DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

TEMPERATURE EFFECTS ON THE PERFORMANCE OF AN ANAEROBIC MEMBRANE BIOREACTOR

by
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İZMİR

TEMPERATURE EFFECTS ON THE PERFORMANCE OF AN ANAEROBIC MEMBRANE BIOREACTOR

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Gökçe PEHLİVANER

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İZMİR

M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"TEMPERATURE EFFECTS ON THE PERFORMANCE OF AN ANAEROBIC MEMBRANE BIOREACTOR"** completed by **GÖKÇE PEHLİVANER** under supervision of **PROF. DR. NURDAN BÜYÜKKAMACI** 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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Gökçe PEHLİVANER

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ABSTRACT

Temperature is the one of the most significant parameter which affects the efficiency of the biological reactors. Treatment efficiency is usually higher in anaerobic biological systems operated at high temperatures. Especially, removal of organic matters under mesophilic conditions is much more than according to the psychrophilic conditions. However, heating the anaerobic reactors requires energy and it causes high operating costs.

In membrane systems, increasing temperature decreases the viscosity and increase of the flux becomes at high temperatures. Thermophilic systems could be accepted more advantageous because increase of the flux is a preferred situation in membrane operating. However, increase of the temperature can change the anaerobic biological reactor as qualification and quantity.

Operating a laboratory scale anaerobic membrane bioreactor at different temperatures and determining how operating temperature affect the system efficiency are the main purpose of this study. A laboratory scale side-stream anaerobic membrane bioreactor was operated under mesophilic and thermophilic conditions for this aim. The model reactor was consisted of an anaerobic bioreactor (UASB) connected to a membrane module (UF). Synthetic wastewater consisted of diluted molasses was used in this study. The anaerobic reactor was operated in two influent COD concentrations as 5,000 and 10,000 milligram per liter at both mesophilic and thermophilic conditions. Efficiency in the system was examined that considering the COD removal and methane formation parameters. Also, the effects of temperature alterations were determined on flux.

Keywords: Anaerobic, membrane, bioreactor, temperature

ANAERОBİK BİYOMEMBRAN REAKTÖRLERİN VERİMİ ÜZERİNE SICAKLIĞIN ETKİSİ

ÖZ

Biyolojik reaktörlerin verimini etkileyen en önemli faktörlerden birisi sıcaklıktır. Genel olarak yüksek sıcaklıklarda çalıştırılan anaerobik biyolojik sistemlerde arıtma verimi daha yüksektir. Özellikle mezofilik sıcaklıklarda elde edilen organik madde giderimi psikofilik sıcaklık koşullarına göre çok daha fazla olmaktadır. Ancak, anaerobik reaktörleri ısıtmak için harcanan enerji dolayısıyla işletim maliyetinin azaltılması için düşük sıcaklıklarda sistemlerin işletilmesi tercih edilmektedir.

Membran sistemlerde ise, sıcaklığın artışı viskoziteyi düşürdüğü için yüksek sıcaklıklarda akı artışı meydana gelmektedir. Akı artışı, membran işletiminde istenen bir durum olduğu için termofilik sistemler daha avantajlı olarak düşünülebilir. Ancak, sıcaklığın artışı anaerobik biyolojik reaktördeki mikroorganizma kütlesinin niteliğinde ve niceliğinde değişime sebep olacağından, sıcaklık artışı membranın verimini olumsuz olarak da etkileyebilir.

Bu tez çalışmasında, laboratuvar ölçekli anaerobik membran biyoreaktör sistemi mezofilik ve termofilik sıcaklıklarda çalıştırılarak, sıcaklığın sistem verimine olan etkilerinin belirlenmesi amaçlanmıştır. Model reaktör, yukarı akışlı çamur yataklı anaerobik (UASB) reaktör olarak tasarlanmış bir anaerobik reaktör ve ultrafiltrasyon (UF) membran sisteminden oluşturulmuştur. Sistem, KOİ konsantrasyonu litrede 5.000 ve 10.000 miligram olacak şekilde seyreltilen melastan hazırlanan sentetik su ile çalıştırılmıştır. Sistemdeki verim KOİ giderimi ve metan gazı oluşumu parametreleri dikkate alınarak incelenmiş, ayrıca sıcaklıktaki değişimin membran akısı üzerindeki etkileri de belirlenmiştir.

Anahtar kelimeler: Anaerobik, membran, biyoreaktör, sıcaklık

CONTENTS

Page

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Anaerobic wastewater treatment is one of the most widely used wastewater treatment technology due to main advantages and it is one of the most investigated treatment category in recent years. Technological developments were increased the advantages of anaerobic treatment which is known for ages and found in nature by itself. Based on the biogas formation, energy production occurs instead of energy consumption. The anaerobic systems require much less area compared to aerobic systems. Less nutrient demand and less excess sludge formation are other advantages of anaerobic systems. Also, effluent is disinfected partially from the pathogens.

In recent years, applications of membrane technologies have been very popular. Shocking developments has observed in polymer technology for recent years and it is affected the membrane technology. Microfiltration and ultrafiltration membrane processes has become competitive with conventional systems for potable water and wastewater treatment from the point of costs because of reducing the production cost of membranes. In addition, utilization of biological systems and membrane systems together, which is called as membrane bioreactors (MBR), has become widespread. It has several advantages comparing to conventional treatment systems, such high effluent quality, less are requirement, less sludge production, high pathogen removal, etc. (sourcing.indiamart.com). Therefore, MBRs used for wastewater treatment has improved and started to operate globally.

MBR systems are commonly operated as the combination of aerobic biological treatment, especially activated sludge system, and membrane unit, microfiltration or ultrafiltration. However, anaerobic biological systems have also been used with membrane unit in combination and this type of reactor is known as "anaerobic membrane bioreactors (AnMBR)". Anaerobic membrane bioreactors are usually implemented for industrial wastewater treatment.

Anaerobic membrane bioreactor (AnMBR) is consisted of an anaerobic bioreactor and membrane separation unit. Membrane applications provide biomass retention and this allows complete biomass retention in the anaerobic reactor. Keeping sufficient amount of active biomass in anaerobic reactor improves the efficiency of AnMBR systems. Membrane separation unit separates solids from the bioreactor and recycle them to the digester (Pillay, Townsend, & Buckley, 1994). AnMBRs are expected to provide more efficient digestion, higher methane production, and better effluent quality, and can be smaller in size than conventional anaerobic digesters. By far most of the AnMBRs have designed in CSTR configuration (Padmasiri et al., 2007, Choo and Lee, 1996, Zhang et al., 2007). However, membranes have been applied with other types of anaerobic reactors, such as up-flow anaerobic sludge bed reactor (UASB), anaerobic fixed bed reactor (Salazar-Pelaez, Morgan-Sagastume, & Noyola, 2011, and Herrera-Robledo, Cid-León, Morgan-Sagastume, & Noyola, 2011).

Anaerobic treatment is affected various factors and one of them is temperature. Anaerobic processes can be operated at psychrophilic, mesophilic, and thermophilic conditions. Among them, mesophilic conditions are most commonly preferred. Domestic and industrial wastewaters are generally discharged at low temperatures because of mild or cold climate dominate to more than half of the earth. Wastewater is heated to provide treatment at mesophilic and thermophilic operation conditions and heating increases the operating costs. However some industrial wastewater effluents are hot and in this case thermophilic reactor application are more reasonable.

Temperature is also one of the most significant operating parameters of membrane systems. In membrane systems, higher flux values can be obtained at higher temperature because viscosity decreases at high temperatures. Another impact of the temperature is scaling on the membrane surface. Scaling increases with increasing temperature because of the solubility of some scalants decreases.

Since temperature affects both anaerobic systems and membrane units operation this parameter also very important for anaerobic membrane bioreactor operation. In the literature there are limited studies about the evaluation of temperature affects on anaerobic membrane bioreactors, especially for the thermophilic conditions.

In the scope of this study, investigation of the temperature affects on anaerobic membrane bioreactors was aimed. For this purpose, a laboratory scale anaerobic membrane bioreactor (AnMBR) was operated at mesophilic and thermophilic conditions. The model reactor was consisted of an up-flow anaerobic sludge bed reactor (UASB) and ultrafiltration (UF) membrane system. AnMBR was operated at 37 °C and 55 °C for the influent COD concentrations of 5,000 mg/L and 10,000 mg/L. System performance was evaluated on the basis of organic material reduction and biogas production.

CHAPTER TWO

AN OVERVIEW OF AN ANAEROBIC MEMBRANE BIOREACTOR SYSTEM

2.1 Introduction

Membrane bioreactor (MBR) is the most efficient and advanced biological treatment available. Membrane bioreactor is the combination of two basic processes, biological degradation and membrane separation. These two processes are combined into a single process where microorganisms and suspended solids are separated from the treated water by membrane filtration unit. The membrane filtration is based on ultra or microfiltration, and it separates biomass from water. The MBR systems produce superior quality effluents, solids free and up to 99% reduction of organic pollution, in a compact and efficient system (sourcing.indiamart.com).

MBR combines activated sludge process with a membrane liquid-solid separation process. The membrane unit uses the low pressure microfiltration or ultrafiltration membranes and eradicates the need for clarification and tertiary filtration. The membranes are plunged in the aeration tank (internal, submerged); however some applications utilize a separate membrane tank (external, side-stream). The key advantage of a membrane bioreactor system is that it effectively overcomes the restrictions associated with ineffective settling of sludge in conventional activated sludge processes (sourcing.indiamart.com). Membrane bioreactors are used for biological treatment of water from municipal, commercial and industrial sources. Also, they are used for water reuse applications. Schematic diagram of membrane bioreactor systems is given in Figure 2.1.

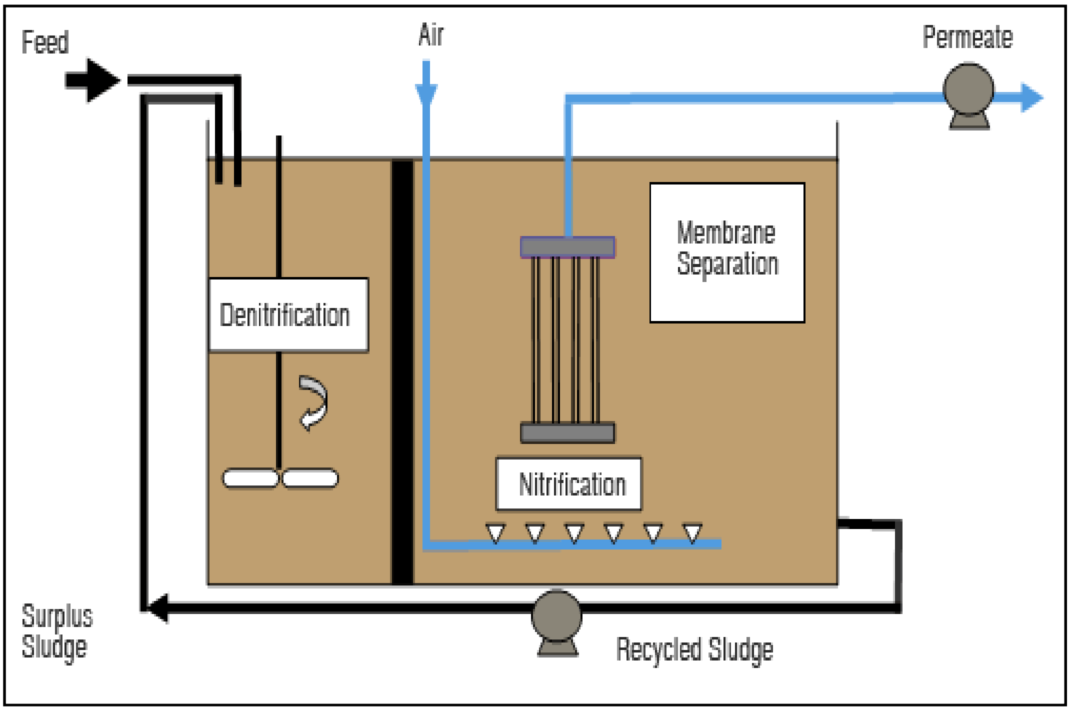

Figure 2.1 Schematic diagram of membrane bioreactor systems (United Environtech Ltd., Membrane Bioreactor (MBR)).

There are numerous advantages of membrane bioreactors over other treatment technologies. They are as follows:

- MBR provides enhanced quality of treated water.
- It requires less space for operation however for module-based design its capacity can be expanded if the situation demanded.
- It is a sustainable technology and is cost effective.
- As these bioreactors use membrane hence it does not require any settling tank.
- Using MBR, hydraulic retention time (HRT) and suspended solids retention time (SRT) can be separated thereby controlling the biological reactions.
- Water so treated contains no suspended solids and micro-organisms.
- Process operation is stable (sourcing.indiamart.com).

In spite of membrane biological reactors have lots of advantages, they also have some disadvantages. They are:

- For municipal applications, the MBR technology is usually related to a higher total life cost, due to the high energy cost.
- Fouling and the replacement costs of the membrane remains an important limiting factor to its broad application (sourcing.indiamart.com).

In case of an anaerobic bioreactor supplemented with a membrane separation unit, this type of reactor is termed as the anaerobic membrane bioreactor (AnMBR). To maintain sufficient amount of active biomass in the bioreactor is significant to improve the efficiency of these systems. Membrane separation techniques afford an effective method to separate solids from the digester suspension and recycle them to the digester (Pillay, Townsend, & Buckley, 1994). Thus, AnMBRs are expected to provide more efficient digestion, higher methane production, and better effluent quality, and can be smaller in size than conventional anaerobic digesters (Padmasiri et al., 2007). Schematic presentation of anaerobic membrane bioreactor system is given in Figure 2.2.

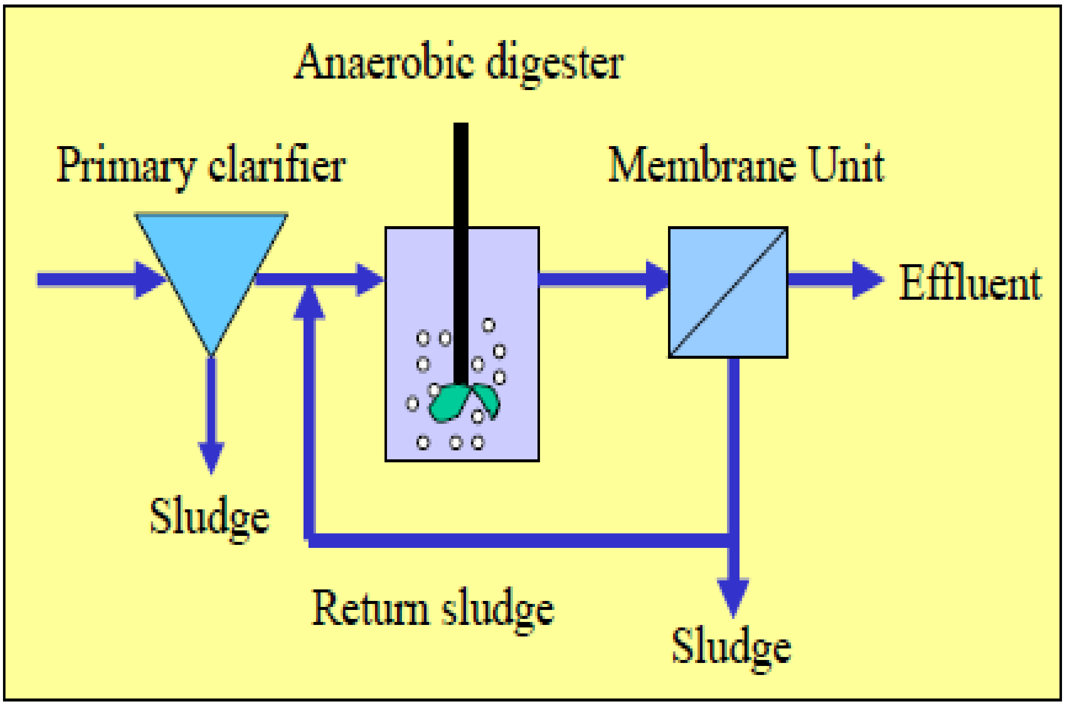

Figure 2.2 Schematic presentation of anaerobic membrane bioreactor system (Ujang, 2003).

2.2 Application of AnMBR Systems

The production of biogas and its using potential as a source of energy is one of the most important advantage of anaerobic treatment. Anaerobic treatment is low costs, enable energy recovery, but does not achieve advanced treatment (low carbon removal, no nutrients removal). In contrary, membrane-based technologies, and especially MBR, enable advanced treatment (disinfection, but also low nutrients), but at high energy cost. If maximum energy recovery is desired, a single anaerobic process will be always superior to a combination with a membrane process. The combination of both can be economically viable only if a compact process for energy recovery is desired, or when disinfection is required after anaerobic treatment (cases of water reuse with nutrients) (www.mbr-network.eu).

Applications of membrane bioreactors (MBR) in wastewater treatment are becoming widespread. MBR systems are operated as the combination of aerobic biological treatment and membrane unit commonly. However, it is available that anaerobic biological treatment and membrane unit can be operated as a combination. Anaerobic membrane bioreactors are usually implemented for industrial wastewater treatment.

AnMBRs can be preferred to treat wastewater which appropriates to anaerobic treatment. It is possible to treat very strong, concentrated wastes, solid and semi-solid wastes and slurries, wastewaters with poor settling characteristics, including; distilleries, wineries (wastewater and pomace), fuel and food-grade ethanol production stillages, syrup and spent grains, food processing wastewaters, chemicals production and biomass digestion for energy production (www.adi.ca). On the other hand, it is possible to treat domestic wastewaters (Smith, Stadler, Love, Skerlos, & Raskin, 2012) or low strength domestic wastewaters (Yoo, Kim, McCarty, & Bae, 2012) with AnMBRs.

2.3 Design and Operating Parameters of AnMBR Systems

Membrane bioreactors are consisted of three parts which are membrane separation bioreactors, membrane aeration bioreactors and extractive membrane bioreactors. Membrane separation bioreactors could be submerged or side-stream. In submerged systems, membrane unit is placed in bioreactor. In side-stream systems, membrane unit is placed after bioreactor and the membrane unit acts as a final clarifier. Side-stream systems could be aerobic or anaerobic. Membrane unit is placed in bioreactor and influent and oxygen are given to the bioreactor in membrane aeration bioreactors. Similarly, the membrane unit is found inside the bioreactor in extractive membrane bioreactors (Ujang, 2003). Schematic diagram of submerged and side-stream membrane bioreactors are given in Figure 2.3 and Figure 2.4, respectively.

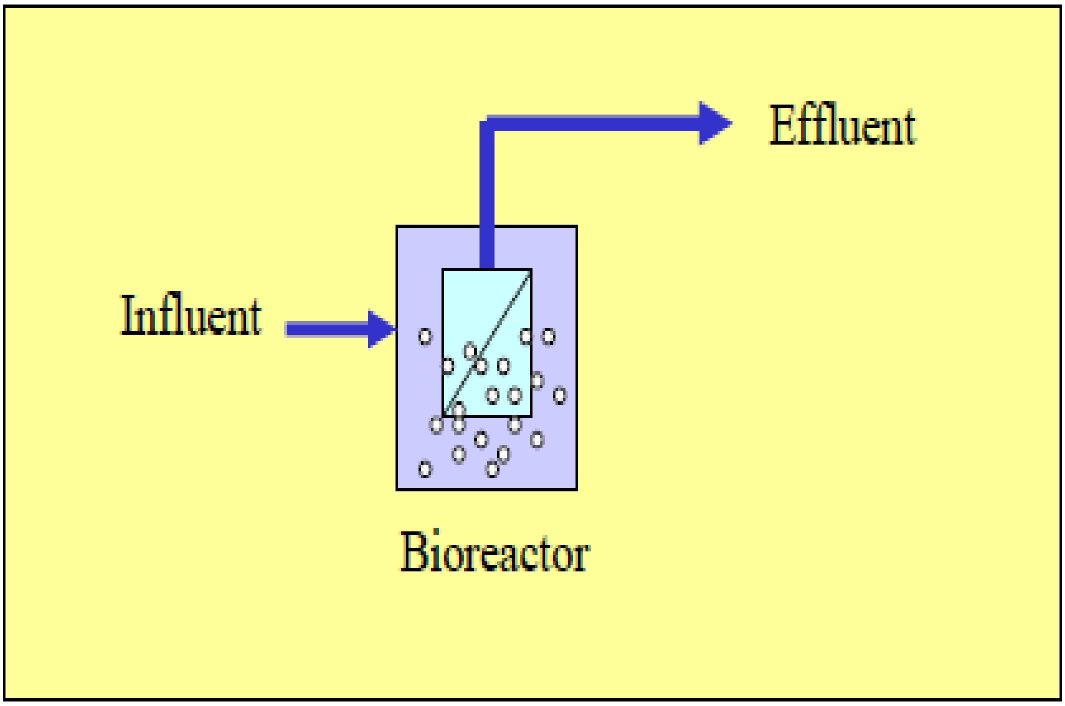

Figure 2.3 Schematic diagram of submerged membrane bioreactors (Ujang, 2003).

