

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**ANAEROBIC ELECTRO DYNAMIC MEMBRANE
BIOREACTOR FOR HIGH STRENGTH WASTEWATER
TREATMENT**

MOHAMMED SAMEER GHANIM GHANIM

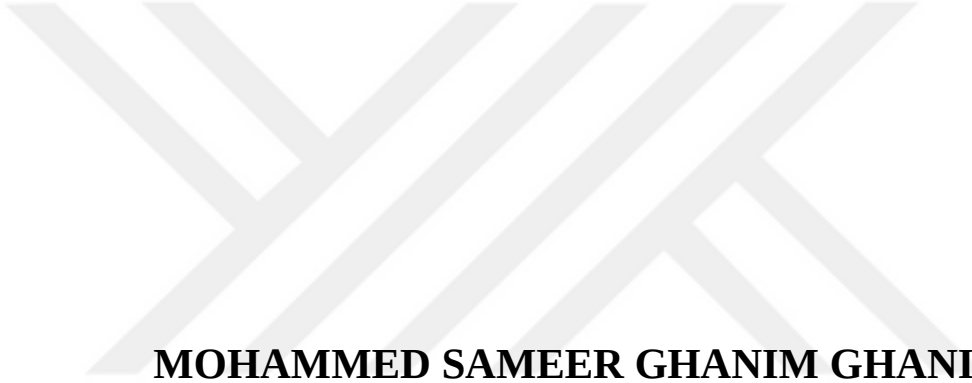
**A THESIS OF DOCTORATE
DEPARTMENT OF ENVIRONMENTAL ENGINEERING**

ADVISOR: PROF. DR. AHMET KARAGÜNDÜZ

JUNE 2025

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T.C.
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LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

YÜKSEK YÜKLÜ ATIKSULARIN ARITIMI İÇİN
ANAEROBİK ELEKTRO DİNAMİK MEMBRAN
BİYOREAKTÖR

MOHAMMED SAMEER GHANIM GHANIM

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DANIŞMAN: PROF. DR. AHMET KARAGÜNDÜZ
2. DANIŞMAN: PROF. DR. NURİYE ALTINAY PERENDECİ

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JURY

MEMBER

(THESIS ADVISOR) : Prof. Dr. Ahmet KARAGÜNDÜZ

MEMBER

: Prof. Dr. Bülent KESKINLER

MEMBER

: Prof. Dr. Nadir DIZGE

MEMBER

: Prof. Dr. Melek ÖZKAN

MEMBER

: Assoc. Prof. Dr. Derya YÜKSEL İMER

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Dedication

To my beloved wife

*I am deeply grateful for your
sacrifices that have enabled me
to pursue my academic
aspirations.*

ABSTRACT

This study compares the performance of an Anaerobic Dynamic Membrane Bioreactor (AnDMBR) and an Anaerobic Electro-Dynamic Membrane Bioreactor (AnEDMBR) in treating high-strength wastewaters for both synthetic wastewater and leachate, with a focus on chemical oxygen demand (COD) removal efficiency, biogas production, and membrane fouling control. Both systems operated at hydraulic retention times (HRTs) of 8 and 5 days for synthetic wastewater and 5 days for real leachate wastewater, applying voltages of 0.8 and 1.2 V in the AnEDMBR. The AnEDMBR demonstrated superior COD removal, achieving up to 98% efficiency for synthetic wastewater, a slight improvement over the AnDMBR. However, for real leachate wastewater, COD removal efficiency dropped to approximately 78%, due to the high presence of refractory organics. Biogas production in the AnEDMBR exceeded that of the AnDMBR by 4.5% and 10% for synthetic wastewater at 8 and 5 HRTs, respectively, but decreased by 36% when treating real leachate wastewater. In terms of membrane fouling, the AnEDMBR displayed enhanced resistance due to lower extracellular polymeric substances (EPS) accumulation, aided by electrostatic repulsion, which reduced fouling pressure. The concentration of biomass in all systems remained high, crucial for treating high-strength wastewater. Methane yields were also higher in the AnEDMBR, reaching by 9.6% at 8 day HRT stage and 7.6% at 5 day HRT stage greater volume per COD removed compared to the AnDMBR system. The results reveals that the applied electric field in the AnEDMBR enhances pollutant removal, biogas production, and membrane performance, making it an effective technique for treating high-strength wastewater. This study provides a significant information for the application of AnEDMBR technology in treating high-strength organic wastewater.

Keywords: Activated Carbon Fabric, Anaerobic Treatment, Anaerobic Electro-Dynamic Membrane Bioreactor, Dynamic Membrane, Membrane Fouling.

ÖZET

Bu doktora tezinin amacı, yüksek konsantrasyonlu atıksuların arıtımında Anaerobik Dinamik Membran Biyoreaktör (AnDMBR) ile Anaerobik Elektro-Dinamik Membran Biyoreaktör (AnEDMBR) performansının hem sentetik atıksu, hem de sızıntı suyu için karşılaştırılmasıdır. Doktora tezi, AnDMBR ve AnEDMBR reaktörlerde sızıntı suyunun arıtımında kimyasal oksijen ihtiyacı (KOİ) giderim verimliliği, biyogaz üretimi ve membran tıkanma kontrolüne odaklanmaktadır. Her iki sistem, sentetik atıksu için 8 ve 5 gün, sızıntı suyu için ise 5 gün hidrolik bekleme sürelerinde (HRT) çalıştırılmış, AnEDMBR'de 0,8 ve 1,2 V voltajlar uygulanmıştır. AnEDMBR, sentetik atıksuda %98'e kadar KOİ giderim verimliliği ile AnDMBR'den daha iyi giderim verimi göstererek üstün performans sergilemiştir. Ancak, gerçek sızıntı suyu için KOİ giderim verimliliği, zor bozunur organiklerin yüksek varlığı nedeniyle yaklaşık %78'e düşmüştür. AnEDMBR'de biyogaz üretimi, sentetik atıksuda 8 ve 5 HRT'lerde sırasıyla %4,5 ve %10 oranında AnDMBR'yi aşarken, sızıntı suyu arıtımında %36 azalmıştır. Membran tıkanması açısından AnEDMBR, elektrostatik itme ile desteklenen daha düşük hücre dışı polimerik madde (EPS) birikimi sayesinde daha fazla direnç göstermiş ve tıkanma basıncını azaltmıştır. Tüm sistemlerde biyokütle konsantrasyonu yüksek kalmış olup, bu durum yüksek konsantrasyonlu atıksuların arıtımı için kritik öneme sahiptir. Metan verimi açısından da AnEDMBR sistemi, AnDMBR'ye kıyasla daha yüksek performans göstermiş; 8 günlük HRT koşulunda %9.6, 5 günlük HRT koşulunda ise %7.6 oranında daha fazla metan üretimi (giderilen KOİ başına hacim) elde edilmiştir. AnEDMBR'de uygulanan elektrik alanının kirletici giderimini, biyogaz üretimini ve membran performansını artırarak yüksek konsantrasyonlu atıksu arıtımı için umut verici bir teknoloji olduğunu ortaya koymaktadır. Bu çalışma, yüksek konsantrasyonlu organik atıksuların arıtımında AnEDMBR teknolojisinin uygulanması için önemli bilgiler sağlamaktadır.

Anahtar Kelimeler: Aktif Karbon Kumaşı, Anaerobik Arıtım, Anaerobik Elektro-Dinamik Membran Biyoreaktör, Dinamik Membran, Membran Kirlenmesi.

