synthetic Wastewater- Third Experimental Trial**

Regarding the results of first two experimental studies, another experimental trial was decided to apply only two layers of MBTF placed on both surface of the membrane cassette as immersed configuration without any MF/UF membrane usage. Synthetic wastewater was fed to the DMBR system as in first and second experimental studies.

The membrane module was operated submerged configuration inside the aerobic tank by placing two layers MBTF to observe whether self-forming dynamic layer will occur or not. The operation period continued up to 15 days. The operation flux was set at 12.85 LMH and change in flux was monitored daily. Initial hydraulic retention time was 16.6 hours. Dissolved oxygen was supplied by aeration diffusers placed bottom of the aerobic DMBR and DO concentration was maintained higher than 2 mg/L. No excess feed sludge was inoculated into the system during entire experimental period and sludge was only withdrawn from aerobic tank for sampling purpose.

The changes in DO, pH, conductivity, and salinity were daily measured. DO concentration in the reactor did not fall below 2 mg/L during the entire period as depicted in Figure 4.28 and the reactor temperature varied between 19.5 °C and 23.1 °C. ORP results showed that the system was kept as aerobic conditions. pH, conductivity, and salinity values as a function of operation time is plotted in Figure 4.29. pH values were about 9 for reactor and effluent samples while it was about neutral range for the influent wastewater. Conductivity value decreased in the reactor and effluent stream. Salinity value is the same in the reactor and the effluent. Those results pointed out that two layer MBTF was partially efficient to decrease conductivity and salinity values like those in previous experimental studies.

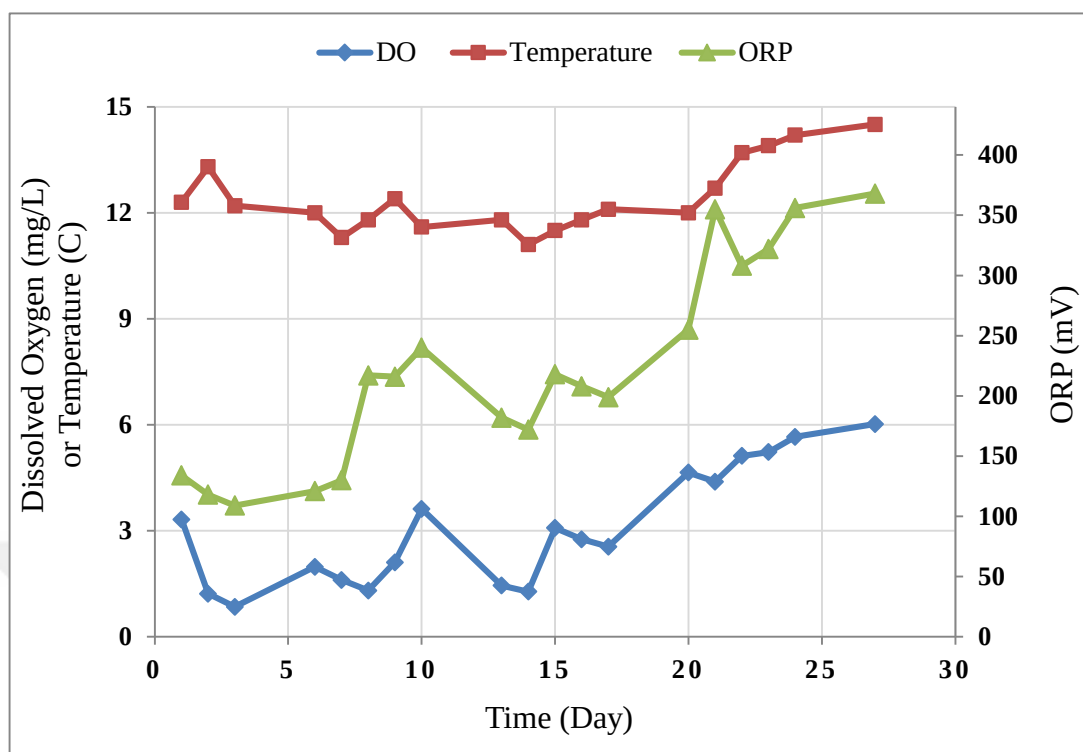


Figure 4.28 Daily changes in DO, temperature and ORP in the reactor at the third experimental trial

The graphical representations of the experimental results were given in Figure 4.30. The removal efficiencies, which were lower in the first days of operation, increased to high rates after formation of the dynamic layer in terms of COD, BOD, SS and  $\text{NH}_4^+\text{-N}$ . Efficiencies reached 98.3%, 98.7%, %100, and % 99.7, respectively. Partial nutrient removal was obtained in the system similar to the first two experimental studies. Average efficiencies of TN and TP were 48% and 5.5%, respectively. The average sulphate removal efficiency was only 17.3% that was significantly lower than the average removal in previous experimental studies. Residual chloride concentration remained the same at influent and effluent. Effluent alkalinity concentration was generally higher than influent alkalinity concentration in this experimental study as well.

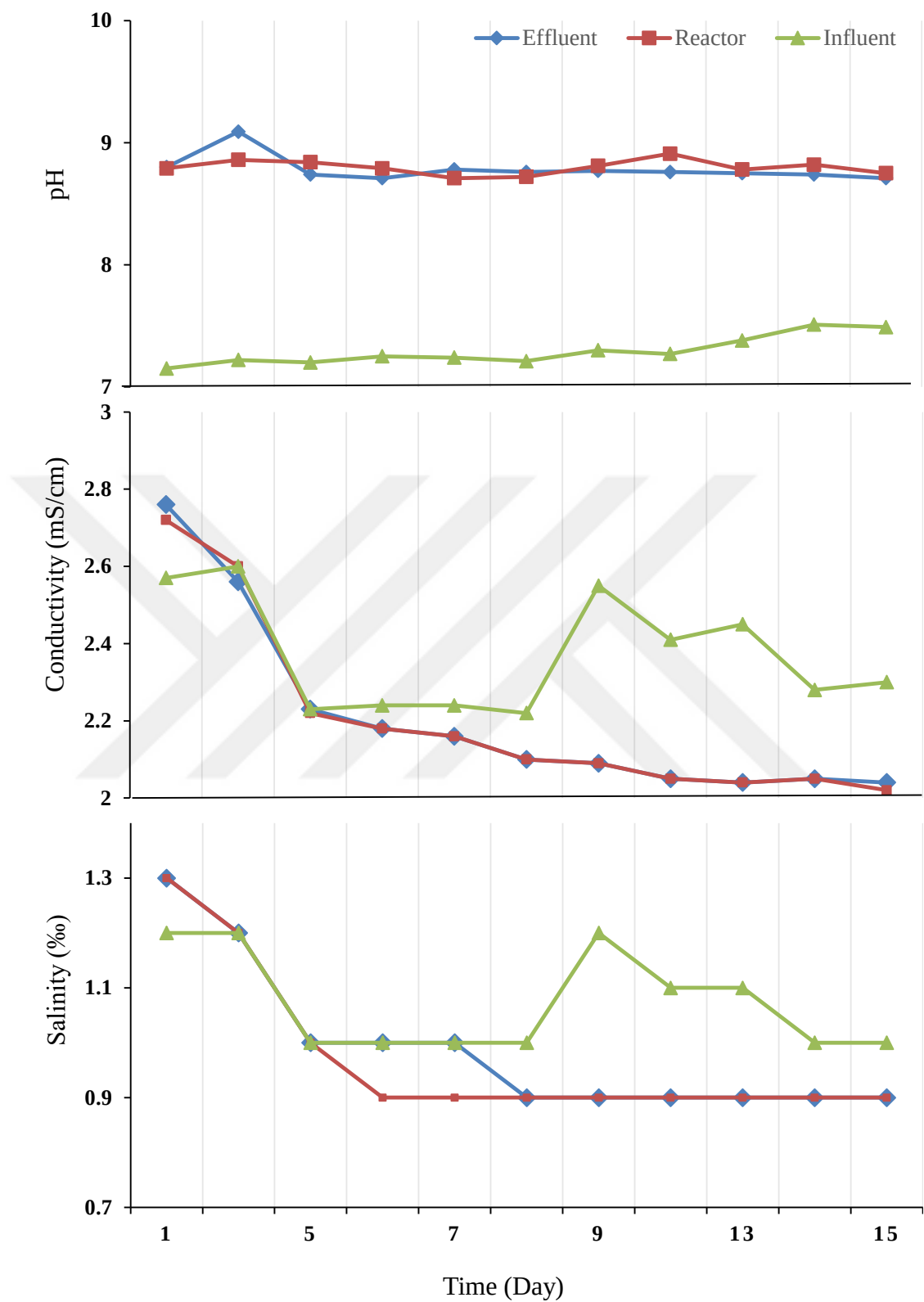


Figure 4.29 Daily changes in pH, conductivity and salinity values of third experimental trial

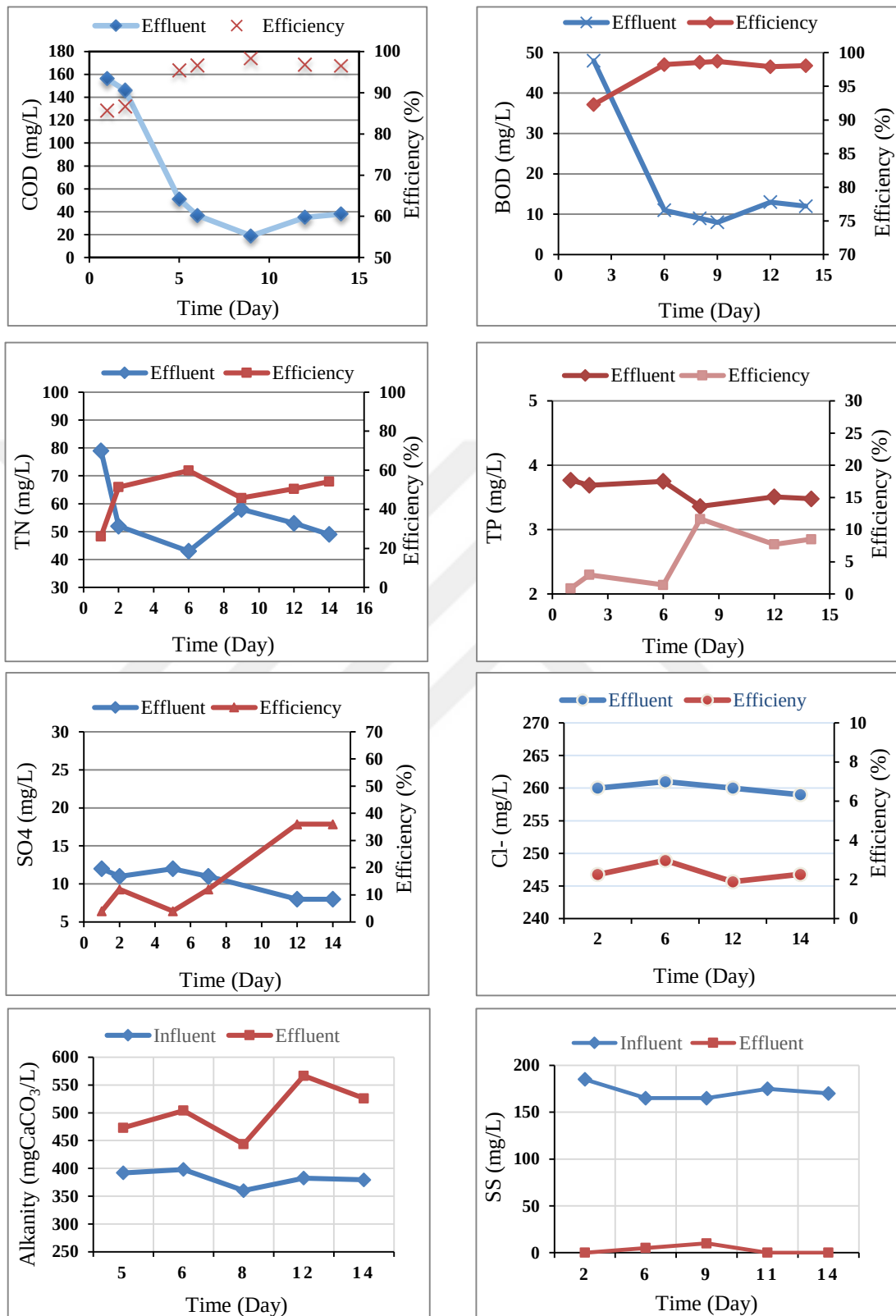


Figure 4.30 Graphical representation of the results of third experimental study

Changes in sludge characterization were given in Figure 4.31. MLSS concentration varied between 4245 mg/L and 3470 mg/L during operation. Average MLVSS/MLSS ratio was about 78.1%. There was a partial change in CST and SVI values. Total EPS concentration fluctuated between 122.5 mg/L and 172.1 mg/L. Mohan and Nagalakshmi (2020) states that low EPS concentration contributes to providing high filterability as EPS increases filtration resistance by affecting sludge that deposits on membrane surface. The protein concentrations were higher than polysaccharide concentrations as expected in aerobic systems. Total EPS got lower values as a function of operation time, it seems the sludge filterability characteristic were good as confirmed by CST values. Zeta potential ranged from -45 mV to -55 mV during the operation.

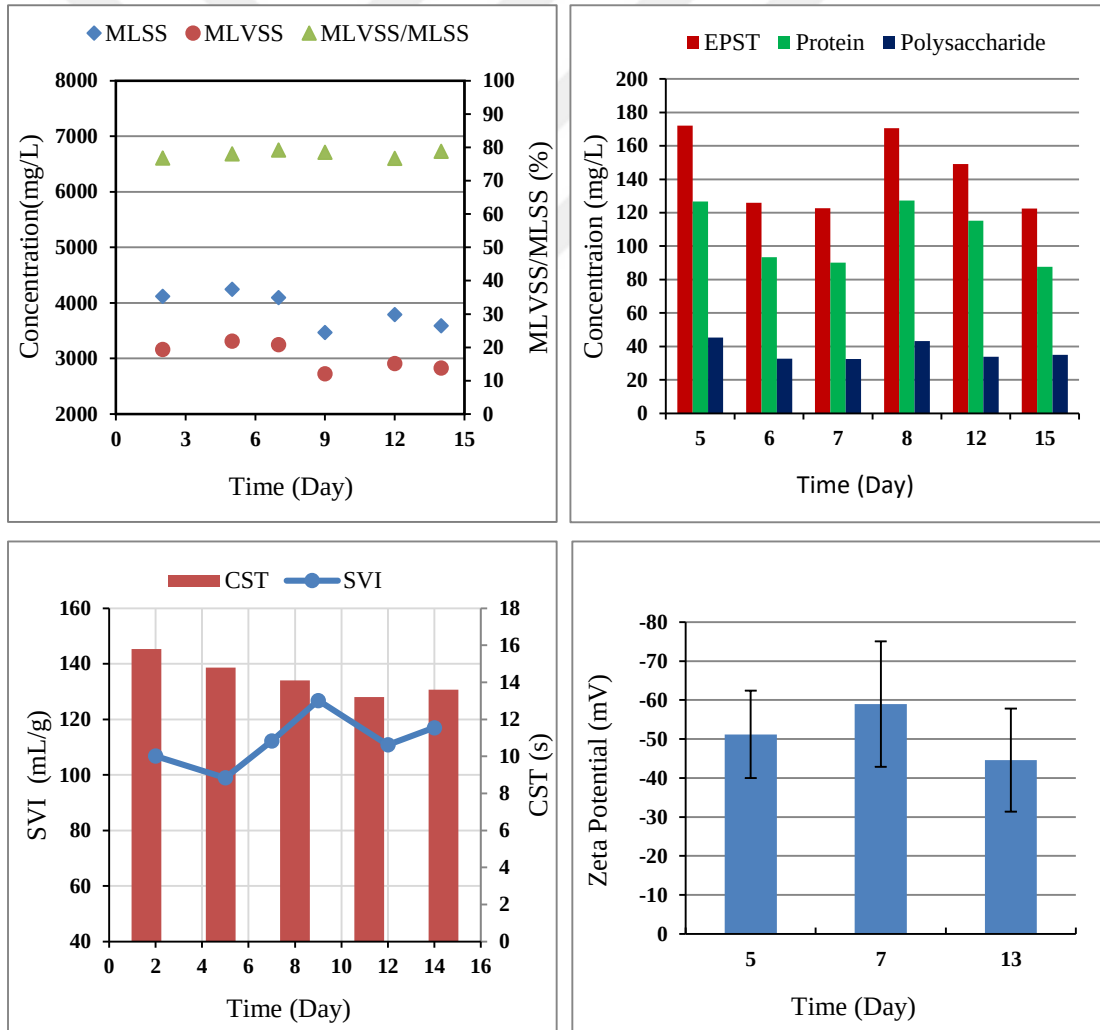


Figure 4.31 Changes in sludge characterization in third experimental study

Particle size distributions of the sludge in the reactor and the treated wastewater in the effluent were analyzed at regular intervals during experimental period as shown in Figure 4.32 and 4.33, respectively. The results were also reported in Table 4.6 and Table 4.7. The volume weighted mean of sludge was 70.316  $\mu\text{m}$ . Although there is little change afterwards, particle size distribution remained almost constant on the following days. The particle size distribution of effluent changed significantly on the later days of operation. Particles sizes decreased after the formation of the dynamic layer on the support material. The average particle size values of the effluent samples were comparable with the pore size of MTBF as 30  $\mu\text{m}$ .

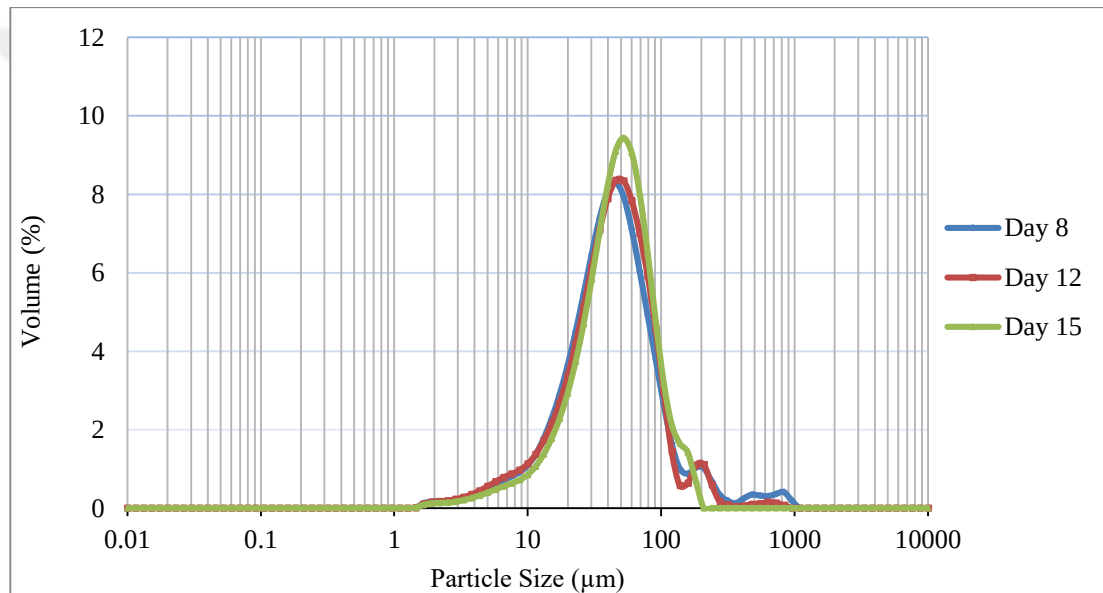


Figure 4.32 Particle size distribution of sludge on different days

Table 4.6 Detailed information on particle size distribution of sludge - third experimental trial

|                                                    | Day 8   | Day 12  | Day 15  |
|----------------------------------------------------|---------|---------|---------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 70.316  | 59.842  | 56.582  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 28.554  | 28.125  | 31.700  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.21    | 0.213   | 0.189   |
| d(0.1) ( $\mu\text{m}$ )                           | 15.644  | 15.144  | 18.249  |
| d(0.5) ( $\mu\text{m}$ )                           | 45.543  | 46.767  | 50.117  |
| d(0.9) ( $\mu\text{m}$ )                           | 113.700 | 102.329 | 101.592 |

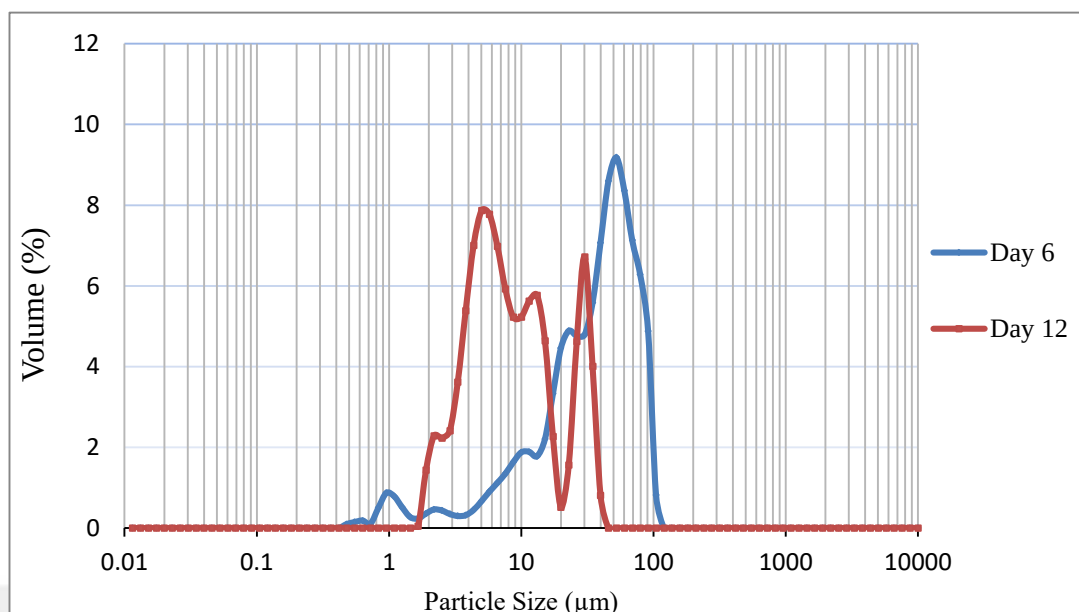


Figure 4.33 Particle size distribution of effluent

Table 4.7 Detailed information on particle size distribution of effluent - third experimental trial

|                                                    | Day 6  | Day 12 |
|----------------------------------------------------|--------|--------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 37.853 | 10.716 |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 11.117 | 6.001  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.54   | 1.00   |
| d(0.1) ( $\mu\text{m}$ )                           | 7.258  | 3.087  |
| d(0.5) ( $\mu\text{m}$ )                           | 36.430 | 7.054  |
| d(0.9) ( $\mu\text{m}$ )                           | 72.147 | 27.199 |

Rheological properties of sludge in the DMBR system were also analyzed periodically. Rheogram- viscosity as a function of shear rate was shown in Figure 4.34. The sludge samples exhibited non-Newtonian flow behavior. Rheological analysis showed that sludge had shear thinning properties. Significant change in viscosity of the sludge was not observed. Partial change was observed because of fluctuation of MLSS concentration.

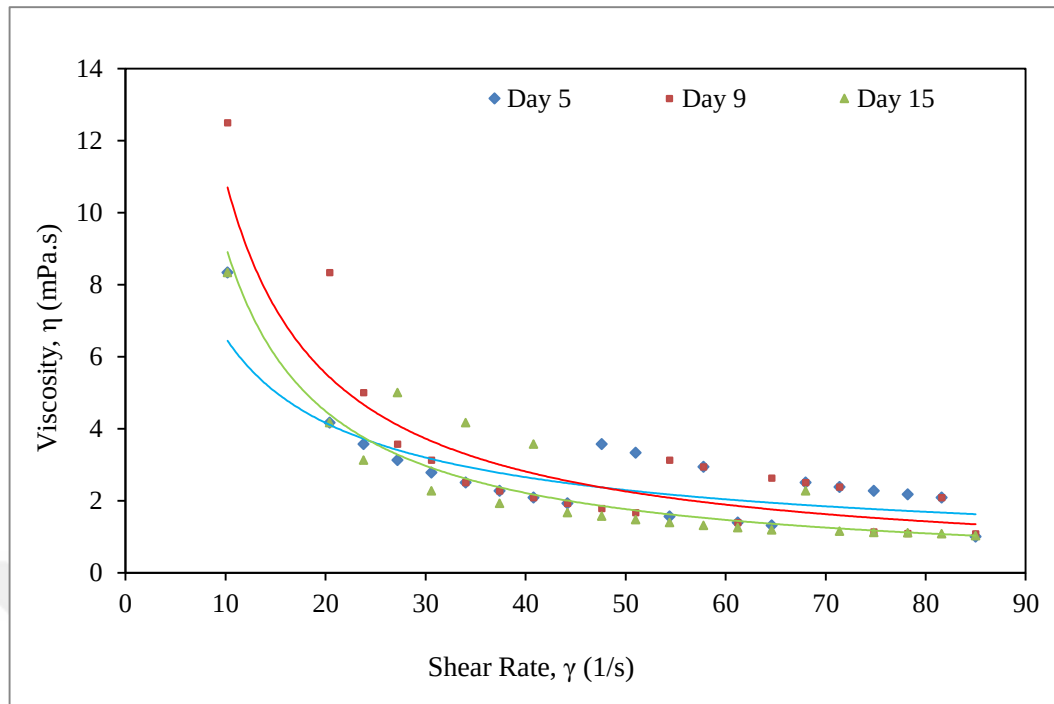


Figure 4.34 Viscosity of sludge as a function of shear rate

SEM-EDS analysis of the double layer MBTF was done. The results were given in Figure 4.35 and Figure 4.36. While the outer support material was completely covered with the dynamic layer, there was a partial accumulation on the inner membrane support material. It is also seen that inorganic substances in the mixed liquid adhere to the dynamic membrane layer. EDS analyze of MBTF revealed that inorganic substances such as Na, Mg, Al, Si, P, S, Cl, K and Ca accumulated in the dynamic layer formed on MTBF. Isik et al. (2019) reported that they found Si, Al, P, Ca, Fe, K, Mg, S, Na, Cl on the dynamic membrane surface. These results are consistent with the data of this study. Ersahin et al. (2016) reveals that those elements have positive effect for formation of dynamic layer as they have charge neutralization and the bridging effect.

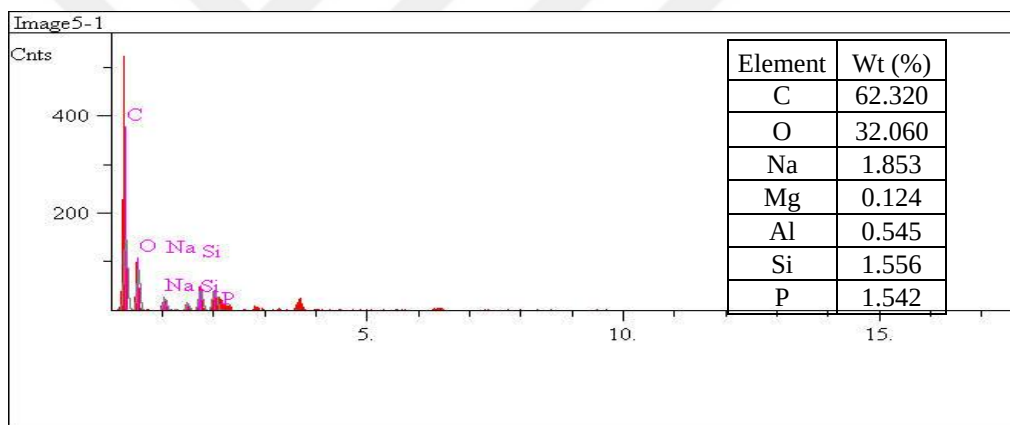
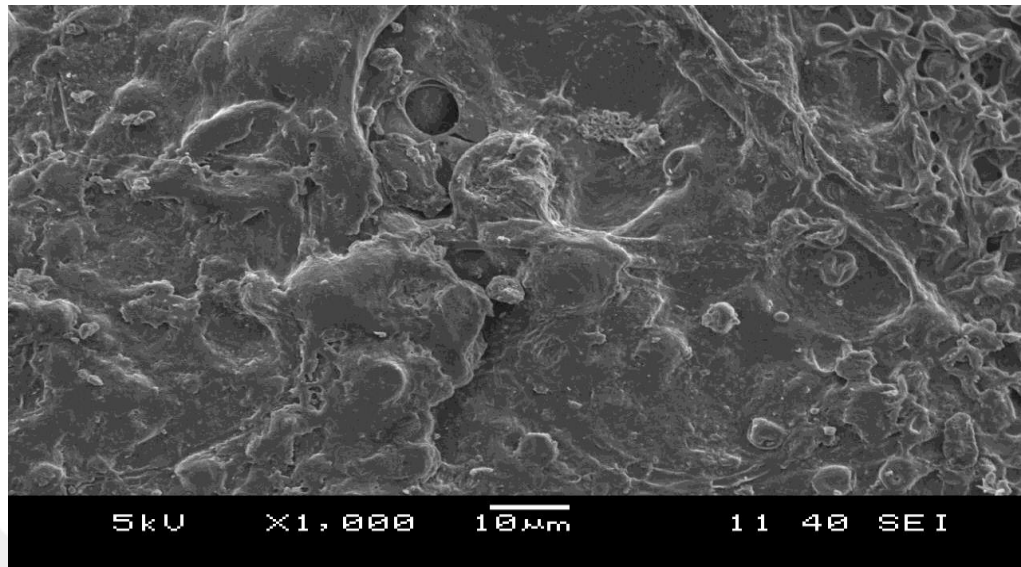


Figure 4.35 SEM photograph and EDS analysis of dynamic layer on outer MBTF

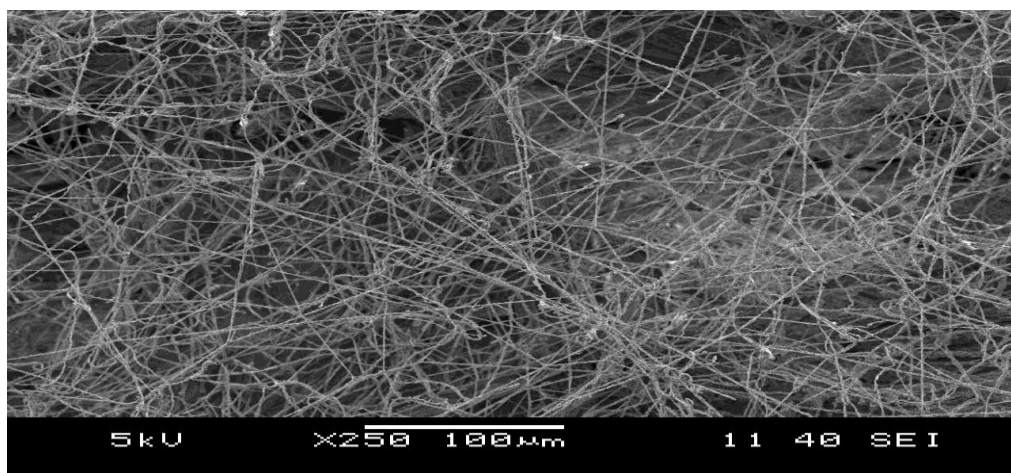


Figure 4.36 SEM photograph of inner MBTF

The filterability of the membrane was measured regularly. 12.85 LMH initial flux declined slowly until 8.46 LMH after 15 days operation. It reveals that only textile fabric represents longer high filterability compared to polymeric membranes. Although TMP increased in the first days of the operation, it reached a plateau in the following days. Isik et al. (2019) operated a DMBR with polyester fabric having 0.39  $\mu\text{m}$  pore size. They stated that TMP increased significantly during first days of operation and reached stable condition as in this study Figure 4.37 showed the relationship between flux and TMP.