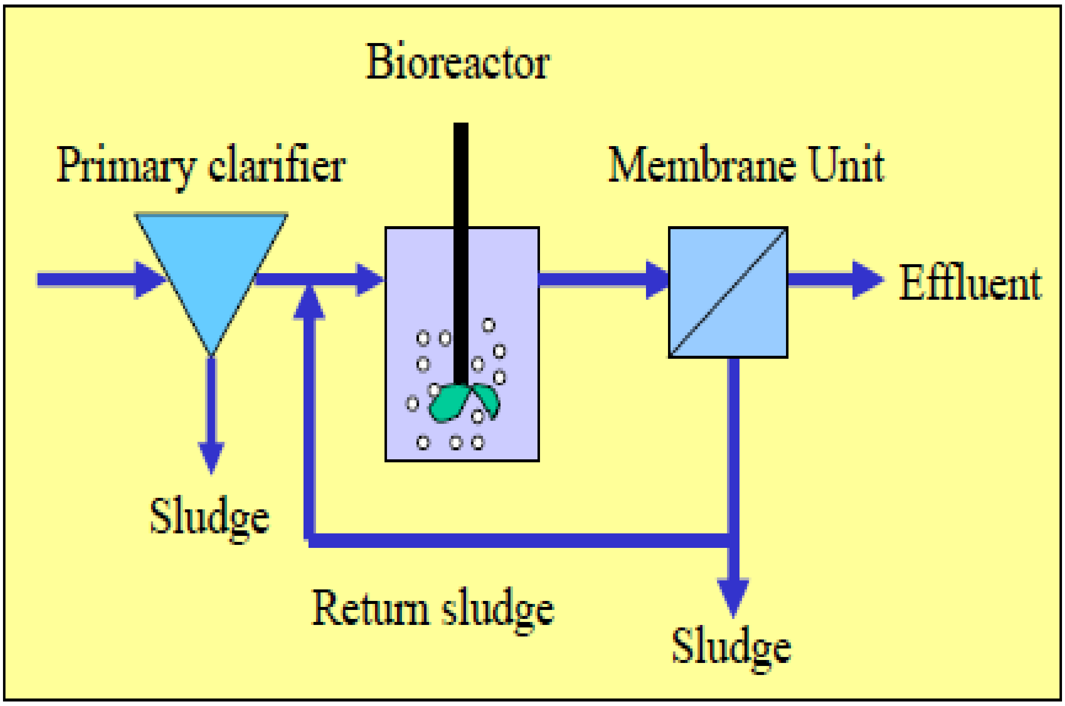

Figure 2.4 Schematic diagram of side-stream membrane bioreactors (Ujang, 2003).

Organic loading rate is the one of the most important design parameters of MBR systems. Organic loading rates are changed between 1.2 to 3.2 kg COD/m^3.d and 0.05 to 0.66 kg BOD/m^3.d for organic removal which exceeds 90%. Loading rates for complete nitrification is 0.05 to 0.66 kg BOD/m^3.d and sludge age is between 10 to 50 days. Loading rate for complete nitrogen removal is 4 kg NH_4-N/m^3.d and 5 kg NO_3-N/m^3.d. MLSS, flux and specific flux are ranging between 10,000 to 20,000 mg/L, 5 to 300 L/m^2.h and 20 to 200 L/m^2.h.bar, respectively (Ujang, 2003).

In the literature, different organic loading rate applications for anaerobic MBR could be seen. For example, Anderson et al. (1986) were operated side-stream MBR in acidogenic phase and 54 kg COD/m^3.d of loading rate was applied. Loading rate was decreased to 12.2 kg COD/m^3.d when the system was operated methanogenic phase. Li et al. (1985) and Kayawake et al. (1991) were applied the organic loading rate as 15 kg COD/m^3.d for submerged MBR (Ujang, 2003).

HRT was taken 19.2 hours and the COD removal rate reached to 90% for anaerobic submerged membrane bioreactor treating municipal wastewater (Martinez-Sosa et al., 2011). HRT and SRT were taken 1.5 days and 30 days, respectively and the COD removal rate was measured as 95% for submerged AnMBR treating municipal solid waste leachate (Trzcinski & Stuckey, 2010). The COD removal rate was tested as 99% when HRT was taken between 4.2 and 5.9 hours for anaerobic fluidized bed membrane bioreactor treating synthetic wastewater (Kim et al., 2011).

Membrane fouling is another significant item for operation of MBR systems. There are several studies related to fouling mechanism and the management of the fouling in the literature. Zhang et al. (2007) evaluated the membrane fouling in a side stream anaerobic membrane bioreactor operated for the treatment of swine manure. They operated the system under low transmembrane pressure (20–70 kPa) and low flux (5–10 L/m^2 h) for a period of 135 days without membrane cleaning. In another study, ultrasound was applied to the control of membrane fouling development on-line in an anaerobic membrane bioreactor. They found that the ultrasonic irradiation can control the membrane fouling (Sui, Wen, & Huang, 2008). Huang, Ong, & Ng (2011) investigated the effect of HRT and SRT on membrane fouling for submerged anaerobic membrane bioreactor for low-strength wastewater treatment.

CHAPTER THREE
LITERATURE REVIEW

3.1 Temperature Effects on Biodegradation

Biodegradation reactions were carried out by enzymes. Enzymes are protein-based biological catalysts. Every biological conversion is catalysed by a specific enzyme. Enzymatic reactions' rate increases to a definite point by temperature (activation). However, from this point, the rate decreases with the temperature rise (inactivation). Therefore, the rate becomes to maximum level in an optimum temperature interval. Activation energy and inactivation energy of enzymatic reactions are 5-20 kcal/g mole and 40-130 kcal/g mole, respectively. Inactivation of enzymes becomes faster than activation. When the temperature increases from 30 °C to 40 °C, activity of enzymes increases to 1.8 times. However, inactivation increases 41 times. Temperature affects the maximum rate of reaction as well as dissociation constant of enzyme-substrate complex (Kargı, 2006).

Organisms are consisted of three groups according to temperature intervals. Psychrophilics which grow at low-temperatures (T<20 °C), mesophilics which can grow best in moderate temperature, typically about 35±2 °C, and thermophilics which grow at relatively high temperatures (T>50 °C). There is an optimum temperature interval for every organism. Until the optimum temperature, growing rate doubles approximately increase of every 10 °C. Over the optimum temperature, the growing rate increases with the temperature rise and death can occur. Growing and death activation energies are 10-20 kcal/mole and 60-80 kcal/mole, respectively. Death is more affected from temperature alterations. Temperature also affects metabolism and efficiency of the cell (Kargı, 2006).

It was studied to assimilate betaine in the temperature range of 27–63 °C at pH of 6.5 and 8.0, using a mixed culture of bacteria of the genus *Bacillus*. Betaine was assimilated at 27–54 °C and the pH of 8.0, as well as at 27–45 °C and the pH of 6.5. A high BOD_5 removal was achieved when betaine was assimilated. BOD_5 removal was exceeded 99.40% over the temperature range of 27–45 °C at the pH of 8.0, as well as at 27 °C and the pH of 6.5. Maximum COD removal was attained as 88.73% at 36 °C and the pH of 6.5 (Cibis, Ryznar-Luty, Krzywonos, Lutosławski, & Miśkiewicz, 2011).

Zhao, Selvam, & Woon-Chung Wong (2011) investigated the synergistic effect of temperature and biosurfactant on the biodegradation of phenanthrene in bioslurry. Experiments were conducted at 25 and 55 °C. The desorption rate coefficients of phenanthrene (K_{des}) were 0.0026 and 0.0035 kg/mg.h at 25 and 55 °C, respectively. Addition of 1,500 mg/L biosurfactant, marginally increased the K_{des} at 25 °C; however, significantly increased the K_{des} to 0.0087 kg/mg.h at 55 °C. That means K_{des} was increased almost 2.5 times. About 78.7% of phenanthrene was degraded in 30 days at 25 °C and addition of biosurfactant did not affect the biodegradation. However, addition of the biosurfactant at 55 °C significantly enhanced the biodegradation by increasing the K_{des}.

The effect of temperature on the extent of aerobic batch biodegradation of potato stillage with a mixed culture of bacteria of the genus *Bacillus* was investigated in another study. The experiments were performed in a 5-l stirred-tank reactor at 20, 30, 35, 40, 45, 50, 55, 60, 63 and 65 ºC with the pH of 7. No reduction in chemical oxygen demand (COD) was found to occur at 65 ºC. Over the temperature range of 20–63 ºC, the removal efficiency was very high. As a result of the study, the authors concluded that the organic pollution load was removed the fastest under typically mesophilic and slightly thermophilic conditions (Krzywonos, Cibis, Miśkiewicz, & Kent, 2008).

Temperature is also very important parameter for anaerobic degradation. The optimum ranges are the mesophilic and the thermophilic. Khanh, Quan, Zhang, Hira, & Furukawa (2011) investigated the feasibility of treating low-strength wastewater with an up-flow anaerobic sludge blanket (UASB) reactor, using a poly(vinyl alcohol)-gel carrier, at various temperatures. The temperature was decreased from 35 ºC to 15 ºC. The COD removal rate reached 28 kg COD m^3 d^{-1} at 35 ºC, 16 kg COD

m^3 d^{-1} at 25 ºC, and 6 kg COD m^3 d^{-1} at 15 ºC. The COD removal rate was reduced by 50% when the temperature was decreased by 10 ºC.

A comparison between the results of start-up at 25 ºC and 30 ºC for hybrid reactor confirms that a heating system to ensure at least a working temperature of 30 ºC is absolutely necessary to achieve both satisfactory COD removal rate and biogas productivity. According to conditions, specific biogas productivity at 30 ºC is 30-170% higher than that observed during the start-up at 25 ºC (Berardino, Bersi, Converti, & Rovatti, 1997).

3.2 Temperature Effects on Membrane Systems

In membrane bioreactors, temperature not only affects the biological process but is also shown to have an effect on the membrane performance (Van Den Brink et al., 2011). In membrane processes, many phenomena such as mass transfer, concentration polarization and membrane fouling are temperature dependent (Zhao & Zou, 2011). The effects of temperature on RO and nanofiltration membranes are the result of an increase in enthalpy of the system. Bonds within the membrane matrix are more relaxed, and salt molecules are more active at higher temperatures (≥25 ºC). Membrane manufacturers generally provide a table or formula for determining TCF (temperature correction factors). The TCF is proportional to the change in pressure needed to maintain the 25 ºC flux rate and is equal to 1.00 at 25 ºC. The TCF increases at temperatures less than 25 ºC and decreases at higher temperatures (www.usbr.gov).

In membrane systems, temperature rise reduces viscosity and flux is getting higher at high temperatures. Flux of a membrane is defined as the amount of permeate produced per unit area of membrane surface per unit time. The flux can be expressed as:

$$J = \frac{\Delta p}{\mu R_m}$$

Where, J: flux ($m^3/m^2.s$)

Δp: transmembrane pressure (Pa)

μ: fluid viscosity (Pa.s)

R_m: resistance of the membrane (m^{-1})

Because viscosity tends to decrease with increasing temperature, temperature has a significant impact upon the flux through the viscosity, which increases by around 3% for each degree drop in temperature below 25°C (Judd & Jefferson, 2003). The change in flux rate with temperature for polyamide membranes is shown in Figure 3.1 (www.membranes.com).

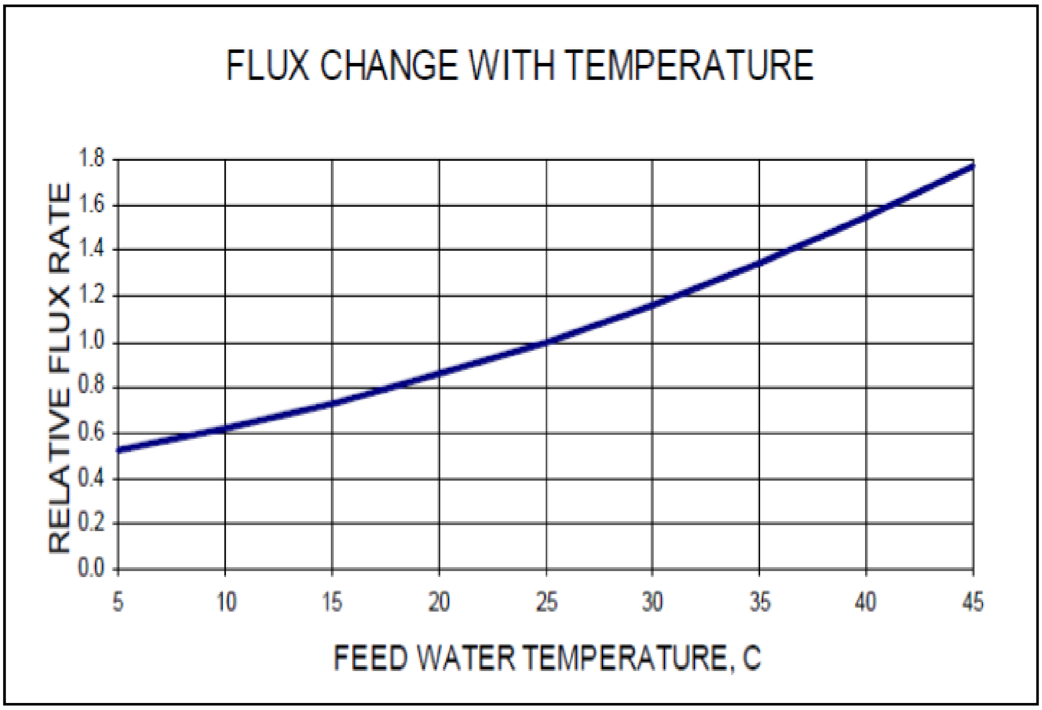

Figure 3.1 Flux changes depending on the feed water temperature.

Reverse osmosis is one of the most popular membrane processes and high pressure in excess of the osmotic pressure is applied for forcing a solvent from a region of high solute concentration through a semi-permeable membrane to a region of low solute concentration. Osmotic pressure arises when two solutions of different concentrations, or a pure solvent and a solution, are separated by a semi-permeable membrane. Molecules such as solvent molecules that can pass through the membrane will migrate from the side of higher concentration to the side of lower concentration in a process known as osmosis. The pressure required to stop osmosis is called the osmotic pressure. In dilute solutions, osmotic pressure (Π) is directly proportional to the molarity of the solution and its temperature in Kelvin. Osmotic pressure of a solution is related to its dissolved solute concentration and is calculated from van't Hoff equation (www.ausetute.com.au):

$$\Pi = MRT$$

Where:
Π = osmotic pressure (kPa)
M = molarity (mol/L)
R = ideal gas constant
T = temperature (K)

According to this equation, it can be seen that the osmotic pressure increases with the increase of temperature. Reverse osmosis elements tolerating operating temperatures up to 80° C have been developed and commercialized. Operating a reverse osmosis plant at temperatures in the 50° C to 80° C range reduces the risk of microorganism growth, which can cause severe fouling of the membrane surface. Low temperatures decrease membrane selectivity because of the higher osmotic pressure gradient and the lower mobility of ions at lower temperatures (www.usbr.gov).

Membrane scaling is one of the significant operation parameter. Scaling means the deposition of particles on a membrane, causing it to plug and it is especially caused by the precipitation of salts. Scaling is more severe with the increase of the operation temperature (Zhao & Zou, 2011). Nghiem and Cath (2011) examined the $CaSO_4$ scaling at the temperature of 20 ºC and 40 ºC. The researchers found that scaling increase depending on the size of the $CaSO_4$ crystals increased as the feed temperature increased.

To overcome from this problem, chemical cleaning is usually applied. In general acid are often used to remove precipitated salts or scalants. A silica scaling problem could be controlled by either raising the pH or the temperature of the feed water. Calcium carbonate, on the other hand, is more soluble at low temperatures and at a pH less than 8.0. A carbonate scaling problem can be relieved by lowering the pH or the temperature (www.membranes.com). The cleaning will be more intensive at higher water temperatures (30°C).

Required operating temperature changes also depending on the membrane structure. Most cellulosic and thin film composite membranes have maximum temperature limits of 40 to 45 ºC, which should be adequate for most surface and ground water sources (www.usbr.gov). Operation temperature of KUBOTA and TORAY membranes are between 5 – 40 ºC. KUBOTA mentions that for every degree centigrade increase in temperature there should be a 2% increase in the flux through the membranes.

It can be concluded that higher temperature would provide higher initial flux but also caused more severe scaling and more obvious flux decline depending on the scaling. So, optimum operation temperature should be applied to obtain maximum benefits.

3.3 Temperature Effects on Aerobic and Anaerobic MBR Systems

Temperature is one of the most affecting factor which affects efficiency of the biological reactors. Treatment efficiency is higher in anaerobic biological systems which are operated at higher temperatures usually. Under mesophilic conditions removal of organic matter is pretty much according to psychrophilic conditions. Anaerobic reactors must be heated and heating requires energy. To reduce the energy costs it is preferred to operate them under low temperatures. In membrane systems, temperature rise reduces viscosity and flux is getting higher at high temperatures. Increase of the flux is a preferred situation therefore thermophilic systems are considered more advantageous. But increase of the temperature can cause alteration for mass of the microorganisms in the anaerobic reactor as qualification and quantity. Therefore increase of the temperature could negatively affect the efficiency of the membrane. In the literature, there are several investigations to find out how temperature affects membrane performances.

A critical review of the current situation of the AnMBR technology was made. Bioreactors were mainly tested under mesophilic or thermophilic conditions. The application of thermophilic conditions allowed treating higher organic loading rates. Chemical oxygen demand removal efficiencies up to 99%, total suspended solids removal efficiencies up to 100% and complete removal of pathogens were reported. Good fuel quality biogas can be produced. Industrial scale AnMBRs is not reported but there are few cases at pilot scale. Membrane fouling is the key problem to solve before industrial implementation (Skouteris, Hermosilla, López, Negro, & Blanco, 2012).

Aerobic side-stream airlift membrane bioreactors (SA-MBRs) were compared for membrane fouling and removal efficiencies of COD, NH_4 and TKN under thermophilic (47 and 60 °C) and mesophilic (30 °C) conditions. These reactors were fed with high strength molasses-based synthetic wastewater at an organic loading rate (OLR) of 24.75 kg COD/m^3.day. The sidestream filtration was conducted with microfilter and ultrafilter. SA-MBRs with microfilter were operated in continuous and intermittent operation modes; while with the ultrafilter only continuous operation mode was employed. The excessive membrane fouling observed in thermophilic SA-MBRs with microfilter under continuous filtration mode. Fouling could be significantly reduced by the application of cake layer precoating or replacing microfilter with ultrafilter. This membrane fouling under the thermophilic condition could be linked to higher protein generation in the reactors. Soluble COD removal efficiencies were higher in thermophilic conditions while the sludge yields were significantly low in thermophilic SA-MBRs (Abeynayaka & Visvanathan, 2011).

Composition of the soluble fraction of the mixed liquor was related to membrane performance after exposing the sludge to temperature shocks. Flux step experiments were performed in an experimental system at 7, 15 and 25° C with sludge that was continuously recirculated from a pilot-scale MBR. After correcting the permeate viscosity for temperature, higher membrane fouling rates were obtained for a lower sludge temperature in combination with low fouling reversibility. The soluble fraction of the MBR mixed liquor was analysed for polysaccharides, proteins and submicron particle size distribution. At low temperature, a high polysaccharide concentration was found in the experimental system as compared to the MBR pilot. Upon decreasing the temperature of the mixed liquor, a shift was found in particle size towards smaller particles. The release of polysaccharides and submicron particles from sludge flocs could explain the increased membrane fouling at low temperatures (Van Den Brink et al., 2011).

Two laboratory-scale anaerobic membrane bioreactors, AnMBR 1 and AnMBR 2, were run in parallel at 25 and 15 °C, respectively. Total chemical oxygen demand (COD) removal efficiency was more than 95% and 85% for AnMBR 1 and 2, respectively. The COD removal of AnMBR 1 was mostly carried out biologically. However, the physical removal on the membrane surface compensated for the decreased biological removal rate in AnMBR 2. The membrane in AnMBR systems was retained all biomass in the reactor and also complemented decreased biological removal efficiency at low temperature by rejecting soluble organics. Methanogenic activity profiles of suspended and attached sludge in AnMBRs treating synthetic municipal wastewater at 25 and 15 °C were tested. The methanogenic activity was almost increased 27% during 75 days for AnMBR 1. However, the methanogenic activity of AnMBR 2 sludge was lower than AnMBR 1. The microbial activity of the suspended sludge was continuously increased, while the attached sludge gradually decreased. The methanogenic activity of the attached sludge was far lower than the suspended sludge. The role of attached sludge on the membrane in AnMBRs as a biofilm was minimum compared to suspended sludge (Ho & Sung, 2010).

A pilot scale anaerobic submerged membrane bioreactor (AnSMBR) with an external filtration unit for municipal wastewater treatment was operated for 100 days under 20 and 35 °C. Membrane fouling was provided with biogas sparging. During the first 69 days, the reactor was operated under mesophilic temperature conditions. A stable filtration resistance was achieved in long term under mesophilic conditions. Afterwards, the temperature was gradually reduced to 20 °C. A slow and linear increase in the filtration resistance was observed under critical flux conditions (7 L/m^2 h) at 35 °C. The filtration resistance increased faster under psychrophilic conditions. However, an increase in the fouling rate probably linked to an accumulation of solids, a higher viscosity and soluble COD concentrations in the reactor was observed at 20 °C. The COD removal efficiency was close to 90% under both temperature ranges (Martinez-Sosa et al., 2011).

A submerged anaerobic membrane bioreactor (SAnMBR) was operated for urban wastewater treatment at 33 °C and 20 °C. The methane recovery efficiency obtained at 20 °C (53.6%) was slightly lower than at 33 °C (57.4%) due to a reduction of the treatment efficiency, as evidenced by the lower methane production and the higher waste sludge per litre of treated wastewater. A temperature drop reduced the treatments' efficiency and increased gases solubility (Giménez, Martí, Ferrer, & Seco, 2012).

A submerged anaerobic membrane bioreactor was operated under mesophilic conditions at 33 °C. Two hollow fiber ultrafiltration membrane modules were used. SRT was taken 70 days and HRT was in a range of between 20 to 6 hours. COD removal was about 87%. Irreversible fouling problems weren't detected, even for high total solid concentrations (Giménez et al., 2011).