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LIST OF SYMBOLS AND ABBREVIATIONS

AnDMBR	: Anaerobic Dynamic Membrane Bioreactor
AnEDMBR	: Anaerobic Electro-Dynamic Membrane Bioreactor
AnOMBRs	: Anaerobic Osmotic Membrane Bioreactors
BOD	: Biological Oxygen Demand
COD	: Chemical Oxygen Demand
DM	: Daynamic membrane
DO	: Dissolved Oxygen
DMBR	: Dynamic Membrane Bioreactor
EPS	: Extracellular Polymeric Substances
FIP	: Formed-In-Place
GC	: Gas Chromatography
HRT	: Hydraulic Retention Time
Kg	: Kilogram
MARS	: Membrane Anaerobic Reactor System
MBR	: Membrane Bioreactor
MEC	: Microbial Electrolysis Cell
MF	: Micro-Filtration
MLSS	: Mixed Liquor Suspended Solids
MLVSS	: Mixed Liquor Volatile Suspended Solids
MRC	: Microbial Recovery Cell
NF	: Nano-Filtration
RO	: Reverse Osmosis
SFDMs	: Self-Forming Dynamic Membranes
SMP	: Soluble Microbial Product
SRT	: Sludge Retention Time
SS	: Suspended Solids
tCOD	: Total Chemical Oxygen Demand
TKN	: Total Kjeldahl Nitrogen
TMP	: Transmembrane Pressure
TN	: Total Nitrogen
TOC	: Total Organic Carbon
TP	: Total Phosphorus
UF	: Ultra-Filtration
V	: Volt
VFA	: Volatile Fatty Acids

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1. INTRODUCTION

The increasing problems of water scarcity and pollution are largely due to population increasing and industrial expansion in recent decades. High-strength wastewater, originating from sources such as food industry waste, landfill runoff, dairy factory effluents, pulp and paper manufacturing discharge, and wastewater from slaughterhouses, represents a complex issue that continues to engage researchers [An et al., 2023], [Mutamim et al., 2012]. Releasing such wastewater without adequate treatment threatens environmental sustainability [Liew et al., 2020]. Conventional aerobic treatment technologies are not well-suited for high-strength wastewater, as they consume huge amounts of energy for aeration and generate excessive sludge that requires further stabilization and disposal [Mutamim et al., 2012]. On the other hand, anaerobic treatment methods prove to be more effective for these types of wastewaters, as they can manage higher organic loads, reduce energy demands, produce less sludge, and enable methane generation for energy recovery [Perendeci et al., 2007], [Kahao, 2021].

The conventional anaerobic digesters typically require long hydraulic retention times (HRT) to reach optimal treatment performance. To address these limitations, several advanced treatment systems have been developed to shorten the HRT and reduce the overall environmental impact. Examples include anaerobic contact process systems, fluidized bed systems, expanded granular sludge bed reactor (EGSBR) systems, up-flow anaerobic sludge blanket reactor (UASBR) systems, and anaerobic sequencing batch reactors. Although these technologies offer notable benefits, they also demand precise operational management to ensure efficiency [Tran et al., 2023].

The anaerobic membrane bioreactor (AnMBR) is recognized as modified treatment system that Integrating both anaerobic digestion and membrane filtration, enabling longer sludge retention time (SRT) and shorter hydraulic retention time (HRT) for effective treatment of high-strength wastewater. AnMBRs offer key advantages, including lower sludge production, higher organic loading rates, compact system design, biogas recovery, and improved effluent quality [Yilmaz et al., 2024]. Moreover, biogas recovery presents substantial potential to significantly contribute to the energy demands of wastewater treatment operations [Song et al., 2018].

Operational issues like membrane fouling remain a major concern, increasing maintenance and energy demands [Kik et al., 2021]. Research has focused on optimizing system parameters such as SRT, HRT, cleaning intervals and exploring fouling control strategies like membrane modification, gas sparging, vibration, and chemical pretreatment. Despite these notable benefits, AnMBR systems are challenged by operational complexities, particularly membrane fouling, which escalates both energy consumption and operational expenditures [Ghanim et al., 2025]. Moreover, the incorporation of pretreatment strategies, like chemical coagulation, has been explored to reduce foulant interactions with membrane surfaces, thereby improving overall system resilience [Min et al., 2024].

The cake layer formation, often stemming from the accumulation of solid particles on the surface of membrane, acts as a dynamic membrane (DM) layer [Ghanim et al., 2025]. This DM layer enhances retention efficiency, even when using cost-effective support membrane materials with large pore sizes, such as woven or mesh filter cloths [Hu et al., 2020]. DM technology offers several advantages over conventional filtration in biological processes, including the elimination of expensive membrane modules (microfiltration or ultrafiltration (MF/UF) membranes) and the provision of a lower-cost, self-regenerating filtering surface with adjustable permeation and high flux rates [Alibardi et al., 2016].

When combined with AnMBR, DM methodology forms the anaerobic dynamic membrane bioreactor (AnDMBR), which uses versatile filter substrates such as micro-meshes and nonwoven textile materials. The system enables independent management of HRT and SRT, sustains anaerobic biomass more effectively, reduces sludge yield, small footprint, and highly resistant to inhibitory substances [Cheng et al., 2020], [Dereli et al., 2012], [Jeong et al., 2017], [Maaz et al., 2019]. The cake layer on the filter allows for online regulation and regeneration of the DM by adjusting flux, which increase membrane life and reduces replacement costs, improving both process stability and economic efficiency [Choi et al., 2022]. Although aerobic dynamic MBRs are widely applied for wastewater treatment, relatively few studies have focused on anaerobic DM systems, and most of which have dealt with low-strength wastewater treatment [Yurtsever et al., 2021]. Samaei et al. (2023) reported that, in the last ten years (2014–2023), only 30 studies evaluated the efficiency of AnDMBRs in handling high-strength wastewater [Samaei et al., 2023].

The evaluating of AnDMBR systems treatment is predominantly measured by COD, TSS, and biogas production rates. Many AnDMBR systems reported achieve high removal of COD and TSS during steady-state operation [Hu et al., 2020]. For instance, Ersahin et al. 2014 noted more than 99% of COD removal efficiency for wastewater treatment (high-strength approximately 20 g/L COD) using AnDMBR [Ersahin et al., 2014]. Evren et al. 2016 also studied the submerged AnDMBR performance for the treating of concentrated wastewater of an average COD of $27,100 \pm 330$ mg/L. The results demonstrated the DM layer's ability to achieve stable and high organic matter removal efficiencies, with 65% for soluble COD and 99% for total COD, and up to 50% for volatile fatty acids (VFAs) [Evren et al., 2016]. While Xie et al. 2014 assessed a pilot-scale of AnDMBR for treatment of landfill wastewater, observing that the DM layer remained fouling-free for 25 days, with an COD removal efficiency of about 62.2% when treating raw leachate containing over 3,000 mg/L of total ammonium and more than 13,000 mg/L of COD [Xie et al., 2014]. Mahat et al. 2021 noted steady operating for over 35-days with a 2.5 L/m².h flux and 5 kg COD/m³.d (OLR) [Mahat et al., 2021]. Xie et al. 2014 operated an AnDMBR at 6 L/m².h flux and observed no clogging of the DM layer until day 25 [Xie et al., 2014].