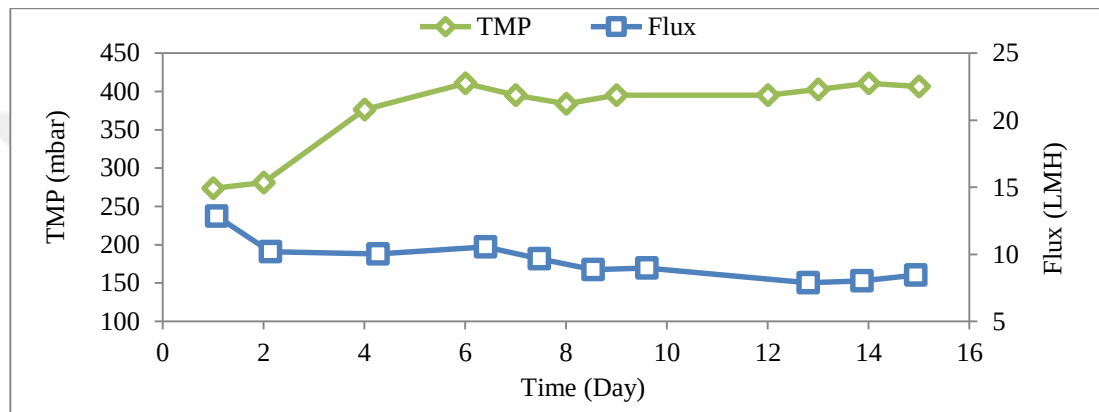


Figure 4.37 Changes in flux and TMP during operation in third experimental study

The membrane support materials were removed from system after 15 days operation. It was observed that proper dynamic layer formed on the exterior MBTF. No significant contamination was found on the interior MBTF. Images of dynamic layer formed on the outer TMBF and the interior TMBF was shown in Figure 4.38.

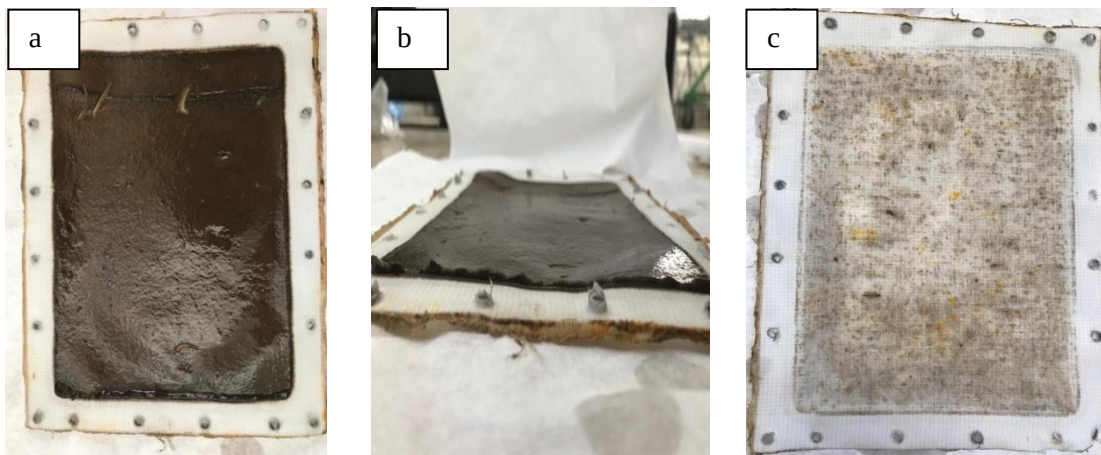


Figure 4.38 Images of surface of materials: (a), (b): exterior MBTF, (c) interior MBTF (Personal archive, 2019)

#### **4.6 Performance of Double Layer MBTF for Treatment of Municipal Wastewater- Fourth Experimental Trial**

During the fourth experimental study, the same two layers of MBTF were placed on both surface of the membrane cassette and immersed in the bioreactor. The first real municipal wastewater (WW1) taken from Izmir, Turkey was used to feed the system in this trial. The municipal wastewater was transferred from influent tank to the DMBR system by a submersible pump according to the change in membrane flux. The operation period continued during 16 days. The operation flux was set at 9.38 LMH and change in flux was observed daily. Initial hydraulic retention time was 22.5 hours. Dissolved oxygen was supplied by aeration diffusers placed bottom of the aerobic DMBR. No excess feed sludge was inoculated into the system during entire experimental period and sludge was only withdrawn from aerobic tank for sampling. DO concentration in the reactor did not fall below 2 mg/L during the entire period as shown in Figure 4.39 and the reactor temperature varied between 24°C and 28°C. ORP results indicated that the system was kept as aerobic conditions. pH, conductivity, and salinity values as a function of operation time is plotted in Figure 4.40. pH values were between 8 and 8.5 for all samples. Salinity and conductivity values increased due to feed wastewater change and approached influent value. It was determined that the values in the reactor and effluent are the same.

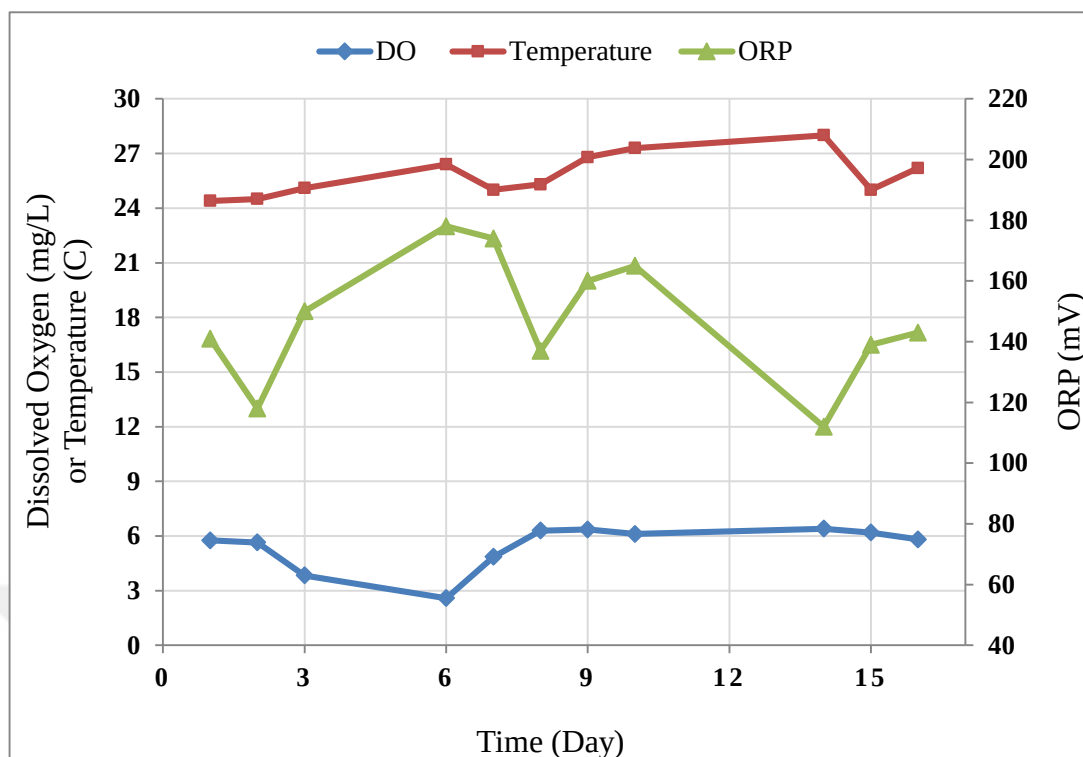


Figure 4.39 Daily changes in DO, temperature and ORP in the reactor- fourth experimental trial

The graphical representations of the experimental results were given in Figure 4.41. The removal efficiencies, which were lower in the first days of operation, increased to high rates after formation of the dynamic layer in terms of COD, BOD, SS and  $\text{NH}_4^+\text{-N}$ . Efficiencies reached 98.3%, 98.7%, %100, and % 99.7, respectively. Partial nutrient removal was obtained in the system similar to previous experimental studies. Average efficiencies of TN and TP were 49.9% and 5.2%, respectively. The average sulphate removal efficiency remained at 14.6%, which was remarkably lower than the average removals in first and second experimental studies. This result showed that polymeric membrane much better than textile fabric in terms of sulphate removal. Residual chloride concentration remained the same at influent and effluent. Unlike previous studies operated with synthetic wastewater, influent alkalinity concentration was generally higher than effluent alkalinity concentration in this experimental study.

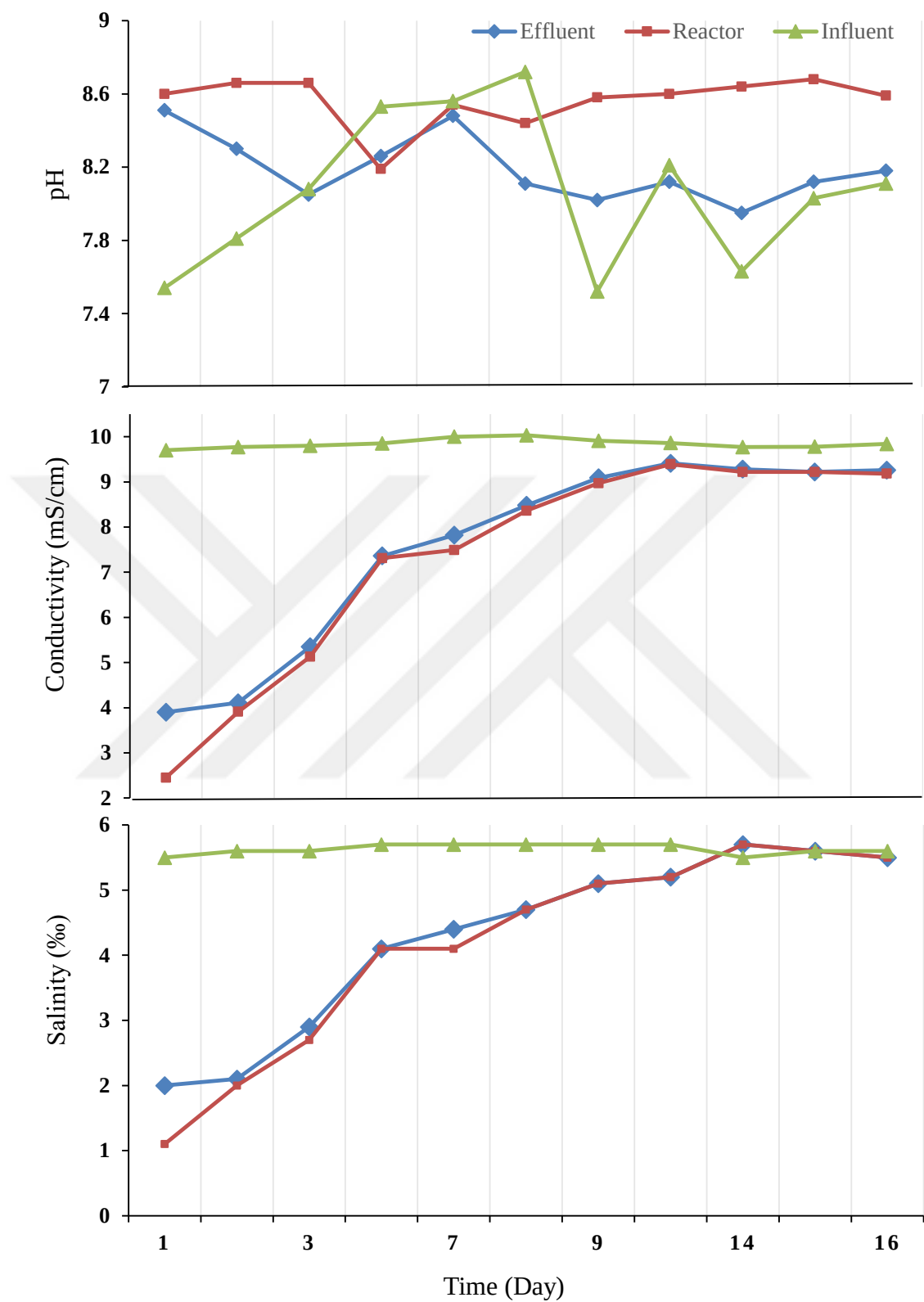


Figure 4.40 Daily changes in pH, conductivity and salinity in DMBR- fourth experimental trial

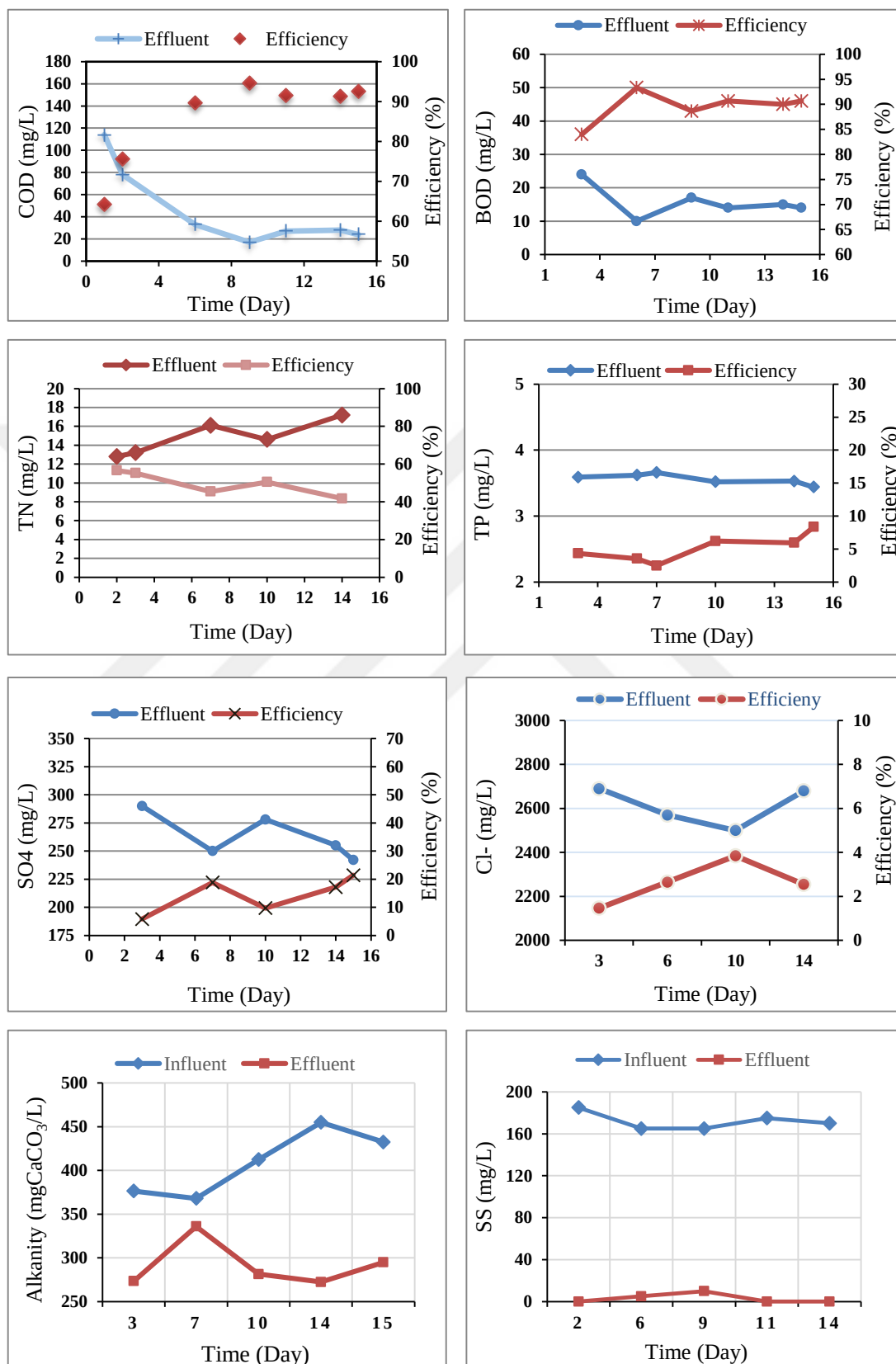


Figure 4.41 Graphical representation of results of fourth experimental study

Changes in sludge characterization were analyzed periodically. Changes in sludge characterization are given in Figure 4.42. MLSS concentration varied between 6190 mg/L and 5055 mg/L during operation. Average MLVSS/MLSS ratio was found as 70.7%. There was a partial change in CST and SVI values. Total EPS concentration varied between 122.2 mg/L and 169 mg/L. The protein concentrations were found as higher than polysaccharide concentrations as expected in aerobic systems. Total EPS got lower values as a function of operation time, it seems the sludge filterability characteristic were good as confirmed by CST values. Zeta potential ranged from -33 mV to -40 mV during the operation. There was a continuous decreasing trend in the zeta potential during operation.

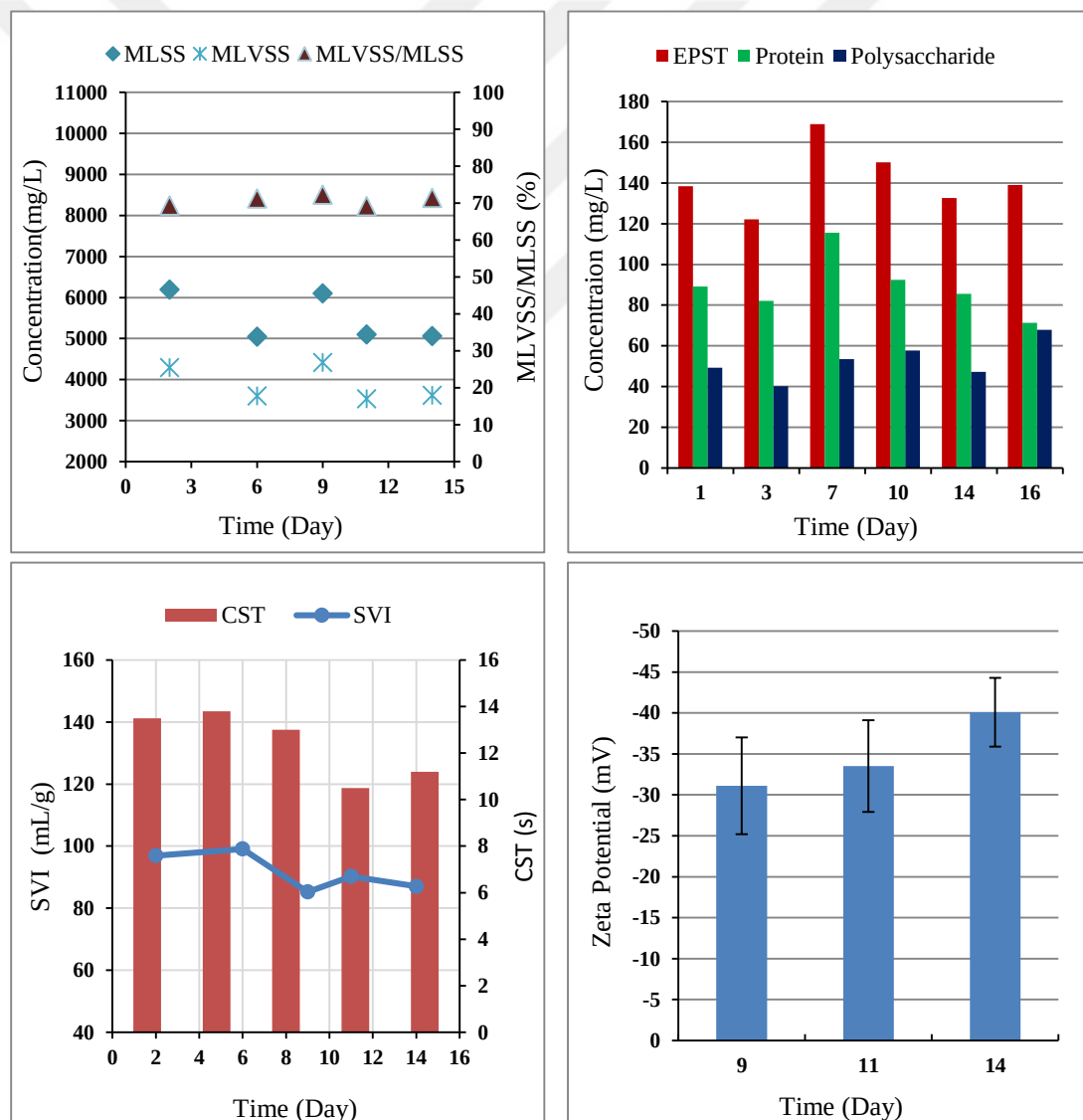


Figure 4.42 Changes in sludge characterization in fourth experimental study

Particle size distributions of the sludge in the reactor and the treated wastewater in the effluent were analyzed at regular intervals during experimental period as shown in Figure 4.43 and 4.44, respectively. The results were also reported in Table 4.8 and Table 4.9. The volume weighted mean of sludge was 54.192  $\mu\text{m}$ . Although there is little change afterwards, particle size distribution remained almost constant on the following days. The particle size distribution of effluent changed significantly on the later days of operation. Particles sizes decreased after the formation of the dynamic layer on the support material. The average particle size values of the effluent samples were comparable with the pore size of MTBF as 30  $\mu\text{m}$ .

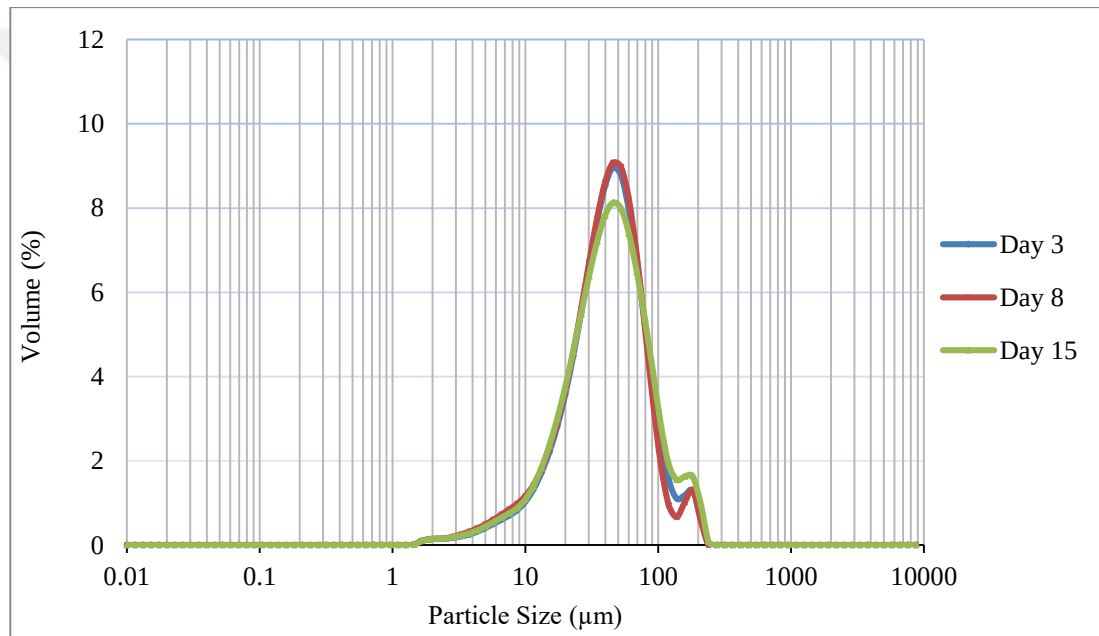


Figure 4.43 Particle size distribution of sludge – fourth experimental trial

Table 4.8 Detailed information on particle size distribution of sludge- fourth experimental trial

|                                                    | Day 3  | Day 8  | Day 15  |
|----------------------------------------------------|--------|--------|---------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 54.192 | 51.599 | 56.392  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 29.482 | 27.893 | 28.955  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.204  | 0.215  | 0.207   |
| d(0.1) ( $\mu\text{m}$ )                           | 16.581 | 15.381 | 15.902  |
| d(0.5) ( $\mu\text{m}$ )                           | 45.717 | 44.432 | 45.846  |
| d(0.9) ( $\mu\text{m}$ )                           | 98.545 | 90.887 | 107.665 |

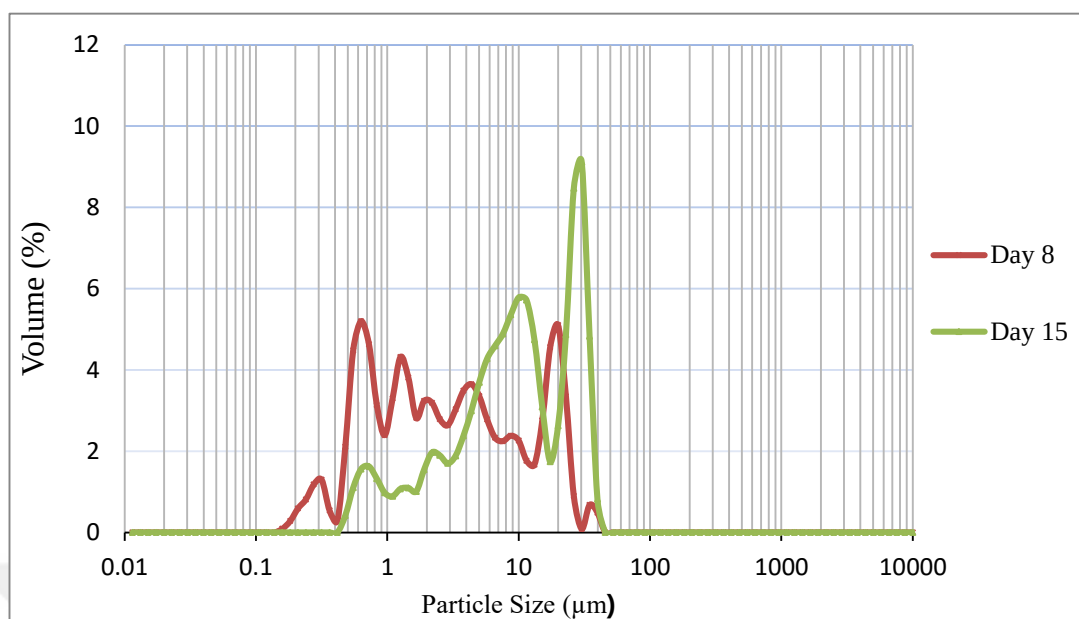


Figure 4.44 Particle size distribution of effluent - fourth experimental study

Table 4.9 Detailed information about particle size distribution of effluent- fourth experimental trial

|                                                    | Day 8  | Day 15 |
|----------------------------------------------------|--------|--------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 5.804  | 12.478 |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 1.253  | 3.816  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 4.79   | 1.57   |
| d(0.1) ( $\mu\text{m}$ )                           | 0.525  | 1.435  |
| d(0.5) ( $\mu\text{m}$ )                           | 2.448  | 9.095  |
| d(0.9) ( $\mu\text{m}$ )                           | 17.653 | 28.237 |

Rheological properties of sludge in the DMBR system were also analyzed periodically. Rheogram- viscosity as a function of shear rate was shown in Figure 4.45. The sludge samples exhibited non-Newtonian flow behavior. Rheological analysis showed that sludge had shear thinning properties. Results showed that there was a decreasing trend in viscosity during operational period. This change can be attributed to the decrease in the MLSS concentration.