Two submerged anaerobic membrane bioreactors (SAMBRs) were operated at a mean solids residence time (SRT) of 30 (SAMBR30) and 300 days (SAMBR300) at mesophilic and psychrophilic temperatures. At 35 °C results showed that SAMBR30 and 300 could achieve 95% soluble chemical oxygen demand (SCOD) removal at 1.5 and 1.1 days HRT, respectively, whereas at 20 °C only SAMBR300 could maintain the same performance. Low temperatures were associated with higher bulk SCOD concentrations, which contributed to reducing the flux, but this was partly reversible once the SCOD was degraded (Trzcinski & Stuckey, 2010).

Gao et al. (2010) were operated an AnMBR at 30 °C. Upflow anaerobic reactor was used as bioreactor, SRT and HRT was taken 50 days and 24 hours, respectively. 100 kDa external coated PVDF and 30 kDa external polyetherimide membranes were used. It was aimed to minimize the membrane fouling with cross-flow filtration. Total COD removal was achieved over 96%

Huang, Ong, & Ng (2011) were operated an AnMBR in a range of 25 to 30 °C. Completely mixed anaerobic reactor was used as bioreactor. SRT was taken 30, 60 and ∞ days and HRT was taken in a range of 8 to 12 hours. 0.45 μm PES flat sheet membrane was used and fouling control was provided with biogas sparging. Total COD removal was achieved over 97%.

Salazar-Pelaez, Morgan-Sagastume, & Noyola (2011) were operated an AnMBR. UASB reactor was used as bioreactor. SRT was taken ∞ days and HRT was taken in a range of 4 to 12 hours. 100 kDa external PVDF tubular membrane was used. It was aimed to minimize the membrane fouling with cross-flow filtration. NaOCl cleaning was done every 6 hours to control the membrane fouling. They obtained 80% COD removal efficiency at these conditions.

Kim et al. (2011) were operated an AnMBR at 35 °C. Two-stage fluidized bed reactor was used as bioreactor. SRT was taken ∞ days and HRT was taken in a range of 4.2 to 5.9 hours. 0.1 μm PVDF hollow fiber membrane was used. Fouling control was provided with GAC fluidization, periodic backflushing and NaOCl/NaOH cleaning. 99% total COD removal efficiency was achieved in this study.

Dagnew et al. (2011) were operated an AnMBR at 22 °C. Completely mixed anaerobic reactor was used as bioreactor. SRT was taken in a range of 80 to 100 days and HRT was taken 8.5 hours. ZeeWeed™ hollow fiber membrane was used. Fouling control was provided with biogas sparging and chemical cleaning was done weekly. Total COD removal efficiency was obtained as 79%.

Composition of the soluble fraction of the mixed liquor was related to membrane performance after exposing the sludge to temperature shocks. Flux step experiments were performed in an experimental system at 7, 15 and 25° C with sludge that was continuously recirculated from a pilot-scale MBR. After correcting the permeate viscosity for temperature, higher membrane fouling rates were obtained for a lower sludge temperature in combination with low fouling reversibility. The soluble fraction of the MBR mixed liquor was analysed for polysaccharides, proteins and submicron particle size distribution. At low temperature, a high polysaccharide concentration was found in the experimental system as compared to the MBR pilot. Upon decreasing the temperature of the mixed liquor, a shift was found in particle size towards smaller particles. The release of polysaccharides and submicron particles from sludge flocs could explain the increased membrane fouling at low temperatures (Van Den Brink et al., 2011).

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Dagnew et al. (2011) were operated an AnMBR at 22 °C. Completely mixed anaerobic reactor was used as bioreactor. SRT was taken in a range of 80 to 100 days and HRT was taken 8.5 hours. ZeeWeed™ hollow fiber membrane was used.

Fouling control was provided with biogas sparging and chemical cleaning was done weekly. Total COD removal efficiency was obtained as 79%.

CHAPTER FOUR

MATERIAL AND METHODS

4.1 AnMBR System

A lab scale AnMBR model reactor was operated during experimental studies. The AnMBR system was purchased from TUBITAK 110Y020 project and it was used for this study following the completion of this project.

The model reactor was consisted of an anaerobic bioreactor (UASB) which connected to a side-stream membrane module (UF). Wastewater was introduced to the anaerobic reactor and effluent was pumped to the Ultrafiltration (UF) unit. Permeate was discharged and concentrate was recycled to the anaerobic unit. The flow scheme of the system is given in Figure 4.1 and photograph of the AnMBR system is shown in Figure 4.2.

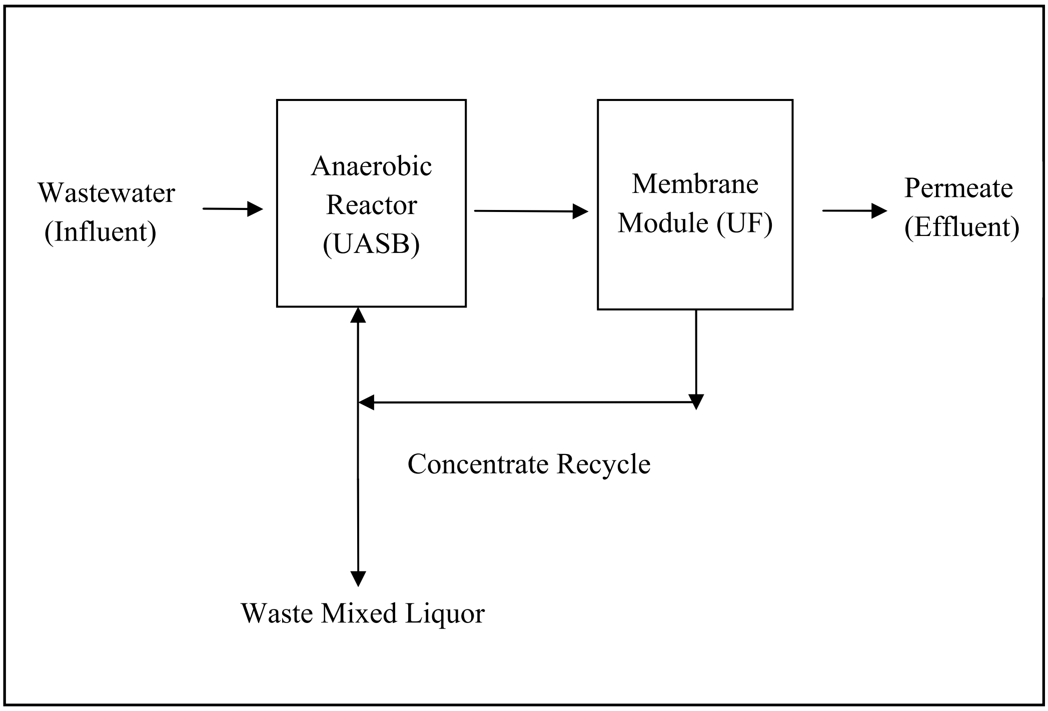


Figure 4.1 Schematic diagram of the anaerobic membrane bioreactor (AnMBR) system.

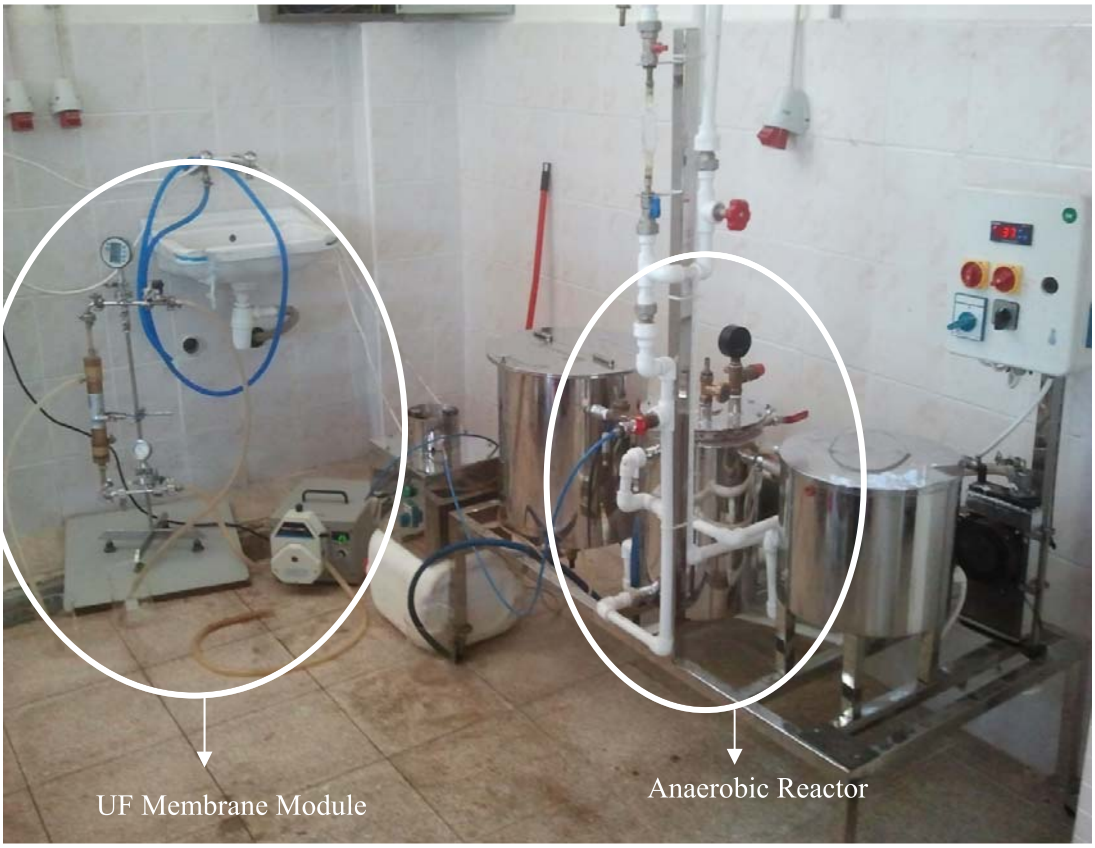


Figure 4.2 Photo of the laboratory scale AnMBR system.

4.2 Anaerobic Reactor

All tanks were made of stainless steel. The anaerobic reactor with 20 cm diameter has a total volume of 10 L and it is equipped with inlet and outlet valves, sampling valves, and gas and sludge outlet valves.

The anaerobic reactor was designed as up-flow sludge bed reactor (UASB). There was no a gas/liquid/solid (G/L/S) separator. The reactor was operated under mesophilic (37 ºC) and thermophilic (55 ºC) conditions. Temperature was kept constant by circulating hot water through the reactor jacket. The photo of the anaerobic model reactor is given in Figure 4.3.

Figure 4.3 The view of the anaerobic model reactor system used in experimental studies.

4.3 Membrane

The anaerobic reactor's effluent was pumped to the Ultrafiltration (UF) membrane module. Hollow fiber membrane in Pall's Microza module (SLP-1053) was used as the membrane module. The molecular weight cut-off (MWCO) of the membrane is 10 kDa. Effective filtration area of this membrane system is 0.1 m^2. The maximum inlet pressure of the system is given as 3 bar (45 psi). The cartridge specifications and operating parameters is given in Table 4.1.

Table 4.1 The cartridge specifications and operating parameter

Module Type	SLP-1053
MWCO	10,000 Dalton
Water Flux	40 L/hr
Area	0.1/1.1 m^2/ft^2
Fiber Bore	1.4 mm
Module Length	347/13.7 mm/inch
Module Outside Diameter	42/1.7 mm/inch
Max. Inlet Pressure	3/45 bar/psi
Max. ΔP	3/45 bar/psi

Wastewater was pumped to the membrane using a peristaltic pump. Using pressure measurement devices attached to the module, inlet and outlet pressure was measured. The inlet pressure was kept constant at 1.5±0.2 bars during the experiments. For the UF membrane maximum wash pressure was 1.7 bars and backwash pressure was 2.5 bars. In Figure 4.4, structure of the UF module is given.

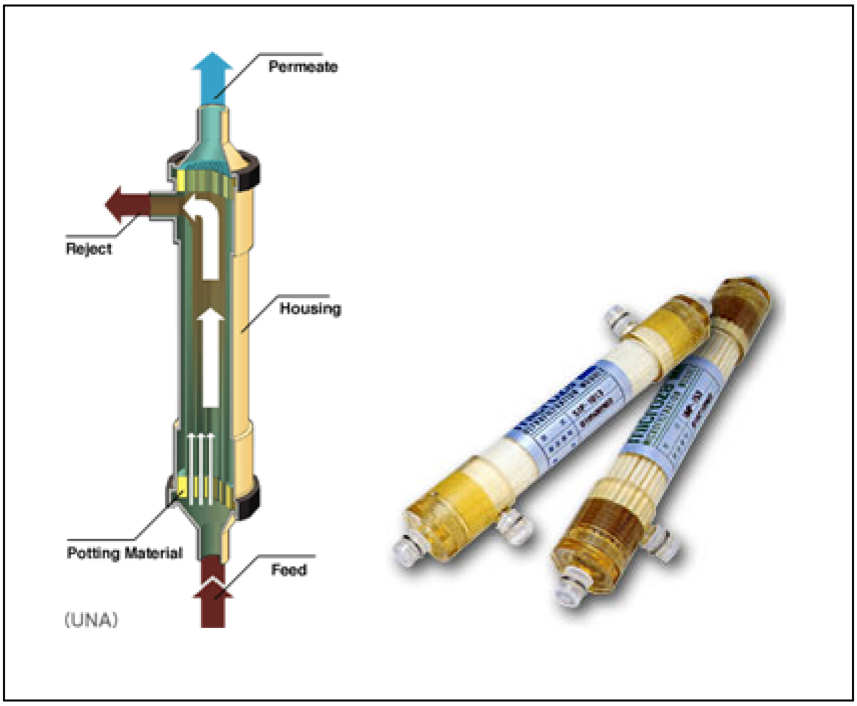


Figure 4.4 The Pall's Microza UF module (SLP-1053) structure.

4.4 Wastewater Properties

Synthetic wastewater consisted of diluted molasses was used in this study. COD concentration of molasses is about 1,000,000 mg/L; and it was diluted to desired influent COD concentration. The anaerobic reactor was operated in two influent COD concentrations as 5,000 and 10,000 mg/L at both mesophilic and thermophilic conditions. When the operational conditions deteriorated, Vanderbilt mineral medium was used as a mineral environment.

The composition of the feeding water for 5,000 and 10,000 mg/L COD influent is shown in Table 4.2.

Table 4.2 The composition of the feeding water

Parameter	**$COD_{influent}$ = 5,000 mg/L**	**$COD_{influent}$ = 10,000 mg/L**
TS, mg/L	6,000 - 7,000	9,000 - 15,000
TVS, mg/L	4,800 – 5,700	5,000 – 10,000
TSS, mg/L	45 - 150	200 - 230
Total nitrogen, mg/L	4.00 - 7.00	5.50 - 15.00
Total phosphorus, mg/L	1.00 - 1.50	0.73 - 1.56
pH	7.06 - 8.02	6.97 - 8.44

4.5 Analytical Procedure

Chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), alkalinity, total solids (TS), total volatile solids (TVS), total suspended solids (TSS), pH, electrical conductivity (EC) analyses were carried out regularly during the experimental studies. TN and TP analyses were measured by using test kits (Merck 14537 – 14543). pH and EC were measured by using WTW Model 340i Multi Analyzer. The analyses of the other parameters were done according to procedures given in Standard Methods that published by American Public Health Association, American Water Works Association, & Water Environment Federation. Total solid concentration of the sludge and the organic material fraction of the solid material measurements were also done according to Standard Methods (APHA, AWWA, WEF, 2005).

Total biogas and methane production volumes were measured with liquid displacement methods. Total biogas was measured by using saturated solution of NaCl and H_2SO_4 % 2, and methane gas production was measured by using solution of NaOH % 3 (w/v) containing distilled water.

The flux was measured from the permeate volume per unit time and effective filtration area of the membrane.

The list of analysis carried out during the experimental studies is summarized in Table 4.3.

Table 4.3 The list of analysis carried out during the experimental studies

Parameter	**Influent**	**Anaerobic Reactor**	**Membrane Unit**
COD, mg/L	√	√	√
TN, mg/L	√	√	√
TP, mg/L	√	√	√
TS, mg/L	√	√	√
TVS, mg/L	√	√	√
TSS, mg/L	√	√	√
EC, mS/cm	√	√	√
pH	√	√	√
Biogas, L/day		√	
Methane, %		√	
Flux, $m^3/m^2.h$			√

4.6 Operational Conditions

As indicated above, the AnMBR system was first operated in the scope of TUBITAK 110Y020 project before. Therefore, there was a sufficient amount of active biomass in the anaerobic reactor. So, at the beginning of the study inoculum was not added.

The system was operated under mesophilic conditions (37 ºC) firstly and two influent COD concentrations were applied as 5,000 and 10,000 mg/L, respectively. At the beginning of the 10,000 mg/L COD application, the inoculums taken from the anaerobic reactors of Izmir PAKMAYA Baker's Yeast Company's Wastewater Treatment Plant were added in order to shorten the adaptation period.

After then, the temperature was raised to thermophilic conditions (55 ºC) and the influent COD concentration was adjusted as 5,000 mg/L and 10,000 mg/L, respectively. In order to accelerate the adaptation phase, the thermophilic inoculums taken from the thermophilic hybrid anaerobic reactors of Manisa Alaşehir Suma Company's Wastewater Treatment Plant were added.

Applied operational conditions were comprised of 4 stages (Table 4.4). When the influent COD concentration was 5,000 mg/L, the anaerobic reactor was operated at an organic loading rate (OLR) of 2.5 kg COD/m^3.day and hydraulic retention time (HRT) of 2 days. Similarly, when the influent COD concentration was 10,000 mg/L, organic loading rate (OLR) of 5 kg COD/m^3.day and hydraulic retention time (HRT) of 2 days were maintained in the anaerobic reactor.

Table 4.4 The applied operational conditions

	Temperature			
	Mesophilic		Thermophilic	
COD (mg/L)	5,000	10,000	5,000	10,000
HRT (day)	2	2	2	2
OLR (kg/m^3.day)	2.5	5	2.5	5

The inlet pressure of the UF membrane module was kept constant at 1.5±0.2 bar. The UF membrane module was operated for 1 hour in a day. The concentrate from the UF unit was returned to the anaerobic reactor by a peristaltic pump with 15±1 L/d flow rate. The anaerobic reactor effluent was pumped to the UF module by a peristaltic pump with a 0.5±0.1 L/min flow rate.

The UF unit was backwashed with distilled water to prevent membrane from clogging. It was stored wet by using 0.025 % Sodium Hydroxide solution.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Mesophilic Conditions

Experimental studies were carried out for two different COD influent concentrations (5,000 - 10,000 mg/L) under mesophilic conditions (37 °C). The results are discussed below on the basis of the parameter.

5.1.1 pH

pH is the one of the most important operating parameters to control biological system stability. Therefore, during the experimental studies, pH values of influent wastewater, reactor effluent, and membrane effluent were monitored regularly.

pH alterations during the experimental studies are given in Figure 5.1.a for the influent COD concentration of 5,000 mg/L. As seen from the figure, there was no significant pH fluctuations for the period of the experiments carried out with 5,000 mg/L influent COD concentration.

Influent wastewater pH was almost stable and changed between 7.33 and 7.79 depending on the tap water properties. The anaerobic reactor effluent pH did not fall to below 6.10, which is lower the adequate value for the growth of methanogenic bacteria. The highest pH value was measured as 6.90 for the reactor effluent. The optimum pH range for methane bacteria growth is between 6.5 and 8.2. pH in the anaerobic reactor must be kept in this range because of methane bacteria that is the most sensitive group in anaerobic treatment. Acidogenesis active in a larger pH range as against the methanogenesis but acidogenesis are inhibited when the pH decreases under the value of 5.5 (Yüceer, 2006). pH value of the membrane effluent showed an alteration between 6.35 and 7.13. Throughout the study, the membrane effluent pH values always kept over the pH values of the anaerobic reactor effluent.