Recent studies have demonstrated that electrically assisted processes integrated into AnMBR can effectively reduce membrane fouling, enhance COD removal, improve biogas content, and overall performance of AnMBR systems [Deng et al., 2022], [Liu et al., 2022]. This hybrid system, which combines AnMBR with an electrochemical process, is known as AnEMBR or electro-AnMBR [Chen et al., 2023]. In mixed liquor, foulants such as sludge flocs and colloids typically carry a negative charge at neutral pH due to presence groups of electronegative functional species. When the electric field is applied to the surface of membrane in AnMBR, these negatively charged particles undergo electrophoresis and are repelled from the conductive membrane surface, similar to the effects of backwashing [Zhang et al., 2021]. In the AnEMBR systems, where an electrical charge is applied to the surface of the membrane to create electrochemically favorable conditions, it has been noted that the electric field stimulates the growth and metabolic activity of electroactive microorganisms both in the reacted medium and on the surface of the electrode. These conditions have been shown to boost methane production efficiency by increasing the

populations of hydrolytic fermentative, acidogenic, and methanogenic bacteria [Li et al., 2022].

In this PhD thesis, an anaerobic electro-dynamic membrane bioreactor (AnEDMBR) was evaluated. A unique AnEDMBR configuration was constructed, featuring an iron (Fe) anode and an activated carbon fabric as membrane and cathode. The continuous AnEDMBR reactor was operated at two distinct voltages (0.8 V and 1.2 V), and the performance evaluated in comparison with a control AnDMBR system (operated at 0 V). Both systems operated at hydraulic retention times (HRTs) of 8 day and 5 day for synthetic wastewater and 5 day for real leachate wastewater. The AnDMBR and AnEDMBR systems were assessed from the point of COD removal efficiency, biogas production yield, and fouling mechanism. Furthermore, it was assessed how electrostatic repulsion affected EPS's adhesion to the conductivity of the membrane surface.

1.1. Aims and Objectives

The primary objective in our study is to pioneer novel approaches by developing a hybrid, economically feasible, and exceptionally efficient system specifically fitted to the treatment of high-strength wastewater. The objectives of our study are:

- Investigate the applicability of combined anaerobic digestion, electrochemical processes, and dynamic membrane filtration, collectively known as an anaerobic electro-dynamic membrane bioreactor (AnEDMBR) for the treating of two types of high-strength wastewater (synthetic and real leachate).
- Understand how reactor operational conditions, including HRT, OLR and the type of wastewater (synthetic and real leachate) influence the system's filtration properties and removal efficiency of the dynamic membrane (DM).
- Determine the effect of different voltages (0.8 V and 1.2 V) on the performance, removal efficiency, production of biogas and membrane fouling of the AnEDMBR system by comparing it with a control AnDMBR system (operated at 0 V).
- Study the properties of the dynamic membrane (DM) cake layer formed on the support layer and its changes under different voltages (0 V, 0.8 V and 1.2 V)

and assess the influence of electrostatic repulsion on the adherence of SEM and EPS to the conductive membrane surface.

1.2. Significance:

- This thesis offering, for the first time in Turkey a new treatment approach where the AnEDMBR is applied for of high-strength wastewater treatment.
- This study investigates, for the first time in Turkey, the use of an activated carbon fabric membrane for leachate wastewater treatment, which is challenging due to the high organic content that affects the performance of both membrane and biological system.
- This study contributes to sustainable development in wastewater treatment by enhancing the water quality of treated high-strength wastewater in general, and leachate specifically.

2. LITERATURE REVIEW

2.1. Anaerobic Digestion Fundamentals

The concerns of climate change and the global energy problem have heightened the emphasis on wastewater treatment, prompting a shift toward the creation of more economical and energy-saving systems. Traditional aerobic wastewater treatment processes are recognized as energy-intensive due to the substantial energy required for the oxidation of organic matter [Robles et al., 2018]. To address this, anaerobic high-rate conversion procedures are gaining traction for the treating of a many spectrum of biologically polluted wastewaters. This includes types of wastewater that were previously considered unsuitable for anaerobic treatment. Significantly, anaerobic systems are currently being used effectively to treat various industrial wastewaters, especially in countries such as the Netherlands [Schultz, 2005]. **Figure 2.1** illustrates the substantial decrease in sludge volume and the generation of valuable methane-rich biogas during aerobic and anaerobic digestion. The equations below compare aerobic and anaerobic treatment processes [Hufnagel, 2014].

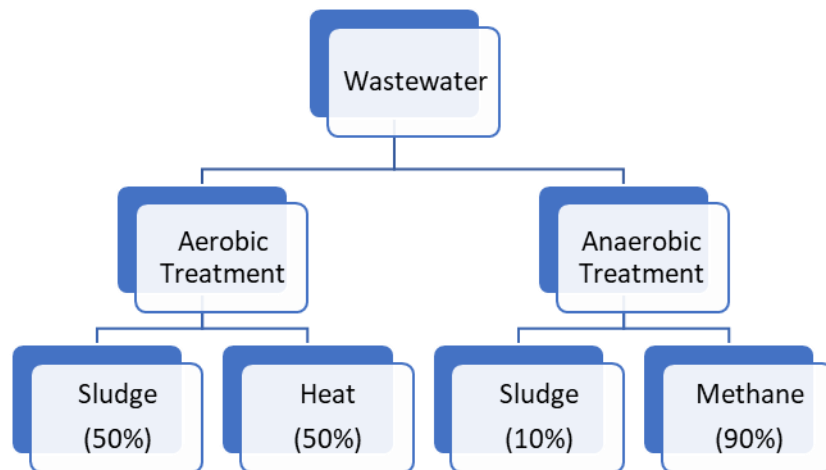
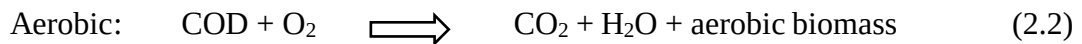


Figure 2.1: The aerobic and anaerobic processes [Adopted from Hufnagel, 2014].

In the aerobic process of wastewater treating, particularly the activated sludge produces a significant amount of sludge. Every kilogram of soluble BOD produced by biological oxidation yields 0.4-0.6 kg of sludge. In contrast, anaerobic treatment processes convert over 90% of the biodegradable organic matter into methane, compared with only 10% or less being transformed into biomass [Khanal, 2009]. In the absence case of oxygen, organic matter decomposed by a abroad group of microorganisms working together, resulting in the formation of digestate and biogas [Bajpai, 2017]. Anaerobic digestion represents the fermentation process where the organic material is degraded, producing biogas, primarily consisting of methane and carbon dioxide. The pathway for the anaerobic decomposition of organic materials involves several series of parallel processes. The four steps of this process of organic matter decomposition are (1) hydrolysis; (2) acidogenesis; (3) acetogenesis; and (4) methanogenesis [Loosdrecht and Brdjanovic, 2008].

Figure 2.2 depicts the steps and chemical reactions occurring during anaerobic digestion. During the hydrolysis step the fermentative bacteria excrete enzymes leading the breakdown of complex and undissolved material into simpler, soluble compounds. The bacteria can then absorb these simpler compounds through their cell walls and membranes. In the Acidogenesis step, soluble compounds in fermentative bacteria cells are transformed into several simple compounds, which are subsequently excreted. This stage produces volatile fatty acids (VFAs), lactic acid, alcohols, CO₂, H₂, NH₃, and H₂S, along with the formation of a new cell material. Acetogenesis is the stage in which digestion byproducts are transforming into acetate, hydrogen (H₂), and CO₂, and a new cell. The final step is methanogenesis in which acetate, carbonate, hydrogen, methanol, or formate are transformed to methane, CO₂, as well as new cell biomass [Loosdrecht and Brdjanovic, 2008].