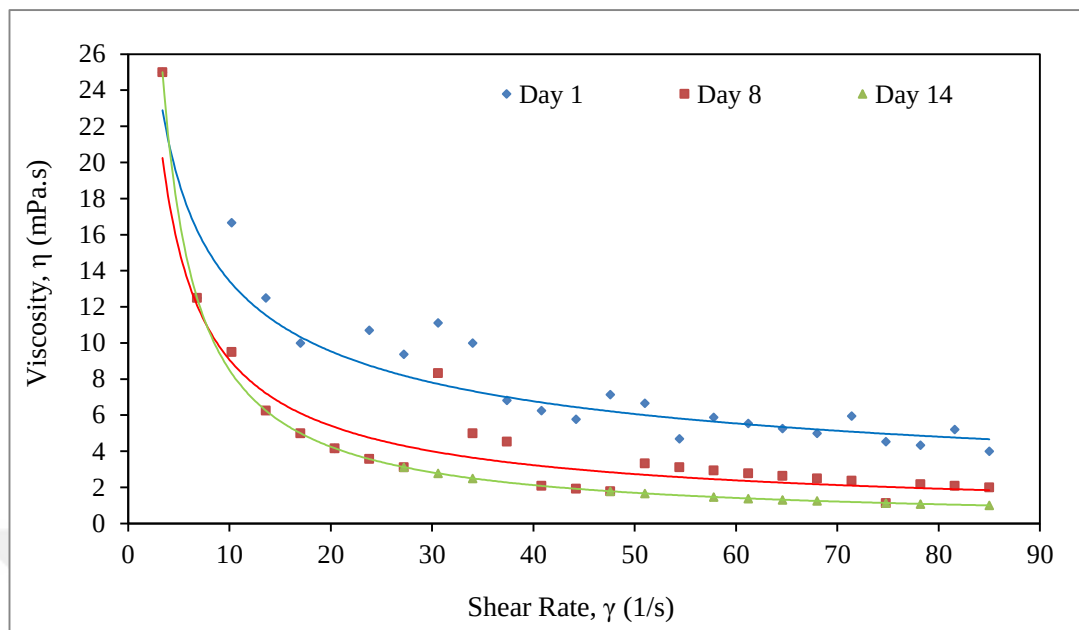


Figure 4.45 Viscosity of sludge as a function of shear rate – fourth experimental trial

In SEM analysis of the double layer MBTF used in this study, it was seen that the dynamic layer formed properly on the outer membrane support material as given in Figure 4.46. But, it is also detected that inner membrane support material was pretty clear compared to outer support material as shown in Figure 4.47. As in the previous studies, the presence of many inorganic substances on the dynamic layer was detected. This result showed that inorganic substances held on to dynamic layer.

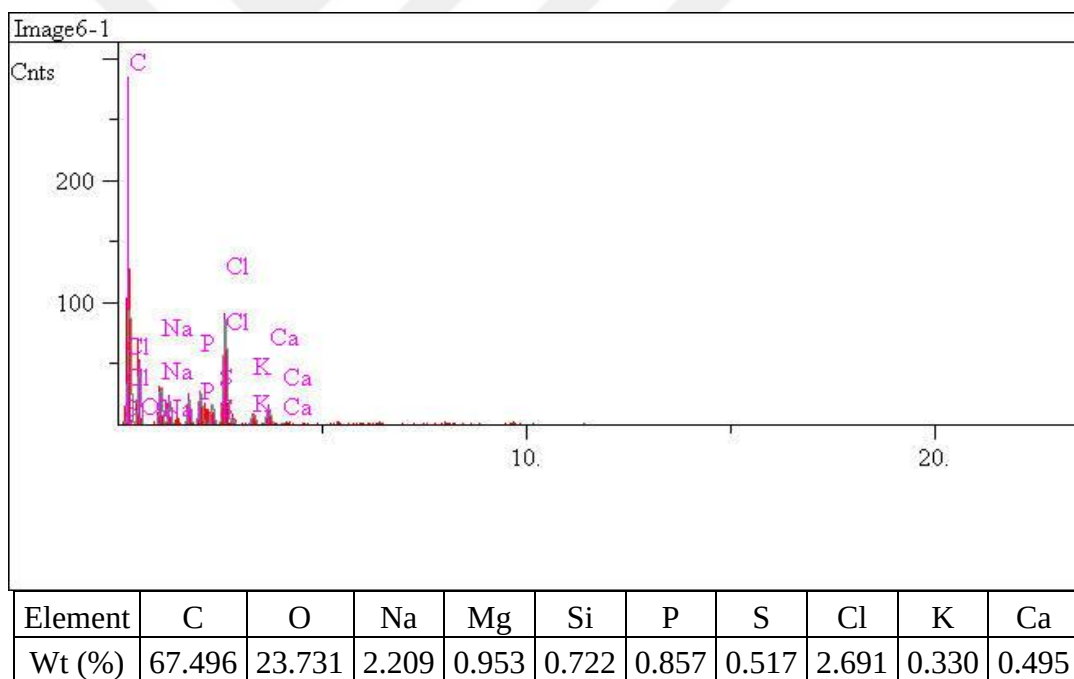
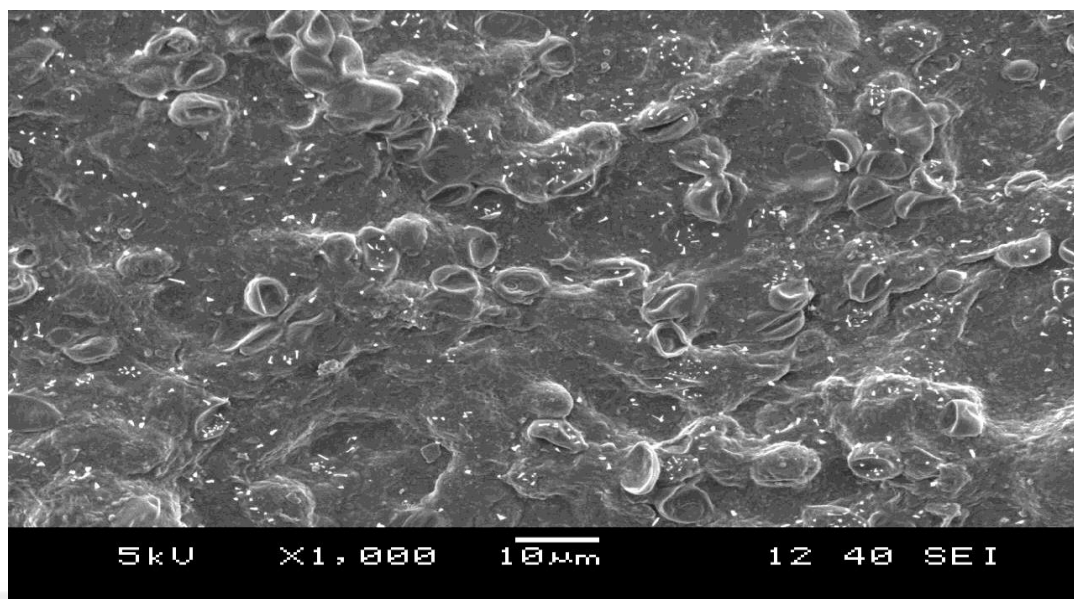


Figure 4.46 SEM photograph and EDS analysis of dynamic layer on outer MBTF

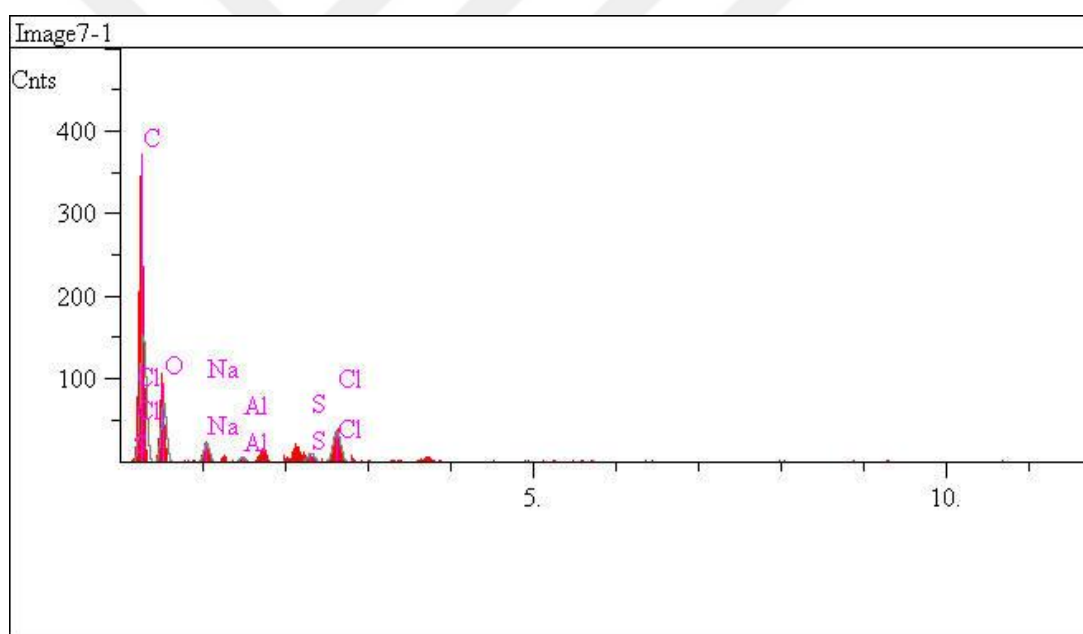
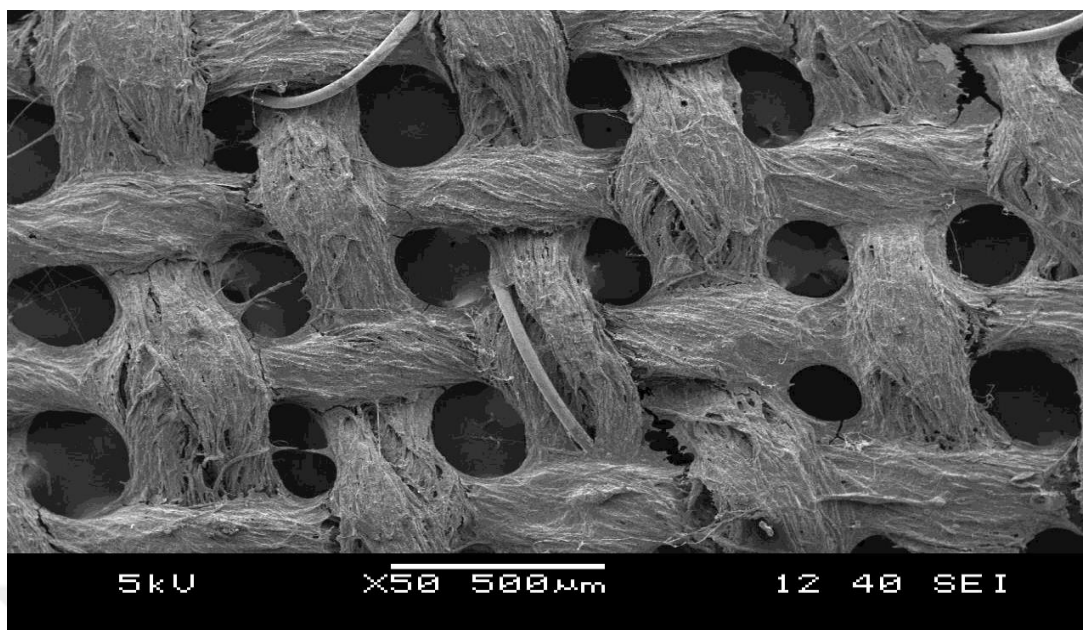


Figure 4.47 SEM photographs and EDS analysis of inner MBTF

Figure 4.48 presented the relationship between flux and TMP. The filterability of the membrane was measured regularly. 9.83 LMH initial flux declined slowly until 8.15 LMH after 15 days operation. The use of only textile material indicated that it gave better results than polymeric membranes in terms of filterability in this experimental study-used real municipal wastewater. Similar to the previous study, TMP remained stable after the increase in the first days.

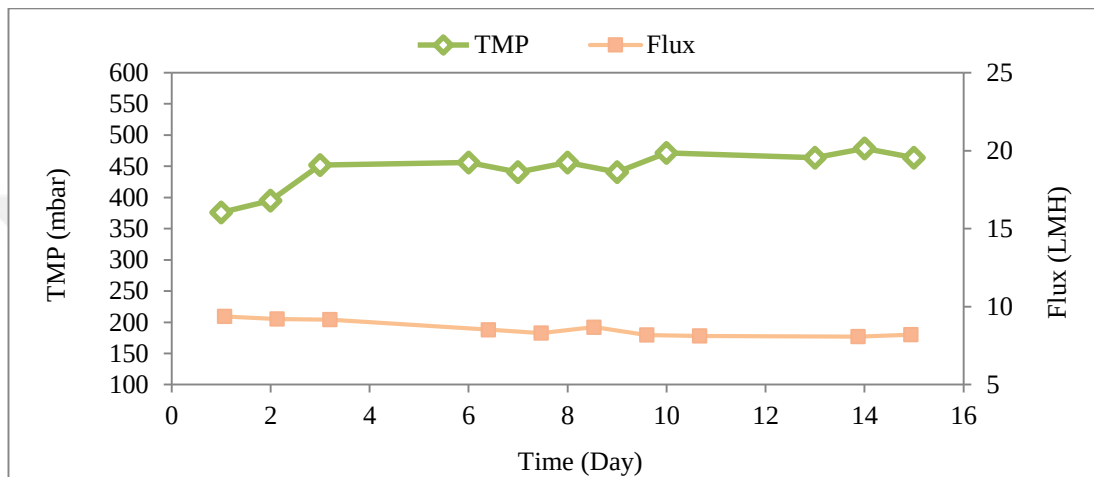


Figure 4.48 Changes in flux and TMP during operation in third experimental study

The membrane support materials were removed from system after 15 days operation. It was observed proper dynamic layer formed on the exterior MBTF. No significant contamination was found on the interior MBTF. Images of dynamic layer formed on the exterior TMBF and the interior TMBF was shown in Figure 4.49.

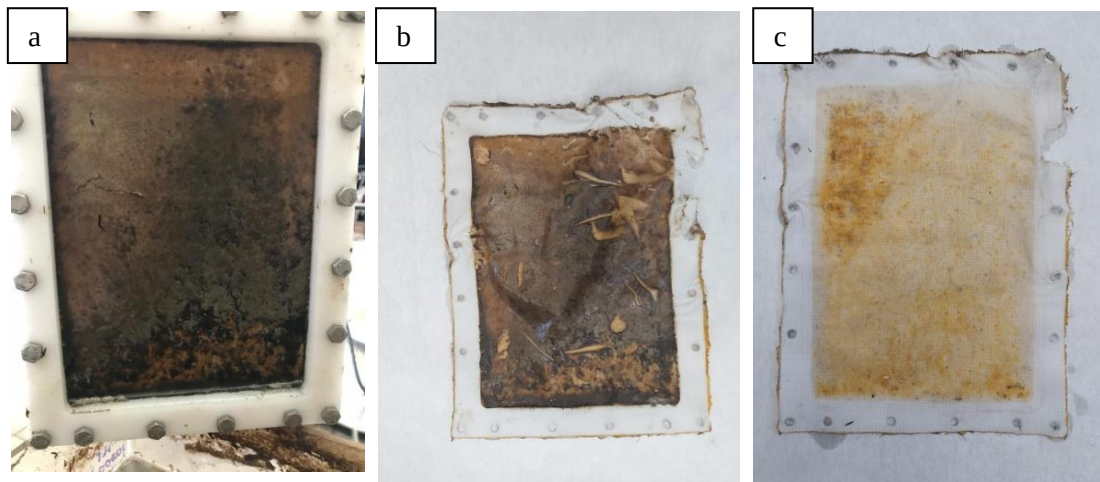


Figure 4.49 Images of surface of materials: (a),(b): exterior MBTF, (c): interior MBTF (Personal archive, 2019)

#### 4.7 Performance of MF022+MBTF for Treatment of Municipal Wastewater

In the fifth experimental study, the MBTF and MF022 microfiltration membrane were used in the cassette to treat the second municipal wastewater (WW2) taken from Manisa. The operation was carried out during 15 days. The flux was set at 9.14 LMH. Initial hydraulic retention time (HRT) was 23 hours. No excess feed sludge was inoculated into the system during entire experimental period and sludge was only withdrawn from aerobic tank for sampling. DO concentration in the reactor did not fall below 2 mg/L during the entire period as shown in Figure 4.50 and the reactor temperature varied between 24 °C and 27°C. ORP results indicated that the system was kept as aerobic conditions. pH, conductivity, and salinity values as a function of operation time is plotted in Figure 4.51. pH values were between 8 and 8.5 for all samples. Salinity and conductivity values decreased on contrary to the previous trial used another real wastewater.

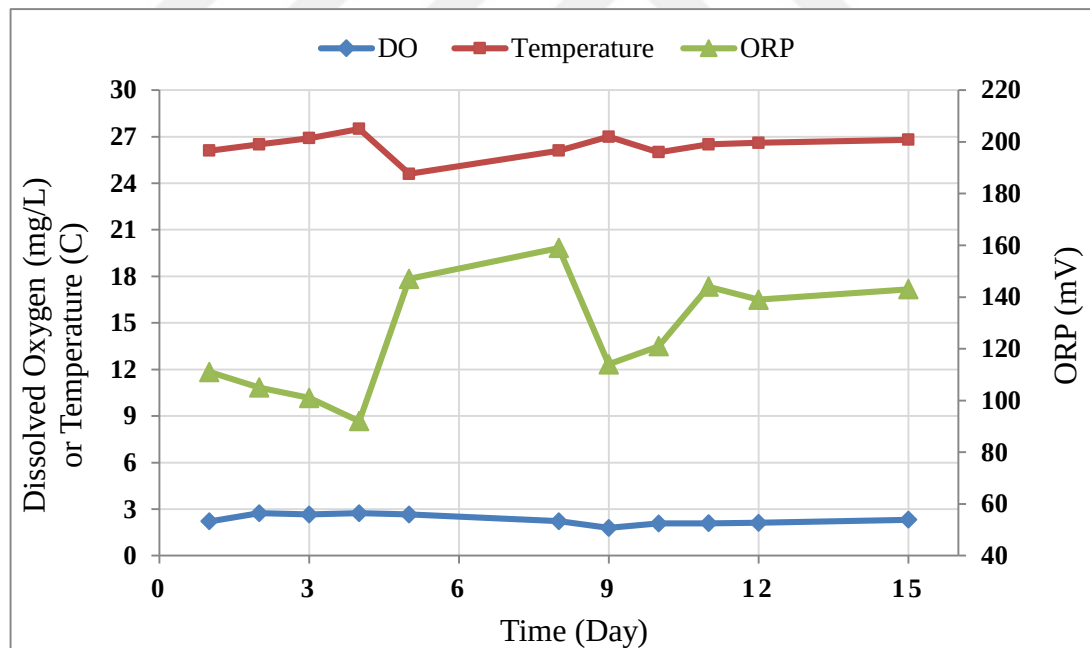


Figure 4.50 Daily changes in DO, temperature and ORP in the reactor- fifth experimental trial

The removal efficiencies of the system in terms of COD, BOD, SS and  $\text{NH}_4^+\text{-N}$  were remarkably high as shown in Figure 4.52. Removal efficiencies reached to 95.8%, 95.9%, 100%, and 99.5%, respectively. The system showed partial removal efficiencies for nutrients. Average efficiencies of TN and TP were 32.6% and 24.7%, respectively. While average sulphate removal rate was 49.6%, residual chloride concentration was almost the same in influent and effluent. Unlike previous studies operated with synthetic wastewater, influent alkalinity concentration was generally higher than effluent alkalinity concentration in this experimental study.



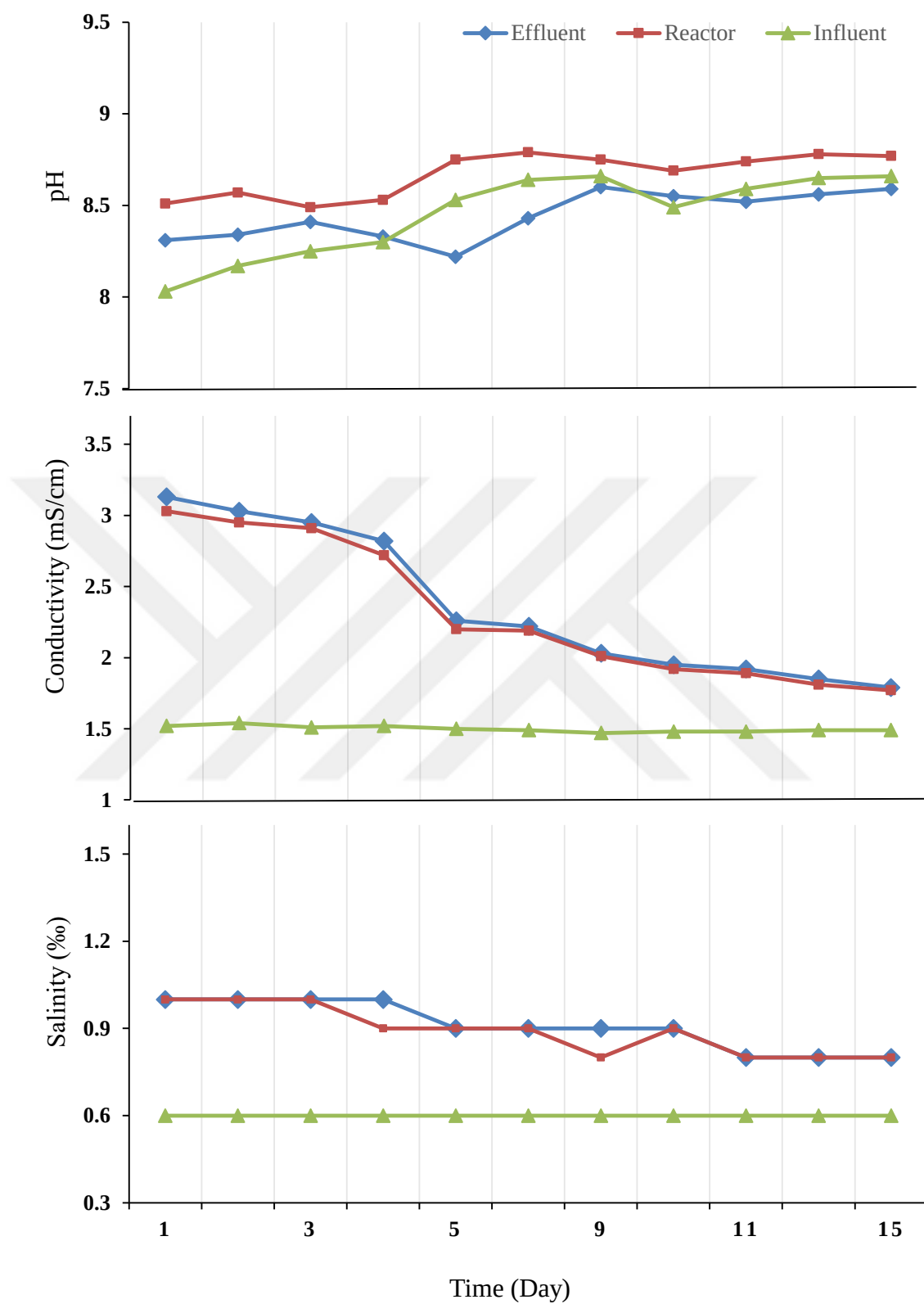


Figure 4.51 Daily changes in pH, conductivity and salinity- fifth experimental trial

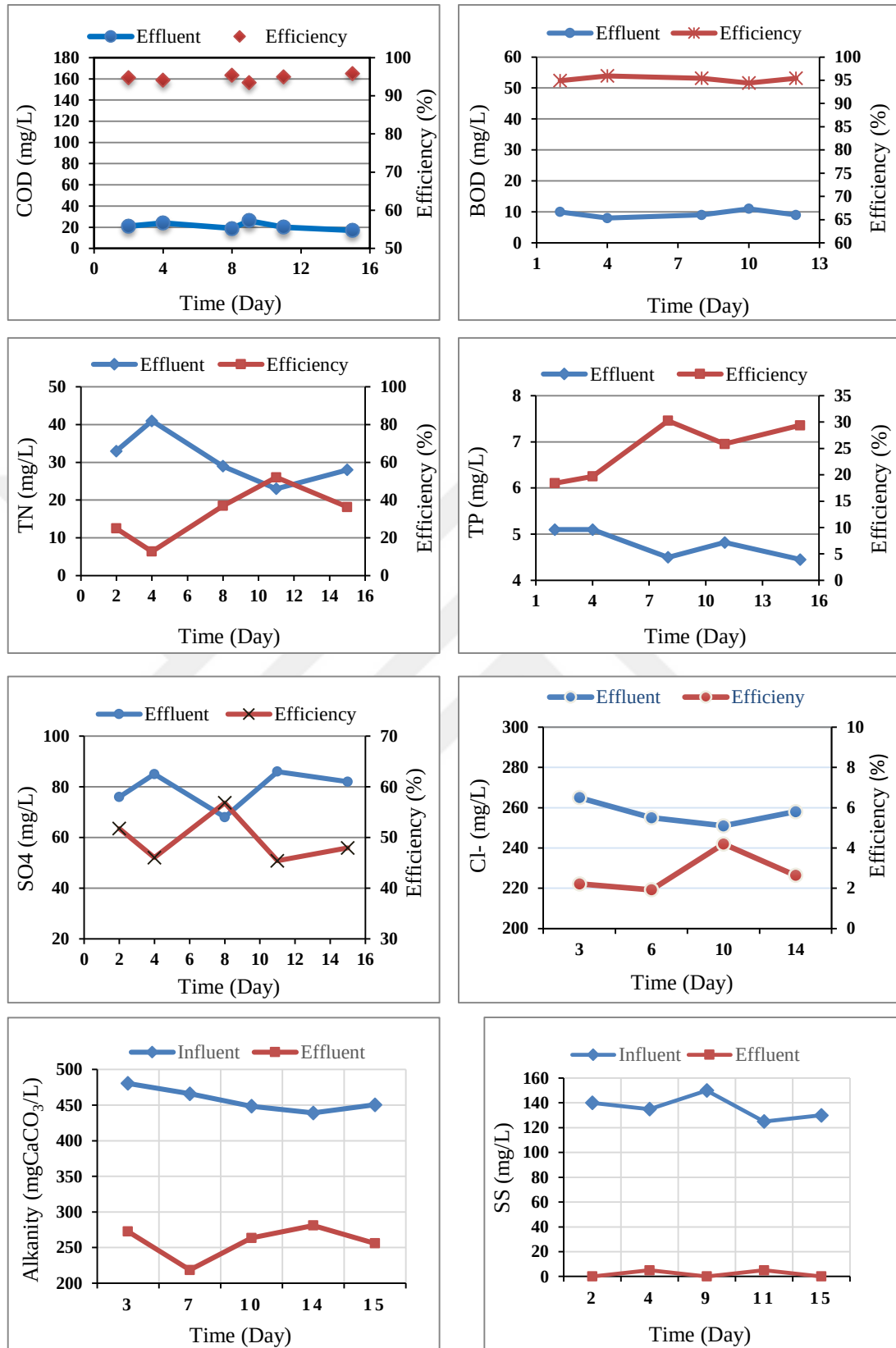


Figure 4.52 Graphical representations of results of fifth experimental study

Changes in sludge characterization analyzed were shown in Figure 4.53. MLSS concentration varied between 5290 mg/L and 5950 mg/L during operation. Average MLVSS/MLSS ratio was 79.1%. It was observed that there was a little change in CST and SVI values. Total EPS concentration varied between 170.5 mg/L and 196.7 mg/L as in the previous trial. Zeta potential, which was -46.6 in the first days of operation, increased to -41.6 in the last days of operation.