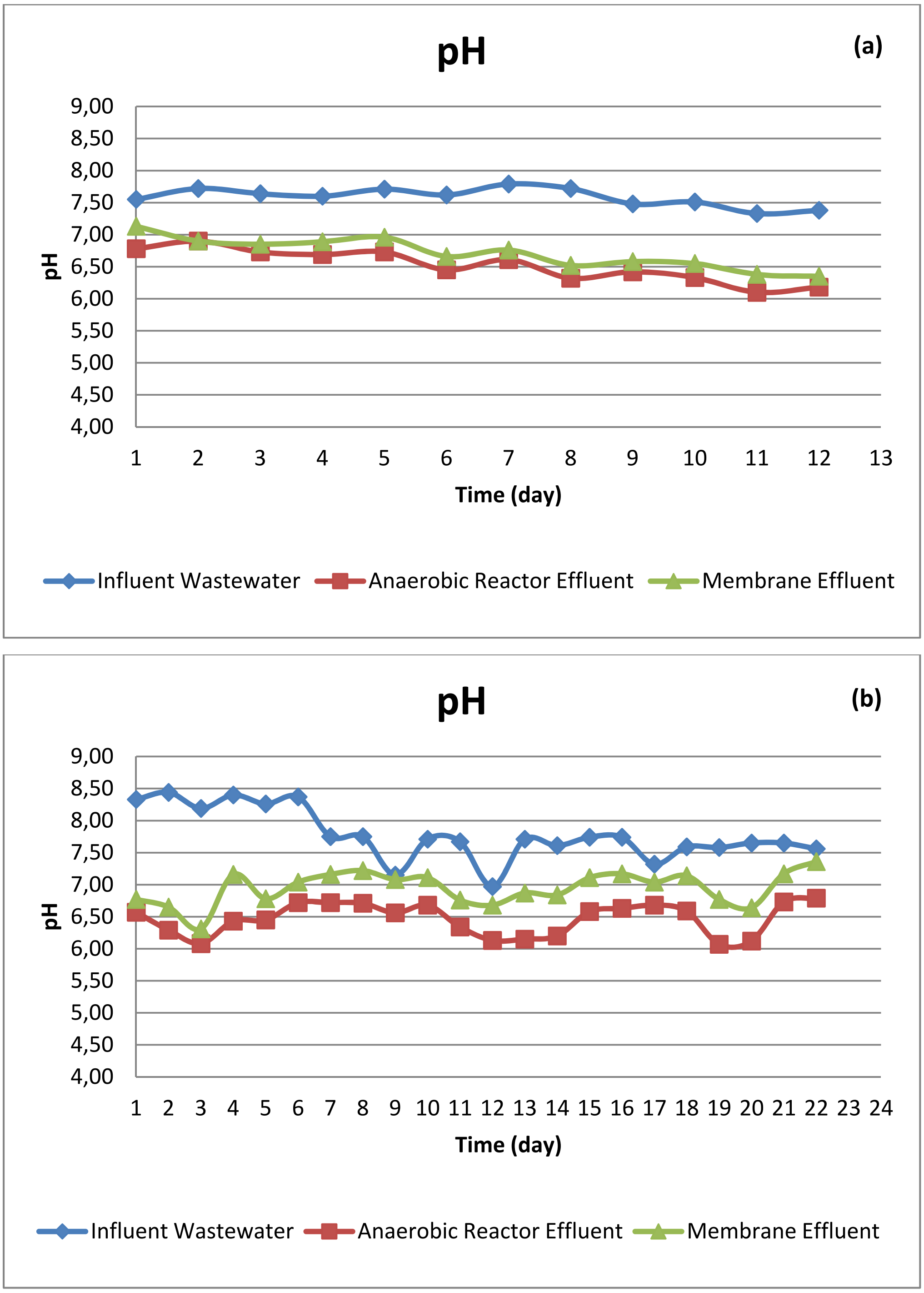


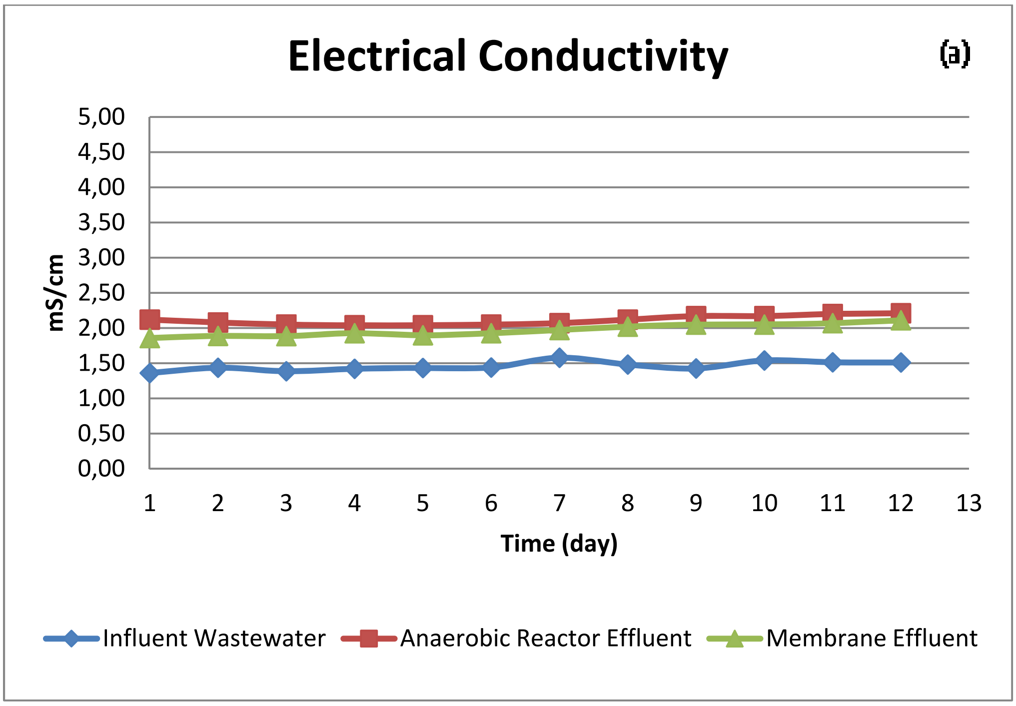
Figure 5.1 pH fluctuations during the studies, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg/L

The results of pH measurements carried out during the experimental studies with the influent COD concentration of 10,000 mg/L are given in Figure 5.1.b Influent wastewater pH was changed between 6.97 and 8.44. The anaerobic reactor effluent pH did not decrease to below 6.07. The maximum pH value was measured as 6.79 for the reactor effluent. The range of 6.07 and 6.79 is enough to accruing the anaerobic treatment. pH value of the membrane effluent showed an alteration between 6.31 and 7.36. The pH of the reactor and membrane effluent were almost parallel. Membrane effluent pH values were always higher than the anaerobic reactor effluent.

5.1.2 Electrical Conductivity (EC)

The results of EC analyses are shown in Figure 5.2.a and 5.2.b for the influent COD concentration of 5,000 and 10,000 mg/L, respectively. As seen from the Figure 5.2.a, EC values were almost stable for 5,000 mg/L influent COD concentration. Electrical conductivity (EC) parameter is generally used for the estimation of salinity. Particles having diameter of less than 0.001 micron cause salinity. Since UF membrane can remove particles having diameter between 0.005 and 0.05 micron, significant salinity removal cannot be achieved with this type of membrane. As it is expected, considerable EC changes were not observed after the membrane application.

Higher EC values were measured during the studies carried out with 10,000 mg/L influent COD concentration comparing to 5,000 mg/L results. Vanderbilt mineral medium is thought the reason of this increase. During the 10,000 mg/L influent COD application, pH tends to decrease and Vanderbilt mineral medium was sometimes added to adjust environmental conditions for efficient anaerobic biodegradation. The EC values in membrane effluent were parallel to the anaerobic reactors. They didn’t exceed the anaerobic reactors. EC alterations during the experimental studies are given in Figure 5.2.b for the influent COD concentration of 10,000 mg/L.



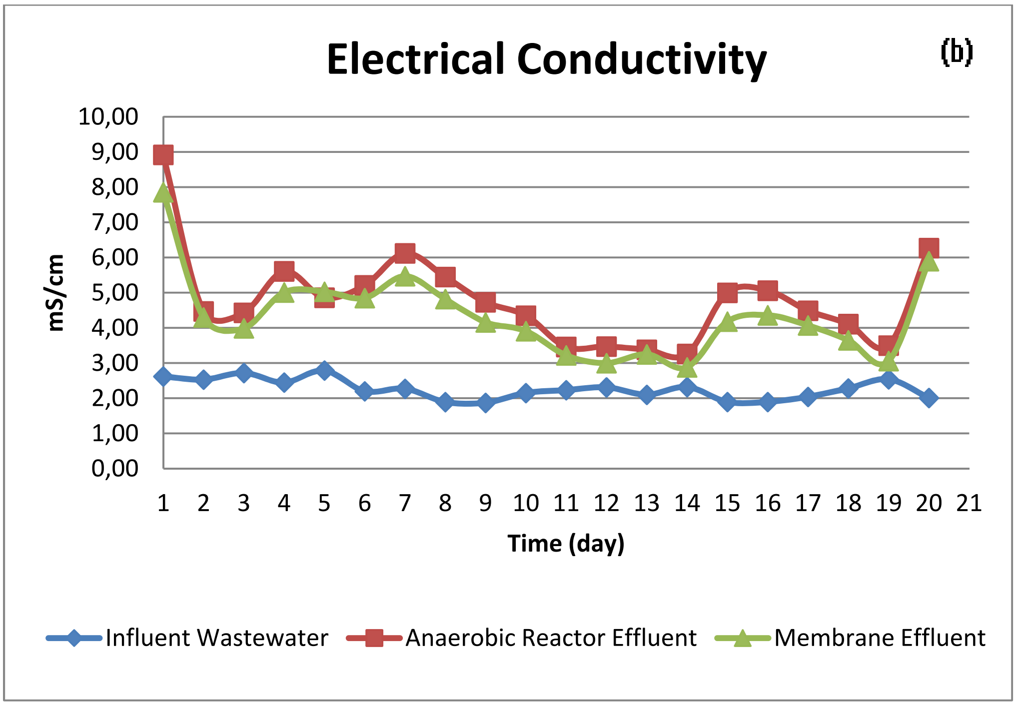


Figure 5.2 Variation of EC, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

5.1.3 Biogas Production

Biogas production potential and methane content of the biogas is accepted as one of the most important indicators of anaerobic degradation and biogas consists of approximately 60% methane and 40% carbon dioxide. In this study, average methane content of the biogas was determined as 57.2% while the maximum was 64.0% for 5,000 mg/L influent COD concentration (Figure 5.3.a).

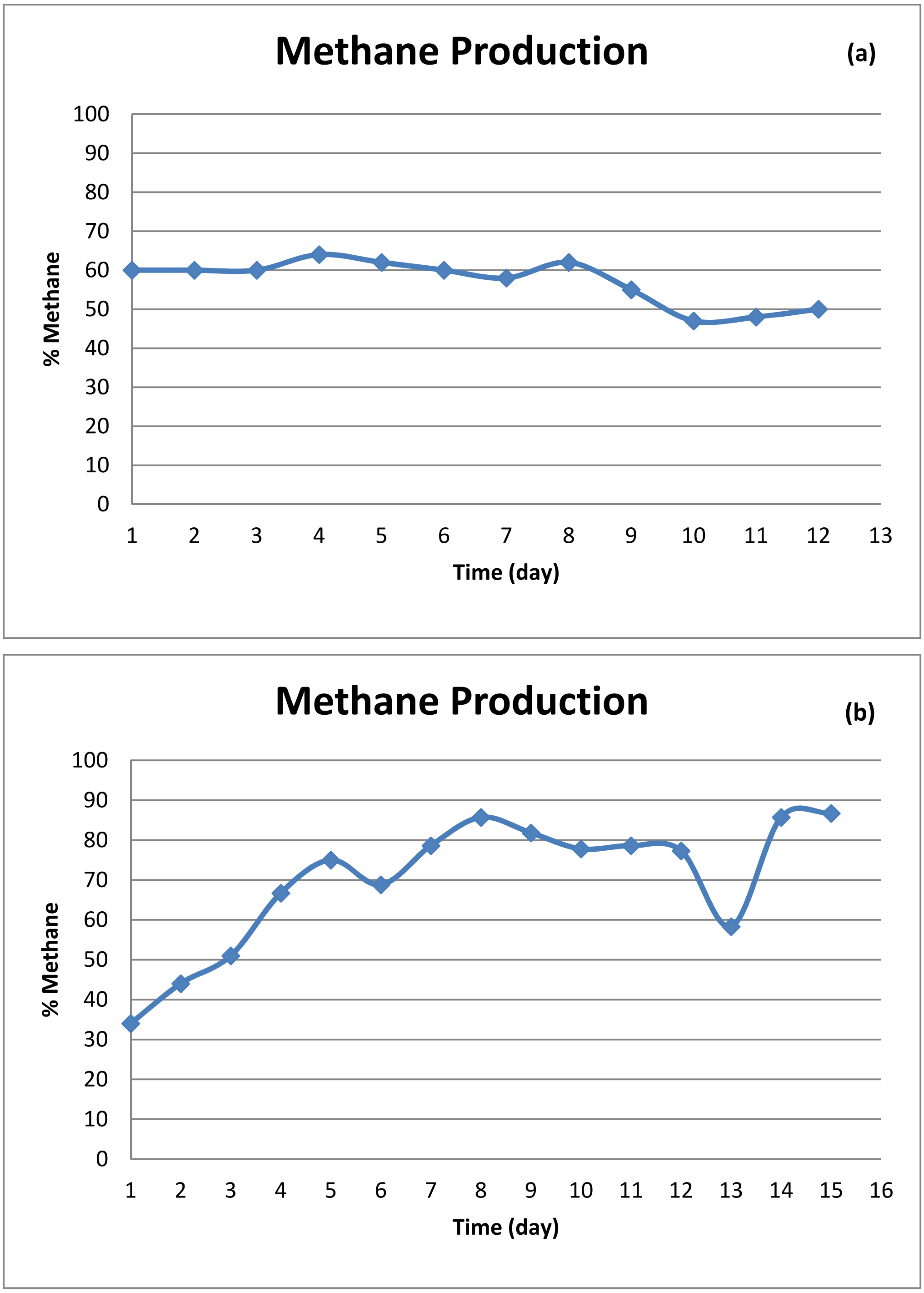


Figure 5.3 Methane gas content of the biogas, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

Increasing the influent organic load had a positive effect on the formation of biogas. Biogas quality produced in 10,000 mg/L COD application is better than biogas quality produced in 5,000 mg/L COD application (Figure 5.3.b). Average and maximum methane gas content was measured as 70% and 86.7%, respectively. Methane percentage of the total biogas changes depending on the wastewater composition and operating conditions of reactors. Several methane gas percentages in the total biogas are reported in the literature. Martinez-Sosa et al. (2011) achieved around 80% methane percentage under mesophilic conditions. Gimènez et al. (2012) reached 57.4% methane recovery efficiency at 33 °C and they obtained biogas methane contents over 55% at 33 °C in 2011.

5.1.4 Solid Fractions

5.1.4.1 Total Solids (TS)

Total solids concentrations of the influent wastewater did not change significantly depending on the influent wastewater COD concentration. Total solids concentrations of influent wastewater were changed between 9,000 and 15,000 mg/L. TS concentrations range of the anaerobic reactor was about 1,200 – 1,800 mg/L and 3,800 – 6,900 mg/L for 5,000 and 10,000 mg/L COD concentration application, respectively. TS removal efficiencies of the membrane were approximately 20% for influent COD of 5,000 mg/L and 30% for 10,000 mg/L influent COD experiments. Figure 5.4 shows the TS concentration variations for 10,000 mg/L influent COD concentration. Because there is no enough data, the graph for 5,000 mg/L is not drawn.

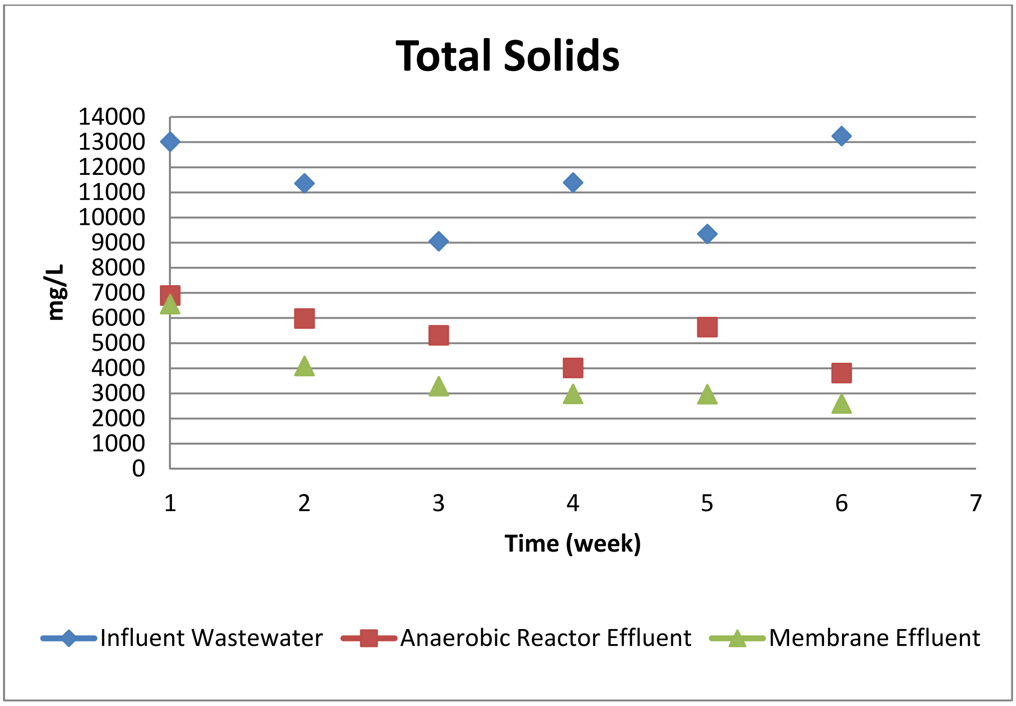


Figure 5.4 Total solids concentrations for the influent COD concentration of 10,000 mg/L

5.1.4.2 Total Volatile Solids (TVS)

TVS concentrations of influent, anaerobic reactor effluent and membrane effluent for 5,000 and 10,000 mg/L COD concentration applications were almost same. In both cases, total volatile solids concentrations of influent wastewater were changed between 6,500 and 9,900 mg/L; TVS concentrations of the anaerobic reactor effluent were changed between 1,800 and 3,500 mg/L; and TVS concentrations of the membrane effluent were changed between 1,100 and 2,600 mg/L. Total volatile solids concentrations during the experimental studies are given in Figure 5.5 for the influent COD concentration of 10,000 mg/L.

TS and TVS content of the sludge were also measured rarely. TS content of the sludge decreased slowly and it kept constant about 4%. In contrast to this situation, TVS content of the sludge increased gradually and it reached to 80%.

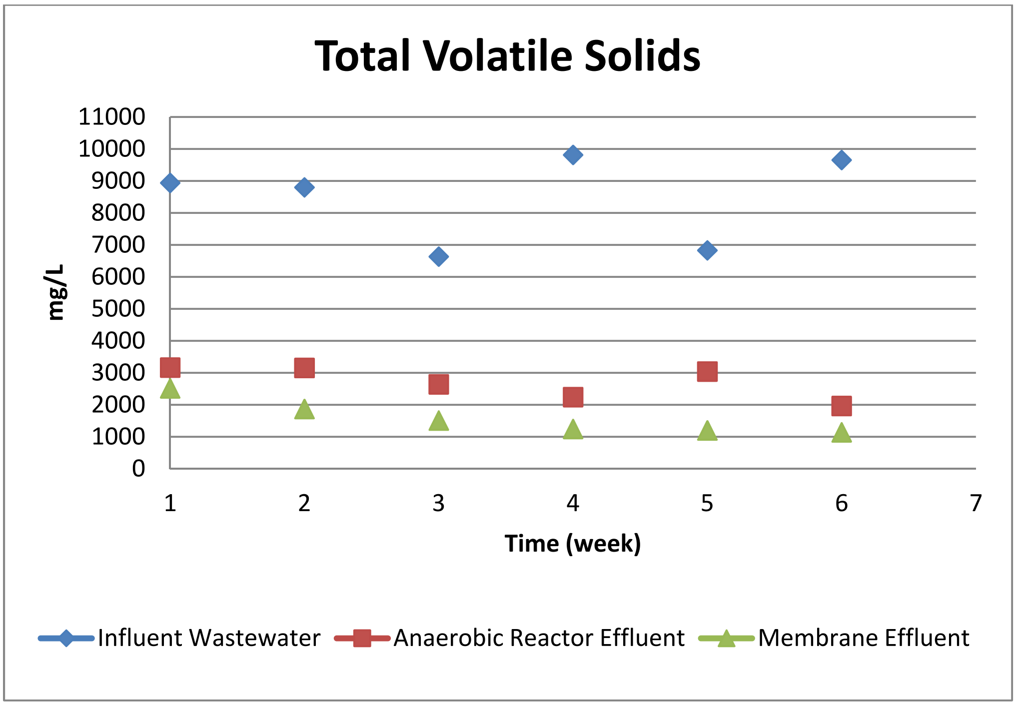


Figure 5.5 Total volatile solids concentrations for the influent COD concentration of 10,000 mg/L

5.1.4.3 Total Suspended Solids (TSS)

Ultrafiltration membrane system can produce high quality water, free of suspended solids, colloidal material and bacteria. As it is expected, high suspended solid removal efficiencies were obtained with UF membrane system, in this study.

Comparable results were obtained with the influent COD concentration of 5,000 and 10,000 mg/L. Total suspended solids concentrations of influent wastewater were changed between 55 and 150 mg/L, TSS concentrations of the anaerobic reactor effluent were changed between 120 and 210 mg/L. TSS removal efficiencies up to 97% were achieved with membrane unit.

5.1.5 Chemical Oxygen Demand (COD)

COD analyses were performed for monitoring of organic material degradation and COD concentrations of influent wastewater, reactor effluent and membrane effluent were monitored regularly.

Although it was aimed to work with constant influent COD concentrations, the constant values could not be obtained depending on the dilution of the molasses. For example, COD concentrations changed between 4,800 and 6,400 mg/L for 5,000 mg/L influent COD applications. In the anaerobic reactor, the maximum COD removal efficiency was obtained as 82.4% with a COD effluent value of 960 mg/L. This result is consistent with the data given in the literature. When HRT was taken 19.2 hours and OLR was taken 0.6-1.1 gr COD/L.day, the COD removal rate was reached to 90% (Martinez-Sosa et al., 2011). HRT, SRT and OLR were taken 1.5 days, 30 days and 10 gr VS/L.day respectively, the COD removal rate was measured as 95% (Trzcinski & Stuckey, 2010). The COD removal rate was 99% when HRT was taken between 4.2 and 5.9 hours and OLR was taken 4.4±0.3 kg COD/m^3.day (Kim et al., 2011).