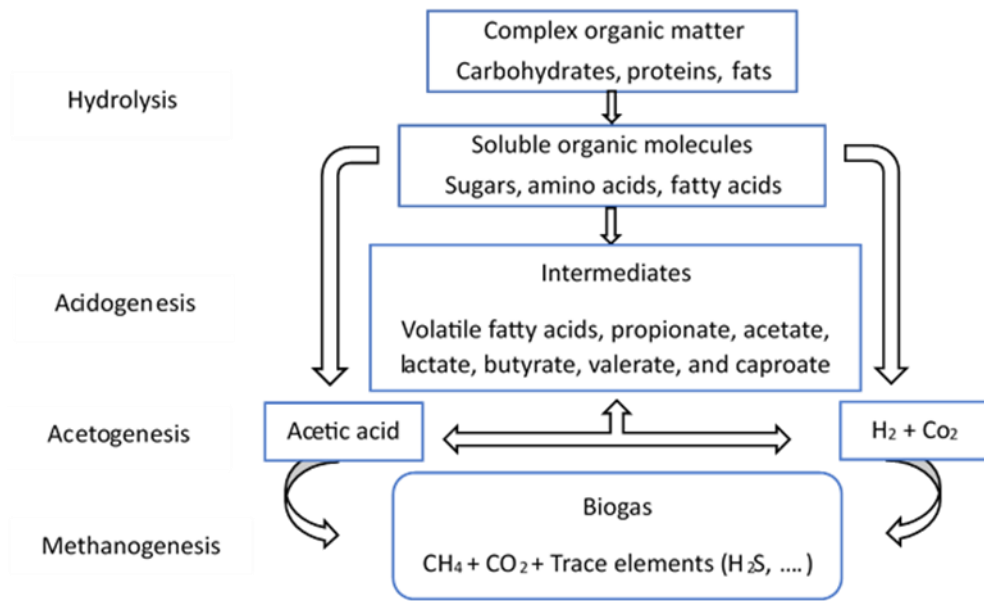


Figure 2.2: The chemical reactions that occur during anaerobic digestion [Adopted from Elmoutez et al., 2023].

2.2. High-Strength Wastewater: Landfill Leachate as a Source

The rapid development in modern industries around the world generates numerous wastewaters including several pollutants, leading to more severe water pollution [An et al., 2023]. High-strength wastewater lacks a precise definition, but it's generally characterized by concentrations of contaminants or organic matter surpassing those found in the domestic wastewater [Hamza et al., 2016]. High-strength wastewater can originate from various sources including food waste, industrial wastewater, landfill leachate, cheese whey, dairy, sugar, paper and pulp mill, distillery, and slaughterhouse wastewater [An et al., 2023]. High-strength wastewater can be categorized into two types: highly particulate, such as wastewater sludge, and highly soluble, such as food processing wastewater [Liao et al., 2006].

According to various studies, high-strength wastewater can be identified by different thresholds: Cakir and Stenstrom (2003) described medium and high-strength wastewater as those having a tCOD with 2,000 mg/L and 20,000 mg/L [Cakir and Stenstrom, 2003]. Chan et al. (2009) identified it as having COD concentrations more than 4000 mg/L [Chan et al., 2009]. Samaei et al. (2023) indicated that in most studies investigating AnDMBRs, the high-strength wastewater had COD concentrations

exceeding 1000 mg/L, concentrations of influent TSS exceeding 3000 mg/L and concentrations of influent TN surpassing of 2000 mg/L [Samaei et al., 2023]. The discharge of untreated high strength wastewater with elevated levels of organic matter can significantly impact the environment by depleting dissolved oxygen levels [Liew et al., 2020].

The remarkable increase in living standards and economic growth has led to a faster rise in the per capita production of solid waste [Keyikoglu et al., 2021]. In contrast to other conventionally used techniques like incineration and composting, sanitary landfill is an economical, widely, and conveniently used technique for disposing of waste [Nabi et al., 2022]. The primary source of landfill leachate is natural precipitation; surface water runoff seeps into landfilling sediments generating a liquid discharge known as landfill leachate, the water solid waste contained, the metabolic water produced by microorganisms breaking down waste [Yu et al., 2022]. The composition of landfill leachate is mainly determined by age and its parameters including pH, BOD, COD, suspended particles, and concentration of ammonia. Research indicates that leachate younger than five years tends to have the highest levels of COD, over 10,000 mg/l and a greater amount of organic content, as shown in Table 2.1 [Abuabdou et al., 2020].

Table 2.1: Composition of landfill leachate based on age [Abuabdou et al., 2020].

Standards	Young	Intermediate	Stabilized
Age (years)	Less than 5	5 to 10	More than 10
pH	Less than 6.5	6.5 to 7.5	More than 7.5
COD (mg/L)	More than 10000	4000 to 10000	Less than 10000
NH ₃ -N (mg/L)	Less than 400	N.A.	More than 400
BOD ₅ to COD ratio	More than 0.3	0.1 to 0.3	Less than 0.1
Biodegradability	High	Medium	Low
Organic components	VFA (80%)	VFA (5-30%), others; Humic & fulvic acid	Humic & fulvic acid
Heavy metals	Low to medium	Low	Low

BOD: Biochemical Oxygen Demand (mg/L); NH₃-N: ammonium nitrogen; COD: Chemical oxygen demand; VFA: Volatile Fatty Acid (mg/L);

The primary environmental risks posed by landfill leachate are groundwater and surface water contamination. Hence, landfill effluents should undergo on-site pretreatment to meet safety standards before being discharged. The quality of leachate

is crucial in selecting the appropriate treatment technology, which can be biological, physical, or chemical. Typically, leachate treatment processes may employ conventional, advanced methods, or a combination of both [Abuabdou et al., 2020].

2.3. Treatment Strategies of High Strength Wastewater

The treatment of high-strength wastewater is a growing challenge that researchers are striving to address. Traditional aerobic treatment methods are often insufficient because they demand high energy for aeration and generate large amounts of sludge that require stabilization and disposal [Mutamim et al., 2012]. In another side, anaerobic processes have been effectively utilized for over a century to treat wastewater from industrial, food processing, and agricultural sources. Anaerobic processes also extensively employed in treating the sludge produce from the plants of municipal wastewater treatment, as well as animal manure [Liao et al., 2006]. Anaerobic technics offer many advantages over aerobic conventional methods. Firstly, they do not require oxygen, eliminating the challenges and energy demands associated with dissolved oxygen. Secondly, anaerobic processes produce methane, which acts as a renewable energy source that can be combusted to generate heat and electricity. Lastly, anaerobic processes produce less biomass compared to aerobic processes [Tran et al., 2023]. Anaerobic treatment processes offer the ability to treat organic loading rates more than aerobic processes, as they are not limited by oxygen transfer [Kahao, 2021].

For complete digestion of the treated influent, conventional anaerobic digesters required extending hydraulic retention times (HRT), typically ranging between 20 to 200 days and large foot print. Consequently, various strategies have been developed, including anaerobic sequencing batch reactors, expanded granular sludge bed reactor (EGSBR) systems, up flow anaerobic sludge blanket reactor (UASBR) systems, anaerobic fluidized bed reactors, and anaerobic contact processes. However, a drawback of these strategies is their requirement for rigorous process control to establish and ensure sludge sustainability granulation [Tran et al., 2023].

2.4. Anaerobic Membrane Bioreactors (AnMBRs)

High-rate anaerobic reactors present an economical and efficient solution to addressing high-strength wastewater treatment challenges. Among of these high-rate reactors, anaerobic membrane bioreactor (AnMBR) is getting a lot of interest from scientific community and industrial sectors [Hamza et al., 2016]. AnMBR is a wastewater treatment system that functions under anaerobic conditions, utilizing a membrane to achieve complete separation of solids and liquids [Liao et al., 2006].