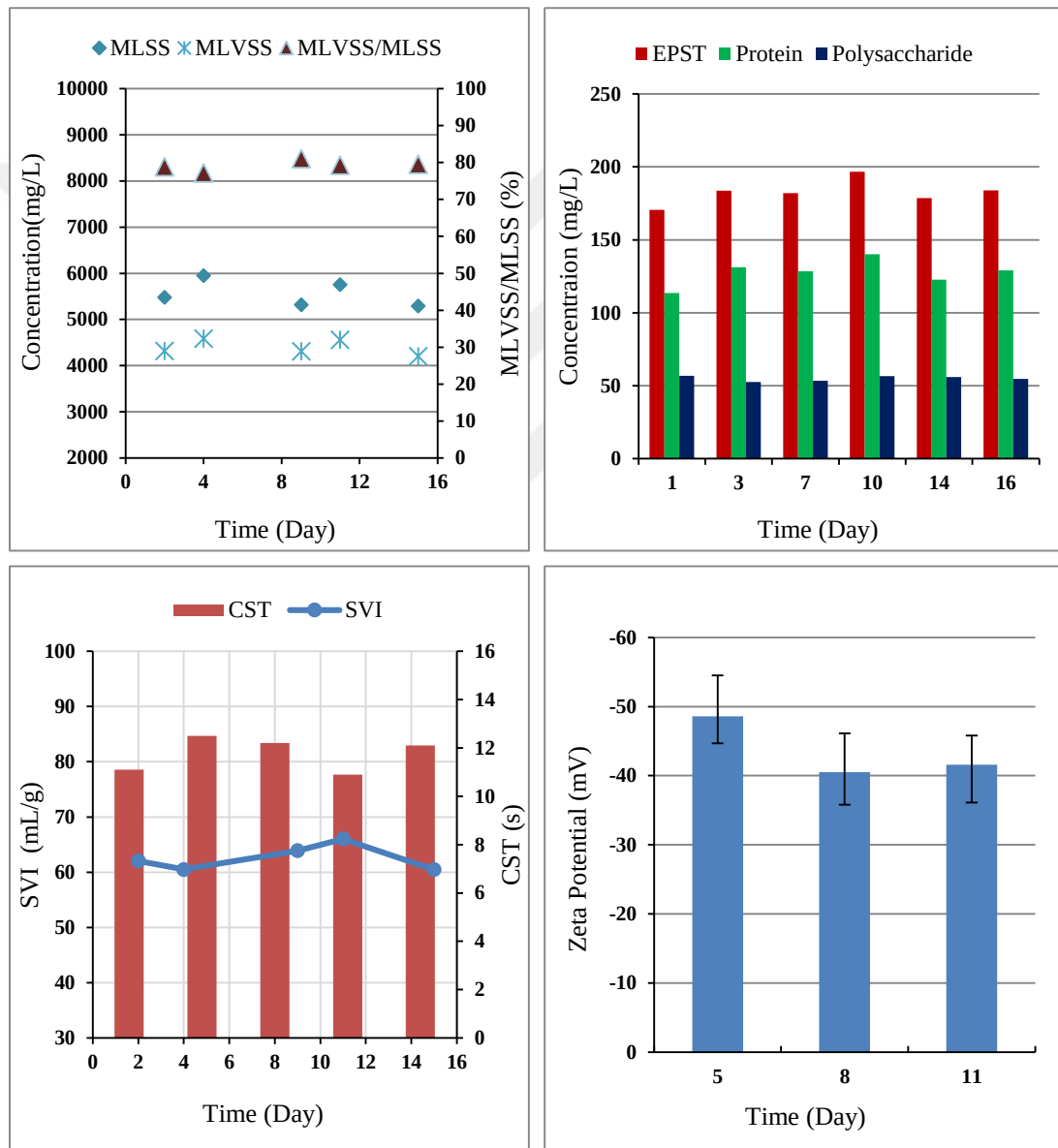


Figure 4.53 Changes in sludge characterization in fifth experimental study

Particle size distributions of the sludge in the reactor and the treated wastewater in the effluent were analyzed at regular intervals during experimental period as shown in Figure 4.54 and Figure 4.55, respectively. The results were also reported in Table 4.10 and Table 4.11. The volume weighted mean of sludge was 85.380  $\mu\text{m}$ . Although there is little change afterwards, particle size distribution remained almost constant on the following days. The particle size distribution of effluent changed significantly on the later days of operation. The average particle size values of the effluent samples were found as high comparing to the membrane sizes as in the first trial. This might be the flocculation of some small particles because of the Ca, Mg, K ions availability in the effluent stream.

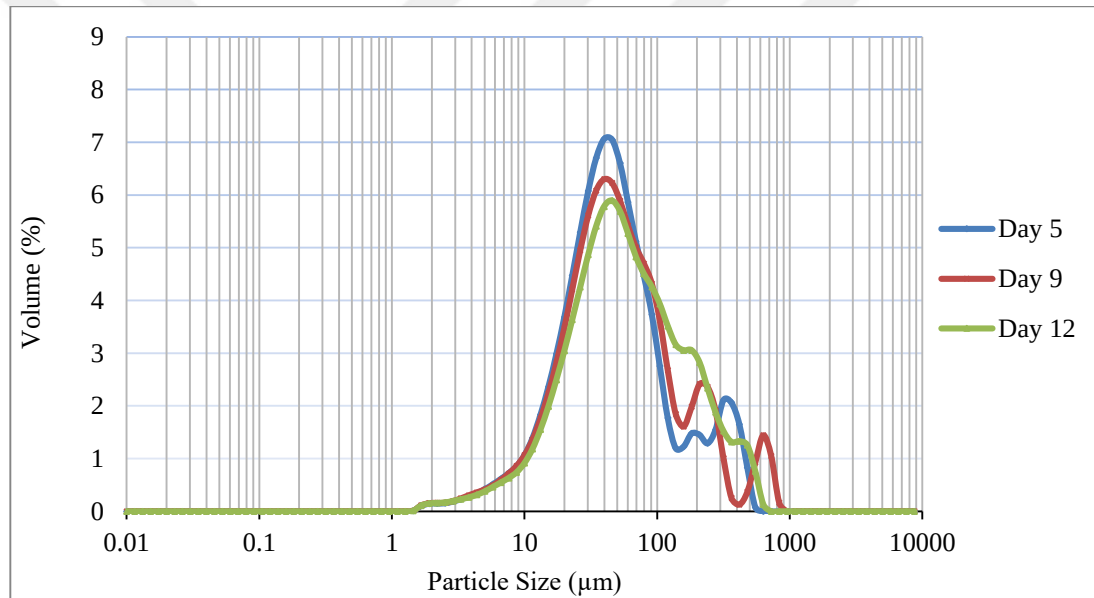


Figure 4.54 Particle size distribution of sludge on different days – fifth experimental trial

Table 4.10 Detailed information on particle size distribution of sludge- fifth experimental trial

|                                                    | Day 5   | Day 9   | Day 12  |
|----------------------------------------------------|---------|---------|---------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 85.380  | 99.111  | 102.028 |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 30.361  | 31.207  | 33.809  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.198   | 0.192   | 0.177   |
| d(0.1) ( $\mu\text{m}$ )                           | 16.057  | 16.189  | 17.377  |
| d(0.5) ( $\mu\text{m}$ )                           | 47.791  | 51.429  | 58.672  |
| d(0.9) ( $\mu\text{m}$ )                           | 230.054 | 234.828 | 246.890 |

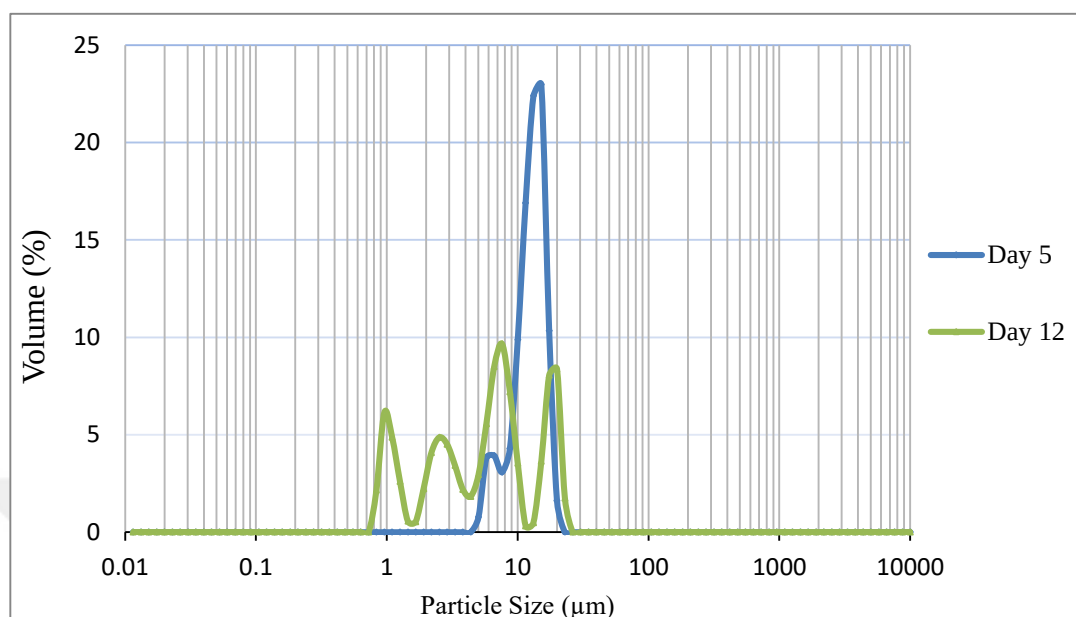


Figure 4.55 Particle size distribution of effluent on different days – fifth experimental trial

Table 4.11 Detailed information on particle size distribution of effluent- fifth experimental trial

|                                                    | Day 5  | Day 12 |
|----------------------------------------------------|--------|--------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 10.760 | 7.190  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 10.771 | 2.978  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.557  | 2.01   |
| d(0.1) ( $\mu\text{m}$ )                           | 7.033  | 0.997  |
| d(0.5) ( $\mu\text{m}$ )                           | 12.049 | 5.916  |
| d(0.9) ( $\mu\text{m}$ )                           | 15.385 | 17.413 |

Rheogram- viscosity as a function of shear rate was shown in Figure 4.56. The sludge samples exhibited non-Newtonian flow behavior with shear thinning properties. Results showed that there was a decreasing trend in viscosity during operational period. This change can be attributed to the decrease in the MLSS concentration.

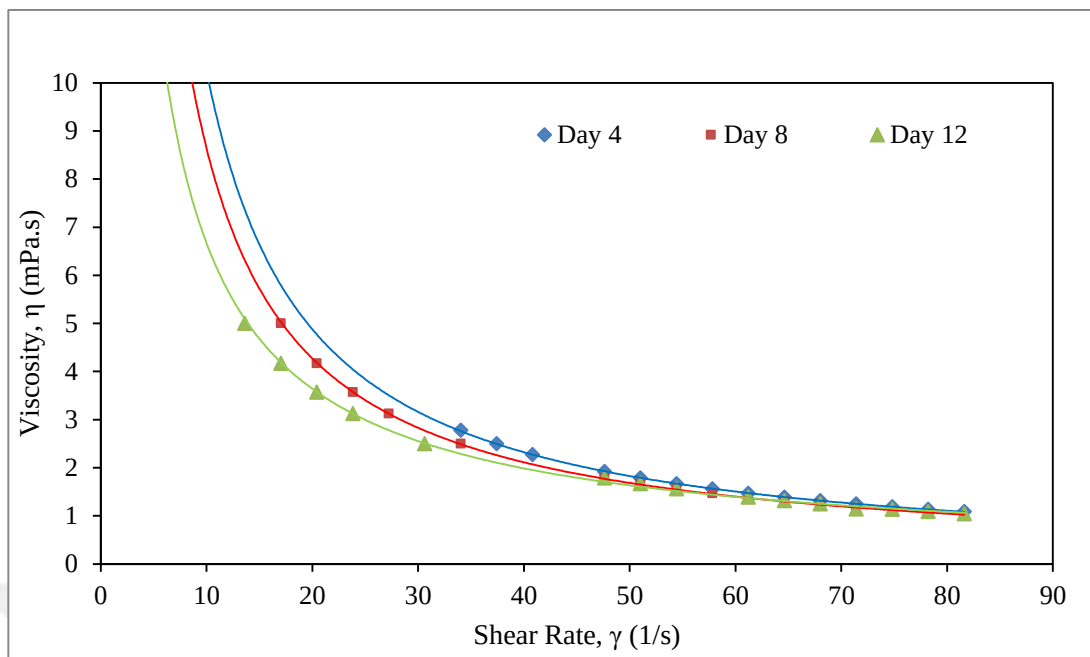


Figure 4.56 Viscosity of sludge as a function of shear rate- fifth experimental study

In SEM analysis of the double layer MBTF used in this study, it was seen that the membrane support material was completely covered with the dynamic layer as shown in Figure 4.57. Various inorganic substances were detected in the EDS analysis of the dynamic layer. However, except for its polymeric components, only O and Ca elements were detected on MF022 membrane as depicted in Figure 4.58.

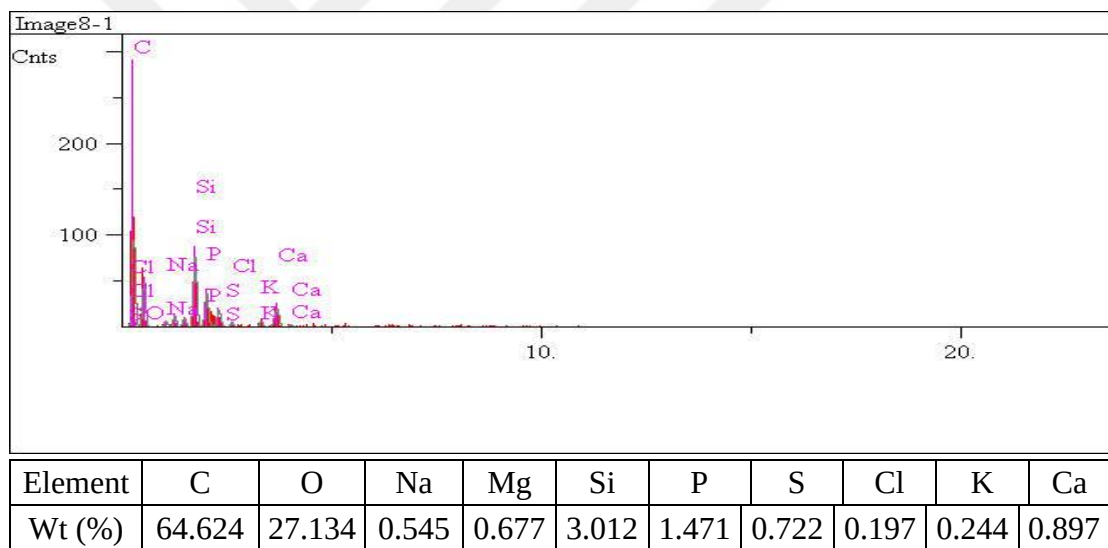
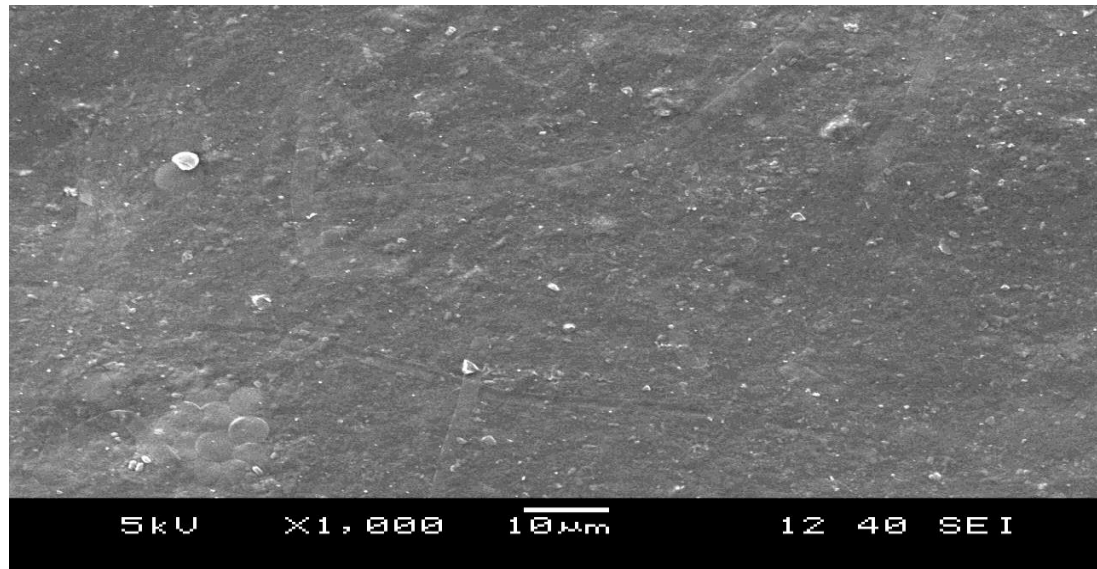


Figure 4.57 SEM photograph and EDS analysis of dynamic layer on MBTF- fifth experimental study

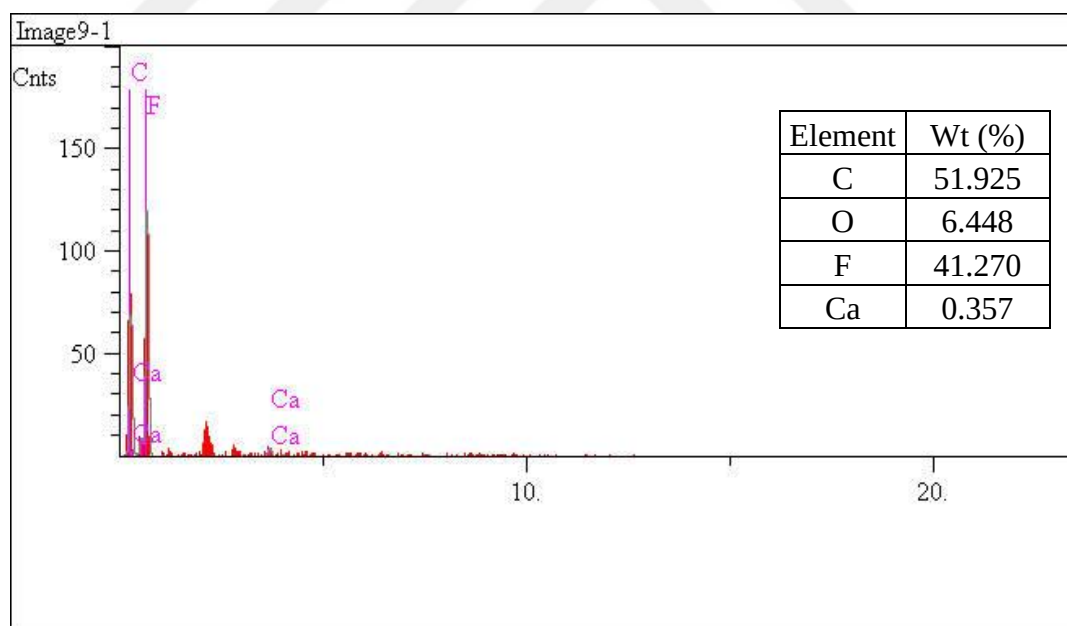
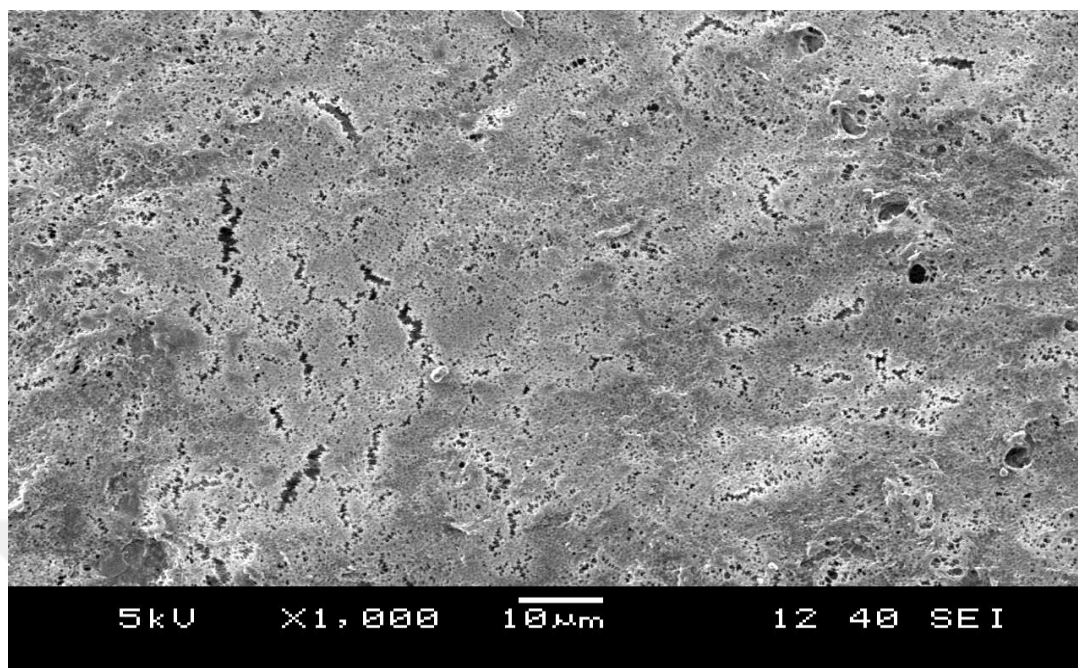


Figure 4.58 SEM photograph and EDS analysis of MF022- fifth experimental study

The filterability of the membrane was measured regularly. 9.14 LMH initial flux decreased gradually to 4.12 LMH after 15 days. Consequently, TMP increased continuously during operation period. Figure 4.59 showed the relationship between flux and TMP.

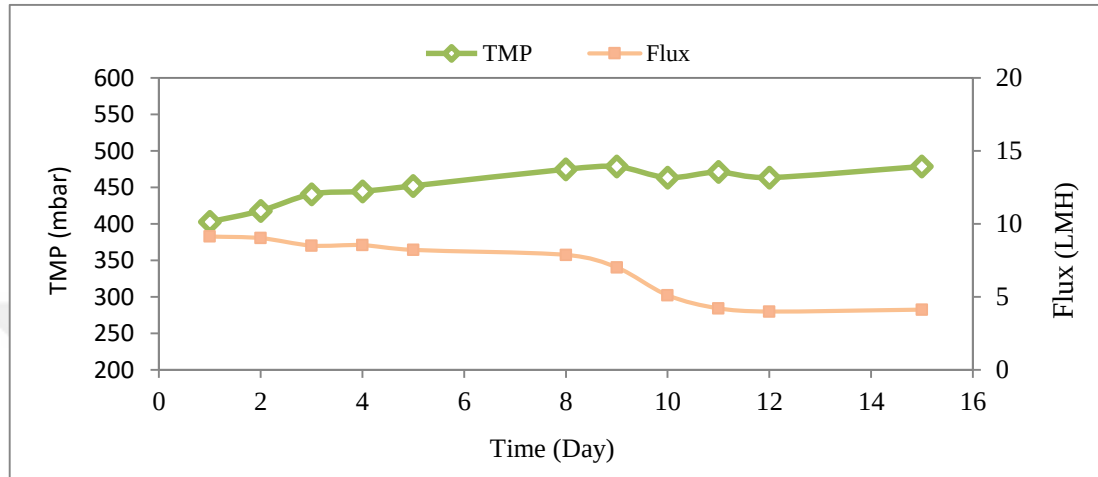


Figure 4.59 Changes in flux and TMP during operation in third experimental study

After 15 days of operation, the membrane support material and membrane were removed from system. Dynamic layer was formed on the surface of MBTF. It was also determined that there was no excessive contamination on the surface of MF022 microfiltration membrane. Images of dynamic layer formed on MBTF and MF022 microfiltration membrane were given in Figure 4.60.

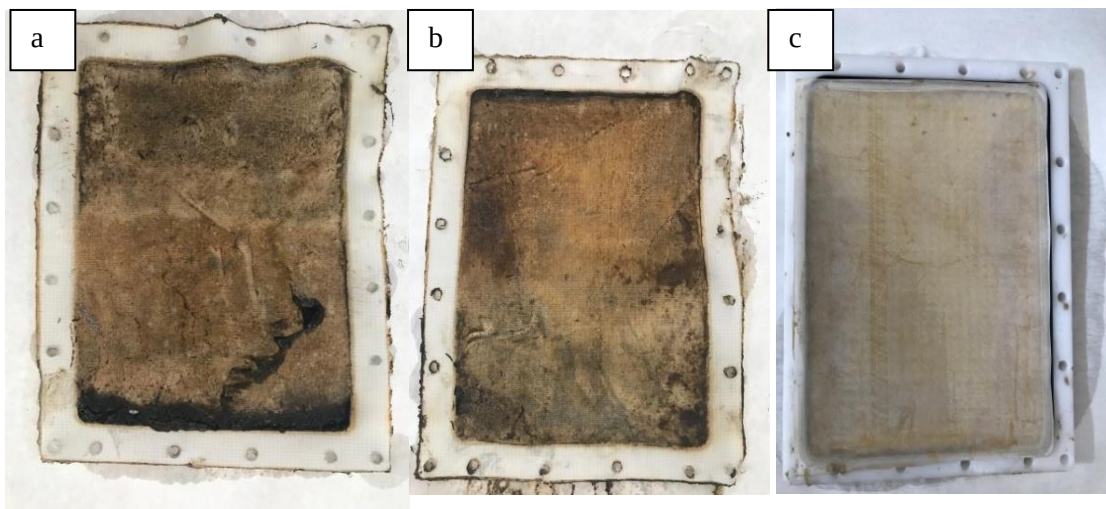


Figure 4.60 Images of surface of materials: (a), (b): MBTF, (c): MF022 (Personal archive, 2019)

#### 4.8 Performance of MF022+MBTF for Treatment of Municipal Wastewater with PAC Addition

Sixth experimental study used MF022 microfiltration membrane and MBTF in membrane cassette. The municipal wastewater (WW2) was fed to the DMBR. 5 g/L powdered activated carbon (PAC) was added to the DMBR system on the first and seventh days of operation in this study. The operation was carried out during 11 days. The flux was set at 9.75 (LMH) and daily changes in flux were observed. Initial HRT was 21.6 hours. No excess feed sludge was inoculated into the system during entire experimental period and sludge was only withdrawn from aerobic tank for sampling. DO concentration was maintained higher than 1 mg/L as shown in Figure 4.61 and the reactor temperature varied between 26.9 °C and 29.8 °C. ORP results indicated that the system was kept as aerobic conditions. pH, conductivity, and salinity values as a function of operation time is plotted in Figure 4.62. pH values were between 8 and 8.8 for all samples. Salinity and conductivity values remarkably decreased on contrary to the previous trial used the same real wastewater.

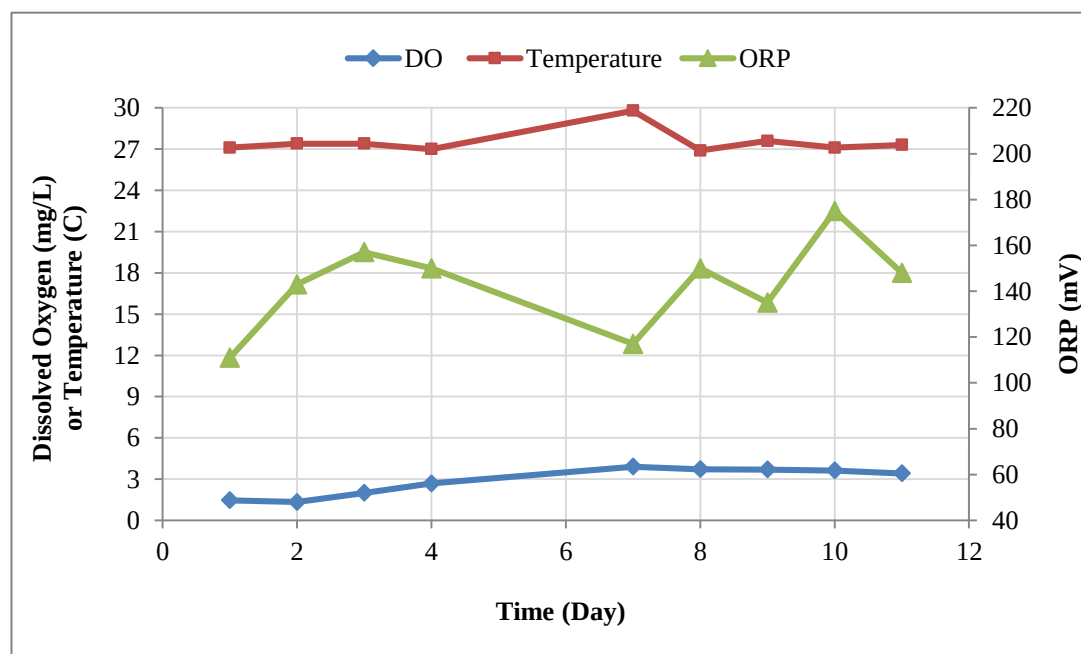


Figure 4.61 Daily changes in DO, temperature and ORP in the reactor- Sixth experimental study

Removal efficiencies continued at high rates throughout the entire operation in terms of COD, BOD, SS and  $\text{NH}_4^+\text{-N}$ . Efficiencies reached 99.2%, 97%, %100, and % 99.8, respectively. Compared to other experimental studies, there was a slight increase in TP removal rather than TN removal. TN and TP removal were obtained as 42% and 41.2%, respectively. Remarkable sulphate removal was realized at the rate of 65%. Although there was almost no chloride removal in other studies, chloride removal reached 36% in this study. Those results showed that PAC addition increased sulphate and chloride removal via adsorption. Influent alkalinity concentration was generally higher than effluent alkalinity concentration in this experimental study like other studies operated with municipal wastewater. Graphical representations of the results were presented in Figure 4.63.