In order to evaluate the whole system (AnMBR) performance, membrane efficiencies are important. Maximum and minimum COD removal efficiencies of membrane were 66.7% and 20.0%, respectively. There were sometimes fluctuations in the membrane effluent and effluent COD concentrations changed between 320 and 1,280 mg/L for the membrane depending on the anaerobic reactor effluent. Maximum COD removal efficiency of the total system (AnMBR) reached to %94.1. COD concentrations and treatment efficiencies during the experimental studies are given in Figure 5.6.a and Figure 5.6.b, respectively, for the influent COD concentrations of 5,000 mg/L.

During the 10,000 mg/L COD applications, COD concentrations changed between 8,160 and 11,040 mg/L for influent wastewater. The highest removal efficiency reached to 73.9% with a COD effluent value of 2,506 mg/L for the anaerobic reactor. Different membrane performances were obtained. Effluent concentrations changed between 710 and 5,763 mg/L for membrane. Maximum and minimum membrane efficiency values were 75.0% and 25.0%, respectively. Maximum COD removal efficiency of the total system (AnMBR) was achieved as %91.3. COD concentrations and treatment efficiencies during the experimental studies are given in Figure 5.7.a and Figure 5.7.b, respectively, for the influent COD concentrations of 10,000 mg/L.

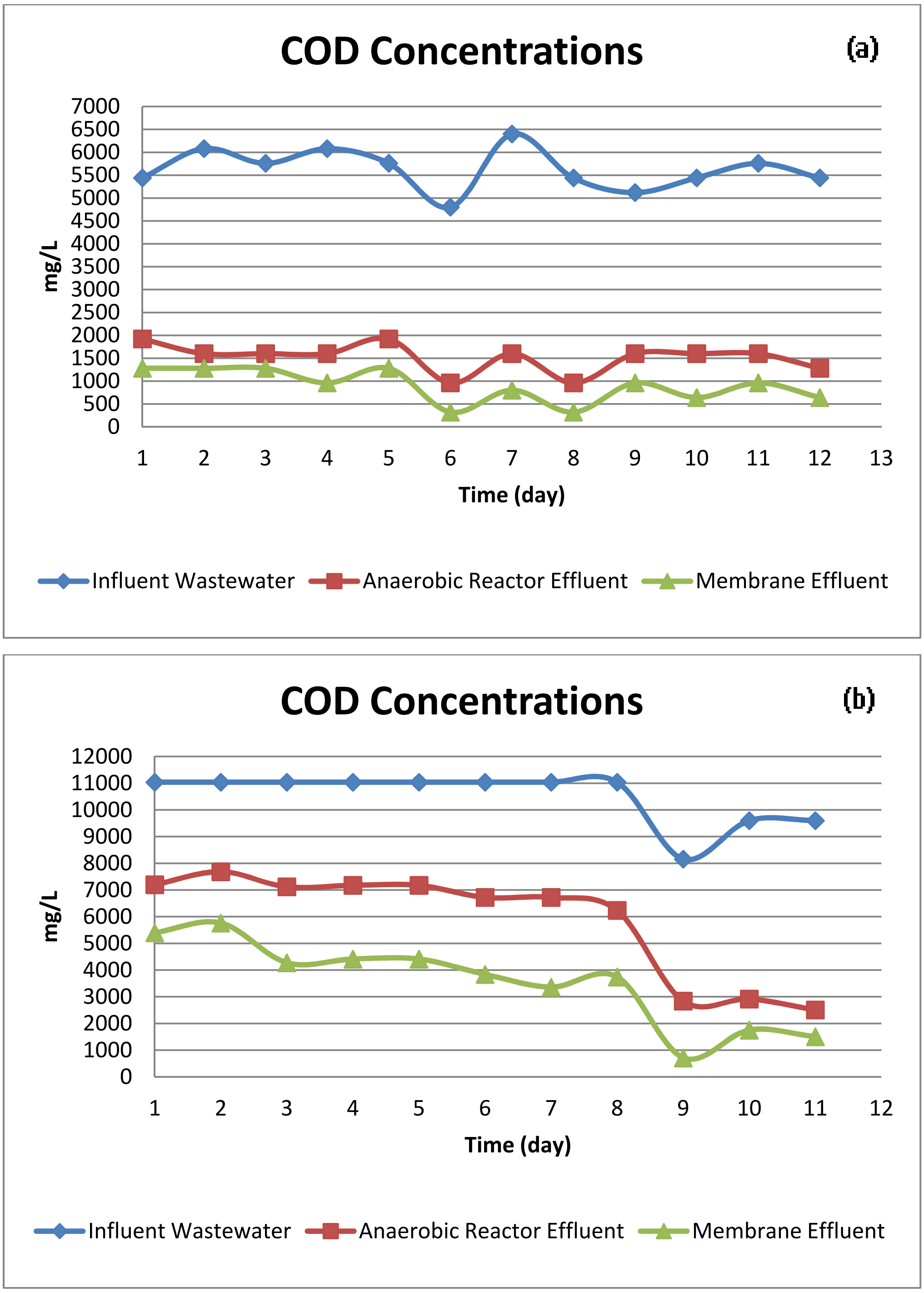
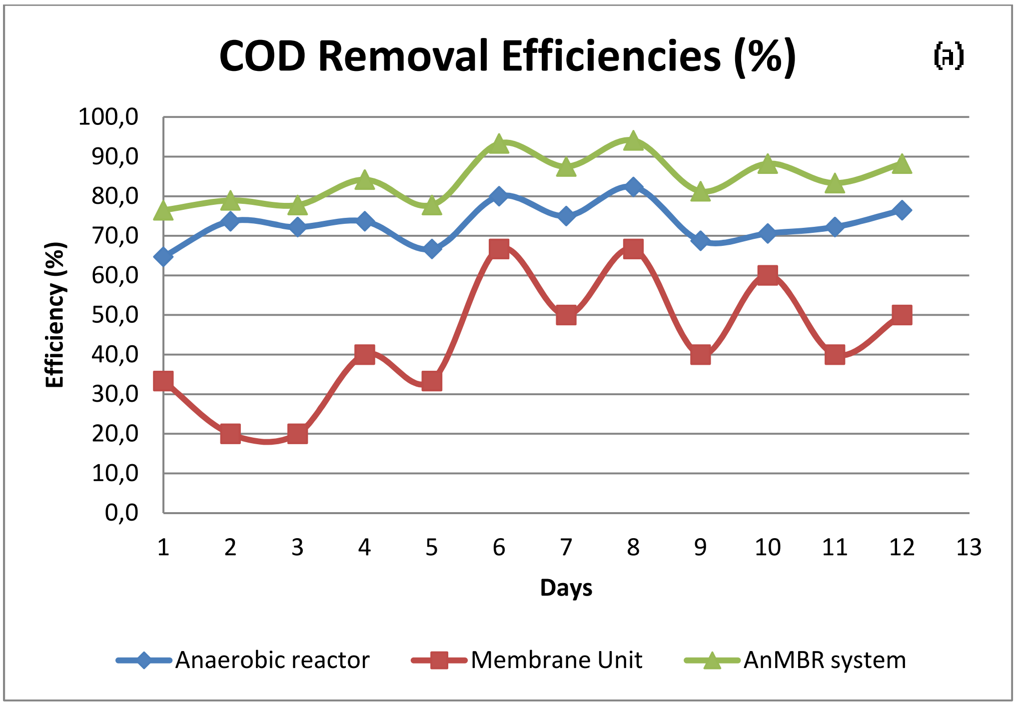


Figure 5.6 Variations of the COD concentrations, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L



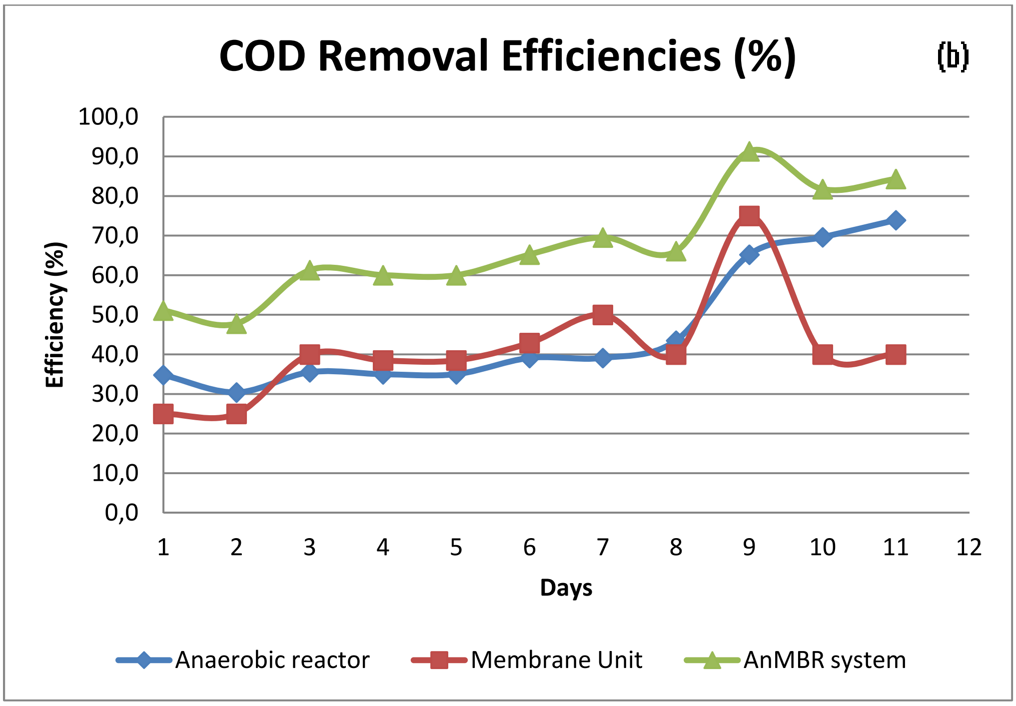


Figure 5.7 COD removal efficiencies, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

5.1.6 Nitrogen (N) and Phosphorus (P)

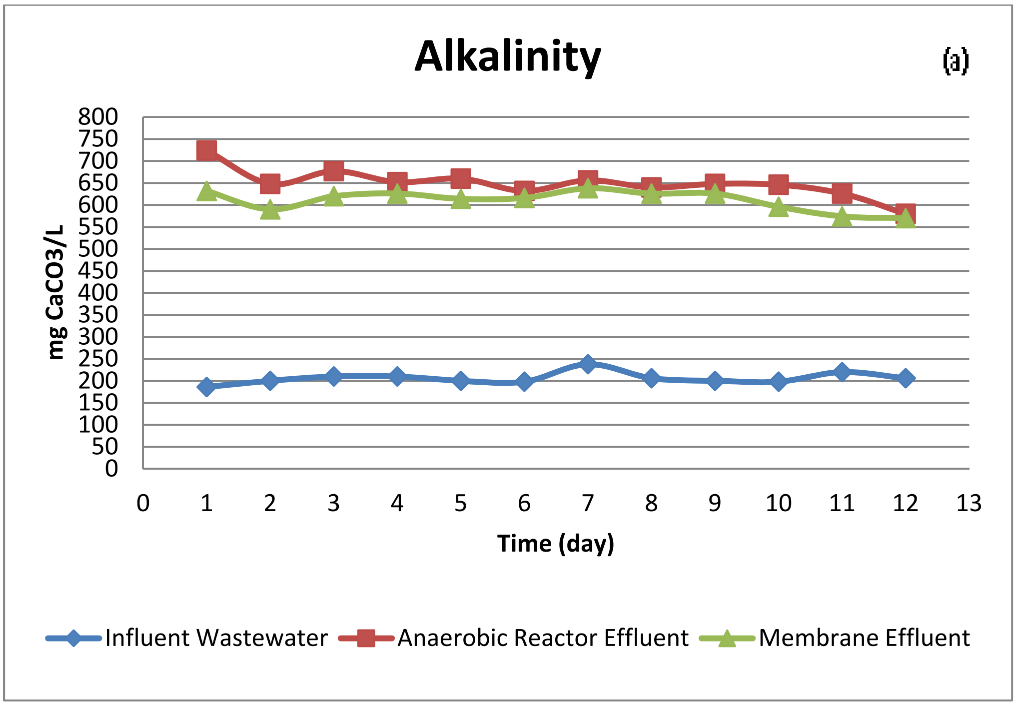
Because nutrient removal is not scope of the theses, N and P parameters were determined only once. Influent wastewater N concentration was determined about 15 mg/L. N concentration of the anaerobic reactor effluent and membrane effluent was measured as 1.4 mg/L and 1.7 mg/L, respectively.

Influent P concentration was 0.73 mg/L. In the anaerobic conditions, phosphorus release occurred and higher P concentration increased to 3.26 mg/L in the anaerobic reactor effluent. In the membrane effluent, the P concentration was decreased to 0.13 mg/L.

5.1.7 Alkalinity

In addition to pH monitoring, determination of the amount of alkalinity and volatile fatty acids is very important for an anaerobic system control. Therefore alkalinity concentrations of influent wastewater, reactor effluent and membrane effluent were monitored regularly.

Alkalinity concentrations were stable for influent wastewater. Alkalinity of the anaerobic reactor effluent and membrane unit effluent were higher than influent. There were no significant fluctuations in alkalinity levels. The concentrations changed between 186 and 238 mg $CaCO_3$/L for influent wastewater, 580 and 724 mg $CaCO_3$/L for anaerobic reactor effluent, 570 and 638 mg $CaCO_3$/L for membrane effluent. The anaerobic reactor and membrane effluent concentrations were almost similar. Alkalinity concentrations measured during the experimental studies are given in Figure 5.8.a for the influent COD concentration of 5,000 mg/L.



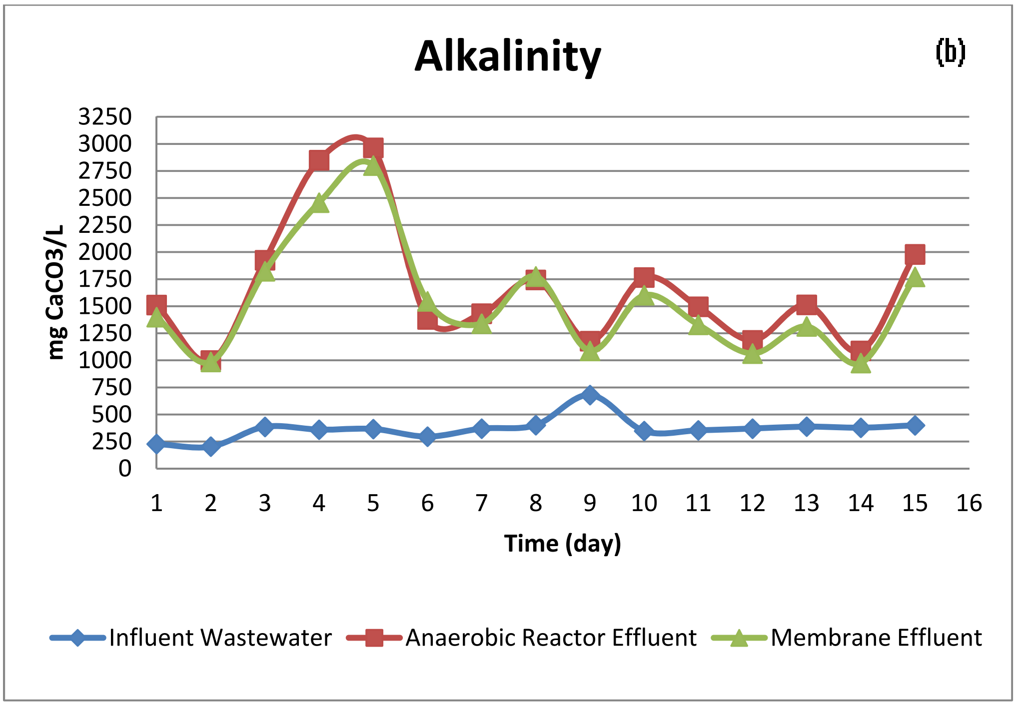


Figure 5.8 Alkalinity changes, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

Alkalinity concentrations during the experimental studies are given in Figure 5.8.b for the influent COD concentration of 10,000 mg/L. Although alkalinity concentrations were stable for influent wastewater, there were alkalinity fluctuations for the anaerobic reactor and membrane effluents for the period of the experimental studies carried out with the influent COD concentrations of 10,000 mg/L. pH values of 10,000 mg/L influent COD concentration was lower than the 5,000 mg/L. In order to obtain stable operating conditions, Vanderbilt mineral medium was sometimes added to the influent wastewater. Vanderbilt mineral medium contains a lot of chemicals that can increase alkalinity. So, the alkalinity fluctuations could be observed because of this reason. The alkalinity changed between 204 and 680 mg $CaCO_3$/L for the influent wastewater, 1,000 and 2,964 mg $CaCO_3$/L for the anaerobic reactor effluent, 976 and 2,800 mg $CaCO_3$/L for the membrane effluent. The anaerobic reactor and membrane effluent concentrations were similar.

5.1.8 Volatile Fatty Acids (VFA)

As indicated in the subsection of 5.1.7, since determination of volatile fatty acids concentration is very important for an anaerobic system control, VFA concentrations of influent wastewater, reactor effluent and membrane effluent were monitored regularly, in this study.

Increasing the volatile fatty acids concentrations causes the inhibition in the system. Total VFA concentrations do not exceed the range of 1,000-1,500 mg/L (Frostell, 1985). The VFA concentrations were kept in an acceptable level for the 5,000 mg/L influent COD concentration in anaerobic reactor effluent. The concentrations were showed an alteration between 778 and 1,219 mg/L. The VFA concentrations in membrane effluent were parallel to the anaerobic reactor effluent. The alterations of VFA concentrations during the experimental studies are given in Figure 5.9.a for the influent COD concentration of 5,000 mg/L.

The VFA concentrations were shown significant fluctuations in the anaerobic reactor effluent during the 10,000 mg/L influent COD concentration applications. As explained in the subsection of 5.1.7, Vanderbilt mineral medium was sometimes added to obtain desired environmental conditions and VFA concentrations increased because of this addition. The VFA concentrations in membrane effluent were parallel to the anaerobic reactor effluent. In Figure 5.9.b, the alterations of VFA concentrations during the experimental studies with the influent COD concentration of 10,000 mg/L are given.

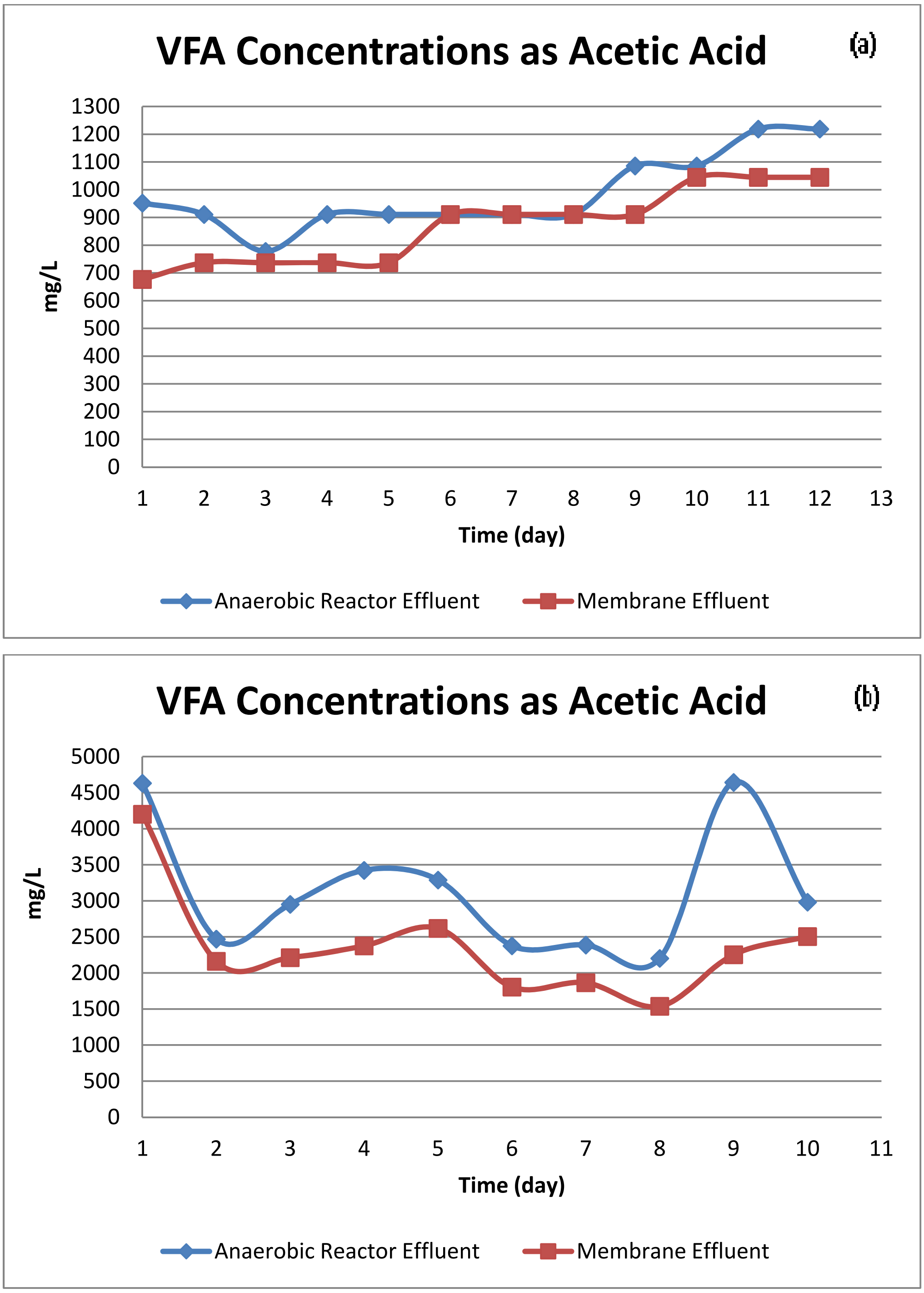


Figure 5.9 VFA variations, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

VFA and alkalinity parameters alone may not be a good indicator to assess the stability of anaerobic reactors. Instead, VFA / alkalinity ratio is a better alternative.