The idea of integrating membrane filtration with anaerobic wastewater treatment was first tested by Grethlein in 1978 [Grethlein, 1978]. After that Dorr-Oliver developed the first commercially available AnMBR during the first years of the 1980s, designed particularly for treating whey with a high organic load, it became known as the Anaerobic Membrane Reactor System. This system combined an anaerobic reactor (mixed suspended-growth) for biodegradation with a membrane module (external cross-flow) to separate the biomass. The anaerobic membrane reactor system has been evaluated at both pilot and full scale, but the main obstacle is the high cost of membranes [Liao et al., 2006]. One notable study work was '90 project of Japan's Aqua Renaissance, a six-year initiative launched in 1985 to explore and develop different designs to treatment of anaerobic membrane bioreactors (AnMBRs) for sewage wastewater and industrial wastewater. The retention of biomass in two kinds (attached growth and suspended) anaerobic bioreactors was investigated for different membrane topologies, this included ceramic and polymeric membranes configured as capillary, tubular, plate-and-frame modules, and hollow fiber. Pilot-scale AnMBRs effectively treated various wastewaters, including: fats, oils and sewage, wheat starch, alcohol fermentation byproducts, paper mill and pulp effluent, and night soil, consistently achieving removal rates of chemical oxygen demand (COD) above 90% [Minami et al., 1991], [Kataoka et al., 1992], [Liao et al., 2006].

Beginning in 1987, in South Africa a technology was developed referred to as ADUF (anaerobic digestion ultrafiltration) for treating industrial wastewater. The ADUF process architecture was similar to the MARS (Membrane Anaerobic Reactor System) process, but eliminated the need for a high-pressure supporting system. Various pilot-scale and full-scale ADUF systems are demonstrating a COD removal efficiency exceeding 90% [Ross et al., 1990]. During the 1990s and after, AnMBR research

activity expanded significantly, focusing on the exploration of diverse membrane materials, the analysis of fouling characteristics, and the creation of innovative methods for cleaning membranes and managing fouling [Liao et al., 2006].

Anaerobic continuous stirred tank reactors (CSTRs) are often integrated with membrane filtration to separate sludge retention time (SRT) from the hydraulic retention time (HRT), thereby functioning as a high-rate digester. Notably, the fully mixed anaerobic membrane bioreactor (AnMBR) configuration represents the most widely applied design among anaerobic membrane technologies. There are two operational modes of membrane bioreactors (MBR): cross-flow and dead-end filtration (as can be seen in **Figure 2.3**). In the cross-flow mode, the feed water flows parallel with the membrane surface, creating a sweeping action that helps minimize fouling by continuously removing accumulated particles and high permeate rate. In contrast, in dead-end mode, the feed water flows directly perpendicular to the surface of membrane, causing particles to accumulating and develop a cake layer, while only clean water passes through the membrane with low permeate rate [Rajabzadeh, 2010].

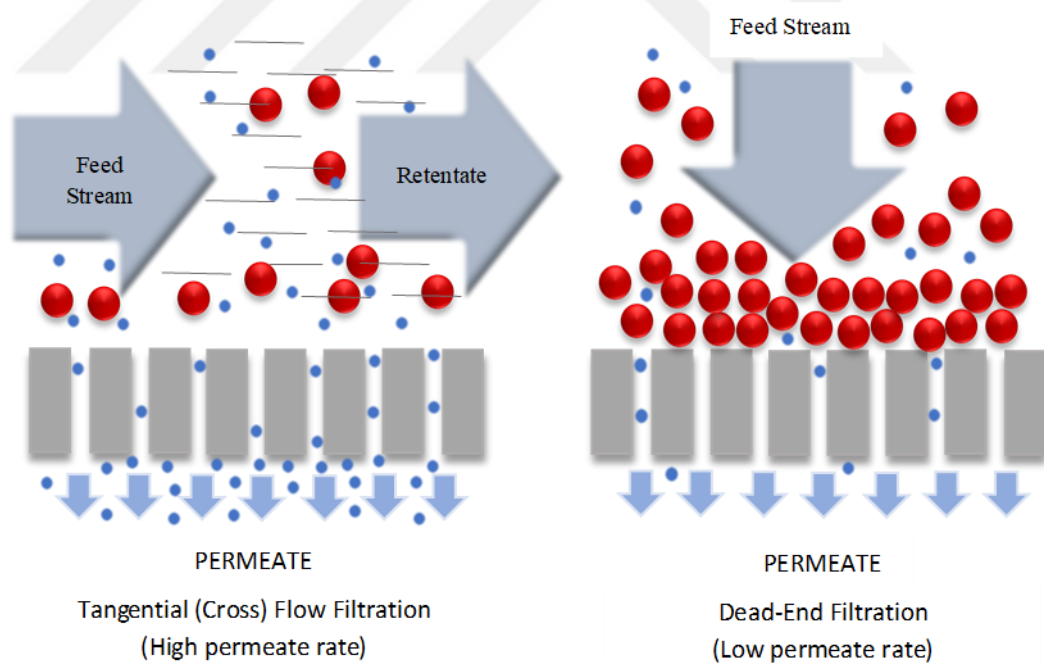


Figure 2.3: Operational modes of membrane bioreactors (MBR) [Adopted from Rajabzadeh, 2010].

There are two typical configuration designs of (AnMBR) system (**Figure 2.4**) include external cross-flow filtration and submerged membrane filtration [**Liao et al., 2006**]. The design of external chamber is commonly utilized in large-scale plants of aerobic wastewater treatment, allowing the submerged membranes to be cleaned by separating the chambers without the need for physical removal [**Liao et al., 2006**]. Two technics are used to manage energy saving and reduce membrane fouling.

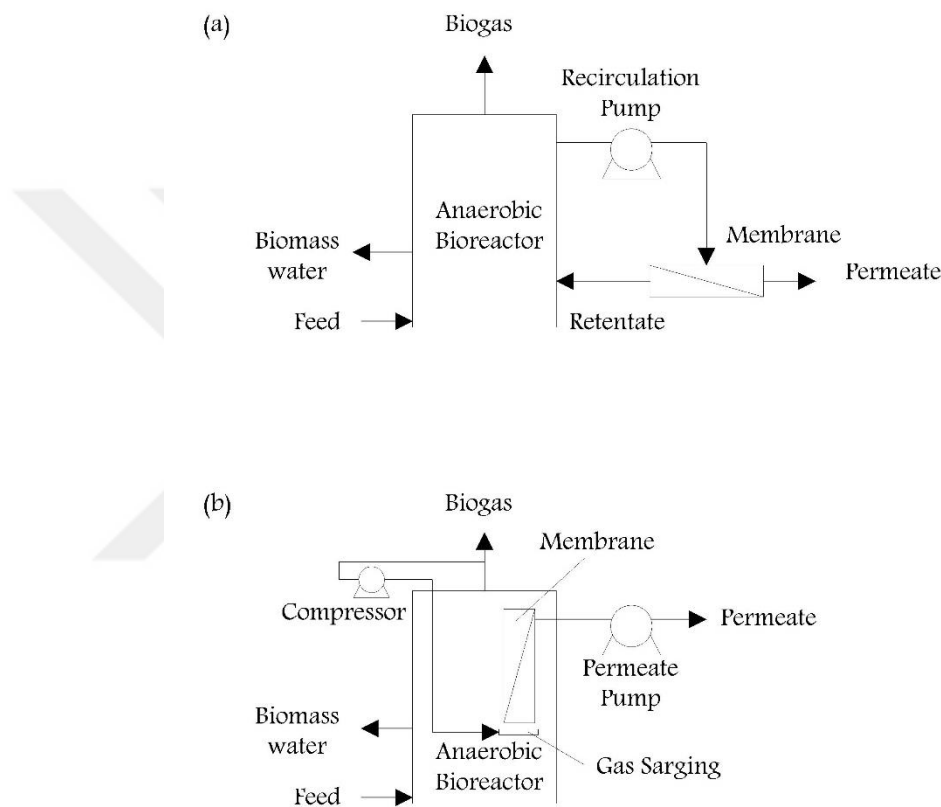


Figure 2.4: Anaerobic membrane bioreactor diagram setups. (a) Externally cross-flow membrane. (b) Submerged membrane [**Adopted from Liao et al., 2006**].