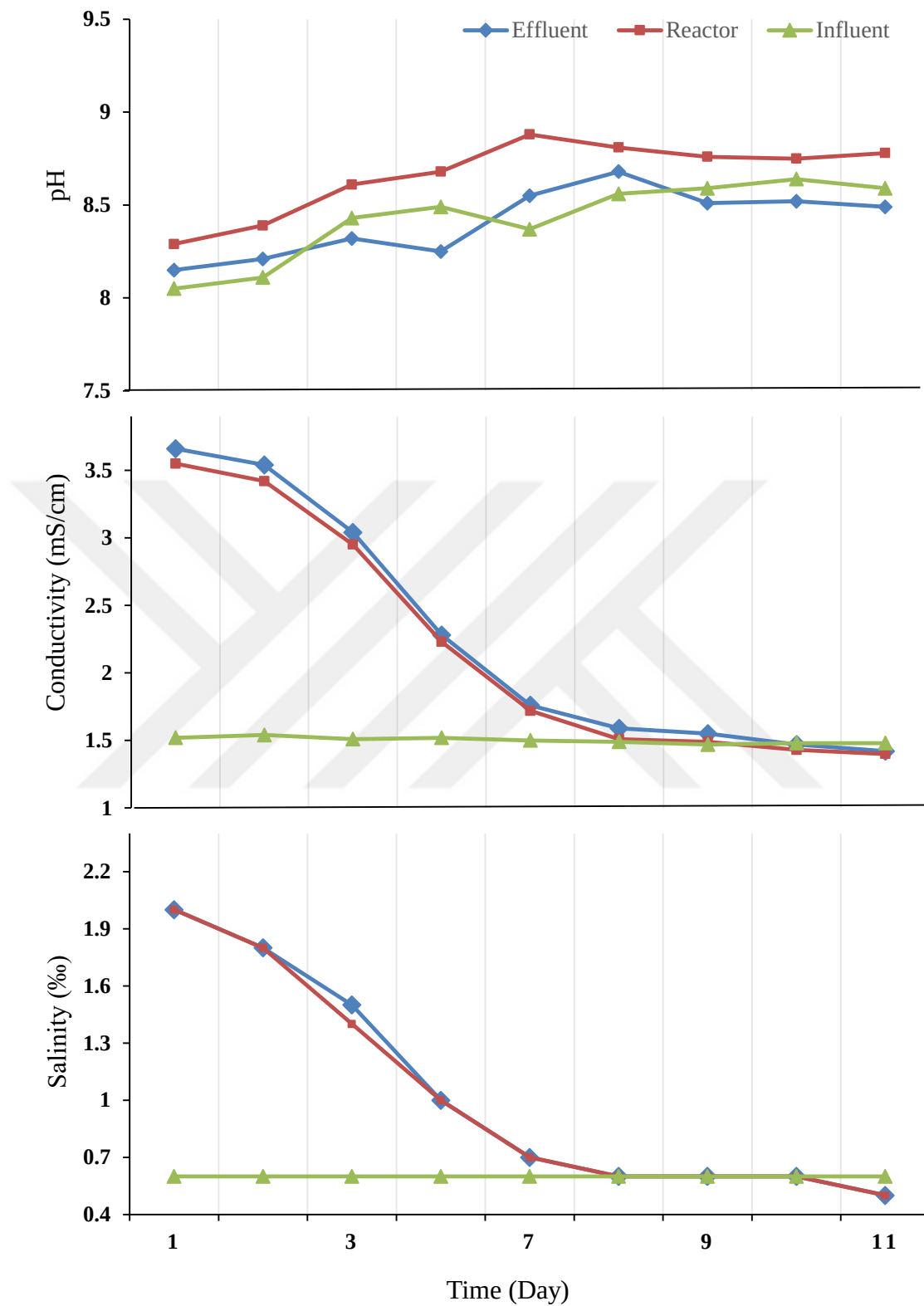


Figure 4.62 Daily changes in pH, conductivity and salinity- Sixth experimental study

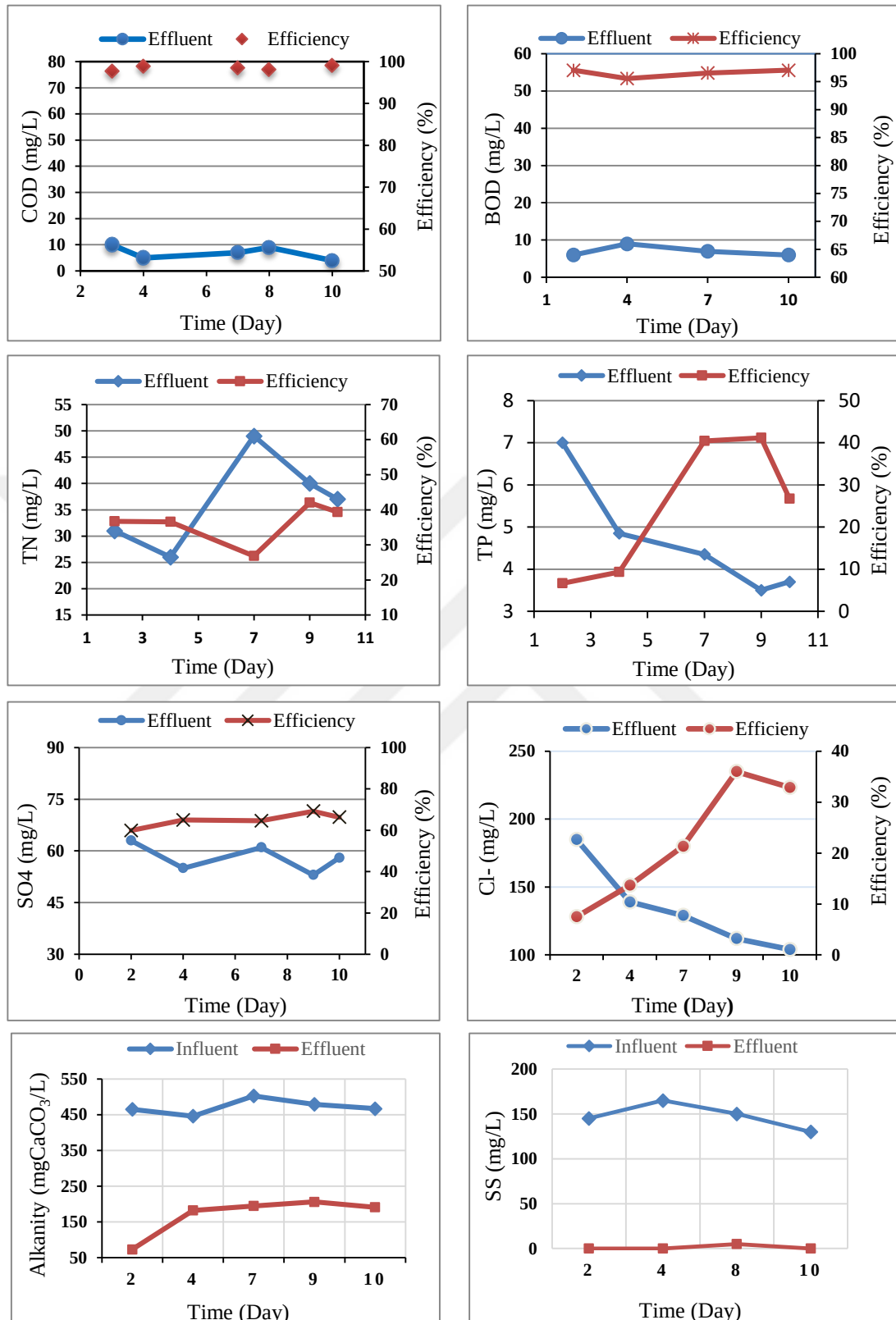


Figure 4.63 Graphical representations of results of sixth experimental study

Changes in sludge characterization analyzed were shown in Figure 4.64. MLSS concentration varied between 5845 mg/L and 6285 mg/L during operation. Average MLVSS/MLSS ratio was 82.9%. It was observed that there was almost no change in CST and SVI values. Moreover, PAC addition declined CST and SVI values effectively. Hu et al. (2017) stated that PAC addition enhance flocculation, settling and dewatering properties of sludge. Total EPS concentration varied between 155.3 mg/L and 163.9 mg/L. There was a continuous increase in the value of zeta potential due to the PAC addition.

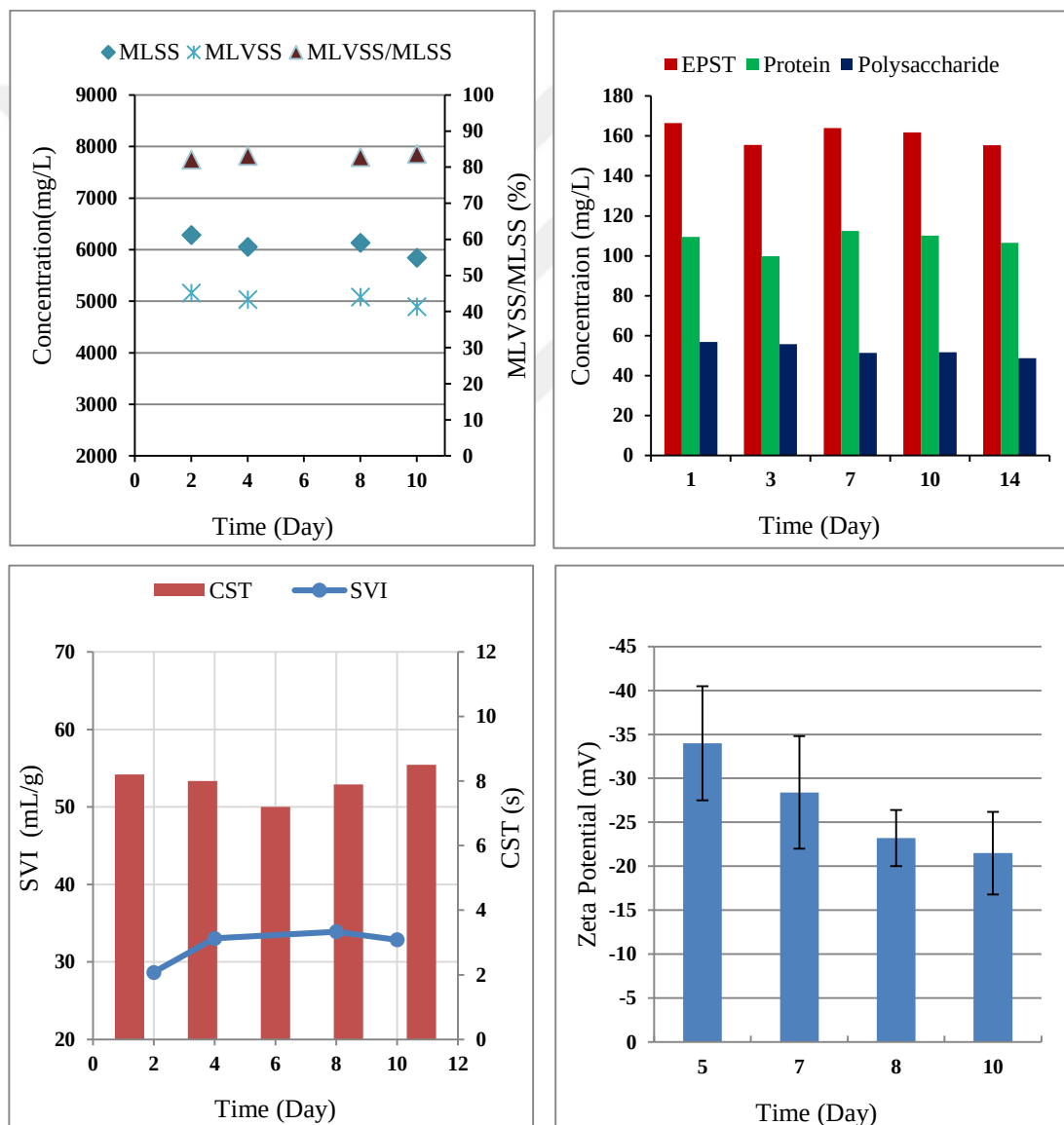


Figure 4.64 Changes in sludge characterization in sixth experimental study

Particle size distributions of the sludge in the reactor and the treated wastewater in the effluent were analyzed at regular intervals during experimental period as shown in Figure 4.65 and Figure 4.66, respectively. The results were also reported in Table 4.12 and Table 4.13. The volume weighted mean of sludge was 88.387  $\mu\text{m}$  in the first analysis after first PAC addition. This result revealed that particle size of sludge with PAC addition was higher than previous studies operated without PAC. Yu et al. (2019) also reported in the same way that PAC addition increased particle size distribution of sludge in DMBR. But particle size distribution remained higher and very stable on the following days. The particle size distribution of effluent changed significantly on the later days of operation. Particles sizes decreased a certain extend after proper formation of dynamic layer.

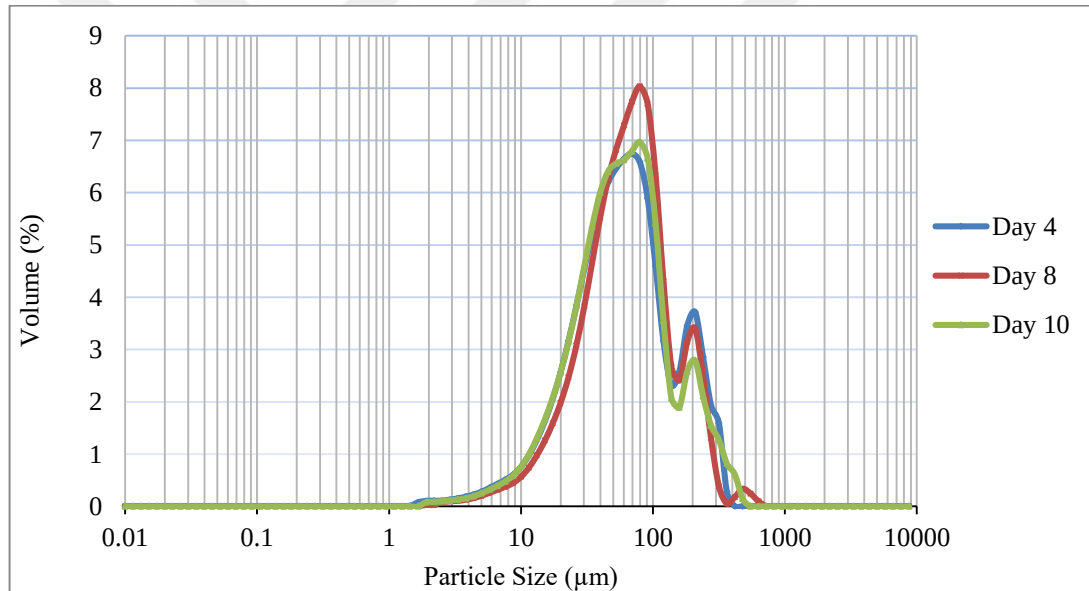


Figure 4.65 Particle size distribution of sludge- sixth experimental trial

Table 4.12 Detailed information on particle size distribution of sludge-sixth experimental trial

|                                                    | Day 4   | Day 8   | Day 10  |
|----------------------------------------------------|---------|---------|---------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 88.387  | 90.566  | 87.461  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 38.010  | 45.008  | 39.205  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.158   | 0.133   | 0.153   |
| d(0.1) ( $\mu\text{m}$ )                           | 20.051  | 23.917  | 20.331  |
| d(0.5) ( $\mu\text{m}$ )                           | 63.247  | 70.176  | 62.640  |
| d(0.9) ( $\mu\text{m}$ )                           | 211.738 | 196.139 | 201.899 |

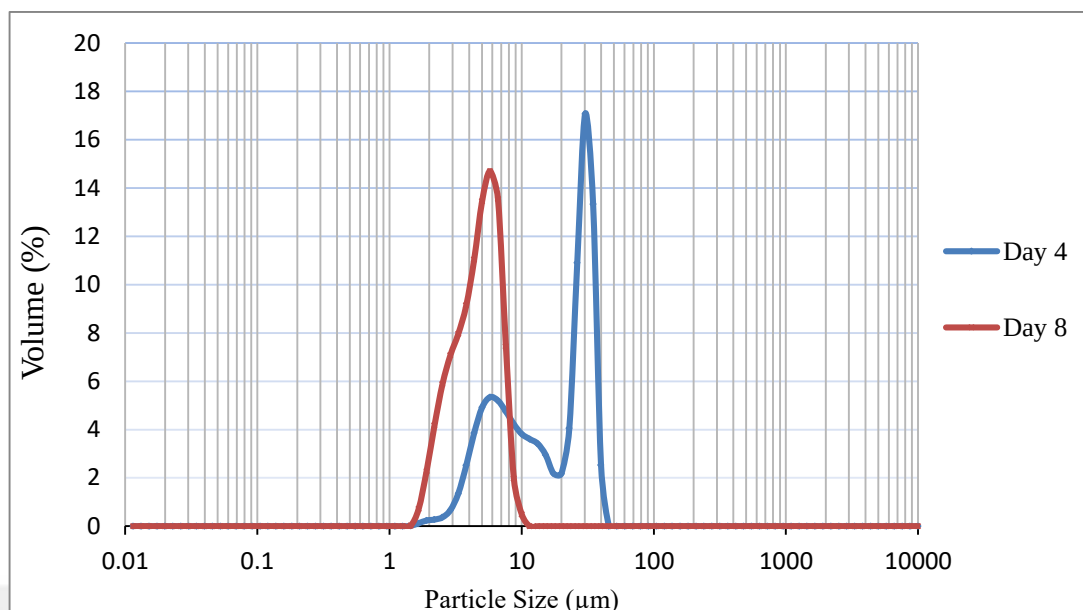


Figure 4.66 Particle size distribution of effluent- sixth experimental trial

Table 4.13 Detailed information about particle size distribution of effluent- sixth experimental trial

|                                                    | Day 4  | Day 8  |
|----------------------------------------------------|--------|--------|
| D [4, 3] - Volume weighted mean ( $\mu\text{m}$ )  | 17.810 | 4.476  |
| D [3, 2] - Surface weighted mean ( $\mu\text{m}$ ) | 9.843  | 3.846  |
| Specific surface area ( $\text{m}^2/\text{g}$ )    | 0.61   | 20.455 |
| d(0.1) ( $\mu\text{m}$ )                           | 4.440  | 2.345  |
| d(0.5) ( $\mu\text{m}$ )                           | 17.514 | 4.446  |
| d(0.9) ( $\mu\text{m}$ )                           | 31.707 | 6.602  |

Rheogram- viscosity as a function of shear rate was shown in Figure 4.67. The sludge samples exhibited non-Newtonian flow behavior with shear thinning properties. Results showed that there was a decreasing trend in viscosity during operational period. This change can be attributed to the decrease in the MLSS concentration.

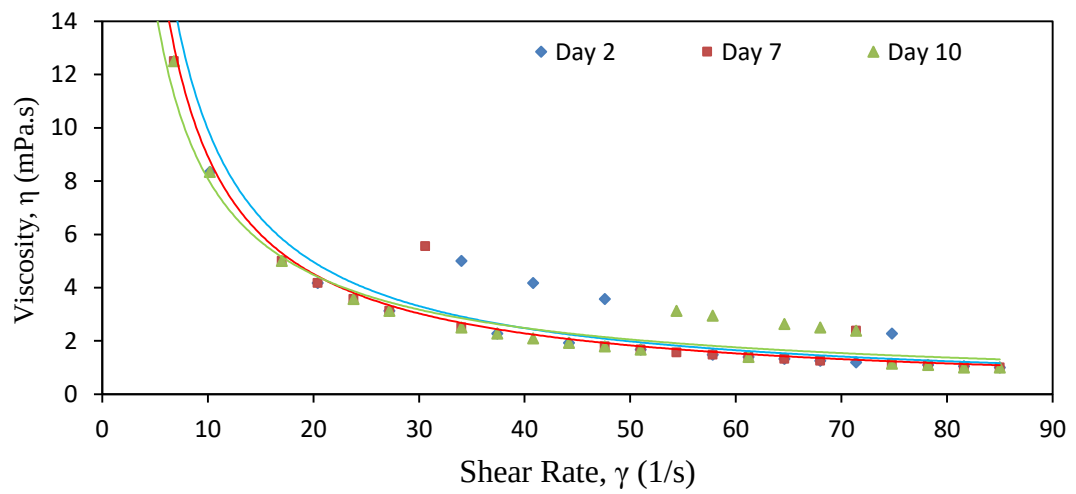


Figure 4.67 Viscosity of sludge as a function of shear rate- sixth experimental study

In SEM-EDS analysis of MF022 and MBTF, it is seen that the surface morphology of the dynamic layer was different from previous studies in this study due to PAC addition as shown in Figure 4.68. EDS analysis of the dynamic layer reveals that carbon content on the surface was higher due to PAC effect. Unlike the other studies, in this study, C, O, F, Na, Mg, Al, Si, S, Cl, Ca elements were observed on MF022 membrane as shown in Figure 4.69, while only C, O, Si elements were detected on dynamic layer of MBTF.

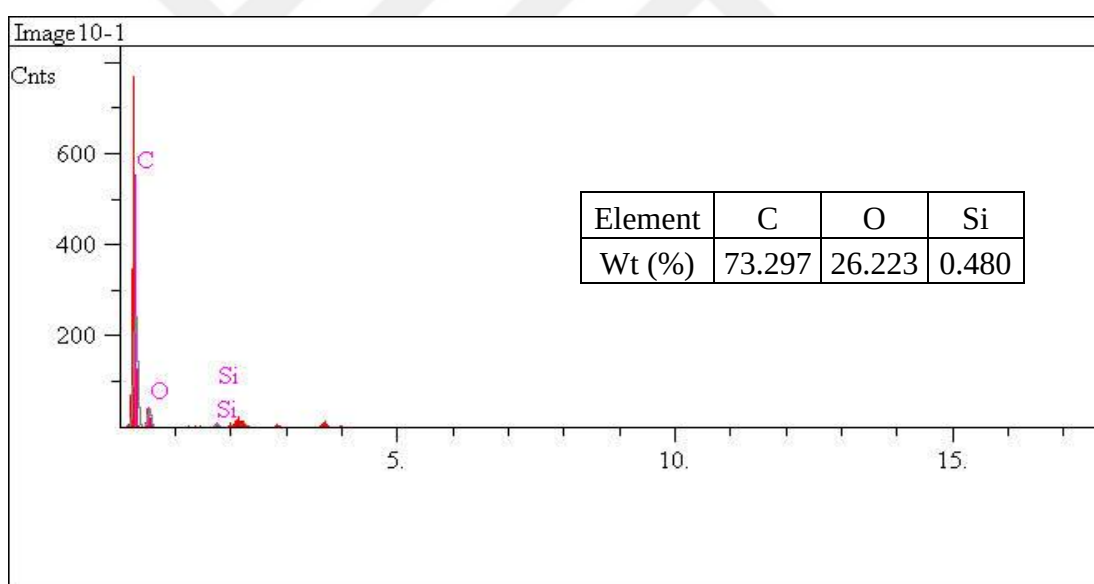
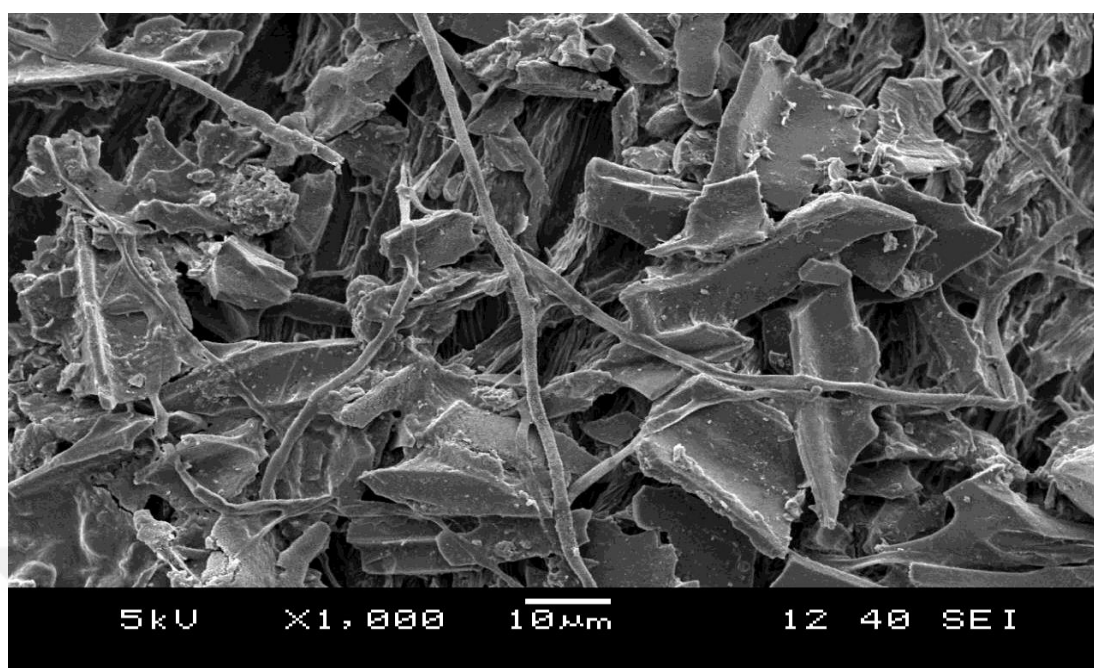


Figure 4.68 SEM image and EDS analysis of dynamic layer on MBTF

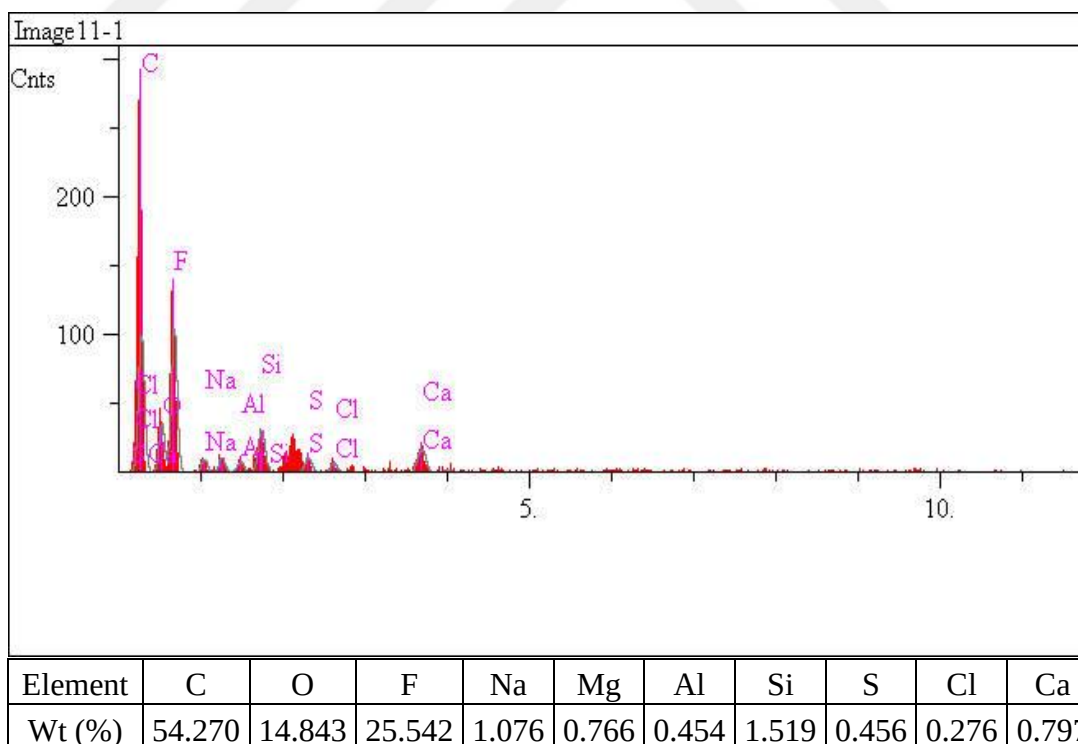
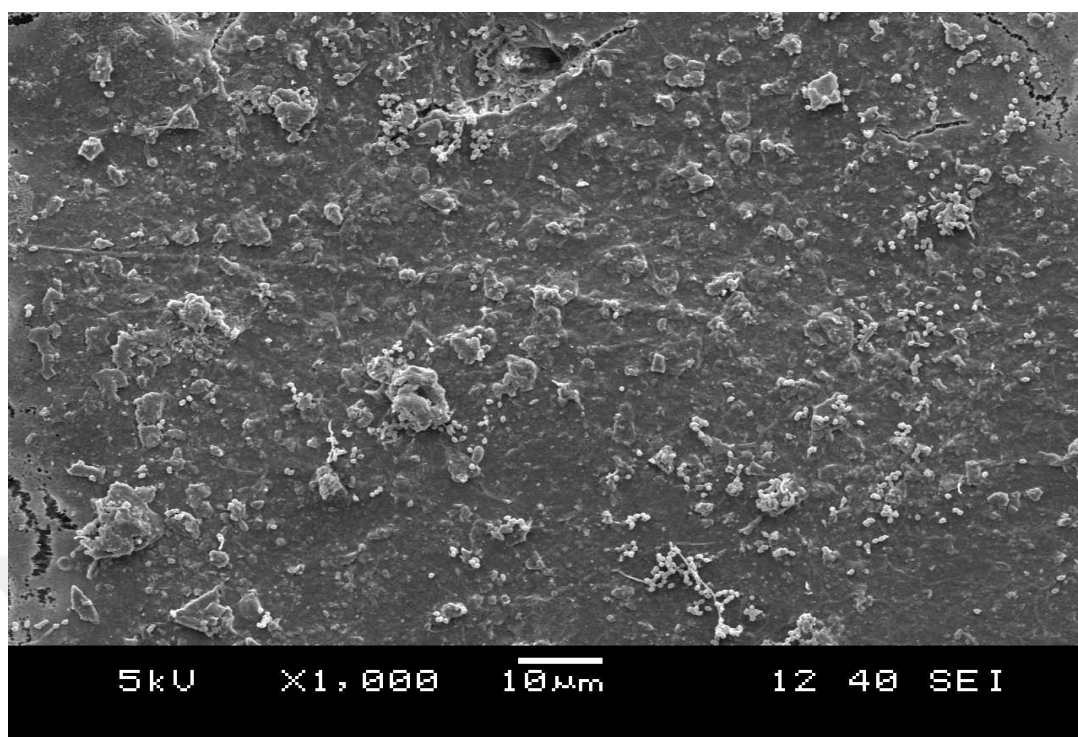


Figure 4.69 SEM image and EDS analysis of MF022- sixth experimental study

The filterability of the membrane was measured regularly. 9.75 LMH initial flux decreased gradually to 3.88 LMH after 11 days. Hu et al. (2019) reported that PAC addition enhances filtration performance. Although PAC addition mitigated flux drop, decreasing trend in flux continued. TMP increased only last days of operation period. Figure 4.70 showed the relationship between flux and TMP.