Sánchez, Borja, Travieso, Martin, & Colmenarejo, (2005) and Malpei, Andreoni, Daffonchio, & Rozzi, (1998) suggested that values lower than 0.3-0.4 are optimum. In this study, VFA to alkalinity ratios during the experimental studies were lower than 1.4 and 0.03 for influent COD concentration of 5,000 mg/L and 10,000 mg/L applications, respectively. So, it can be concluded that there was an acidification problem during the 5,000 mg/L COD application. This result was surprise because in general, when the organic loading rate increase volatile fatty acids (VFAs) accumulation may be run (Skouteris et al., 2012).

5.1.9 Flux

The flux is a flow quantity which passes through the membrane unit area at a unit time. It is described as m^3/m^2.day or L/m^2.hour. The average permeate flux is the most commonly used parameter to indicate the performance of a membrane process (Chen, Song, Ong, & Ng, 2004). The flux is directly proportional to the membrane pressure and inversely proportional to the viscosity (Wang, Way, & La Valle, 2001). Decreasing pore length enhances the permeate flux (Ma & Song, 2006). The flux must be stable and the energy consumption must be minimized in membrane processes. The process must be optimized with the permeate flux, pressure and temperature to achieve the minimization (Özkan, 2007). The alteration of flux as a function of pressure for different types of membranes is given in Figure 5.10 (Wagner, 2001).

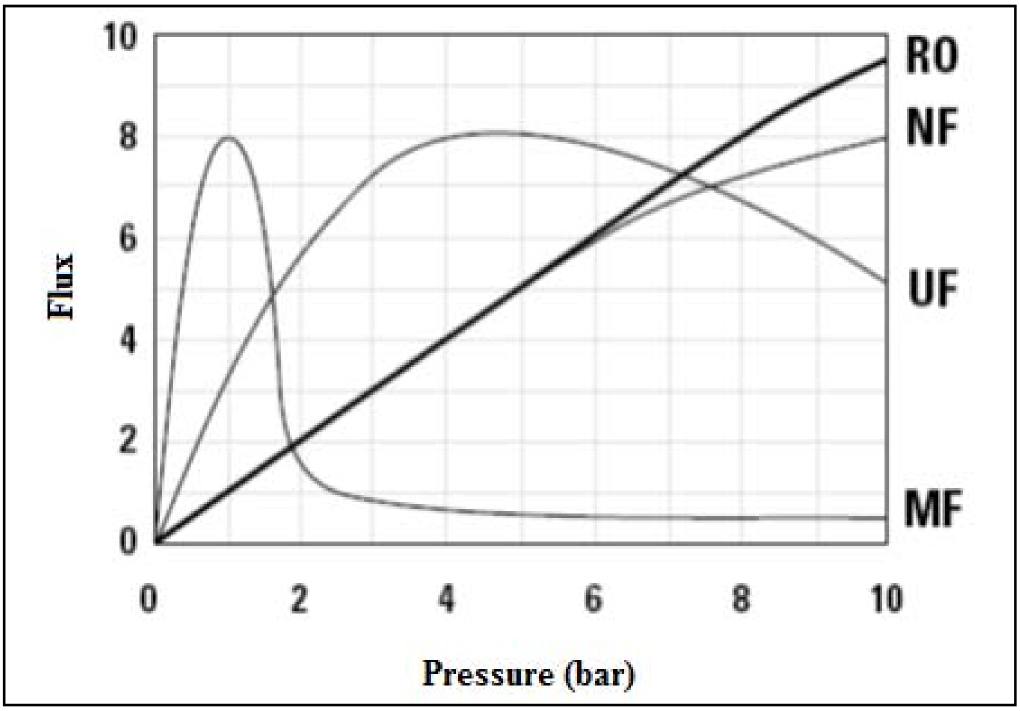


Figure 5.10 The alteration of flux as a function of pressure (Wagner, 2001)

The flux decreases in UF systems when the feed pressure is increased. The pressure could be used a variable to optimize the permeate flux in RO and NF systems. However it doesn't determine the permeate flux in UF and MF systems (Özkan, 2007).

The variations of flux during the experimental studies are given in Figure 5.11 for the mesophilic conditions. The graphic was shown fluctuations in itself after first two minutes. However, the amount of permeate were kept between 21 and 34 mL/minute while the average was 25 mL/minute. The effective filtration area of the membrane system is 0.1 m^2. Consequently, the flux was calculated as 15 $L/m^2.h$ for the mesophilic conditions.

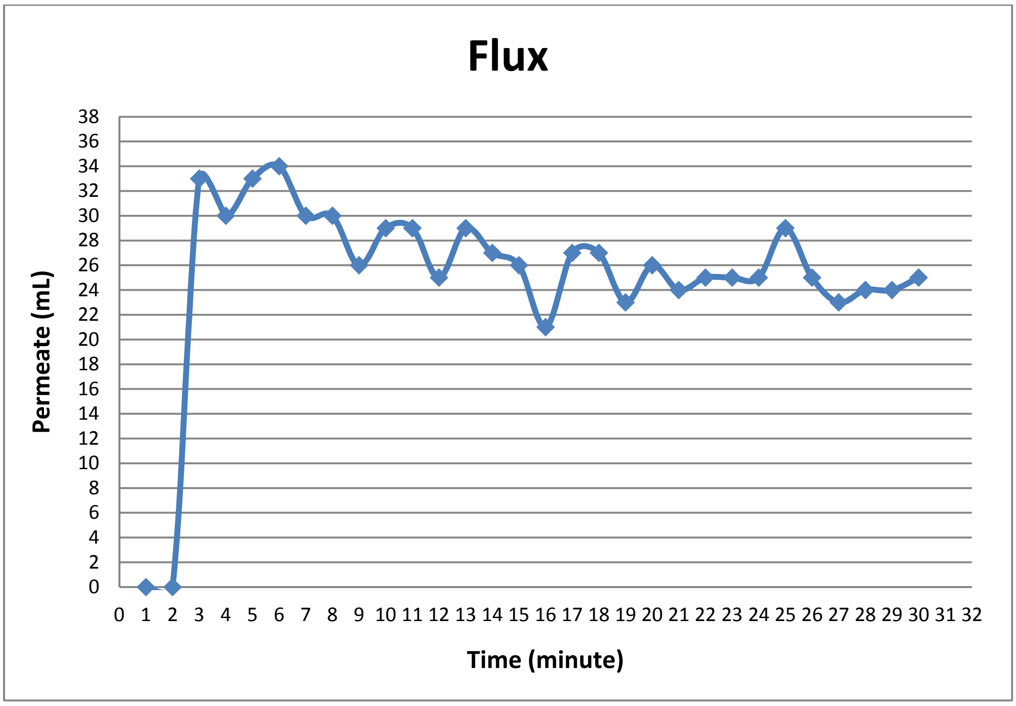


Figure 5.11 The alterations of flux for the mesophilic conditions

5.2 Thermophilic Conditions

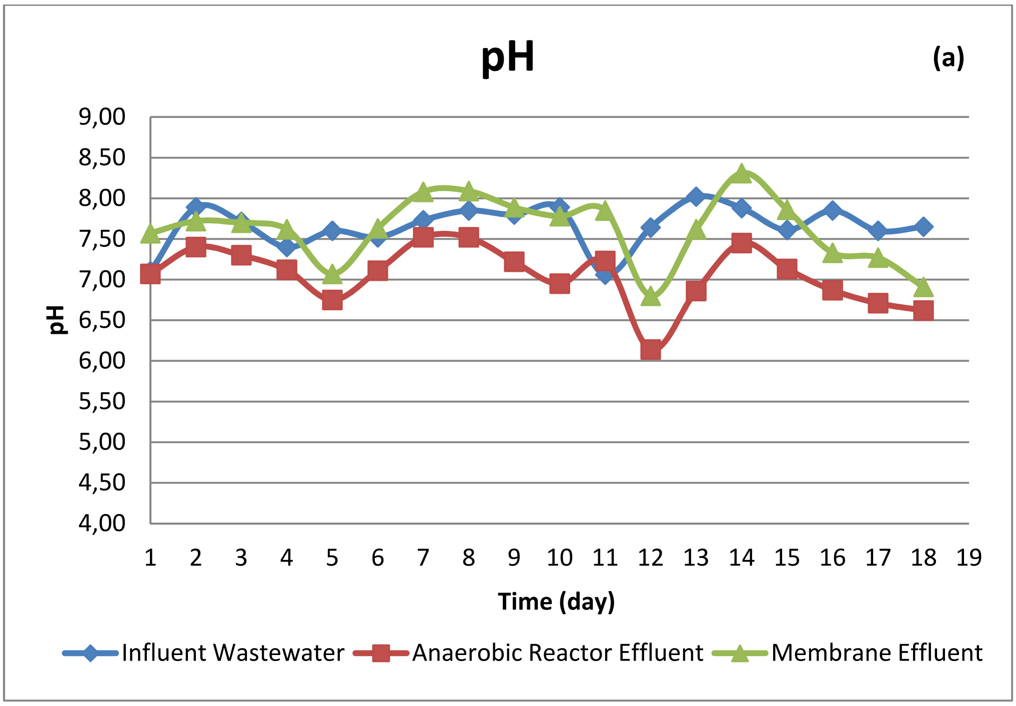
In order to evaluate the effects of high temperature on the treatment efficiency of the AnMBR model system, temperature was increased to 55 °C. Experimental studies were carried out for two different COD influent concentrations (5,000 - 10,000 mg/L) under thermophilic conditions (55 °C). The results are discussed below on the basis of the parameter.

5.2.1 pH

pH alterations during the experimental studies are given in Figure 5.12.a for the influent COD concentration of 5,000 mg/L for thermophilic conditions. Influent wastewater pH was changed between 7.06 and 8.02 depending on the tap water properties. The anaerobic reactor effluent pH did not fall to below 6.14, which is lower the adequate value for the growth of methanogenic bacteria. The highest pH value was measured as 7.52 for the reactor effluent. pH value of the membrane effluent showed an alteration between 6.80 and 8.31. The pH of the reactor and membrane effluent were almost parallel. Throughout the study, the membrane effluent pH values always kept over the pH values of the anaerobic reactor effluent.

The results of pH measurements carried out during the experimental studies with the influent COD concentration of 10,000 mg/L are given in Figure 5.12.b. Influent wastewater pH was almost stable and changed between 7.19 and 7.64. During 14 days, the anaerobic reactor effluent pH did not fall to below 6.19, which is lower the adequate value for the growth of methanogenic bacteria. The anaerobic reactor effluent pH decrease to 5.51 on the 15th day of the study and Vanderbilt mineral medium was added. Thereafter, the anaerobic reactor effluent pH did not fall to below 6.33. The maximum pH value was measured as 7.07 for the reactor effluent. The range of 6.19 and 7.07 is enough to accruing the anaerobic treatment. pH value of the membrane effluent showed an alteration between 5.86 and 7.75. The pH of the reactor and membrane effluent were almost parallel. Membrane effluent pH values were always higher than the anaerobic reactor effluent.

Comparing to mesophilic conditions, a little bit higher pH values were determined for thermophilic conditions. The reason of this increase may be the reduction of CO_2 solubility with temperature.



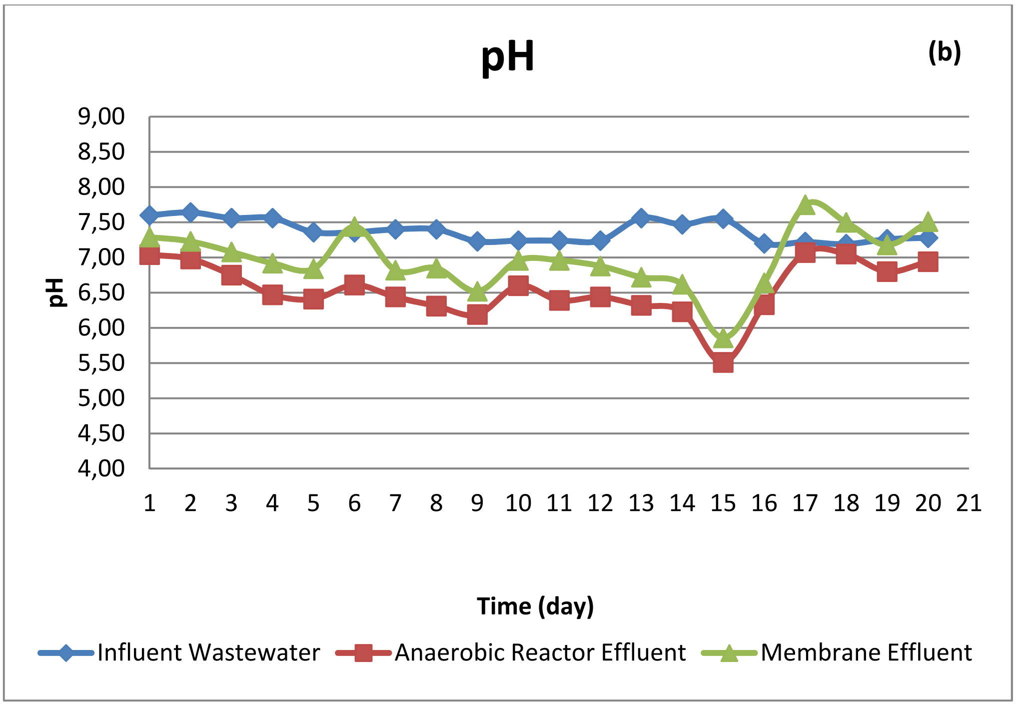
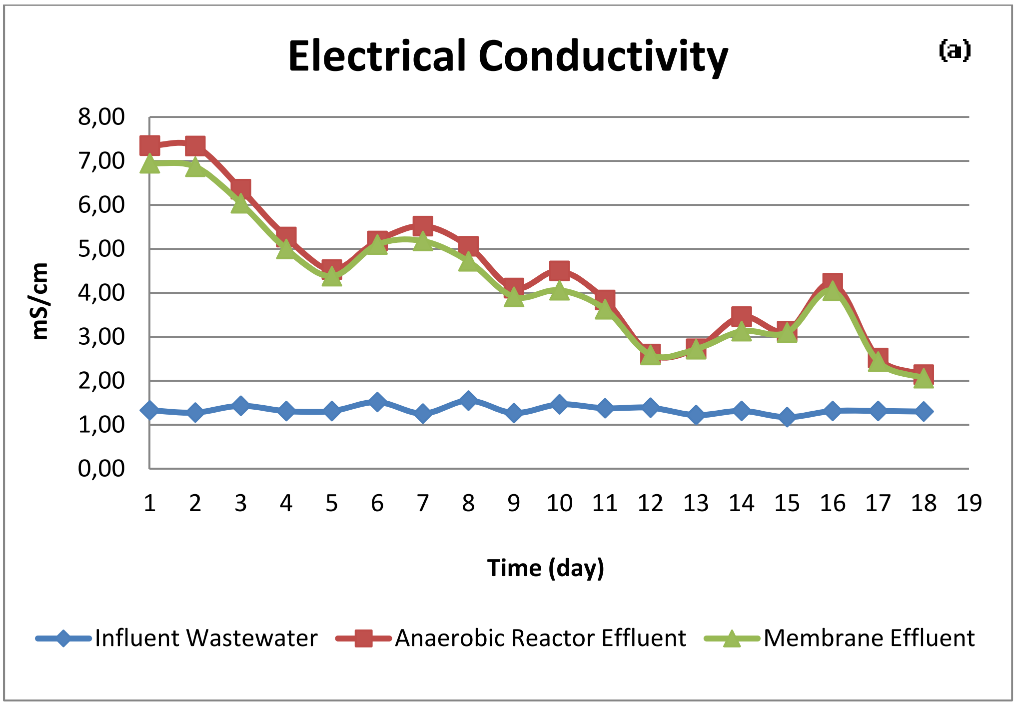


Figure 5.12 pH fluctuations during the studies, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg/L

5.2.2 Electrical Conductivity (EC)

The results of EC analyses are shown in Figure 5.13.a and 5.13.b for the influent COD concentration of 5,000 and 10,000 mg/L, respectively.



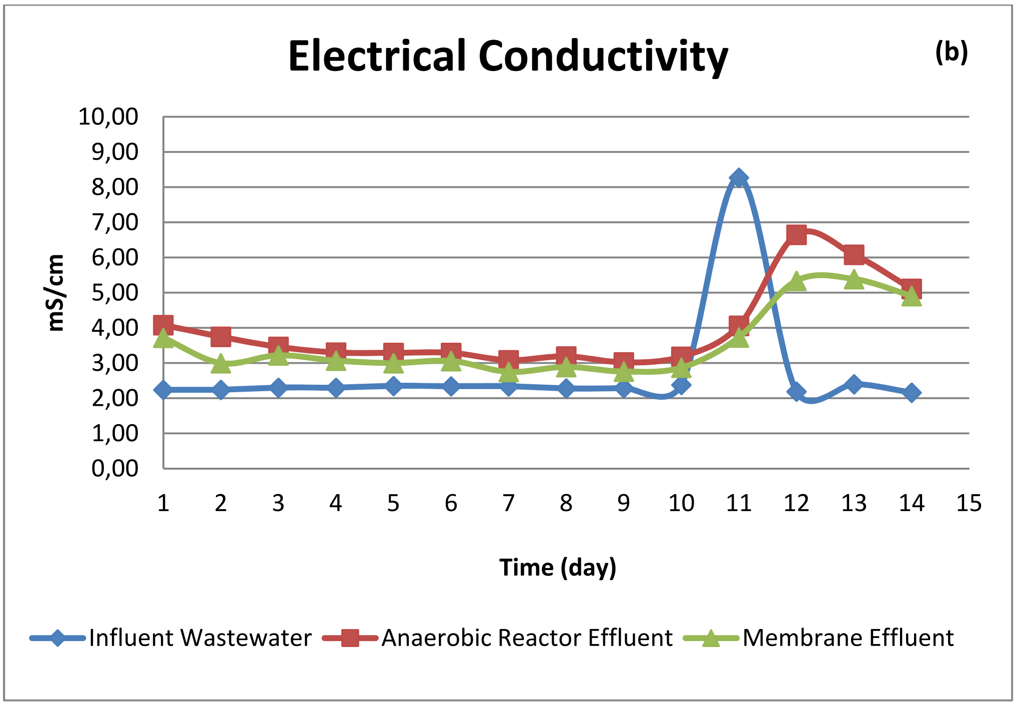


Figure 5.13 Variation of EC, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

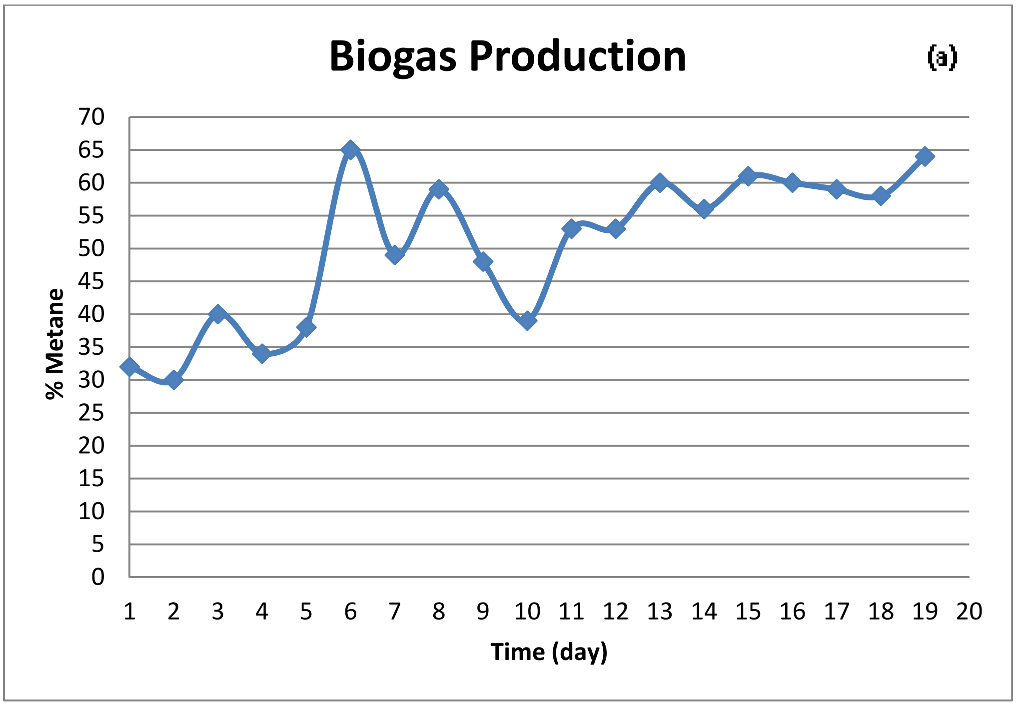
EC values of influent wastewater were almost stable but anaerobic reactor and membrane effluent EC values were shown a downward tendency during the studies carried out with 5,000 mg/L influent COD concentration. It dropped from about 7 mS/cm to 2 mS/cm throughout the study.

During the studies carried out with the influent COD concentration of 10,000 mg/L, EC values of the effluent of the anaerobic reactor and membrane unit were almost stable and parallel to each other until the 11^{th} measurement. At this time pH decreased to 5.51 (see Figure 5.12.b) and Vanderbilt mineral medium was added to adjust environmental conditions. Influent wastewater EC value sharply increased from 2 to 8 mS/cm after Vanderbilt mineral medium addition. It is thought that, Vanderbilt mineral medium was caused increasing EC values for anaerobic rector and membrane effluent after the 11^{th} measurement.