The three categories of membrane fouling mitigation methods are physical, chemical, and biological, as shown in **Figure 2.5 a**. Physical methods include membrane relaxing (which stops filtration), biogas sparging, and membrane back flushing (which reverses the flow of permeate across the membrane). Chemical technics include adding flocculants/coagulants, modifying the materials of membrane, cleaning in-site with alkalis/oxidants/acids, or employing electrochemical technologies to mitigate membrane clogging through cleaning of membrane or the conditioning of sludge.

Figure 2.5 b illustrate the transmembrane pressure (TMP) progression throughout the filtration of membrane and the cleaning procedure for physical and chemical methods. Biological approaches try to reduce membrane fouling by utilizing microbial consortiums or specific bacterial species [An et al., 2023].

Furthermore, AnMBR's configurations play a significant role of improving the system performance. To improve anaerobic performance and reduce membrane fouling, numerous unique forms of AnMBR developed in recent years, included anaerobic dynamic MBR (AnDMBR) systems, anaerobic vibrating MBR (AnVMBR) systems, anaerobic electrochemical MBR (AnEMBR) systems, and anaerobic osmotic MBR (AnOMBR) [An et al., 2023].

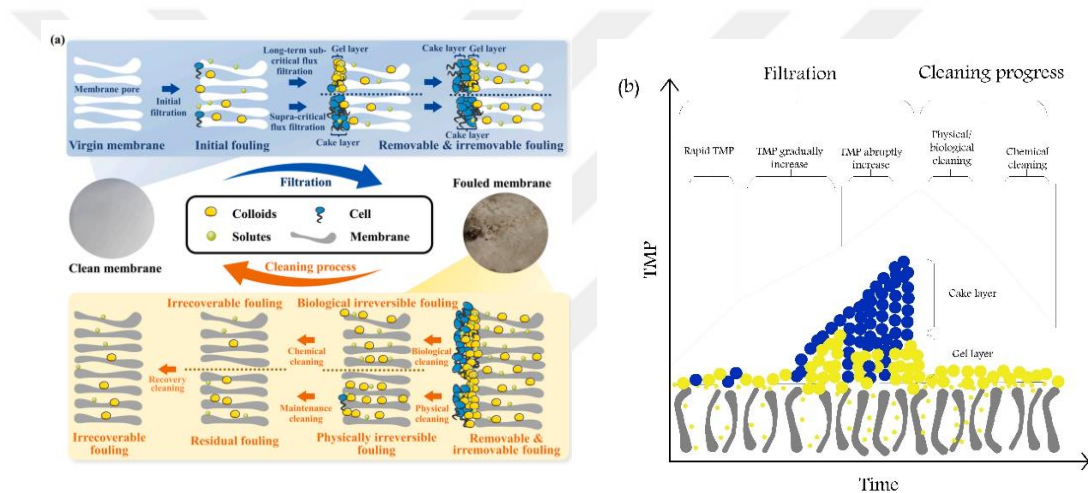


Figure 2.5: (a) Graphical representation the fouling in the AnMBR system (development and removal process). (b) Transmembrane pressure (TMP) rising along both the cleaning and filtration process [Adopted from An et al., 2023].

2.5. Anaerobic Dynamic Membrane Bioreactors (AnDMBRs)

2.5.1. Introduction

Membranes have long been employed for separation of solid-liquid in both aerobic and anaerobic biological treatments, as well as in various physical applications. There has been increasing interest in membrane bioreactors (MBRs) by integrating

membranes with biological wastewater treatment, which offer significant benefits like enhanced effluent quality and a reduced system footprint. On the other hand, MBR processes face challenges such as high costs of membrane, energy demands, fouling control, and low flux. [Erşahin, 2015]. The main reason for fouling in AnMBR systems is the development of the cake layer on the surface of membrane, which acts as either a dynamic membrane (DM) or a secondary membrane [Hu et al., 2018]. A DM develops on the supporting material (e.g., mesh, membrane, filter cloths), when the filtrate includes suspended solids like flocs and microbial cells. The biomass layer acts as a secondary filtration barrier, capturing organic and colloidal particles and thereby protecting the underlying support material from direct fouling [Ersahin et al., 2012]. In DM technology, the membrane may become unnecessary as solids rejection is achieved by the in situ forming of a cake layer. Numerous studies have explored the use of fabrics or meshes as support materials for separation of solid and liquid in wastewater treatment [Zhang et al., 2010].

Figure 2.6 illustrates the forming of a dynamic cake layer. This layer, accumulating on membrane surface, can alter the system's filtration efficiency by acting as a "secondary" barrier, effectively supplementing the filtration characteristics of the primary membrane or support structure [Ersahin et al., 2012].

Over the past few years, the anaerobic dynamic membrane bioreactors (AnDMBRs) have received significant attention as a viable solution to the difficulties of AnMBRs [Sun et al., 2025]. The dynamic membrane (DM) layer can naturally form on an inexpensive support material, thereby removing the requirement for costly microfiltration or ultrafiltration membranes. DMBR offers multiple benefits over traditional MBRs, like reduced membrane costs, low energy requirements, and simplified the controlling of fouling [Ersahin et al., 2016]. Nevertheless, comprehensive studies on high-strength wastewater treatment employing AnDMBR are remain lacking [Samaei et al., 2023].

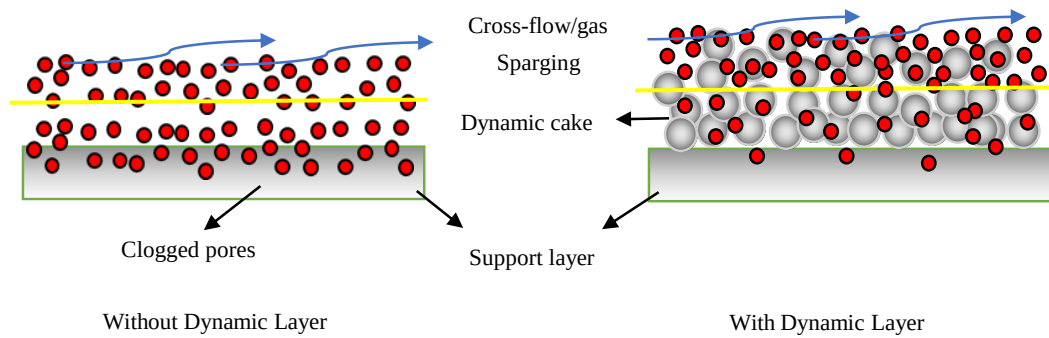


Figure 2.6: Description of membrane with and without dynamic layer [Adopted from Ersahin et al., 2012].