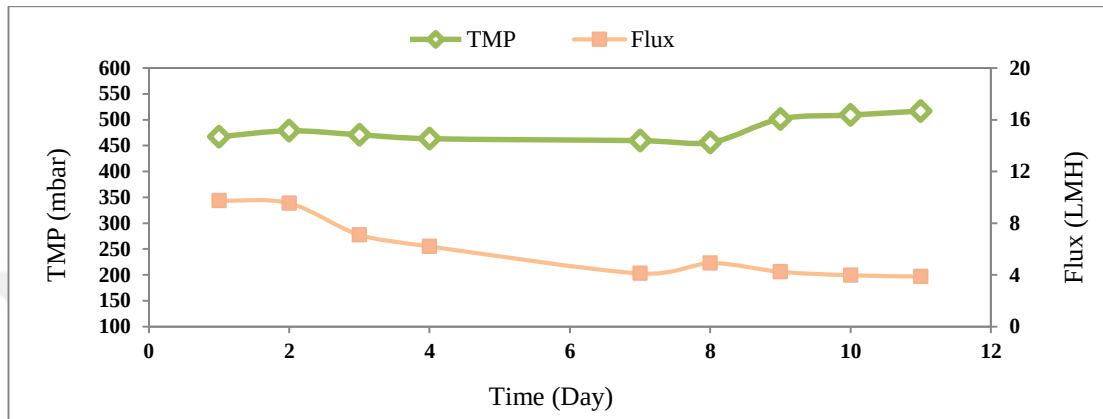


Figure 4.70 Changes in flux and TMP during operation - sixth experimental study

After 11 days of operation, the membrane support material and membrane were removed from system. Dynamic layer was formed on the surface of MBTF. It was also determined that there was no excessive contamination on the surface of microfiltration membrane. Images of dynamic layer formed on MBTF and MF022 microfiltration membrane were shown in Figure 4.71.

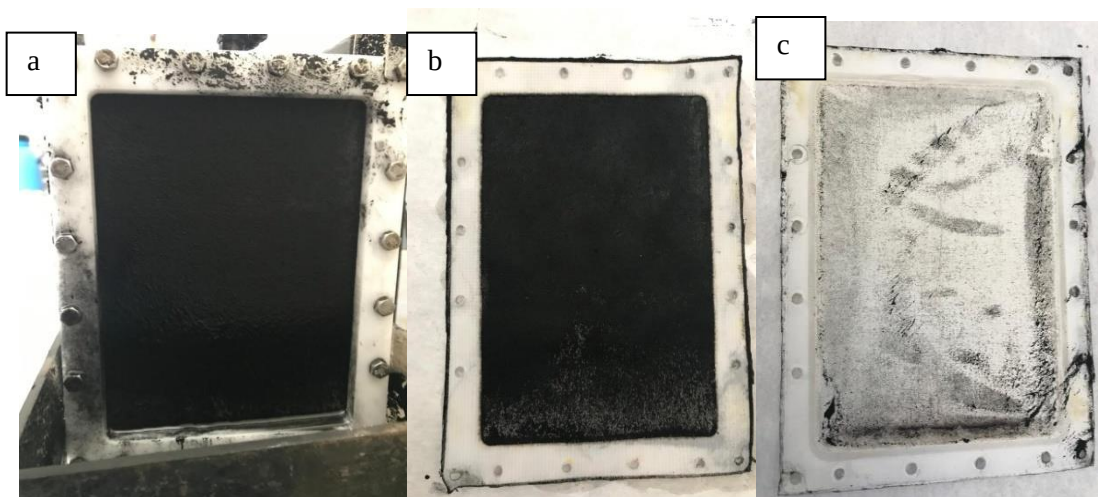


Figure 4.71 Images of surface materials: (a), (b): MBTF, (c): MF022 (Personal archive, 2019)

Influents as synthetic wastewater, municipal wastewater, sludge or PAC added sludge and effluent were sampled in all studies. Clear and turbidity-free effluent was obtained in all experimental studies. Figure 4.72 showed photographs of the samples. Table 4.14 compares the experimental results of this study. MF022+ MBTF and MF010+ MBTF applications gave better removals. However, the results of the MBTF application were also good. Table 4.15 gives the comparison of the experimental results with other studies in the literature.

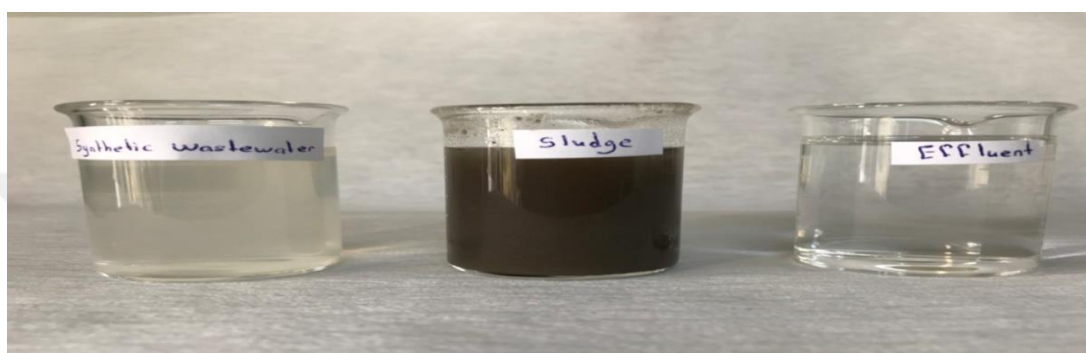


Image from the third experimental study operated with synthetic wastewater



Image from the fourth experimental study operated with WW1



Image from the sixth experimental study operated with WW2 and PAC addition

Figure 4.72 Photographs of influent, sludge and effluent (Personal archive, 2019)

Table 4.14 Comparison of the results of experimental studies

| Type of wastewater     | Material          | Removal Range (%) |             |     |             |                    |             |                 |                 |
|------------------------|-------------------|-------------------|-------------|-----|-------------|--------------------|-------------|-----------------|-----------------|
|                        |                   | COD               | BOD         | SS* | TN          | NH <sub>4</sub> -N | TP          | Cl <sup>-</sup> | SO <sub>4</sub> |
| Synthetic wastewater   | MF010+ MBTF       | 90.9 - 98.6       | 92.6 - 98.5 | <10 | 16.9 - 40   | >99                | 8 - 39.4    | 0.8 - 4.2       | 29.4 - 57.1     |
| Synthetic wastewater   | MF022+ MBTF       | 92.9 - 99         | 93.1 - 99.3 | <10 | 21.6 - 42.7 | >99                | 7.3 - 24.2  | 1.2 - 4.1       | 66.7 - 75       |
| Synthetic wastewater   | Double Layer MBTF | 85.6 - 98.3       | 92.3 - 98.7 | <10 | 26.8 - 59.8 | >99                | 0.9 - 11.7  | 1.9 - 3         | 4 - 36          |
| Municipal wastewater   | Double Layer MBTF | 64.3 - 94.7       | 84 - 93.3   | <10 | 41.7 - 56.6 | >99                | 2.5 - 8.3   | 1.5 - 3.8       | 5.8 - 21.4      |
| Municipal wastewater   | MF022+ MBTF       | 94 - 95.8         | 94.4 - 95.9 | <10 | 25 - 52.1   | >99                | 18.4 - 30.2 | 1.9 - 4.2       | 46 - 56.8       |
| Municipal wastewater** | MF022+ MBTF       | 97.9 - 99.2       | 95.6 - 97   | <10 | 26.9 - 42   | >99                | 6.7 - 41.2  | 7.5 - 36        | 59.9 - 69.2     |

\*Effluent concentration, mg/L

\*\* with PAC addition

Table 4.15 Comparison of the results of the studies with the results of other studies in the literature

| Type of wastewater   | Process      | Material          | Pore Size | MLSS (mg/L) | DO (mg/L) | COD (%)     | BOD (%)     | SS (mg/L)  | TN (%)      | NH <sub>4</sub> -N (%) | TP (%)      | Reference           |
|----------------------|--------------|-------------------|-----------|-------------|-----------|-------------|-------------|------------|-------------|------------------------|-------------|---------------------|
| Municipal wastewater | Aerobic DMBR | Nylon Mesh Filter | 80 µm     | 3.9         | 3 - 4     | 83.3 ± 8.4  | n.s         | n.s        | 15.7 ± 6.4  | 98.1 ± 1.9             | 53.4 ± 15.4 | Wang et al. (2012)  |
| Synthetic wastewater | Aerobic DMBR | Non-Woven Fabric  | 0.45 µm   | 5           | n.s       | 91-94       | n.s         | n.s        | n.s         | n.s                    | n.s         | Veral et al. (2017) |
| Synthetic wastewater | Aerobic DMBR | Polyester Fabric  | 0.39 µm   | 6.2 ± 0.8   | >2        | 97.5        | n.s         | <10        | 25.6        | n.s                    | 6           | Isik et al. (2019)  |
| Household wastewater | Aerobic DMBR | Non-Woven Fabric  | 100 µm    | 4.4 - 10.4  | 3.6       | 85.5-89.3   | 96.7-97.9   | 93.3-95.7* | 33.6-37.8   | 91.4-99.4              | 18.3-32.3   | Ren et al. (2010)   |
| Synthetic wastewater | Aerobic DMBR | MBTF              | 30 µm     | 3.9 ± 0.3   | 2 - 4.6   | 85.6 - 98.3 | 92.3 - 98.7 | <10        | 26.8 - 59.8 | >99                    | 0.9 - 11.7  | This Study          |
| Municipal wastewater | Aerobic DMBR | MBTF              | 30 µm     | 5.5 ± 0.6   | 2.6 - 6.3 | 64.3 - 94.7 | 84 - 93.3   | <10        | 41.7 - 56.6 | >99                    | 2.5 - 8.3   | This Study          |

n.s: not specified

\*% removal

#### 4.9 FTIR Result of Dynamic Layer

FTIR method used to analyze the composition of organic and inorganic materials based on chemical bonds. According to FTIR analysis, the peak observed at  $3330\text{ cm}^{-1}$  shows stretching of the O-H bounds, which also include polysaccharides. The peak at  $2980\text{ cm}^{-1}$  points out aliphatic C-H stretching groups and C=O amides groups. The peaks at  $1387$ ,  $1248$  and  $1036\text{ cm}^{-1}$  represent the existence of  $\text{NO}_2$  stretching bonds, C-O-C stretching bonds and carbohydrates, C-OH stretching bonds. The peak at  $644\text{ cm}^{-1}$  indicates C-Cl bonding groups on DM layer (Jawaid & Khan, 2018). It is obvious that protein- and polysaccharide-like compounds are found on the dynamic layer. Similar results obtained in other dynamic membrane application (Isik et al., 2019; Yurtsever et al., 2020). FTIR result of virgin MBTF and dynamic layer are shown in Figure 4.73 and Table 4.16 presented the chemical groups according to FTIR results.

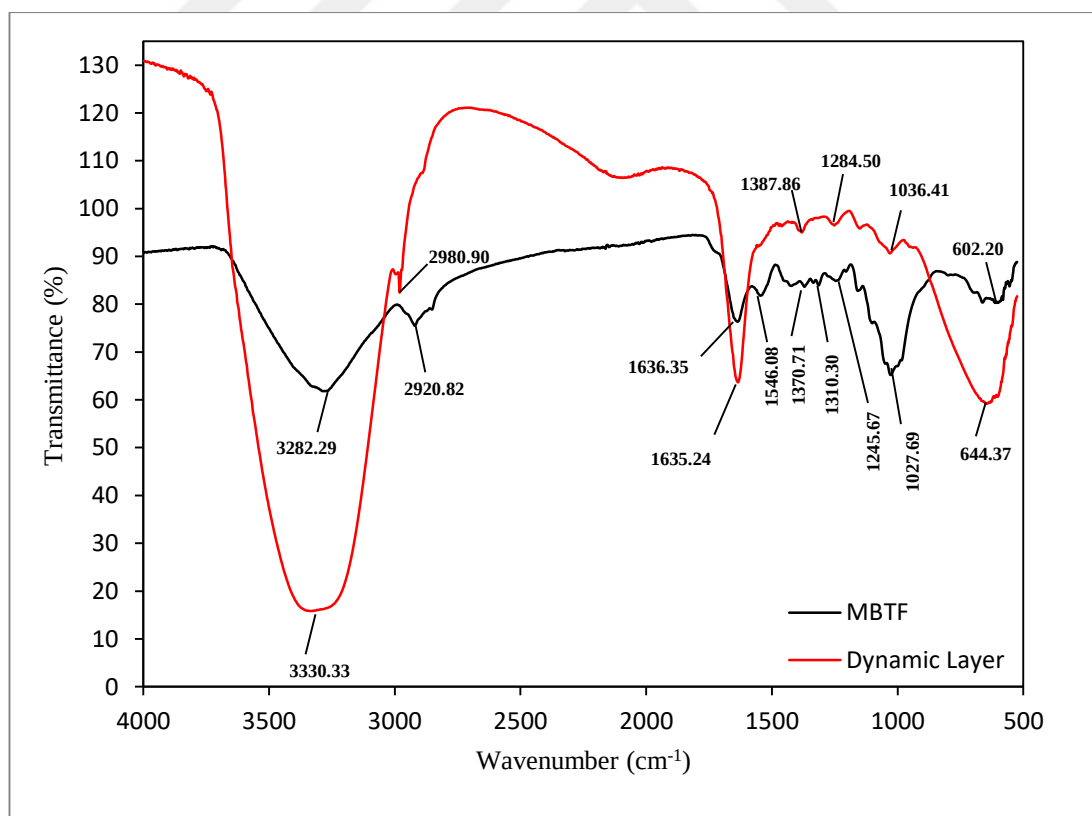


Figure 4.73 FTIR results of virgin MBTF and dynamic layer

Table 4.16 Chemical groups according to FTIR result

| Wavelengths | Chemical Groups                                                                       |
|-------------|---------------------------------------------------------------------------------------|
| 3600-3200   | OH, Carboxyls, NH groups                                                              |
| 3100-2800   | Methyl and methylen aliphatic groups, =C-H, -C-H, -C-H aldehydic groups.              |
| 1600-1200   | Carboxylic acids, ketones, aldehydes, phenyl and flouride (C-OH, C=C aromatic, C-O-C) |
| 1400-1000   | C-O carbohydrates, C-F bonding                                                        |
| 800-600     | C-Cl bonding, carboxyl functional groups                                              |

#### 4.10 Results of PCR-DGGE Studies

16S rRNA by using PCR-DGGE metagenomics analysis (16S Metagenom Analysis, QIIME2) was applied to the sludge samples taken from the dynamic layers obtained in fourth and fifth experimental series. The family of microorganisms and the relative abundance of dominant microbial communities for the samples was depicted in Figure 4.74 and Figure 4.75, respectively. Although some microbial species were found in both of the samples, most of them were quite different. The same MLSS was used in both series; however, the feeding wastewaters had different origins. Therefore, some microbial communities determined in the dynamic layer were obtained differently from each other.

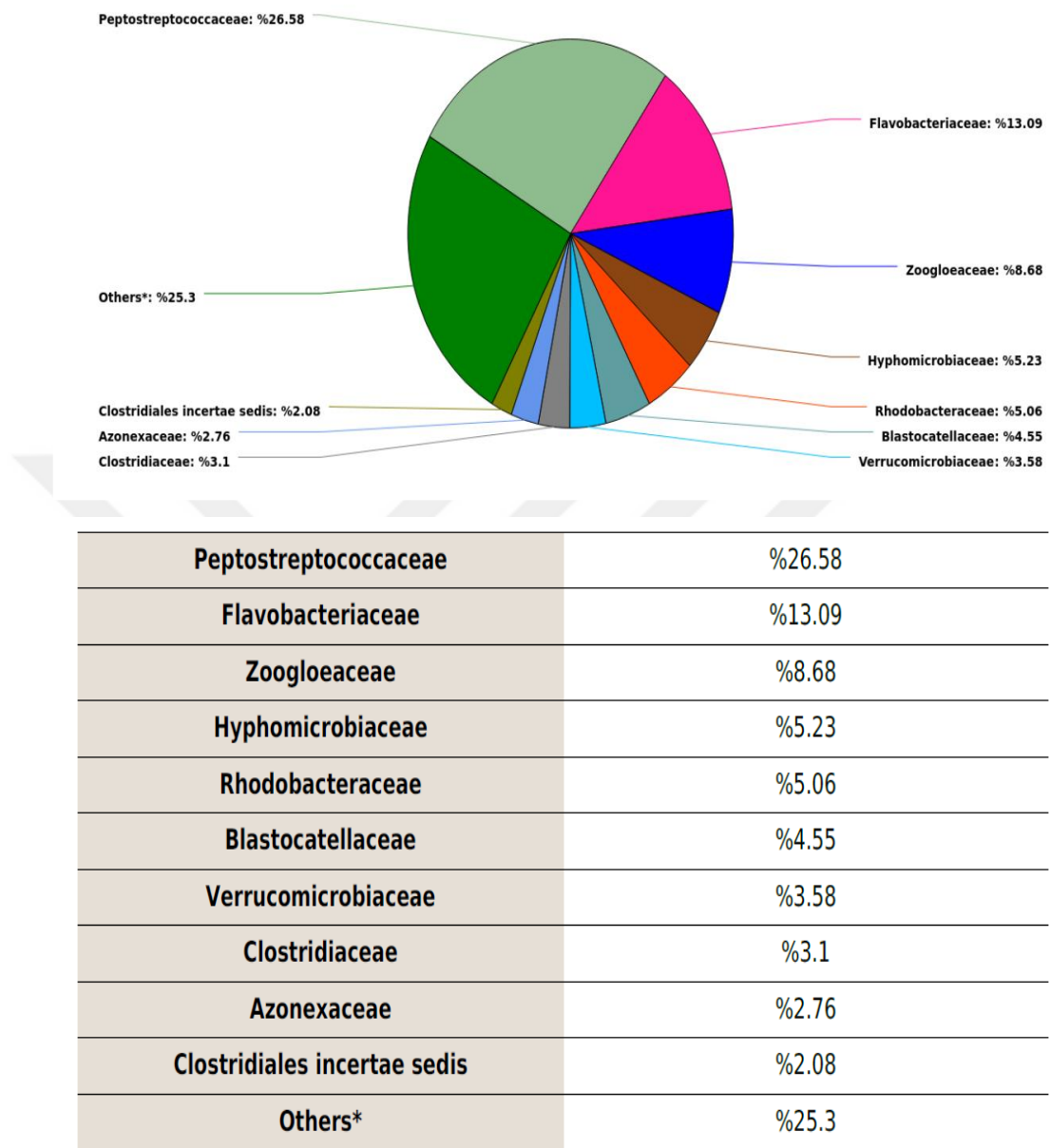
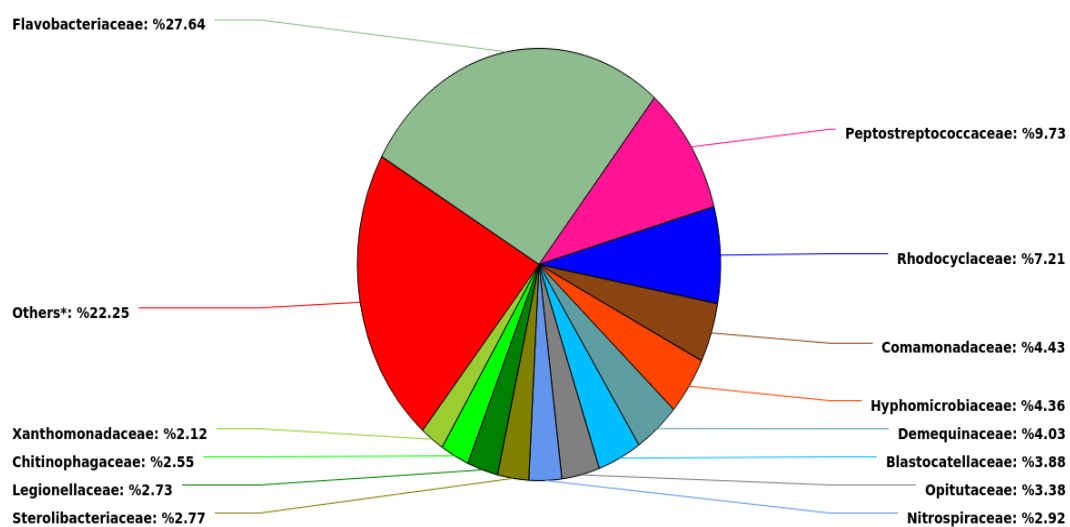


Figure 4.74 Metagenomic analysis results of the dynamic layer obtained in fourth experimental study by using WW1



|                              |               |
|------------------------------|---------------|
| <b>Flavobacteriaceae</b>     | <b>%27.64</b> |
| <b>Peptostreptococcaceae</b> | <b>%9.73</b>  |
| <b>Rhodocyclaceae</b>        | <b>%7.21</b>  |
| <b>Comamonadaceae</b>        | <b>%4.43</b>  |
| <b>Hyphomicrobiaceae</b>     | <b>%4.36</b>  |
| <b>Demequinaceae</b>         | <b>%4.03</b>  |
| <b>Blastocatellaceae</b>     | <b>%3.88</b>  |
| <b>Opitutaceae</b>           | <b>%3.38</b>  |
| <b>Nitrospiraceae</b>        | <b>%2.92</b>  |
| <b>Sterolibacteriaceae</b>   | <b>%2.77</b>  |
| <b>Legionellaceae</b>        | <b>%2.73</b>  |
| <b>Chitinophagaceae</b>      | <b>%2.55</b>  |
| <b>Xanthomonadaceae</b>      | <b>%2.12</b>  |
| <b>Others*</b>               | <b>%22.25</b> |

Figure 4.75 Metagenomic analysis results of the dynamic layer obtained in fifth experimental study by using WW2

#### 4.11 Determination of Biokinetic Coefficients of DMBR Operating in Continuous Mode

Monod model was used to determine biokinetic model of DMBR system. Monod model describes the interaction between the growth of microorganisms and the utilization of growth-limiting substrate in a sludge process. The impact of limiting substrate may be defined using the following expression (Tchobanoglous, 2003):

$$\mu = \mu_m \cdot \frac{S}{K_s + S} \quad (4.1)$$

where  $\mu$  is the specific growth rate,  $S$  is the concentration of growth-limiting substrate,  $K_s$  the saturation constant and  $\mu_m$  is the maximum specific growth rate. Following assumptions was taken into account to develop the model of DMBR system:

1. The reactor is properly mixed (mixing was provided by aerators placed at the bottom of the bioreactor)
2. Influent substrate concentration is constant throughout the study
3. No microbial solids exist in the influent substrate
4. The reactor volume is constant (it was provided by keeping inflow rate constant with the permeate flux)
5. Complete rejection of MLSS (the membrane was capable of withholding all solids in the system)
6. Steady-state conditions prevail along the system.

Mass balance must be established for both the microorganism and the substrate to find the necessary equations. The mass balance can be mathematically defined by (Tchobanoglous, 2003):

$$\frac{dX}{dt} \cdot V = Q \cdot X_0 - Q \cdot X + r_g \cdot V \quad (4.2)$$

where,

$dX/dt$ = rate of change of biomass concentration, gVSS/m<sup>3</sup>.day

$V$ = inlet wastewater flow, m<sup>3</sup>/day

$X_0$ = inlet biomass concentration, gVSS/m<sup>3</sup>

$r_g$ = net bacterial growth rate, gVSS/m<sup>3</sup>.day

Similar to biomass, the mass balance for the substrate can be mathematically expressed as follows:

$$\frac{dS}{dt} \cdot V = Q \cdot S_0 - Q \cdot S + V \cdot r_s \quad (4.3)$$

where,

$dS/dt$ = rate of change of substrate concentration, g/m<sup>3</sup>.day

$S_0$ = soluble substrate concentration in the inlet, g/m<sup>3</sup>

$S$ = soluble substrate concentration in the outlet, g/m<sup>3</sup>

$r_s$ = substrate utilization rate, g/m<sup>3</sup>.day

Table 4.17 presents the typical values of the biokinetic coefficients of the sludge processes. The equations of the Monod model for determination of biokinetic coefficients can be defined as follows:

$$\theta_c = \mu^{-1} = \frac{K_s}{\mu_m} \cdot \frac{1}{S} + \frac{1}{\mu_m} \quad (4.4)$$

$$Y = \frac{dX}{dS} \quad (4.5)$$

$$\frac{1}{\theta_c} = \mu = \frac{Y \cdot (S_0 - S)}{\theta \cdot X} - k_d \quad (4.6)$$

Table 4.17 Typical values of biokinetic coefficient of activated sludge processes (Al-Malack, 2006)

| Coefficient              | Basis             | Range     |
|--------------------------|-------------------|-----------|
| k ( $k = \mu_{\max}/Y$ ) | day <sup>-1</sup> | 2-8       |
| k <sub>d</sub>           | day <sup>-1</sup> | 0.03-0.07 |
| K <sub>s</sub>           | mg/L, BOD         | 40-120    |
|                          | mg/L, COD         | 20-80     |
| Y                        | MLVSS/BOD         | 0.3-0.7   |
|                          | MLVSS/COD         | 0.2-0.5   |

Determination of biokinetic coefficients of the system was done as a result of evaluation of the obtained experimental data of experimental studies after the system reaches equilibrium. The biokinetic coefficients of this study were found to be close to the typical values.

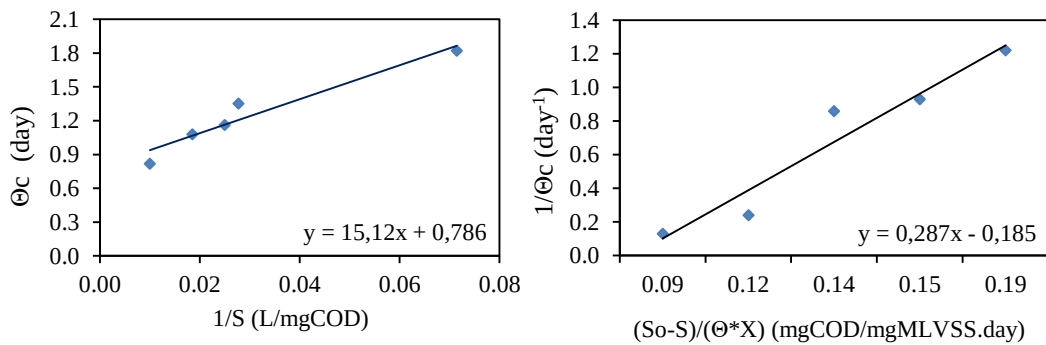


Figure 4.76 Determination of  $\mu_{\max}$ ,  $K_s$ ,  $Y$  and  $k_d$  at MLVSS of 6000 mg/L for first study

Determination of coefficients was done as shown in Figure 4.76. Values of  $\mu_{\max}$ ,  $K_s$ ,  $Y$ ,  $k_d$  were  $1.27 \text{ day}^{-1}$ ,  $19.2 \text{ mg/L}$ ,  $0.29 \text{ mgMLVSS/mgCOD}$ ,  $0.185 \text{ day}^{-1}$ , respectively.

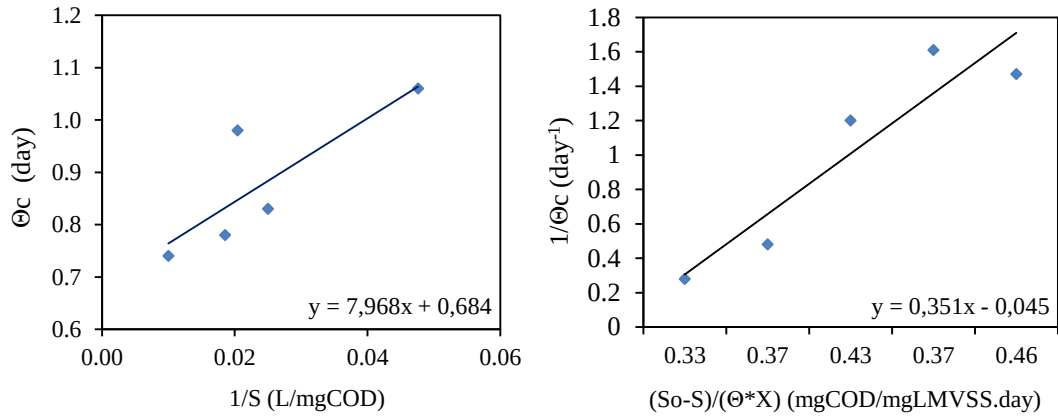


Figure 4.77 Determination of  $\mu_{\max}$ ,  $K_s$ ,  $Y$  and  $k_d$  at MLVSS of 4000 mg/L for fourth study

Determination of coefficients was done as shown in Figure 4.77. Values of  $\mu_{\max}$ ,  $K_s$ ,  $Y$ ,  $k_d$  were  $1.46 \text{ day}^{-1}$ ,  $11.6 \text{ mg/L}$ ,  $0.35 \text{ mgMLVSS/mgCOD}$ ,  $0.045 \text{ day}^{-1}$ , respectively.