5.2.3 Biogas Production

In this study, average methane content of the biogas was determined as 50.4% while the maximum was 65.0% for 5,000 mg/L influent COD concentration (Figure 5.14.a). Methane percentage of the total biogas changes depending on the wastewater composition and operating conditions of reactors. Wijekoon, Visvanathan, & Abeynayaka, (2011) investigated the effect of organic loading rates of 5.1, 8.1 and 12.0 kg COD m^3 d^{-1} on microbial activity of a two-stage thermophilic anaerobic membrane bioreactor and they concluded that methane generation has increased with an increasing loading rate and methane composition of biogas was about 55–65%. Yang, Tsukahara, & Sawayama, (2008) reported that the methane concentration under thermophilic conditions was relatively higher and more stable than under mesophilic conditions.

Increasing the influent organic load had a positive effect on the formation of biogas. Biogas quality produced in 10,000 mg/L COD application is better than biogas quality produced in 5,000 mg/L COD application (Figure 5.14.b). Average and maximum methane gas content was measured as 59.8% and 77.8%, respectively.



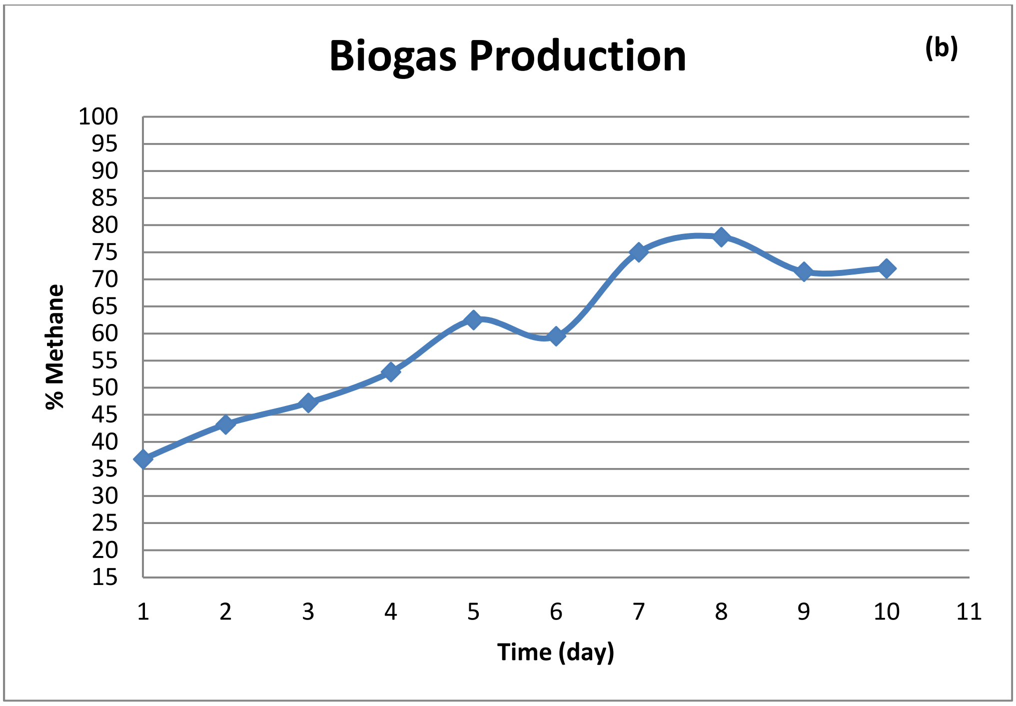


Figure 5.14 Methane gas content of the biogas, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

5.2.4 Solid Fractions

5.2.4.1 Total Solids (TS)

Total solids concentrations of the influent wastewater did not change significantly depending on the influent wastewater COD concentration. Total solids concentrations of influent wastewater were changed between 6,000 and 15,000 mg/L. TS concentrations range of the anaerobic reactor was about 1,200 – 1,800 mg/L and 3,800 – 5,900 mg/L for 5,000 and 10,000 mg/L COD concentration application, respectively. Figure 5.15 shows the TS concentration variations for 10,000 mg/L influent COD concentration. Because there is no enough data, the graph for 5,000 mg/L is not drawn.

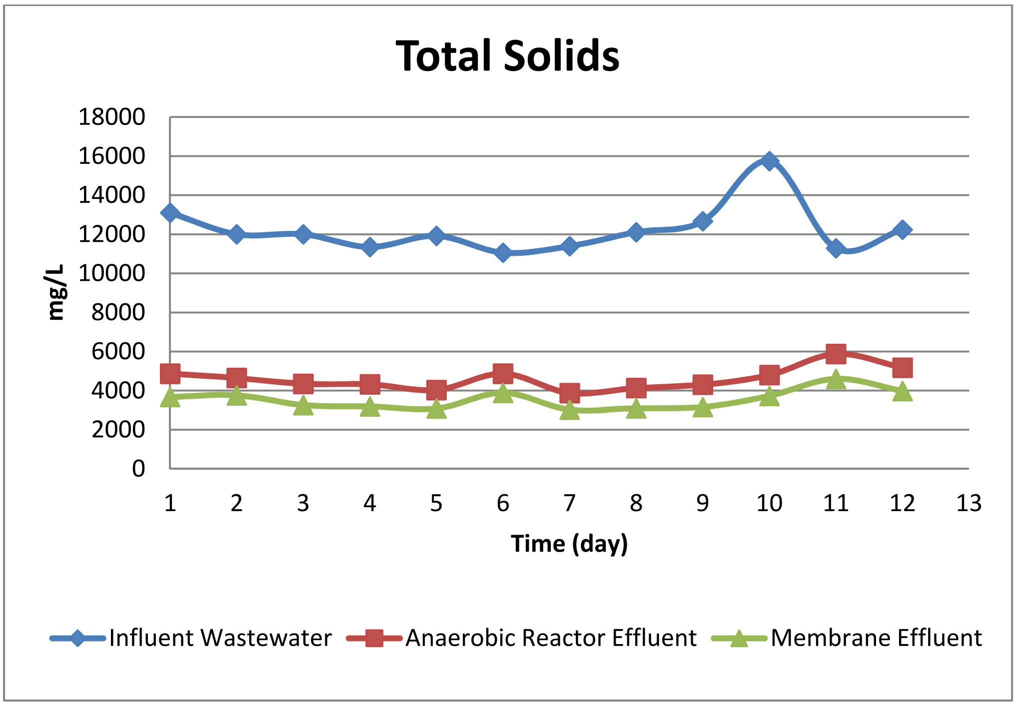


Figure 5.15 Total solids concentrations for the influent COD concentration of 10,000 mg/L

5.2.4.2 Total Volatile Solids (TVS)

TVS concentrations of influent, anaerobic reactor effluent and membrane effluent for 5,000 and 10,000 mg/L COD concentration applications were almost same. In both cases, total volatile solids concentrations of influent wastewater were changed between 8,600 and 10,500 mg/L; TVS concentrations of the anaerobic reactor effluent were changed between 2,000 and 3,100 mg/L; and TVS concentrations of the membrane effluent were changed between 1,300 and 2,400 mg/L. Total volatile solids concentrations during the experimental studies are given in Figure 5.16 for the influent COD concentration of 10,000 mg/L.

TS and TVS content of the sludge were also measured rarely. TS content of the sludge decreased slowly and it was constant about 1.8%. In contrast to this situation, TVS content of the sludge increased gradually and it reached to 67%.

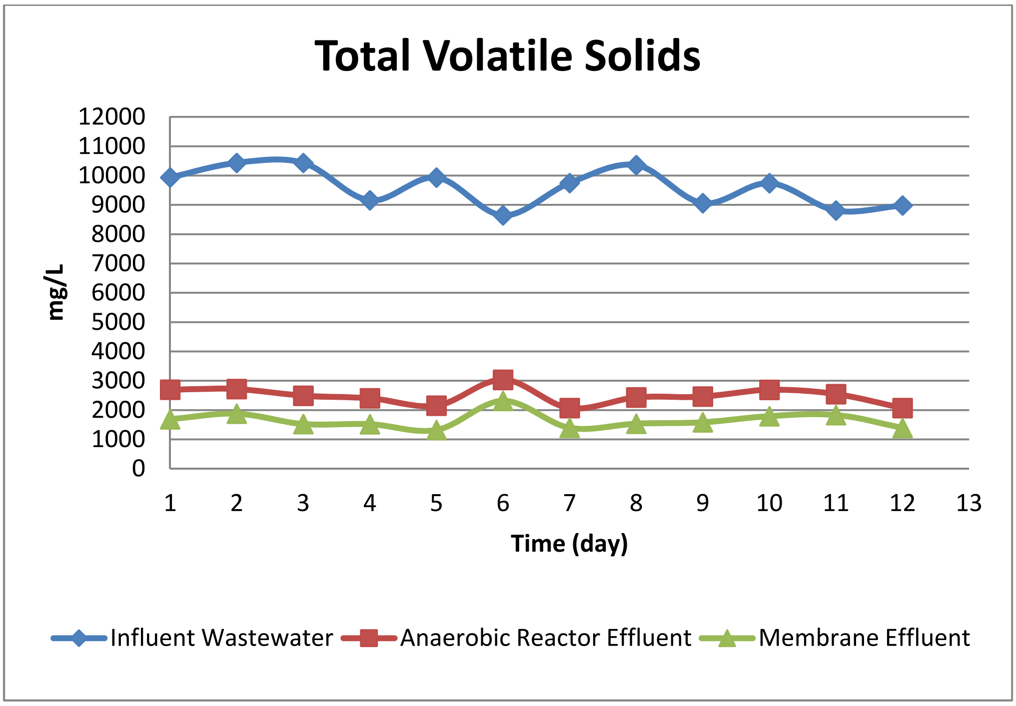


Figure 5.16 Total volatile solids concentrations for the influent COD concentration of 10,000 mg/L

5.2.4.3 Total Suspended Solids (TSS)

As it is expected, high suspended solid removal efficiencies were obtained with UF membrane system, in this study.

Similar results were obtained with the influent COD concentration of 5,000 and 10,000 mg/L. Total suspended solids concentrations of influent wastewater were changed between 45 and 230 mg/L, TSS concentrations of the anaerobic reactor effluent were changed between 280 and 550 mg/L. TSS removal efficiencies up to 97% were achieved with membrane unit.

5.2.5 Chemical Oxygen Demand (COD)

COD analyses were performed for monitoring of organic material degradation and COD concentrations of influent wastewater, reactor effluent and membrane effluent were monitored regularly.

Although it was aimed to work with constant influent COD concentrations, the same values could not be obtained depending on the dilution of the molasses. For example, COD concentrations changed between 4,800 and 6,080 mg/L for 5,000 mg/L influent COD applications. In the anaerobic reactor, the maximum COD removal efficiency was obtained as 76.0% with a COD effluent value of 770 mg/L.

In order to evaluate the whole system (AnMBR) performance, membrane efficiencies are important. Maximum and minimum COD removal efficiency of membrane values were 50.0% and 29.0%, respectively. There were sometimes fluctuations in the membrane effluent and effluent COD concentrations changed between 770 and 2,200 mg/L for the membrane depending on the anaerobic reactor effluent. Maximum total system COD removal efficiency reached to %86.0. COD concentrations and treatment efficiencies during the experimental studies are given in Figure 5.17.a and Figure 5.17.b, respectively, for the influent COD concentrations of 5,000 mg/L.

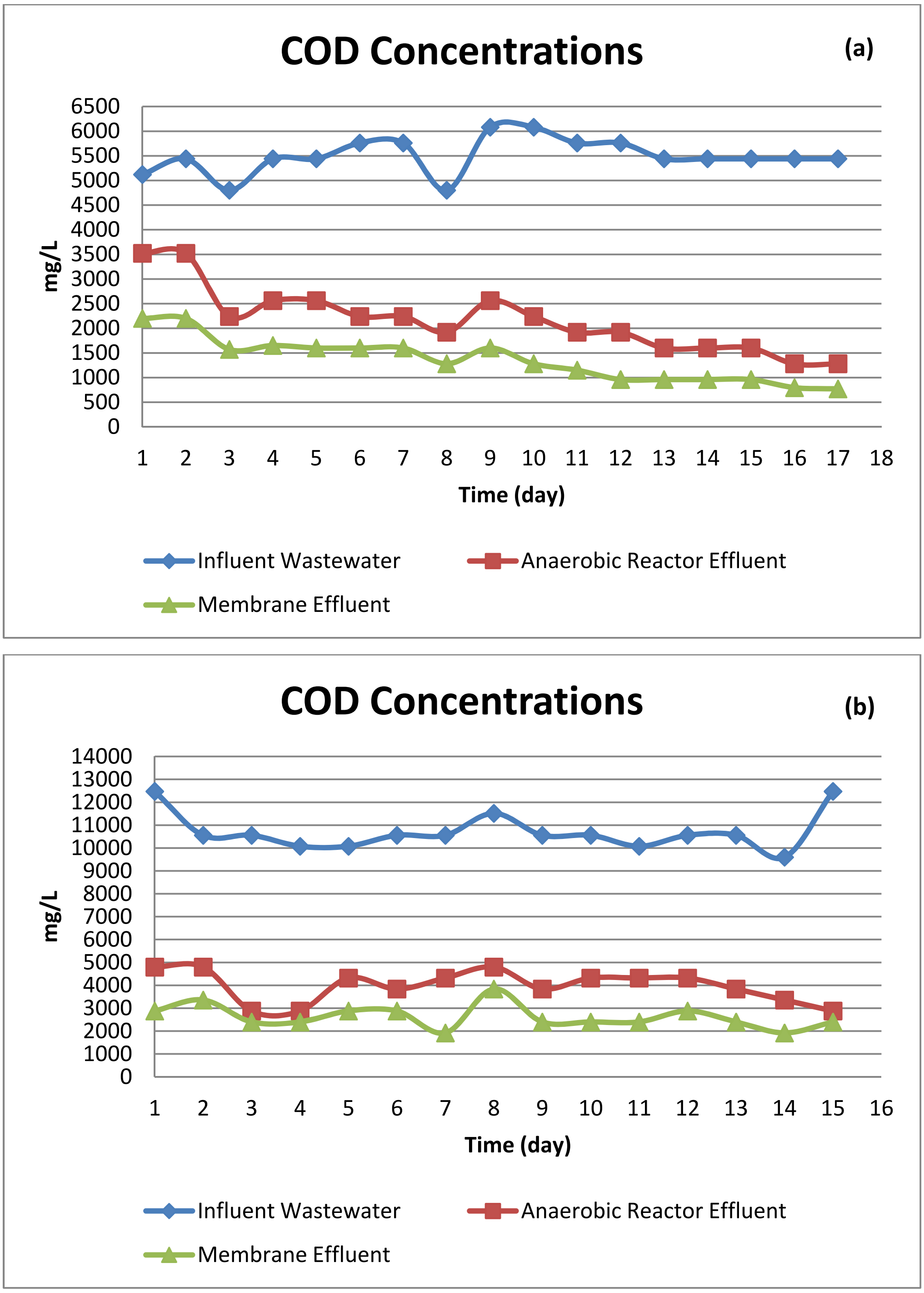
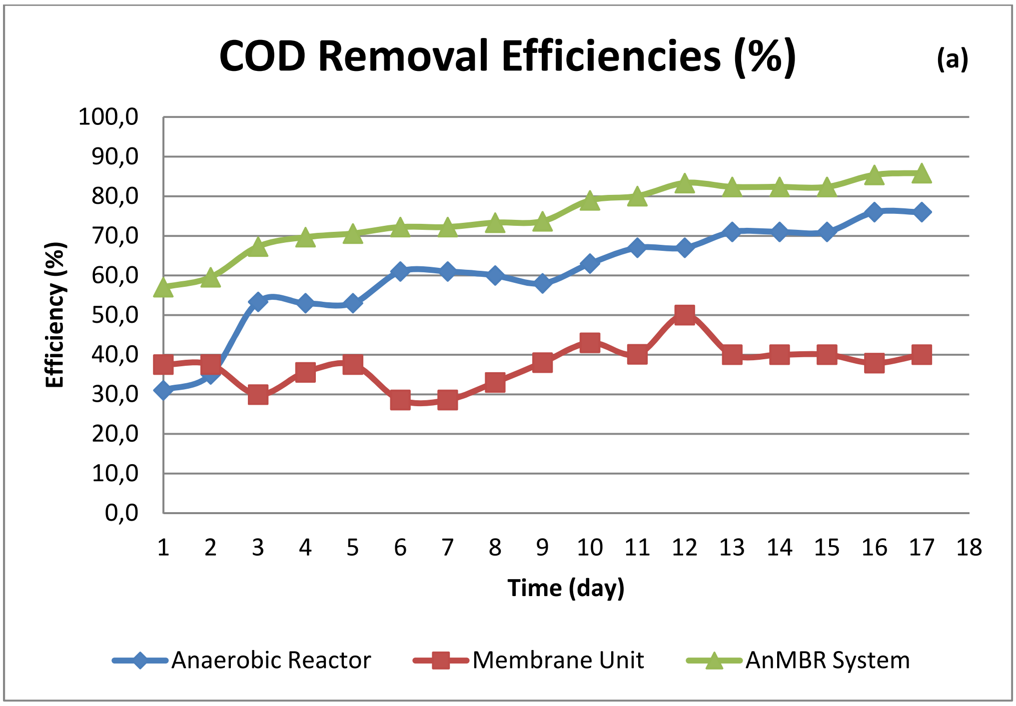


Figure 5.17 Variations of the COD concentrations, a) COD_i = 5,000, b) COD_i = 10,000 mg /L



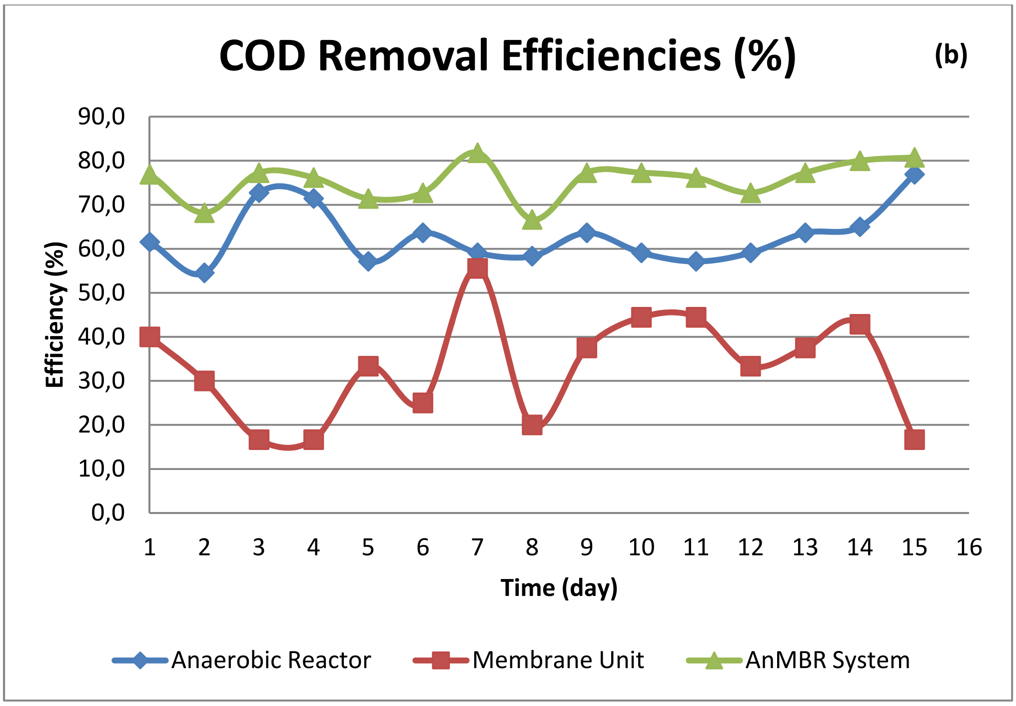


Figure 5.18 COD removal efficiencies, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

During the 10,000 mg/L COD applications, COD concentrations changed between 9,600 and 12,480 mg/L for influent wastewater. The highest removal efficiency reached to 76.9% with a COD effluent value of 2,880 mg/L for the anaerobic reactor. Variable membrane efficiencies were obtained. Effluent concentrations changed between 1,920 and 3,840 mg/L for the membrane unit. Maximum and minimum membrane efficiency values were 55.6% and 16.7%, respectively. Maximum total COD removal efficiency was achieved as %81.8. COD concentrations and treatment efficiencies during the experimental studies are given in Figure 5.18.a and Figure 5.18.b, respectively, for the influent COD concentrations of 10,000 mg/L.