The formation of DM and their filtration performance are greatly influenced by factors such as fouling rate, cleaning methods, and type of support material. AnDMBR systems designed for treatment of high-strength wastewater utilize a range of support materials, such as polypropylene monofilament woven fabric, nylon mesh, Dacron mesh, polypropylene woven filters, polyamide/nylon monofilament mesh, polyester screen mesh, carbon cloth, stainless steel mesh, and woven filter cloth. These materials differ in their structural durability, porosity, and ease of cleaning. Nylon mesh is frequently utilized due to its high porosity, which effectively traps sludge particles [Samaei et al., 2023].

The support membranes pore size plays an essential role in dynamic membrane (DM) forming and affects the resulting permeate flux. To achieve the greatest separation performance, the dynamic membrane's particle size -forming components and the supporting material pore size must be evaluated simultaneously. Since the pores of supporting materials are larger than those in traditional UF/MF membranes, the initial filtration phase may result in reduced effluent quality as particles pass through the membrane pores [Erşahin, 2015]. Kiso et al. (2000) investigated the effluent quality and filtration characteristics of mesh support materials with three pore sizes of 100, 200, and 500 μm . They found that the 100 μm mesh delivered the highest effluent quality and efficiently retained activated sludge flocs [Kiso et al., 2000]. Similarly, Jeison et al. (2008) also showed that in anaerobic systems fed with volatile fatty acids, forming a cake layer on meshes with pore sizes larger than 60–70 μm was not feasible [Jeison et al., 2008]. Zhang et al. (2010) successfully applied a DM on a Dacron mesh of a pore size of 61 μm [Zhang et al., 2010]. Hu et al. (2016) were utilized for filtering

38, 48, and 75 μm meshes, after 4 hours the flux was roughly 100, 120, and 130 $\text{L}/\text{m}^2/\text{h}$, respectively; nevertheless, the time required for DM formation varied, taking 10, 30, and 90 minutes, respectively [Hu et al., 2016].

A dynamic membrane (DM) formed on a larger-pore mesh typically exhibits slightly higher flux and takes longer to form compared to a smaller-pore mesh. This is because small particles likely are less to attach to the larger pores initially, leading to delayed DM formation. However, the larger-pore meshes offer a greater effective filtration area and lower filtration resistance, resulting in higher filtration flux at the same operational pressure [Li et al., 2018].

2.5.2. Historical Evolution, Membrane Materials, Configurations and Operation Mode

2.5.2.1. Historical Evolution

The initial research on physical dynamic membranes (DMs) was carried out by Marcinkowsky et al. (1966), he employing a zirconium oxychloride (ZrOCl_2) dynamic membrane for salt rejecting in a reverse osmosis process [Marcinkowsky et al., 1966]. Following this work, up until 1978, much of the DM research focused on the effectiveness of RO processes in rejecting salt. Applications of DM in UF processing started in the 1980s. The major goals of those studies were the elimination of dye and protein, the food industry, as well as wastewater treatment. Since the 1990s, DM application in MF processes, particularly for the treatment of wastewaters, has been tested [Ersahin et al., 2012].

Pillay et al. (1994) were the first to describe the implementation of the DM technique in anaerobic systems utilizing woven fiber material in a side-stream configuration within an AnDMBR system [Pillay et al., 1994]. After that, since 2007 research into AnDMBRs intensified, with numerous studies dedicated to optimizing operating conditions, improving membrane performance, and membrane fouling mitigation [Ersahin et al., 2012].

Alibardi et al. (2016) assessed a bench-scale anaerobic dynamic membrane bioreactor operating at ambient temperature for treating of synthetic municipal wastewater. Using a large-pore (200 μm) mesh, the system achieved over 80% total COD and 90% filtered COD removal [Alibardi et al., 2016]. Yurtsever et al. (2021) examined the

performance of an AnDMBR for treating synthetic textile wastewater containing 500 mg/L NaCl and sulfate concentration of 1000 mg/L. They reported that using of a 20 μm nylon support layer, the system consistently achieved COD removal rates between 79–96% and eliminated more than 97% of Remazol Brilliant Violet 5R dye, operating steadily at an approximate flux of 8 LMH [Yurtsever et al., 2021]. Sun et al. (2025) utilized anaerobic dynamic membrane bioreactor (AnDMBR) system to treat swine wastewater containing sulfonamide antibiotics (SMs) and heavy metals. The filtration module consisted of non-woven fabrics with large pores, measuring 25 μm in size. The system demonstrated high removal efficiencies for COD (91.2%), sulfamethoxazole (94.2%), sulfadiazine (51.2%), sulfamethazine (52.8%), Cu^{2+} (88.5%), and Zn^{2+} (73.3%) [Sun et al., 2025].

2.5.2.2. Membrane Materials

Various inexpensive support materials can be utilized to forming DM layer, potentially leading to a low-cost filtration process. By reducing the of expenses filter material and producing energy from the biogas, anaerobic dynamic membrane bioreactor (AnDMBR) systems present a cost-effective and promising alternative for wastewater treating [Ersahin et al., 2013].

In AnDMBR systems designed for treatment of high-strength wastewater, different support materials are employed. Various support materials are utilized for treating high-strength wastewater in AnDMBR system. These include ultrafiltration (UF) and microfiltration (MF) membranes, ceramic tubes, polymeric membranes, as well as different types of meshes such as nylon mesh, Dacron mesh, filters, and polypropylene woven fabric, polyester screen mesh, carbon cloth, woven filter cloth, polyamide/nylon monofilament woven mesh, and stainless steel mesh [Li et al., 2018], [Samaei et al., 2023]. Each material exhibits different properties regarding structural stability, porosity, and cleaning efficiency. Nylon mesh is frequently used due to its high porosity, which is beneficial for capturing sludge particles. Nevertheless, some researchers have explored more creative support materials to enhance performance of AnDMBR treatment [Samaei et al., 2023]. Membrane modules can be categorized into three kinds such as hollow fiber, flat-sheet, or tubular. Hollow fiber DM modules are rarely assembled with coarse pore support material, in contrast to their frequent

use in tubular DM and flat-sheet module designs. This is due to the low material intensity and difficult production techniques **[Hu et al., 2018]**.

DM can be categorized into two main types: those that form naturally (self-forming) and those that are applied (pre-coated). Self-forming dynamic membranes (SFDMs) develop naturally from components found in the filtered liquid, including suspended solids (SS) in wastewater. In contrast, the pre-coated dynamic membranes, called formed-in-place membrane systems (FIP), are created by applying a specific solution containing specific colloidal particles onto the surface of a porous support **[Ye et al., 2006]**, **[Ersahin et al., 2012]**.

The main drawback of pre-coated approach compared to self-forming dynamic membranes (SFDM) is the need for an externally substance. Pre-coated dynamic membranes can be further divided into two types: composite (bi-layer) membrane material and single additive membrane material. Single additive membranes are usually fabricated in a single step using one material **[Erşahin, 2015]**.

Research on dynamic membranes (DMs), particularly in the context of wastewater treating, has predominantly focused on the utilization of mesh types as well as non-woven and woven fabrics as supporting materials. Mesh comprises a permeable barrier constructed from interconnected strands of fiber, metal, other flexible materials. However, a potential disadvantage of mesh filter materials is their inefficient sludge handling **[Kiso et al., 2005]**. Woven fabrics are created using multifilament and/or monofilament yarns. Monofilament yarns are individual synthetic filaments with smooth exteriors, while multifilament yarns consist of multiple monofilament fine fibers twisted together to form single yarns, which are then interlaced to create the fabric. In contrast, non-woven fabrics are defined as sheets or webs composed of natural or synthetic fibers or filaments, excluding the paper, which has not been spun into yarns but is instead of that bonded together. Despite their thinness, non-woven fabrics are capable of trapping floc particles within the pores of the fiber matrix, making it too difficult to removing the adhered particles of sludge result from the filter interstices during extended operation **[Erşahin, 2015]**.