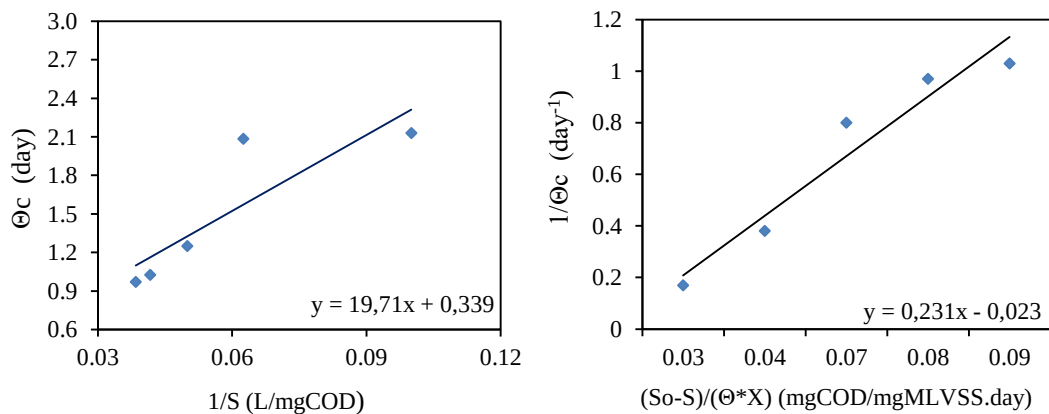


Figure 4.78 Determination of  $\mu_{\max}$ ,  $K_s$ ,  $Y$  and  $k_d$  at MLVSS of 4400 mg/L for fifth study

Determination of coefficients was done as shown in Figure 4.78. Values of  $\mu_{\max}$ ,  $K_s$ ,  $Y$ ,  $k_d$  were  $2.94 \text{ day}^{-1}$ ,  $58.1 \text{ mg/L}$ ,  $0.23 \text{ mgMLVSS/mgCOD}$ ,  $0.023 \text{ day}^{-1}$ , respectively.

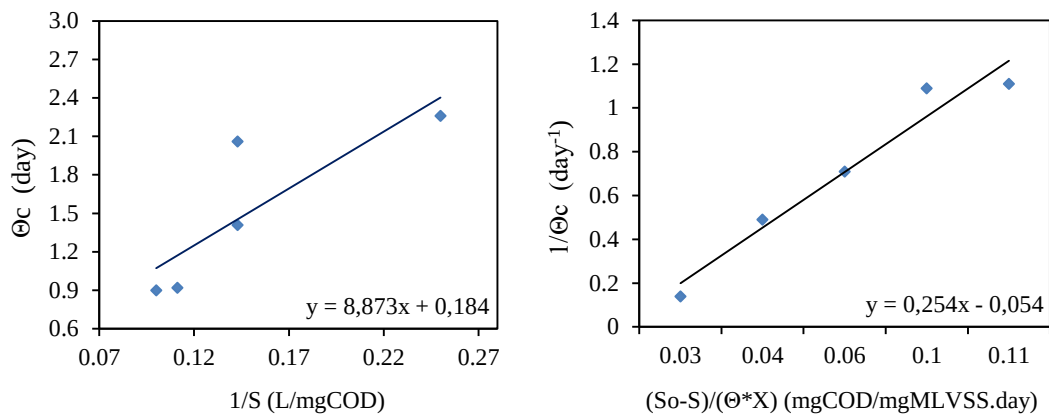


Figure 4.79 Determination of  $\mu_{\max}$ ,  $K_s$ ,  $Y$  and  $k_d$  at MLVSS of 4400 mg/L for sixth study

Determination of coefficients was done as shown in Figure 4.79. Values of  $\mu_{\max}$ ,  $K_s$ ,  $Y$ ,  $k_d$  were 5.43 day<sup>-1</sup>, 48.2 mg/L, 0.25 mgMLVSS/mgCOD, 0.054 day<sup>-1</sup>, respectively.

Table 4.18 Biokinetic coefficients obtained from different studies

| Type of Wastewater    | Process | Y    | $k_d$ | $\mu_{\max}$ | $K_s$ | Reference                 |
|-----------------------|---------|------|-------|--------------|-------|---------------------------|
| Synthetic wastewater  | MBR     | 0.57 | 0.06  | 1.4          | 326   | Al-Malack, 2006           |
| Municipal wastewater  | CAS     | 1.34 | 0.17  | 2.78         | 8.6   | Hadei et al., 2015        |
| Municipal wastewater  | CAS     | 0.49 | 0.03  | 0.95         | 52.1  | Mardini et al., 2011      |
| Industrial wastewater | MBR     | 6.14 | 0.10  | 0.22         | 38.9  | Hekim, 2019               |
| Synthetic wastewater  | DMBR    | 0.15 | 0.04  | 1.27         | 19.2  | First experimental study  |
| Municipal wastewater  | DMBR    | 0.35 | 0.05  | 1.46         | 11.6  | Fourth experimental study |
| Municipal wastewater  | DMBR    | 0.23 | 0.02  | 2.94         | 58.1  | Fifth experimental study  |
| Municipal wastewater  | DMBR    | 0.25 | 0.05  | 5.43         | 48.2  | Sixth experimental study  |

It appears that in various studies that the biokinetic coefficients change depending on the operating conditions and processes. Differences in MLSS concentration play an important role in the change of biokinetic coefficients and all coefficients are directly proportional to effluent COD concentration (Hadei et al. 2015). Al-Malack (2016) investigated the sensitivity of coefficients in MBR process and reported that  $k_d$  and  $K_s$  are directly proportional to effluent substrate concentration, whereas  $\mu_{max}$  is inversely proportional to effluent substrate concentration. As a result, small changes in  $\mu_{max}$  may affect effluent substrate concentration remarkably. In this context, researchers should take care of optimization of  $\mu_{max}$  for efficient operation of MBR systems.

The effect of hydraulic retention time (HRT) on substrate consumption in the system was investigated. HRT increased in proportional to the decrease in membrane flux. The increase in HRT in the bioreactor contributed to the decrease in the effluent substrate concentration. Figure 4.80 indicates the relationship between HRT and the effluent COD concentration.

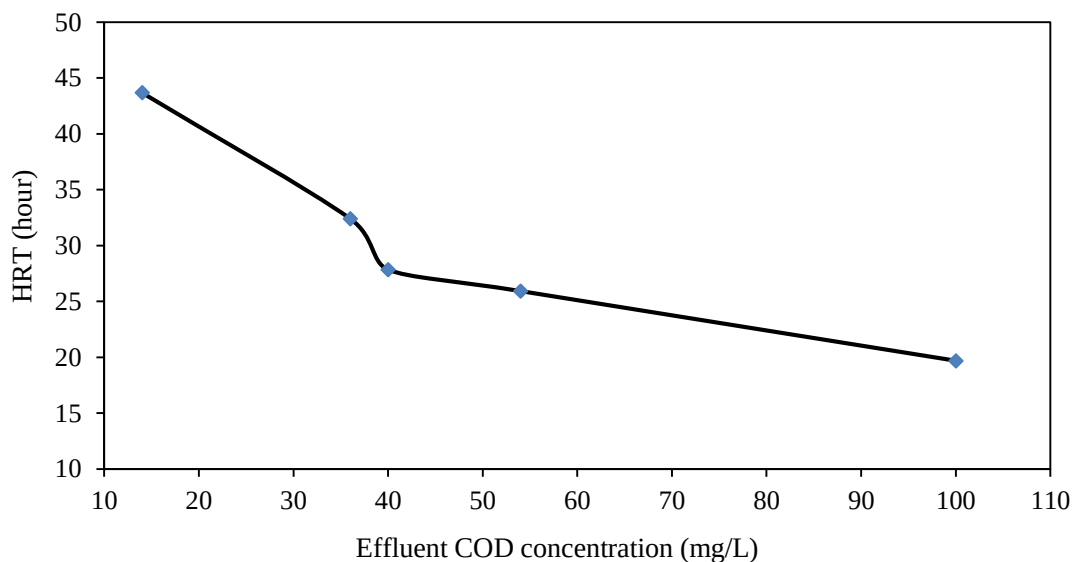


Figure 4.80 Relationship between HRT and effluent COD concentration

#### 4.12 Comparison of Results with Irrigation Water Criteria

The fourth, fifth and sixth experimental studies operated with municipal wastewater were compared with the irrigation water quality standards given in “Wastewater Treatment Plants Technical Procedures Communiqué, App.7, 2010”, Ministry of Environment and Urbanization of Republic of Turkey published in Official Gazette (No: 27527, 20.03.2010). Regarding the irrigation water quality parameters based on the classification of irrigation water, the maximum allowable heavy metal and toxic elements concentrations were compared. In addition to this, specific equations such as sodium adsorption ratio (SAR), exchangeable sodium percent (ESP) and residual sodium carbonate (RSC) were used to determine the irrigation water class. These equations are as follows:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (4.7)$$

$$ESP(\%) = \frac{Na^+}{Na^+ + Mg^{2+} + Ca^{2+}} \times 100 \quad (4.8)$$

$$RSC = (CO_3^{-2} + HCO_3^-) - (Ca^{2+} + Mg^{2+}) \quad (4.9)$$

Figure 4.81 gives the diagram used for the classification of irrigation waters.

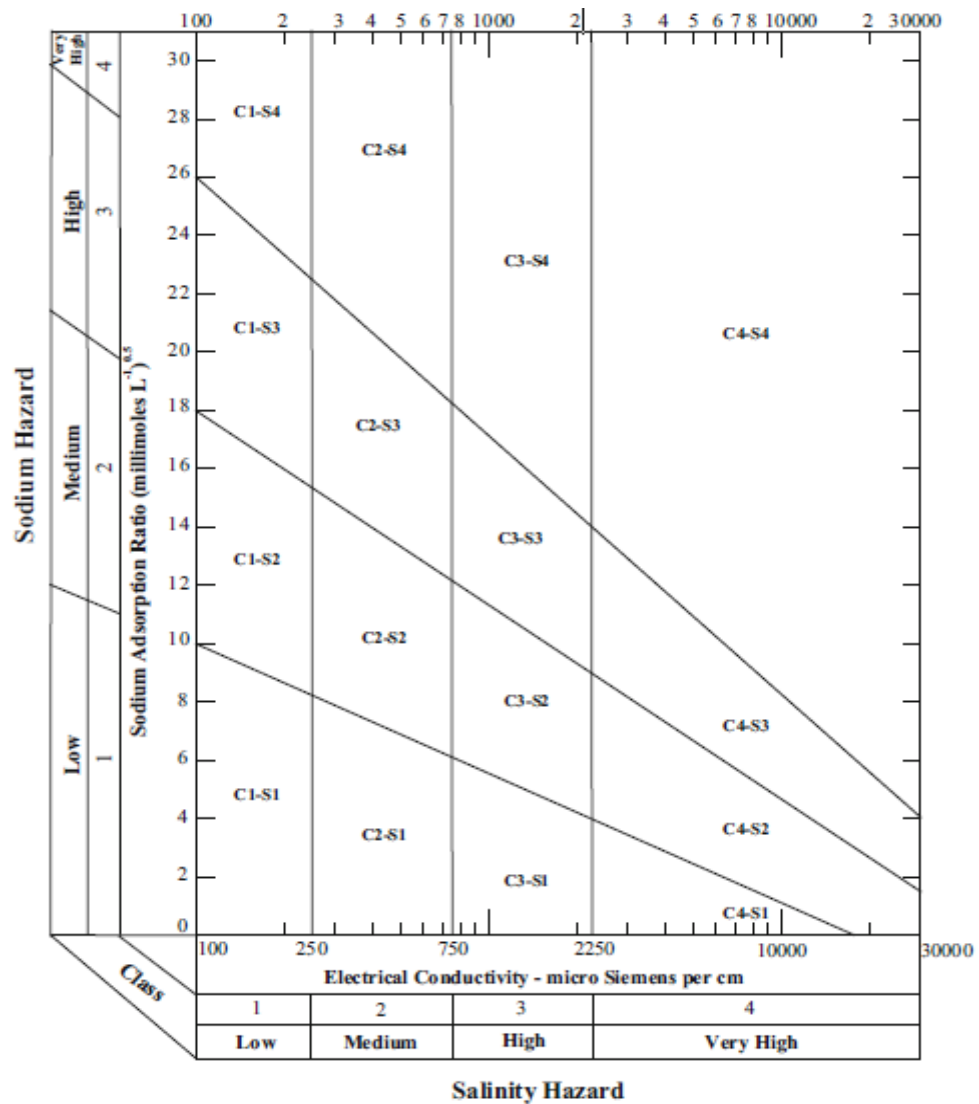


Figure 4.81 Diagram for the classification of irrigation waters (Zaman et al., 2018)

#### 4.12.1 Changes in Heavy Metal Concentrations

Heavy metal concentrations were analyzed in all experimental studies operated with municipal wastewater. Table 4.10 showed the analysis done in influent, sludge, and effluent samples. Similar results were obtained at heavy metal concentrations in the influent and effluent samples for many parameters. However, slight increase was observed in some parameters due to the effect of sludge. Consequently, all parameters of the effluent samples remained below the limit values.

Table 4.19 Comparison of heavy concentrations with limit values in the regulation (wastewater treatment plants technical procedures communiqué, App.7, 2010)

| Elements        | Limit values in case of continuous irrigation on all kinds of ground (mg/L) | Influent of double layer MBTF (mg/L) | Effluent of double layer MBTF (mg/L) | Influent of MF022+ MBTF (mg/L) | Effluent of MF022+ MBTF (mg/L) | Influent of MF022 +MBTF with PAC (mg/L) | Sludge of MF022+ MBTF with PAC (mg/L) | Effluent of MF022+ MBTF with PAC (mg/L) |
|-----------------|-----------------------------------------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------|--------------------------------|-----------------------------------------|---------------------------------------|-----------------------------------------|
| Aluminum (Al)   | 5.0                                                                         | 0.06                                 | 0.06                                 | 0.06                           | 0.02                           | 0.20                                    | 0.03                                  | 0.02                                    |
| Arsenic (As)    | 0.1                                                                         | 0.01                                 | 0.01                                 | <0.01                          | 0.01                           | <0.01                                   | 0.01                                  | 0.02                                    |
| Beryllium (Be)  | 0.1                                                                         | <0.01                                | <0.01                                | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | <0.01                                   |
| Boron (B)       | -                                                                           | 0.73                                 | 0.77                                 | 0.20                           | 0.27                           | 0.16                                    | 0.34                                  | 0.25                                    |
| Cadmium (Cd)    | 0.01                                                                        | <0.01                                | <0.01                                | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | <0.01                                   |
| Chromium (Cr)   | 0.1                                                                         | <0.01                                | <0.01                                | <0.01                          | <0.01                          | 0,01                                    | <0.01                                 | <0.01                                   |
| Cobalt (Co)     | 0.05                                                                        | <0.01                                | <0.01                                | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | <0.01                                   |
| Copper (Cu)     | 0.2                                                                         | <0.01                                | 0.08                                 | 0.01                           | 0.19                           | 0.01                                    | <0.01                                 | 0.08                                    |
| Iron (Fe)       | 5.0                                                                         | 0.21                                 | 0.37                                 | 0.10                           | 0.04                           | 0.29                                    | 0.02                                  | <0.01                                   |
| Lead (Pb)       | 5.0                                                                         | <0.01                                | <0.01                                | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | <0.01                                   |
| Lithium (Li)    | 2.5                                                                         | 0.04                                 | 0.03                                 | 0.01                           | 0.01                           | 0.01                                    | 0.01                                  | 0.02                                    |
| Manganese (Mn)  | 0.2                                                                         | 0.12                                 | 0.02                                 | 0.04                           | 0.01                           | 0.06                                    | 0.02                                  | <0.01                                   |
| Molybdenum (Mo) | 0.01                                                                        | <0.01                                | 0.01                                 | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | 0.01                                    |
| Nickel (Ni)     | 0.2                                                                         | 0.01                                 | 0.07                                 | 0.02                           | 0.05                           | <0.01                                   | 0.01                                  | 0.01                                    |
| Selenium (Se)   | 0.02                                                                        | <0.01                                | <0.01                                | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | <0.01                                   |
| Vanadium (V)    | 0.1                                                                         | <0.01                                | <0.01                                | <0.01                          | <0.01                          | <0.01                                   | <0.01                                 | 0.01                                    |
| Zinc (Zn)       | 2.0                                                                         | 0.03                                 | 0.15                                 | 0.04                           | 0.28                           | 0.09                                    | 0.02                                  | 0.11                                    |

#### 4.12.2 Irrigation Water Quality Parameters

All parameters in terms of irrigation water quality were analyzed and also calculated. The results were given in Table 4.20. As the DMBR system was insufficient in removal of some ions in fourth study operated with municipal water (WW1), the fourth study is in a lower water quality class compared to other studies.

The fifth and sixth studies effluents operated with the same municipal wastewater (WW2) were generally in the first, second and third water quality classes regarding the parameters. According to Figure 4.81 where the water quality class is determined based on SAR and conductivity values, the effluent water in the fourth study has fourth class water quality but the effluent water in the fifth and sixth studies has third class water quality. These results showed that DMBR systems can meet irrigation water criteria depending on the characterization of influent water. Additional processes should be included to the DMBR effluent for high strength wastewater treatment.

Racar et al. (2020) investigated impact of nanofiltration (NF) and reverse osmosis (RO) to treat MBR effluent for irrigation purpose. They state that MBR is inefficient to remove conductivity, TN and ions. However, it is also indicated that reclaimed water with NF and RO decrease conductivity by 93.6% and 94.9%, respectively. Likewise, ion concentrations were reduced by over 90% for many parameters. High removal rates can be achieved with the combination of DMBR-NF and DMBR-RO for wastewater reuse. Similar to these results, Falizi et al. (2018) investigated enhancement of water quality of MBR effluent with the combination of NF and RO. They stated that solo use of NF and RO effluents were evaluated as low class water type in respect to their SAR and EC values. On the other hands, combination of MBR and RO decreased conductivity, specific ion toxicity and SAR parameters effectively. As a result, RO and NF may be used to enhance the quality of effluent of DMBR to meet high quality irrigation water standards.

Table 4.20 Classification of DMBR effluents for irrigation purpose (Zaman et al., 2018)

| Quality Criterion                                                                                                                           | Irrigation Water Class                    |                                                                                                     |                                                                                                                                                                           |                                                                                                                                                                                                                                                 |                                         | Results of This Study         |                               |                               |
|---------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|-------------------------------|-------------------------------|-------------------------------|
|                                                                                                                                             | 1 <sup>st</sup> quality water (very good) | 2 <sup>nd</sup> quality water (good)                                                                | 3 <sup>rd</sup> quality water (utilizable)                                                                                                                                | 4 <sup>th</sup> quality water (restricted use)                                                                                                                                                                                                  | 5 <sup>th</sup> quality water (harmful) | Double Layer MBTF             | MF022+ MBTF                   | MF022+MB TF with PAC addition |
| EC <sub>25</sub> ×10 <sup>6</sup>                                                                                                           | 0-250                                     | 250-750                                                                                             | 750-2000                                                                                                                                                                  | 2000-3000                                                                                                                                                                                                                                       | >3000                                   | 9180                          | 1770                          | 1400                          |
| Exchangeable Sodium Percentage (Na%)                                                                                                        | <20                                       | 20-40                                                                                               | 40-60                                                                                                                                                                     | 60-80                                                                                                                                                                                                                                           | >80                                     | 76                            | 58                            | 59                            |
| Sodium Adsorption Rate (SAR)                                                                                                                | <10                                       | 10-18                                                                                               | 18-26                                                                                                                                                                     | >26                                                                                                                                                                                                                                             | -                                       | 21.26                         | 5.32                          | 5.84                          |
| Residual Sodium Carbonate (mg/L)                                                                                                            | <66                                       | 66-133                                                                                              | >133                                                                                                                                                                      | -                                                                                                                                                                                                                                               | -                                       | -                             | -                             | -                             |
| Chloride (Cl <sup>-</sup> ) (mg/L)                                                                                                          | 0-142                                     | 142-249                                                                                             | 249-426                                                                                                                                                                   | 426-710                                                                                                                                                                                                                                         | >710                                    | 2500                          | 251                           | 104                           |
| Sulphate (SO <sub>4</sub> <sup>2-</sup> ) (mg/L)                                                                                            | 0-192                                     | 192-336                                                                                             | 336-575                                                                                                                                                                   | 575-960                                                                                                                                                                                                                                         | >960                                    | 242                           | 68                            | 53                            |
| Total Salinity Concentration (mg/L)                                                                                                         | 0-175                                     | 175-525                                                                                             | 525-1400                                                                                                                                                                  | 1400-2100                                                                                                                                                                                                                                       | >2100                                   | 5600                          | 800                           | 500                           |
| Boron (mg/L)                                                                                                                                | 0-0.5                                     | 0.5-1.12                                                                                            | 1.12-2.0                                                                                                                                                                  | >2.0                                                                                                                                                                                                                                            | -                                       | 0.77                          | 0.27                          | 0.25                          |
| Irrigation water class                                                                                                                      | C <sub>1</sub> S <sub>1</sub>             | C <sub>1</sub> S <sub>2</sub> ,<br>C <sub>2</sub> S <sub>2</sub> ,<br>C <sub>2</sub> S <sub>1</sub> | C <sub>1</sub> S <sub>3</sub> ,<br>C <sub>2</sub> S <sub>3</sub> ,<br>C <sub>3</sub> S <sub>3</sub> ,<br>C <sub>3</sub> S <sub>2</sub> ,<br>C <sub>3</sub> S <sub>1</sub> | C <sub>1</sub> S <sub>4</sub> ,<br>C <sub>2</sub> S <sub>4</sub> ,<br>C <sub>3</sub> S <sub>4</sub> ,<br>C <sub>4</sub> S <sub>4</sub> ,<br>C <sub>4</sub> S <sub>3</sub> ,<br>C <sub>4</sub> S <sub>2</sub> ,<br>C <sub>4</sub> S <sub>1</sub> | -                                       | C <sub>4</sub> S <sub>4</sub> | C <sub>3</sub> S <sub>1</sub> | C <sub>3</sub> S <sub>1</sub> |
| NO <sub>3</sub> <sup>-</sup> or NH <sub>4</sub> <sup>+</sup> (mg/L)                                                                         | 0-5                                       | 5-10                                                                                                | 10-30                                                                                                                                                                     | 30-50                                                                                                                                                                                                                                           | >50                                     | 6.9                           | 19.1                          | 24.9                          |
| Fecal Coliform 1/100 mL                                                                                                                     | 0-2                                       | 2-20                                                                                                | 20-100                                                                                                                                                                    | 100-1000                                                                                                                                                                                                                                        | >1000                                   | -                             | -                             | 0                             |
| BOD <sub>5</sub> (mg/L)                                                                                                                     | 0-25                                      | 25-50                                                                                               | 50-100                                                                                                                                                                    | 100-200                                                                                                                                                                                                                                         | >200                                    | 10                            | 8                             | 6                             |
| Suspended Solids (mg/L)                                                                                                                     | 20                                        | 30                                                                                                  | 45                                                                                                                                                                        | 60                                                                                                                                                                                                                                              | >100                                    | 0                             | 0                             | 0                             |
| pH                                                                                                                                          | 6.5-8.5                                   | 6.5-8.5                                                                                             | 6.5-8.5                                                                                                                                                                   | 6.5-9                                                                                                                                                                                                                                           | <6 or >9                                | 7.9-8.5                       | 8.3-8.6                       | 8.2 - 8.5                     |
| Temperature (°C)                                                                                                                            | 30                                        | 30                                                                                                  | 35                                                                                                                                                                        | 40                                                                                                                                                                                                                                              | >45                                     | 24-28                         | 26-28                         | 27-30                         |
| <div> <div>First Quality</div> <div>Second Quality</div> <div>Third Quality</div> <div>Fourth Quality</div> <div>Fifth Quality</div> </div> |                                           |                                                                                                     |                                                                                                                                                                           |                                                                                                                                                                                                                                                 |                                         |                               |                               |                               |

Table 4.21 Classification of treated water to be reused in irrigation (wastewater treatment plants technical procedures communiqué, App.7, 2010)

| Recovery Type                                                                                             | Treatment Type                                | Quality of Recycled Water                                                                                | Monitoring Period                                                             | Application Distance                                            |
|-----------------------------------------------------------------------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Class A                                                                                                   |                                               |                                                                                                          |                                                                               |                                                                 |
| a- Agricultural Irrigation - Non-commercially processed food products                                     |                                               |                                                                                                          |                                                                               |                                                                 |
| b - Irrigation of urban areas                                                                             |                                               |                                                                                                          |                                                                               |                                                                 |
| a- All kinds of food products irrigated with surface and drip irrigation and can be eaten directly as raw | Secondary treatment, filtration, disinfection | pH= 6-9, BOD <sub>5</sub> <20 mg/L, Turbidity < 2 NTU, Fecal Coliform 0/100 mL, Residual Chloride>1 mg/L | pH: weekly, BOD: weekly, Fecal Coliform: daily, Residual Chloride: Continuous | At a distance of at least 50 m from drinking water supply wells |
| b- All kinds of green area irrigation (parks, golf courses etc.)                                          |                                               |                                                                                                          |                                                                               |                                                                 |

Table 4.22 Table developed for the assessment of the chemical quality of irrigation water (wastewater treatment plants technical procedures communiqué, App.7, 2010)

| Parameters            | Units | Degree of Harm in Use |                           |                       |
|-----------------------|-------|-----------------------|---------------------------|-----------------------|
|                       |       | No harm (First Class) | Low-Medium (Second Class) | Harmful (Third Class) |
| Salinity              |       |                       |                           |                       |
| EC                    | μS/cm | <700                  | 700-3000                  | >3000                 |
| TDS                   | mg/L  | <500                  | 500-2000                  | >2000                 |
| Transmittance         |       |                       |                           |                       |
| SAR                   | 0-3   | EC > 0.7              | 0.7-0.2                   | <0.2                  |
|                       | 3-6   | >1.2                  | 1.2-0.3                   | <0.3                  |
|                       | 6-12  | >1.9                  | 1.9-0.5                   | <0.5                  |
|                       | 12-20 | >2.9                  | 2.9-1.3                   | <1.3                  |
|                       | 20-40 | >5.0                  | 5.0-2.9                   | <2.9                  |
| Specific Ion Toxicity |       |                       |                           |                       |
| Sodium (Na)           |       |                       |                           |                       |
| Surface Irrigation    | mg/L  | <3                    | 3-9                       | >9                    |
| Drip Irrigation       | mg/L  | <70                   | >70                       |                       |
| Chloride (Cl)         |       |                       |                           |                       |
| Surface Irrigation    | mg/L  | <140                  | 140-350                   | >350                  |
| Drip Irrigation       | mg/L  | <100                  | >100                      |                       |
| Bor (B)               | mg/L  | <0.7                  | 0.7 - 3                   | >3                    |

Table 4.21 and Table 4.22 show the classification of treated water to be reused in irrigation and assessment of the chemical quality of irrigation water according to “Wastewater Treatment Plants Technical Procedures Communiqué, App.7, 2010”. Whereas, the fourth experimental study operated with WW1 is harmful for irrigation because its high conductivity value, fifth and sixth experimental studies operated with WW2 are considered usable for irrigation as they are in first and second class water quality.

Treated water of fifth and sixth experimental studies can be used with the condition of drip irrigation for irrigation of non-commercially processed food products and irrigation of urban areas like parks and golf courses. Because of high chloride concentration of effluent of fifth and sixth experimental studies, they are not appropriate for surface irrigation.