5.2.6 Nitrogen (N) and Phosphorus (P)

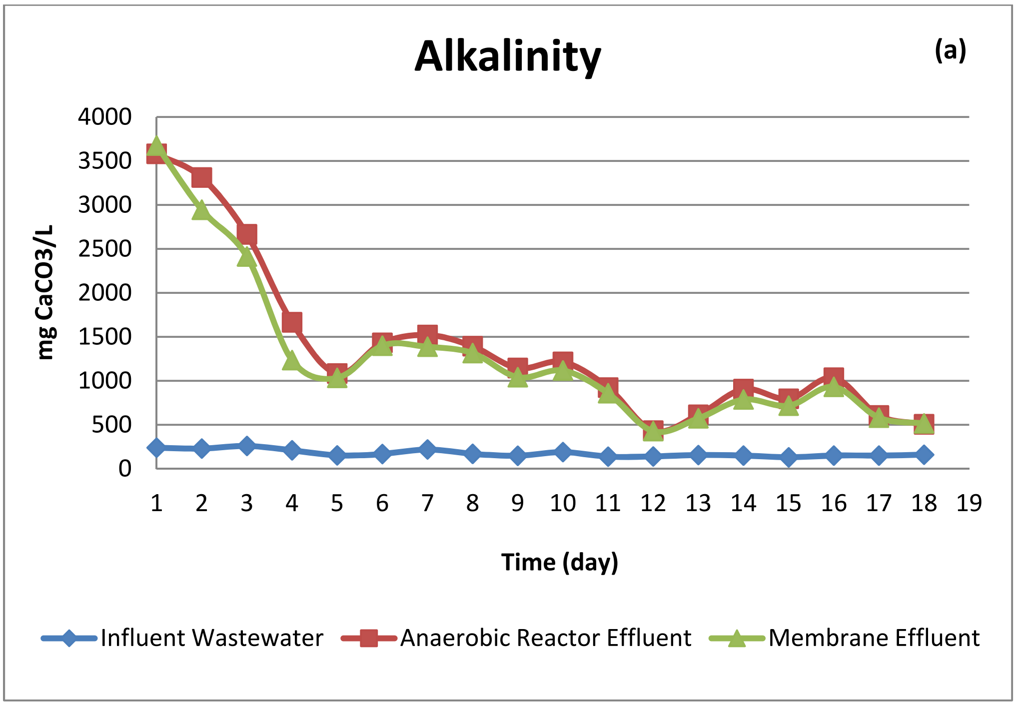
N and P parameters were determined only once. N concentration of influent wastewater was determined about 5.5 mg/L. The anaerobic reactor effluent and membrane effluent was measured as 4.5 mg/L and 2.7 mg/L, respectively.

Influent P concentration was 1.56 mg/L. In the anaerobic conditions, phosphorus release occurred and higher P concentration was measured as 3.97 mg/L in the anaerobic reactor effluent. In the membrane effluent, the P concentration was decreased to 2.89 mg/L.

5.2.7 Alkalinity

Alkalinity concentrations of influent wastewater, reactor effluent and membrane effluent were monitored regularly.

Alkalinity concentrations were stable for influent wastewater. Alkalinity of the anaerobic reactor effluent and membrane unit effluent were higher than influent. Alkalinity concentrations were shown a downward tendency during the study. The concentrations changed between 130 and 260 mg $CaCO_3$/L for influent wastewater, 434 and 3582 mg $CaCO_3$/L for anaerobic reactor effluent, 428 and 3676 mg $CaCO_3$/L for membrane effluent. The anaerobic reactor and membrane effluent concentrations were almost similar. Alkalinity concentrations measured during the experimental studies are given in Figure 5.19.a for the influent COD concentration of 5,000 mg/L.



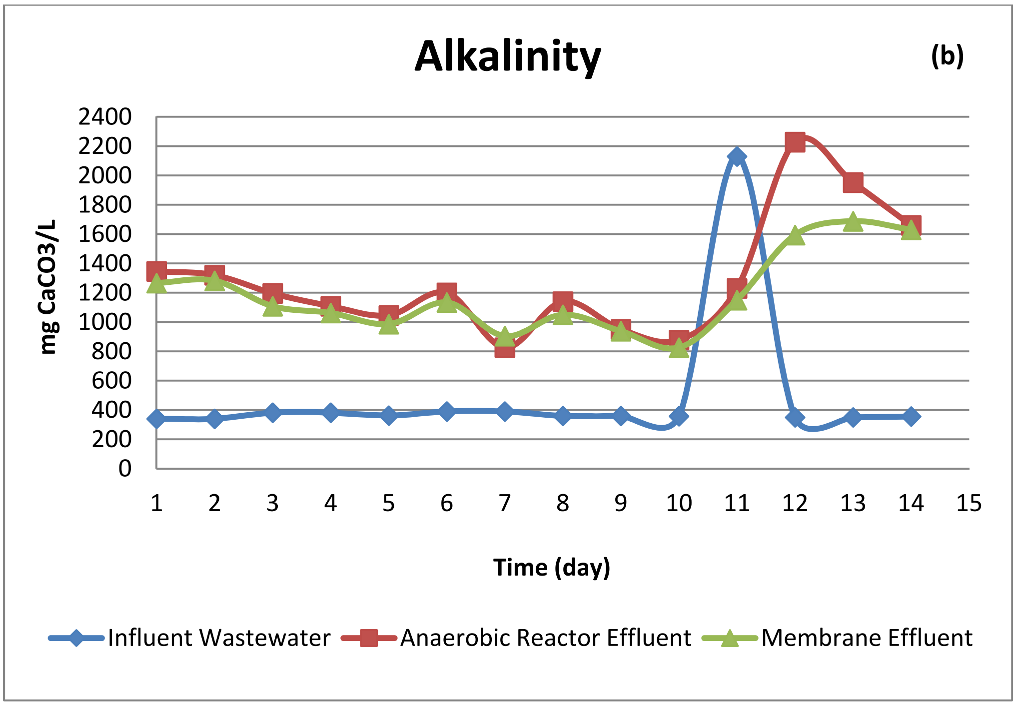


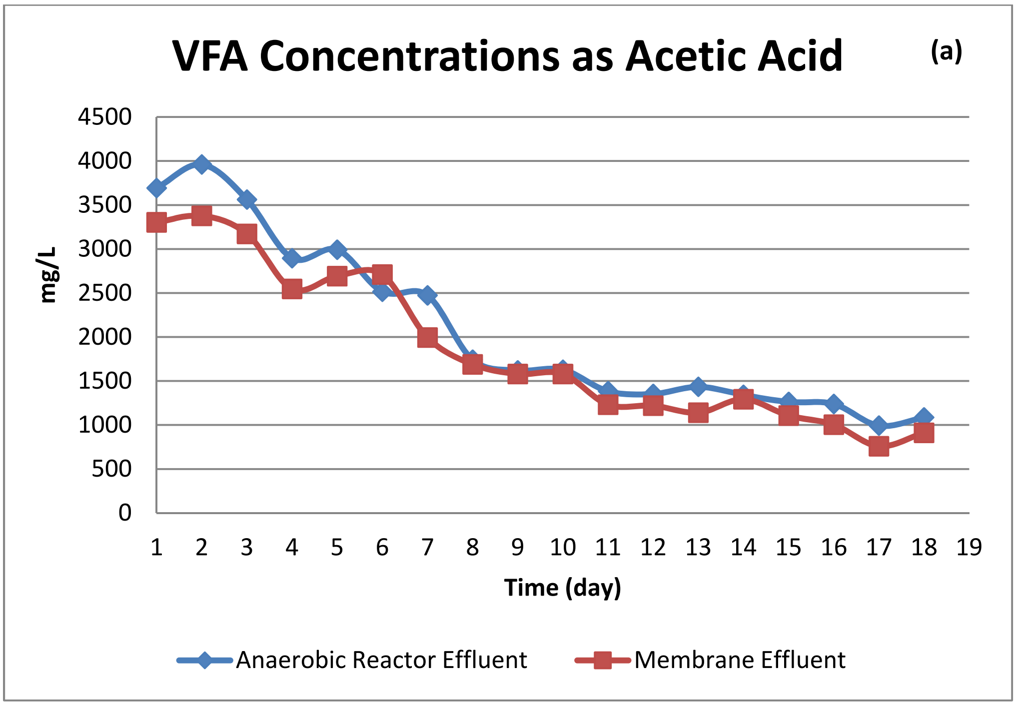
Figure 5.19 Alkalinity changes, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

Alkalinity concentrations of influent wastewater, anaerobic rector and membrane effluent were stable until the 11th measurement for the influent COD concentration of 10,000 mg/L. pH decreased to 5.51 and Vanderbilt mineral medium was added to obtain stable operating conditions. Vanderbilt mineral medium contains a lot of chemicals that can increase alkalinity. Vanderbilt mineral medium was caused increasing alkalinity concentrations for influent wastewater, anaerobic rector and membrane effluent from the 11th measurement. The alkalinity changed between 340 and 2,130 mg $CaCO_3$/L for the influent wastewater, 826 and 2,228 mg $CaCO_3$/L for the anaerobic reactor effluent, 826 and 1,688 mg $CaCO_3$/L for the membrane effluent. The anaerobic reactor and membrane effluent concentrations were similar. Alkalinity concentrations during the experimental studies are given in Figure 5.19.b for the influent COD concentration of 10,000 mg/L.

5.2.8 Volatile Fatty Acids (VFA)

To provide an anaerobic system control VFA concentrations of influent wastewater, reactor effluent and membrane effluent were monitored regularly. The VFA concentrations were shown a downward tendency and kept in an acceptable level after 10 days for the 5,000 mg/L influent COD concentration in anaerobic reactor effluent. The concentrations were showed an alteration between 993 and 3,961 mg/L. The VFA concentrations in membrane effluent were almost parallel to the anaerobic reactor effluent. The alterations of VFA concentrations during the experimental studies are given in Figure 5.20.a for the influent COD concentration of 5,000 mg/L.

The VFA concentrations were shown small fluctuations in the anaerobic reactor effluent during the 10,000 mg/L influent COD concentration applications. The VFA concentrations in membrane effluent were similar to the anaerobic reactor effluent. In Figure 5.20.b, the alterations of VFA concentrations during the experimental studies with the influent COD concentration of 10,000 mg/L are given.



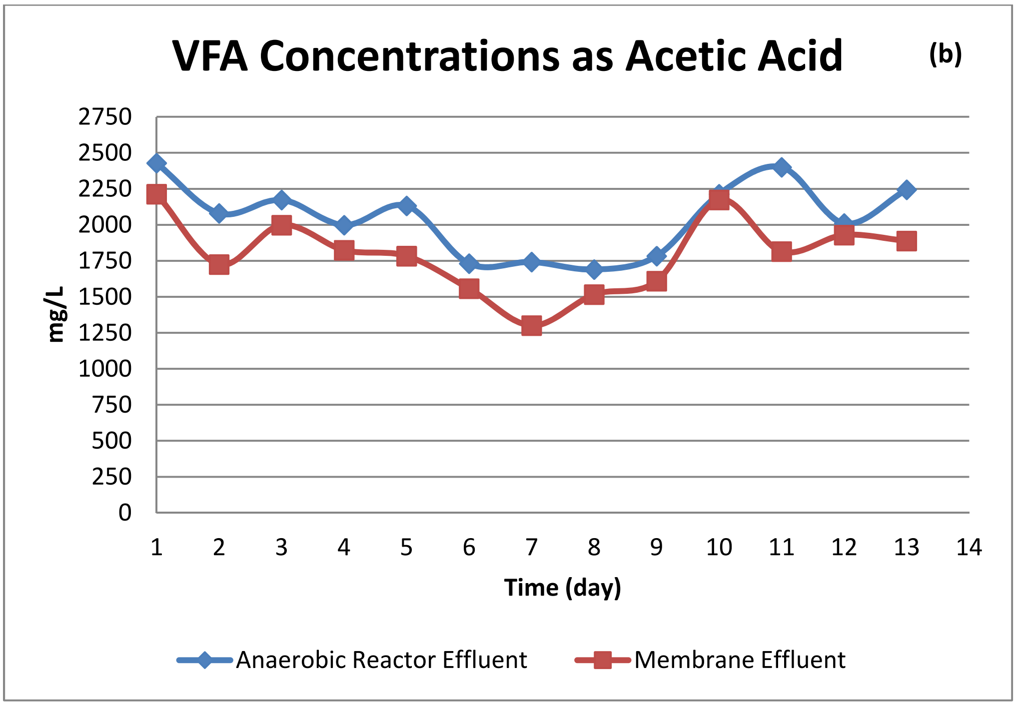


Figure 5.20 VFA variations, a) COD_i = 5,000 mg/L, b) COD_i = 10,000 mg /L

In this study, average VFA to alkalinity ratios during the experimental studies were 1.63 and 1.69 for influent COD concentration of 5,000 mg/L and 10,000 mg/L applications, respectively. However, as it is mentioned the subsection of 5.1.8, VFA / alkalinity ratio lower than 0.3-0.4 is optimum. In thermophilic conditions there was VFA accumulation in the reactor.

5.2.9 Flux

The variations of flux during the experimental studies are given in Figure 5.21 for the thermophilic conditions. The graphic was shown fluctuations in itself after first two minutes. However, the amount of permeate were kept between 41.5 and 70 mL/minute while the average was 48 mL/minute. The effective filtration area of the membrane system is 0.1 m^2. Consequently, the flux was calculated as 28.8 $L/m^2.h$ for the thermophilic conditions.

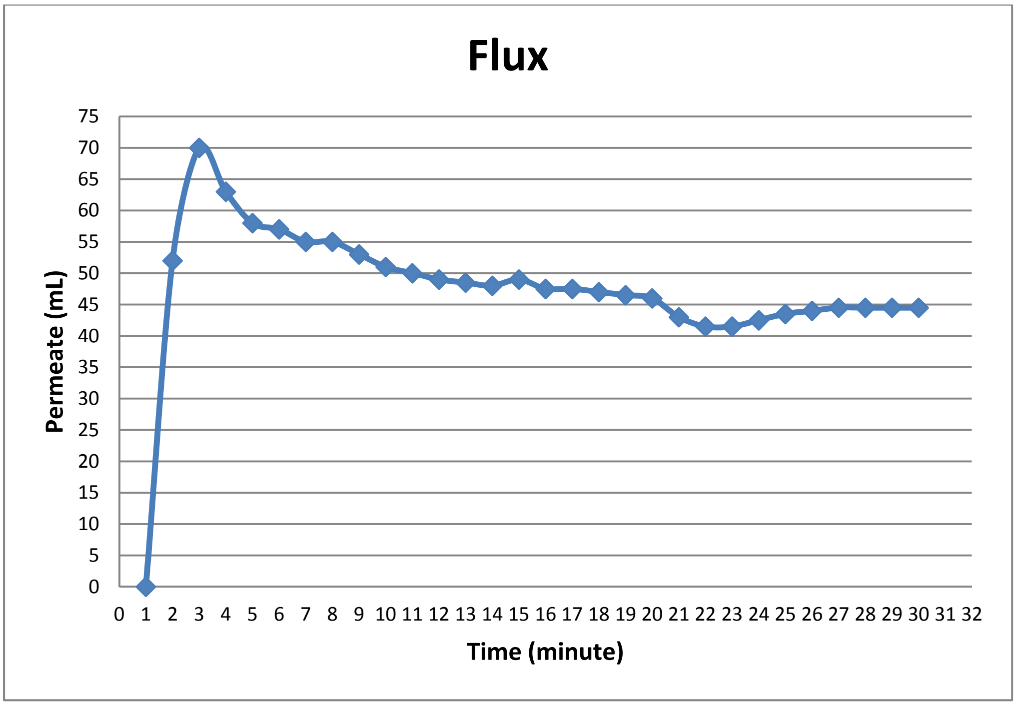


Figure 5.21 The alterations of flux for the thermophilic conditions

5.3 Comparison of Mesophilic and Thermophilic Conditions

5.3.1 Chemical Oxygen Demand (COD)

All COD analyses results are summarized in Table 5.1. In general more COD removal efficiencies were achieved at mesophilic conditions than thermophilic conditions. As seen from the table maximum COD removal efficiency (94.1%) was obtained for 5,000 mg/L COD applications at mesophilic conditions. Negative effect of temperature on COD removal efficiency was observed for all units (anaerobic reactor, membrane system, and total system). Increasing organic load also decreased the system performance. In both temperature conditions, lower efficiencies were obtained at higher loads.

In thermophilic conditions higher VFA to alkalinity ratio was calculated, so at these conditions lower COD removal efficiencies may be achieved due to inhibition of methanogenic bacteria activity. Another reason to decrease in efficiency may be changing system temperature depending on the experimental conditions. In anaerobic systems, it is important to keep constant temperature. Fluctuations in temperature negatively affect the methane formers.

Table 5.1 COD analyses results

Applied Operating Conditions	Maximum COD Removal Efficiencies (%)		
	Anaerobic Reactor	Membrane Unit	Total (AnMBR) System
Mesophilic-5000	82.4	66.7	94.1
Mesophilic-10000	73.9	75.0	91.3
Thermophilic-5000	76.0	50.0	86.0
Thermophilic-10000	76.9	55.6	81.8

5.3.2 Biogas Production

Table 5.2 shows the maximum methane percentage in the total biogas obtained at different operational conditions. In both cases higher methane gas production was observed at higher organic loading.

Maximum methane content of the biogas was determined as 86.7% for the influent COD concentration of 10,000 mg/L at mesophilic conditions. Almost similar result was achieved for the influent COD concentration of 5,000 mg/L. However, although methanogenic activity increases with temperature generally, decreases in methane content of the biogas with increasing temperature were monitored for 10,000 mg/L COD application. This may be because of the decreasing methanogenic activity depending on VFA accumulation at thermophilic conditions.

Table 5.2. Maximum methane gas productions

Applied Operating Conditions	Maximum Methane Production (%)
Mesophilic-5000	64.0
Mesophilic-10000	86.7
Thermophilic-5000	65.0
Thermophilic-10000	77.8

5.3.3 Flux

As explained in detail in section 3.2, in membrane systems, increasing temperature reduces viscosity and flux is getting higher at high temperatures. The results obtained in this study are in accordance with this explanation. In thermophilic conditions about 2 times flux was measured comparing to mesophilic conditions. The amount of measured permeate versus time is shown in Figure 5.22 for both mesophilic and thermophilic conditions.

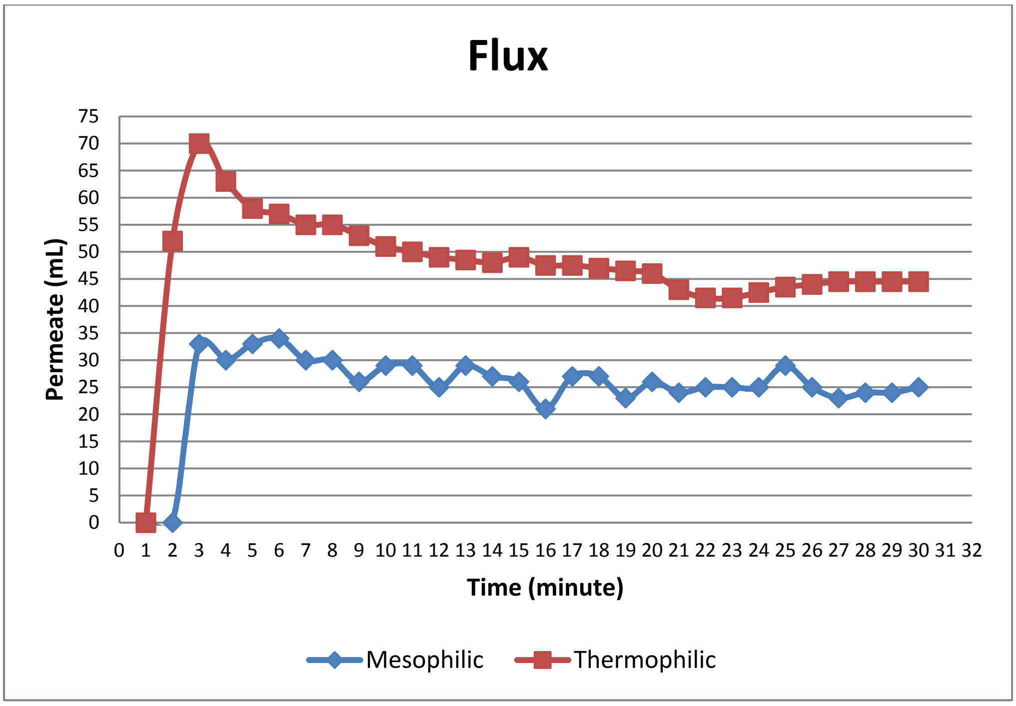


Figure 5.22 The results of flux experiments

CHAPTER SIX

CONCLUSIONS

6.1 Conclusions

Anaerobic membrane bioreactors are becoming widespread and they usually implemented for industrial wastewater treatment. System performance depends on both anaerobic unit efficiency and membrane unit efficiency. Temperature is the one of the most significant operating parameters for anaerobic and membrane systems. In this study, temperature effects on anaerobic membrane bioreactor performances were examined by using lab scale model reactor. In accordance with this study, the following conclusions were obtained:

- No significant pH and EC variations were obtained for mesophilic and thermophilic conditions. A little bit more pH values were measured at high temperature.
- TSS removal efficiencies up to 97% were achieved with membrane unit.
- Average TS removal of the anaerobic system was 55% and 65% for mesophilic and thermophilic conditions.
- COD removal efficiencies of the mesophilic AnMBR system were better than that of the thermophilic reactor.
- Maximum AnMBR system COD removal efficiency was obtained as 94.1% for 5,000 mg/L COD applications at mesophilic conditions.
- Negative effect of temperature on COD removal efficiency was achieved for both the anaerobic unit and membrane unit.
- Maximum methane content of the biogas was determined as 86.7% for the influent COD concentration of 10,000 mg/L at mesophilic conditions.
- Decreases in methane content of the biogas with increasing temperature were monitored for 10,000 mg/L COD application.
- VFA/alkalinity ratio is very important parameter for the monitoring of anaerobic system stability and higher VFA/alkalinity ratio was obtained at thermophilic conditions.

- Flux is directly affected from the wastewater temperature. It increases with increasing temperature. In thermophilic conditions about 2 times flux was measured comparing to mesophilic conditions.

6.2 Recommendations

In the scope of this thesis, effects of mesophilic and thermophilic conditions were examined. Experimental studies under psychrophilic conditions are also being continued. After completion of this study, the comparison should also be performed to understand the temperature affects on the system performances at all conditions.

As a result of the study, mesophilic conditions found more efficient than thermophilic. Since large amount of energy for heating is required to obtain thermophilic conditions, this system should only be evaluated as an alternative treatment unit if the original wastewater temperature is high.

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