#### 4.13 Energy Consumption of DMBR Systems

MBR systems are advanced treatment systems that require certain energy since those systems are operated with the use of various pumps. In this study, a submersible pump that transfers wastewater to the reactor, an air pump that supplies oxygen to the system and a diaphragm pump that allows treated water to pass through membrane surface were used. Submersible pump, air pump and diaphragm pump have 60W, 8W and 24W power, respectively. The electricity cost was calculated as 0,74 ₺/kWh as of the study date. The total energy cost of the system is calculated according to the formula below:

$$\text{Total Cost} = \sum_{n=1}^3 (P * OT * EC) \quad (4.10)$$

where,

P= Power (kW)

OT= Operation time (h)

EC= Energy cost (₺/kWh)

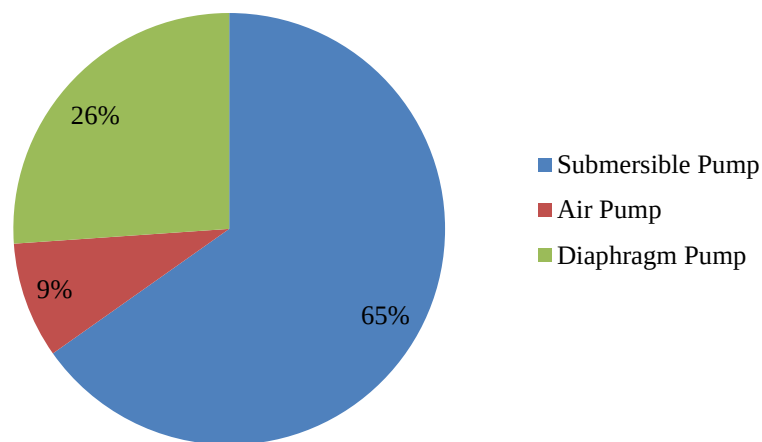


Figure 4.82 Percentage distribution of energy consumption of pumps

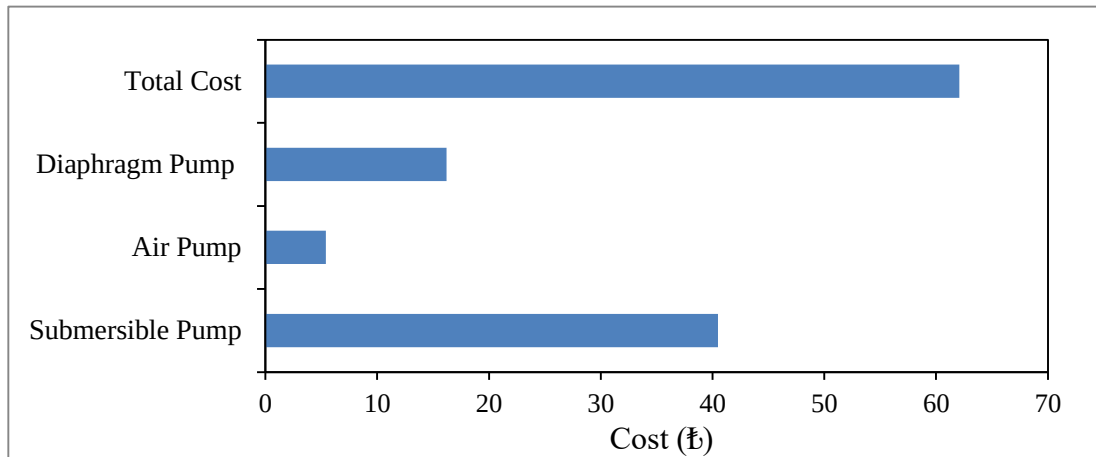


Figure 4.83 Energy consumption of first experimental study

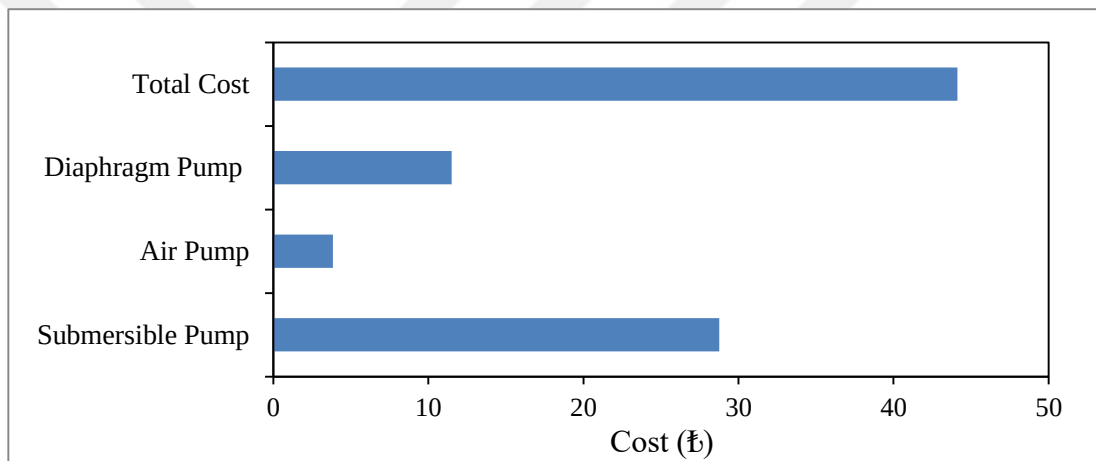


Figure 4.84 Energy consumption of second experimental study

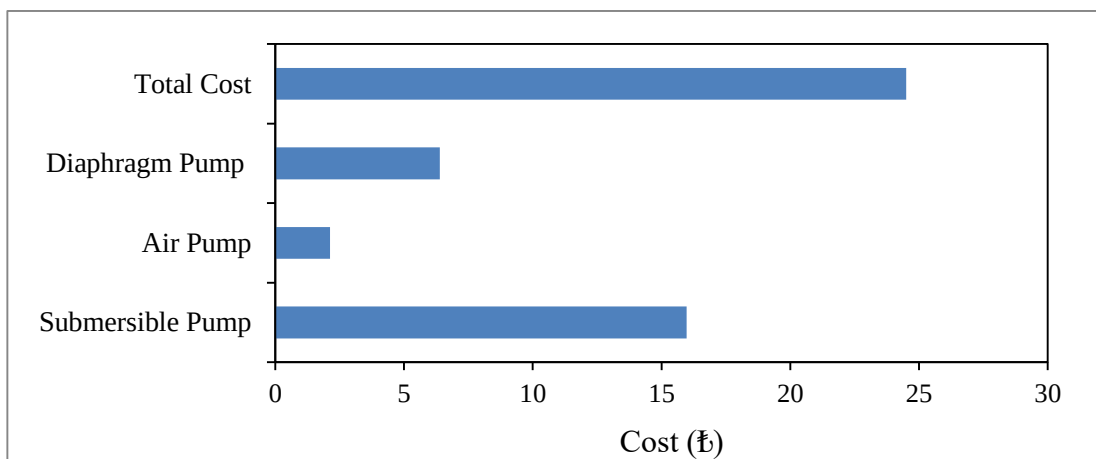


Figure 4.85 Energy consumption of third experimental study

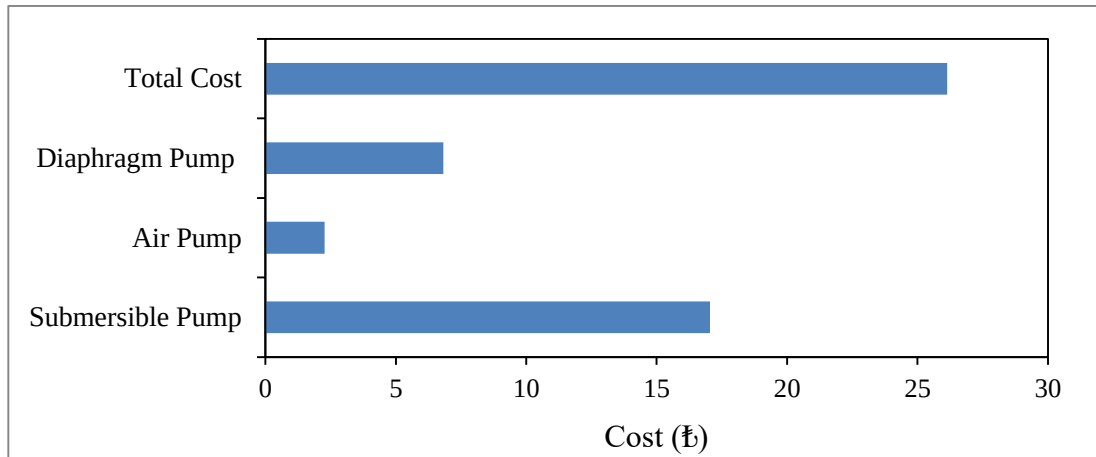


Figure 4.86 Energy consumption of fourth experimental study

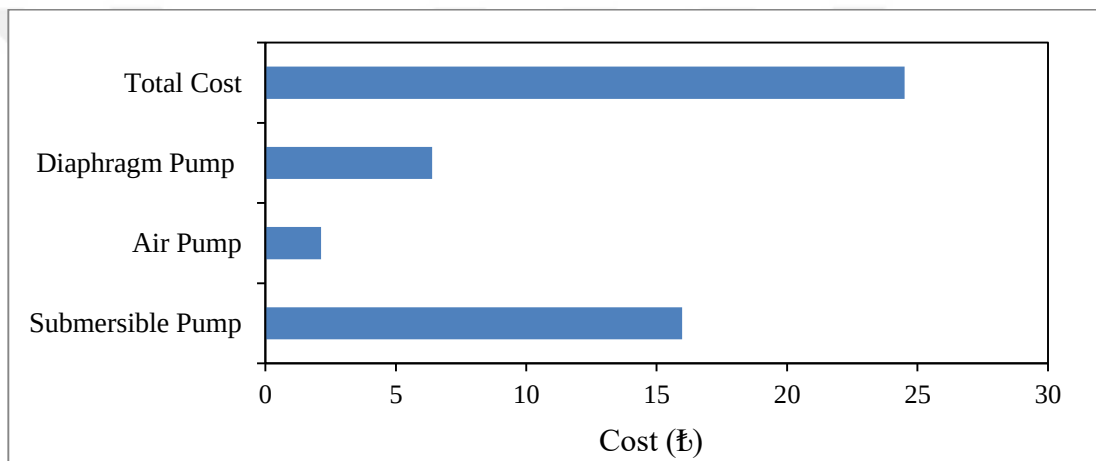


Figure 4.87 Energy consumption of fifth experimental study

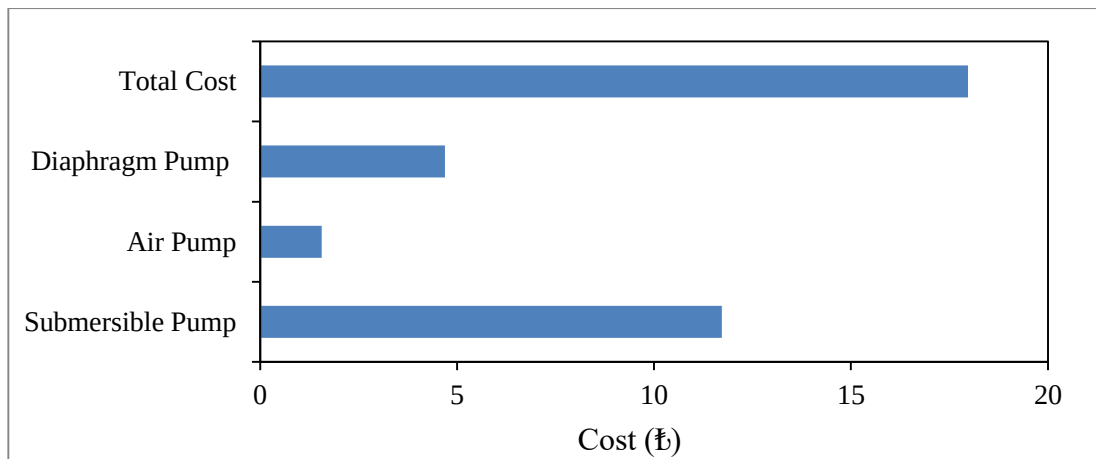


Figure 4.88 Energy consumption of sixth experimental study

## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATIONS

#### 5.1 Conclusion

Operation of dynamic membrane bioreactors was carried out in six different laboratory scale experimental studies using synthetic wastewater and two different type of municipal wastewater within the scope of this thesis. In this context, a DMBR unit with total volume of 15 L and a flat sheet membrane cassette system performing solid-liquid separation were designed. Preliminary studies were performed to determine the best membrane support material to use in experimental studies. After start-up studies, experimental studies were started by adding sludge taken from the sludge recycling line of a municipal wastewater treatment plant. Treatment performances of the systems, changes in the sludge and DMBR operating parameters were observed periodically during the studies. Some concluding remarks from the thesis are given as follows:

- Firstly, filtration tests were carried out to determine the most suitable membrane support material to be used in experimental studies. Two different membrane support materials, namely cotton textile fabric (TF) and metal braided one (MBTF), were tested with mixture of sludge and municipal wastewater. It was determined that MBTF exhibited better performance in terms of SS and COD removal efficiencies. This result shows that the selection of suitable membrane support material is one of the most important criteria affecting the performance of DMBR.
  
- Removal rates based on the parameters such as salinity, conductivity and temperature changed depending on the inlet wastewater and environmental conditions. Despite fluctuations in the inlet wastewater and environmental conditions, high removal efficiencies of organic and nitrogenous substance oxidation occurred in all operational series. Likewise, the effluent quality was not affected by the time-dependent changes in the organic loading rate, dissolved oxygen, SRT, HRT, and MLSS parameters. In all experimental studies, BOD, COD and  $\text{NH}_4^+\text{-N}$

removal was generally above 95% and SS removal exceeded 99%.

- There was partial nutrient removal in all series. The aerobic operation of DMBR unit and the absence of anaerobic/anoxic sections caused restriction of nutrient removal. Excellent physical disinfection was achieved as a result of the high rejection as confirmed by E. coli analysis and successful solid-liquid separation.
- It was determined that the membranes were clogged as a result of the first (MF022+TMBF) and second (MF010+TMBF) experimental studies that were run for a long time without backwashing. Membrane flux decreased sharply and TMP values increased at the end of the operation in these series. In the first and second experimental studies started with approximately the same flux value and the flux fell below 1 LMH at the end of the 27<sup>th</sup> and 38<sup>th</sup> day of operation time, respectively. This result shows that the reduction of the membrane pore size negatively affected the filterability. However, it was observed that there was a partial decrease in the membrane flux and the TMP reached a plateau after dynamic layer formation in the third and fourth experimental studies where only the double layer membrane support material TMBF was used. These results show that DMBR systems using textile materials offer better filterability properties compared to systems using only polymeric membranes.
- When the settling and dewatering properties of the sludge were examined, it was seen that there was no significant change in these properties of the sludge in all experimental series. However, with the addition of PAC in the sixth experimental study, it was observed that there was an improvement in the dewatering and settling properties of the sludge. Moreover, the zeta potential of the sludge that was -34 mV reached -21.5 mV at the end of the operation. As a result, the decreased zeta potential value enhanced the adsorption capacity of the sludge and formation of the dynamic layer by increasing the particle sizes.
- It was found that protein concentration is higher than polysaccharide concentration in EPS analysis for sludge. Protein is the main component of EPS in

this system. FTIR analysis performed on the dynamic layer on the support material revealed that aliphatic C-H bonded groups, polysaccharide containing O-H bonds and C=O amide groups and more chemically bonded groups were detected in the dynamic layer. This analyzes indicate that protein-like and polysaccharide-like compounds exist on the dynamic membrane layer.

- The SEM images of the virgin membrane support material and membrane support material with dynamic layer clearly find out that the dynamic layer completely covered the membrane support material and changed the surface morphology. SEM images show that the dynamic layer is formed on the surface like a secondary membrane. EDS analysis shows that inorganic elements such as Na, Mg, Si, P, S, Cl, K, and Ca in the mixed liquid were accumulated on the dynamic layer. Those elements have a positive impact for dynamic membrane formation as they have neutralization and bridging effect.
- Permeates obtained from fourth, fifth and sixth experimental studies operated with municipal wastewater was compared with the irrigation water criteria. Whereas good and medium quality irrigation water was obtained for many parameters in the fifth and sixth experimental studies, poor quality irrigation water obtained in the fourth experimental study. The main reason for this situation is that high strength municipal wastewater is used in fourth study compared to the fifth and sixth studies and DMBR system is ineffective for ion removal.
- Textile membrane support material MBTF was used either with microfiltration membranes or as a double layer alone in experimental studies. High removal efficiencies were obtained in all series. One of the most important results of this research is that high removal efficiencies and effective solid-liquid separation can be achieved with the dynamic layer formed on the textile membrane support material without using polymeric membranes. Consequently, membrane cost of MBR systems may be reduced and wastewaters can be treated in a cost effective way.

## 5.2 Recommendations

Many good experimental findings were obtained in terms of operation of the DMBR systems in the studies conducted within this thesis. The following studies can be done in order to improve DMBR systems:

- Long-term operations can be realized with different membrane support materials or configurations to determine the most suitable material.
- Anaerobic and anoxic tanks can be added before the aerobic DMBR system to achieve high nutrient removal. In addition, the presence of anaerobic tank may increase sulfate removal.
- Additional nanofiltration or reverse osmosis systems can be included after DMBR to obtain better irrigation water.
- Energy consumption and operating cost are the most important criteria in wastewater treatment. Operation cost can be dropped by optimization of energy consumption. Detailed studies should be carried out to reveal the energy needs of DMBR systems within this framework.

## REFERENCES

- Al-Malack, M.H. (2006). Determination of biokinetic coefficients of an immersed membrane bioreactor. *Journal of Membrane Science*, 217, 47-58.
- An, Y., Wu, B., Wong, F. S., & Yang, F. (2010). Post-treatment of upflow anaerobic sludge blanket effluent by combining the membrane filtration process : fouling control by intermittent permeation and air sparging. *Water and Environment Journal*, 24 (1), 32–38.
- APHA (2005) *Standard methods for the examination of water and wastewater* (21st ed.). Washington DC: American Public Health Association.
- Azami, H., Sarrafzadeh, M., & Mehrnia, M. H. (2011). Influence of sludge rheological properties on the membrane fouling in submerged membrane bioreactor. *Desalination and Water Treatment*, 34, 117-122.
- Buer, T., & Cumin, J. (2010). MBR module design and operation. *Desalination*, 250 (3), 1073–1077.
- Cai, D., Huang, J., Liu, G., Li, M., Yu, Y., & Meng, F. (2018). Effect of support material pore size on the filtration behavior of dynamic membrane bioreactor. *Bioresource Technology*, 255, 359–363.
- Clouzot, L., Roche, N., & Marrot, B. (2011). Effect of membrane configurations on sludge structure and microbial activity. *Biosource Technology*, 102 (2), 975-981.
- Cinar, O., Kizilet, A., Isik, O., Cemanovic, A., Veral, Mehmet A., & Duman, S. (2016). A review on dynamic membrane bioreactors : comparison of membrane bioreactors and different support materials, transmembrane pressure. *ICENS International Conference on Engineering and Natural Sciences*, May, 2505–2513.

- Du, X., Shi, Y., Jegatheesan, V., & Ulhaq, I. (2020). A review on the mechanism, impacts and control methods of membrane fouling in MBR system. *Membranes* 10 (2), 24.
- Ersahin, M. E., Ozgun, H., Dereli, R. K., Ozturk, I., Roest, K., & van Lier, J. B. (2012). A review on dynamic membrane filtration: materials, applications and future perspectives. *Bioresource Technology*, 122, 196–206.
- European Commission (2020). *Regulation of the european parliament and the council of 25 May 2020 on minimum requirements for water reuse*. Luxembourg: Official Journal of the European Union.
- Ezugbe, E. O., & Rathilal, S. (2020). Membrane technologies in wastewater treatment: a review. *Membranes*, 10 (5), 89.
- Fan, B., & Huang, X. (2002). Characteristics of a self-forming dynamic membrane coupled with a bioreactor for municipal wastewater treatment. *Environmental Science and Technology*, 36 (23), 5245–5251.
- Fazili, N.J., Hacifazlioglu, M.C., Parlar, I., Kabay, N., Pek, T.O., & Yuksel, M. (2018). Evaluation of MBR treated industrial wastewater quality before and after desalination by NF and RO processes or agricultural reuse. *Journal of Water Process Engineering*, 22, 103-108.
- Hadei M., Aalipour M., Fatehizadeh A., Safavi H.R, Ghasemian M., Sahbaei A.R, et al. (2015). Determination of biokinetic coefficients for an adsorption/bio-oxidation process on municipal wastewater in pilot-scale. *International Journal of Environmental Health Engineering*, 4 (35), 1-6.

- Hankins, N. P., & Singh, R. (2016). *Emerging membrane technology for sustainable water treatment*. Oxford: Elsevier.
- Hu, Y., Wang, X. C., Ngo, H. H., Sun, Q., & Yang, Y. (2018). Anaerobic dynamic membrane bioreactor (AnDMBR) for wastewater treatment: a review. *Bioresource Technology*, 247, 1107–1118.
- Hu, Y., Wang, X. C., Sun, Q., Ngo, H. H., Yu, Z., & Tang, J., et al. (2017). Characterization of a hybrid powdered activated carbon-dynamic membrane bioreactor (PAC-DMBR) process with high flux by gravity flow: operational performance and sludge properties. *Bioresource Technology*, 223, 65–73.
- Hu, Y., Wang, X. C., Tian, W., Ngo, H. H., & Chen, R. (2016). Towards stable operation of a dynamic membrane bioreactor (DMBR): operational process, behavior and retention effect of dynamic membrane. *Journal of Membrane Science*, 498, 20–29.
- Huang, X., Xiao, K., & Shen, Y. (2010). Recent advances in membrane bioreactor technology for wastewater treatment in China. *Frontiers of Environmental Science and Engineering in China*, 4 (3), 245–271.
- Iorhemen, O. T., Hamza, R. A., & Tay, J. H. (2016). Membrane bioreactor (mbr) technology for wastewater treatment and reclamation: membrane fouling. *Membranes*, 6 (2), 13–16.
- Isik, O., Abdelrahman, A. M., Ozgun, H., Ersahin, M. E., Demir, I., & Koyuncu, I. (2019). Comparative evaluation of ultrafiltration and dynamic membranes in an aerobic membrane bioreactor for municipal wastewater treatment. *Environmental Science and Pollution Research*, 26 (32), 32723–32733.

- Jadhao, R. K., & Dawande, S. D. (2012). A review on application of membrane bioreactor for wastewater treatment. *International Journal of Biotechnology, Chemical & Environmental Engineering (IJBCEE)*, 1 (2), 46-54.
- Jawaid M., & Khan M.M. (2018) *Polymer-based nanocomposites for energy and environmental applications*. Woodhead: Elsevier.
- Jeison D. (2007). *Anaerobic membrane bioreactor for wastewater treatment feasibility and potential application*. PhD Thesis, Wageningen University, Wageningen.
- Judd, S. (2011). *The MBR book* (2th ed.). Oxford: Elsevier.
- Katz, S., Owerdieck, C., & Arntsen, B. (2017). What is membrane bioreactor technology's role in water reuse? *Opflow*, 43 (5), 20–23.
- Kizilet, A., Veral, M. A., Cemanović, A., Isik, O., & Bahramian, M. (2017). The use of membrane processes to promote sustainable environmental protection practices. *European Journal of Sustainable Development Research*, 2 (1), 17–22.
- Kootenaei, F. G., & Aminirad, H. (2014). Membrane biological reactors (MBR) and their applications for water reuse. *International Journal of Advanced Biological and Biomedical Research*, 2 (7), 2208–2216.
- Koros, W. J., Ma, Y. H., & Shimidzu, T. (1996). Terminology for membranes. *Pure and Applied Chemicals*, 68 (7), 1479–1489.
- Le-Clech, P. (2010). Membrane bioreactors and their uses in wastewater treatments. *Applied Microbiology and Biotechnology*, 88 (6), 1253–1260.
- Le, P., Jefferson, B., Soung, I., & Judd, S. (2003). *Critical flux determination by the flux-step method in a submerged membrane bioreactor*. 227 (1), 81–93.

- Li, J., Garry, K., Neu, T., He, M., Lindenblatt, C., & Horn, H. (2007). Comparison of some characteristics of aerobic granules and sludge flocs from sequencing batch reactors. *Water Science and Technology*, 55 (8), 403–411.
- Li, L., Xu, G., & Yu, H. (2018). Dynamic membrane filtration: formation, filtration, cleaning, and applications. *Chemical Engineering and Technology*, 41 (1), 7–18.
- Li, L., Xu, G., Yu, H., & Xing, J. (2018). Dynamic membrane for micro-particle removal in wastewater treatment: Performance and influencing factors. *Science of the Total Environment*, 627, 332–340.
- Mardani, S.H., Mirbagheri, A., Amin M.M, & Ghasemian, M. (2011). Determination of biokinetic coefficients for sludge processes on municipal wastewater. *Iran Journal of Environmental Health Science Engineering*, 1, 25-34.
- Melin, T., Jefferson, B., Bixio, D., Thoeye, C., De Wilde, W., De Koning, J., et al. (2006). Membrane bioreactor technology for wastewater treatment and reuse. *Desalination*, 187 (3), 271–282.
- Mohan, S. M., & Nagalakshmi, S. (2020). A review on aerobic self-forming dynamic membrane bioreactor: formation, performance, fouling and cleaning. *Journal of Water Process Engineering*, 37, 101541.
- Mulder, M. (1996). *Basic principles of membrane technology*. Dordrecht: Kluwer Academic Publishers.
- Official Gazette (2010). *Wastewater treatment plants technical procedures communiqué (No: 27527, 20.3.2020)*. Retrieved December 2, 2020 from <https://www.mevzuat.gov.tr/mevzuat?MevzuatNo=13873&MevzuatTur=9&MevzuatTertip=5>

- Park, H. D., Chang, I. S., & Lee, K. J. (2015). *Principles of membrane bioreactors for wastewater treatment*. Boca Raton: CRC Press.
- Racar, M., Dolar, D., Karadakic, K., Cavarovic, N., Glumac, N., Asperger, D., et al. (2020). Challenges of municipal wastewater reclamation for irrigation by MBR and NF/RO: Physico-chemical and microbiological parameters and emerging contaminants. *Science of the Total Environment*, 722, 25-32.
- Ren, X., Shon, H. K., Jang, N., Lee, Y. G., Bae, M., Lee, J., et al. (2010). Novel membrane bioreactor (MBR) coupled with a nonwoven fabric filter for household wastewater treatment. *Water Research*, 44 (3), 751–760.
- Santos, A., Ma, W., & Judd, S. (2011). Membrane bioreactors: Two decades of research and implementation. *Desalination*, 273 (1), 148–154.
- Serpil M.H. (2019). *Mezbaha atıksularının membran biyoreaktör (MBR) sistemi ile arıtılmasının incelenmesi*. MSc Thesis, Balıkesir University, Balıkesir.
- Shen, Y., Xiao, K., Liang, P., Sun, J., Sai, S., & Huang, X. (2012). Characterization of soluble microbial products in 10 large-scale membrane bioreactors for municipal wastewater treatment in China. *Journal of Membrane Science*, 415, 336–345.
- Singh, R. (2005). *Hybrid membrane systems for water purification: technology, systems design and operation*. Oxford: Elsevier.
- Tchobanoglous, G., Stensel, H., Tsuchihashi, R., & Burton, F. (2013) *Metcalf & Eddy, Inc. wastewater engineering: treatment and reuse* (5th ed.). Boston: McGraw-Hill.
- The World Bank (2020). *Water in agriculture*. Retrieved September 12, 2020, from <https://www.worldbank.org/en/topic/water-in-agriculture>

- UNESCO, UN-Water, (2020). *United nations world water development report 2020: water and climate change*. Paris: UNESCO.
- Veral, M.A., Kizilet, A., & Cinar, O. (2017). Comparison of performance of conventional membrane bioreactor with dynamic membrane bioreactor. *EJENS*, 2, 21–28.
- Veral, M.A, Cinar, O., & Kizilet, A. (2020). Membrane bioreactor and dynamic membrane bioreactor performance comparison under the same conditions. *European Journal of Science and Technology*, 18, 30–41.
- Wang, Y. K., Sheng, G. P., Li, W. W., & Yu, H. Q. (2012). A pilot investigation into membrane bioreactor using mesh filter for treating low-strength municipal wastewater. *Bioresource Technology*, 122, 17–21.
- Wenten, I. G., & Khoiruddin. (2016). Reverse osmosis applications: prospect and challenges. *Desalination*, 391, 112–125.
- WHO, (2006). *Wastewater use in agriculture: guidelines for the safe use of wastewater, excreta and greywater*. Geneva: WHO press.
- Xiao, Y., Chen, T., Hu, Y., Wang, D., Han, Y., Lin, Y., & Wang, X. (2014). Advanced treatment of semiconductor wastewater by combined MBR-RO technology. *Desalination*, 336 (1), 168–178.
- Yang, T., Liu, F., Xiong, H., Yang, Q., Chen, F., & Zhan, C. (2019). Fouling process and anti-fouling mechanisms of dynamic membrane assisted by photocatalytic oxidation under sub-critical fluxes. *Chinese Journal of Chemical Engineering*, 27 (8), 1798–1806.

- Yigit, N. O., Civelekoglu, G., Harman, I., Koseoglu, H., & Kitis, M. (2009). Effects of various backwash scenarios on membrane fouling in a membrane bioreactor. *DES*, 237 (1–3), 346–356.
- Yu, Z., Hu, Y., Dzakpasu, M., & Wang, X. C. (2019). Thermodynamic prediction and experimental investigation of short-term dynamic membrane formation in dynamic membrane bioreactors: Effects of sludge properties. *Journal of Environmental Sciences (China)*, 77, 85–96.
- Yu, Z., Hu, Y., Dzakpasu, M., Wang, X. C., & Ngo, H. H. (2019). Dynamic membrane bioreactor performance enhancement by powdered activated carbon addition: Evaluation of sludge morphological, aggregative and microbial properties. *Journal of Environmental Sciences (China)*, 75, 73–83.
- Yurtsever, A., Basaran, E., Ucar, D., & Sahinkaya, E. (2020). Self-forming dynamic membrane bioreactor for textile industry wastewater treatment. *Science of The Total Environment*, 751, 141572.
- Zaman M., Shahid S.A., Heng L. (2018). *Guideline for salinity assessment, mitigation and adaptation using nuclear and related techniques*. Cham: Springer.
- Zhu, Y., Cao, L., & Wang, Y. (2019). Characteristics of a self-forming dynamic membrane coupled with a bioreactor in application of anammox processes. *Environmental Science and Technology*, 53 (22), 13158–13167.