Ersahin et al. (2013) studied the impact of supporting material characteristics on dynamic membrane (DM) forming and effectiveness in a laboratory-scale submerged AnDMBR system, utilizing six different polypropylene woven fabrics. These fabrics

included two mono-monofilament, two mono-multifilament, two staple varieties. The study demonstrated that DM filtration technology could achieve high removal efficiency of total suspended solids, exceeding 98%. Among the materials tested, staple filter cloths and mono-monofilament were found to be most suitable, with critical fluxes of 17–19 L/m²·h and 9.2 L/m²·h, respectively. The study focused on how properties such as pore size and structure of support materials influenced the performance of dynamic membranes [Ersahin et al., 2013]. Summary of the membrane material characteristics are presented in **Table 2.2**.

Table 2.2: Summary of the membrane material characteristics.

Membrane material	Wastewater type	Membrane type	Pore size (µm)	Critical flux (L/m²h)	Ref.
Dacron mesh	Landfill leachate	Flat sheet	40	6	[Xie et al., 2014]
Polyamide/nylon woven mesh	synthetic municipal	Flat sheet	200	15–20	[Alibardi et al., 2016]
Monofilament woven fabric	Synthetic concentrated	Flat sheet	10	2.6	[Ersahin et al., 2014]
Dacron mesh	municipal	Flat sheet	61	65	[Zhang et al., 2010]
Hydrophilic nylon mesh	synthetic textile	Flat-double sided sheet	20	8	[Yurtsever et al., 2021]
Conductive/carbon cloth	brewery	Flat sheet	200	4.125	[Jia et al., 2020]
Acrylonitrile Butadiene styrene Filament	textile	Flat sheet	100	14-28	[Berkessa et al., 2020]
Silk	Sewage sludge	Tubular	100	6.25-13.89-25	[Liu et al., 2019]
Polyamide nylon meshes	Sewage sludge	Tubular	10, 52, 85, 135, 200	329 to 9880	[Saleem et al., 2017]

2.5.2.3. Configurations and Operation Mode

Membrane configurations can be classified as side-stream or submerged (including internal and exterior submerged) based on their location between the membrane module and anaerobic bioreactor [Hu et al., 2018]. The major difference between the two setups is in the placement and operation of the membrane module. In the submerged setup, the installation of membrane is directly inside the reactor, either externally or internally, and operates under vacuum conditions. This setup enables the membrane to come into direct contact with the mixed liquor [Samaei et al., 2023]. Conversely, in the side-stream configuration, the membrane module is located outside the reactor within a separate membrane tank, where it functions under pressure. This arrangement requires pumping the mixed liquor extracted from the reactor to the external membrane tank and back, allowing for a different operational approach and potentially higher flux rates [Ersahin et al., 2017]. Figure 2.7 illustrates the configurations of different DMBRs.

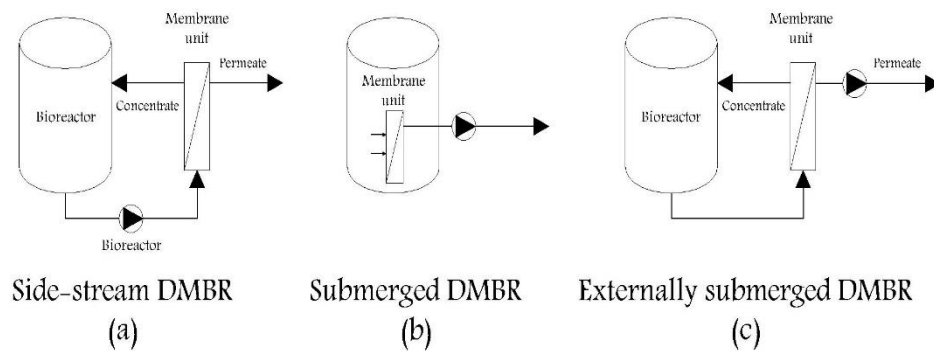


Figure 2.7: Configurations of DMBR [Adopted from Maaz et al., 2019].

Ersahin et al. (2017) assessed the effectiveness of different AnDMBR configurations in treating high-strength wastewater. Their study compared submerged and external AnDMBR systems, emphasizing the removal efficiency and filtration properties. To assess the configuration impact of AnDMBR on treatment performance and filtration ability, the researchers utilized a woven fabric made of polypropylene monofilament, featuring a 10 μm pore size, as the support material. The results showed that both configurations achieved removal efficiency over 99% of COD. The external AnDMBR required more time to form an effective DM layer but had lower total filtration

resistance due to a less compact DM layer [Ersahin et al., 2017]. Seo et al. (2007) studied the filtration properties of two different configurations modules (flat sheet in vertical configuration and tubular (horizontal and vertical configuration) membrane modules with the same filtration area of 0.052 m²) in the oxic compartment of anaerobic/oxic (A/O) type reactors for domestic wastewater treatment. the tubular module exhibited more stable pressure at a higher flux than the flat plate type. Horizontal tube installation led to rapid pressure increases due to sludge cake formation on the top. The sludge layer formed on the tubular one was observed to be over twice as thick as the layer developed on the flat-sheet filter [Seo et al., 2007]. Jeison et al. (2008) investigated the utilizing a self-forming dynamic membranes in the AnMBRs under mesophilic and thermophilic conditions, utilizing non-woven and woven support materials. Results indicated that dynamic membrane formation in AnMBRs is practical and supplies adequate biomass retention, but achieved low flux levels (up to 3 L/m²·h) and experienced unstable operation due to excessive cake layer formation [Jeison et al., 2008].

2.6. Anaerobic Electro- Membrane Bioreactors (AnEMBRs)

The electrochemical process could be implemented with MBR. This integrated method is an innovative technology for wastewater treatment with enormous promise. Recently, integrating electrochemical process into typical AnMBR has been recognized as an effective strategy to reducing membrane fouling and enhancing biogas quality [Sun et al., 2024].

An application of an electric field was evaluated for the first time (aerobically) in MBR by Chen et al. (2007) to reduce membrane fouling. Recent developments indicate that introducing an electric field into membrane bioreactors, known as electro membrane bioreactors (eMBRs) or electrically enhanced MBRs can significantly decrease fouling [Chen et al., 2007], [Akamatsu et al., 2010], [Liu et al., 2012]. This technique triggers electrochemical processes like electrocoagulation, electrophoresis and electroosmosis, which assist in pollutant degradation while simultaneously controlling the transport and foulants cumulating on membrane surface [Ensano et al., 2016].

When voltage is applied, negatively charged contaminants including activated sludge and excreted polymers are repelled from the membrane (cathode) through

electrophoretic movement toward anode (**Figure 2.8 a**) [Akamatsu et al., 2010]. Hence, the electroosmotic force facilitates bound water removing from the electrical double layer of microbial flocs, thereby reducing the specific filtration resistance of the sludge, thus promoting membrane fouling (**Figure 2.8 b**) [Ensano et al., 2016]. The commonly preferred method for removing organic substances with high pollution potential from wastewater is electrocoagulation. This technique involves the on-site electrochemical generation of coagulants breakdown of submerged sacrificial anodes, which are typically composed of iron or aluminum (**Figure 2.8 c**) [Chen et al., 2007], [Ensano et al., 2016]. Depending on the electrode material (sacrificial or nonsacrificial) and the current density, membrane fouling tendency is suppressed via anodic oxidation, electrocoagulation, electrophoresis, or/and electroosmosis mechanisms [Asif et al., 2020].

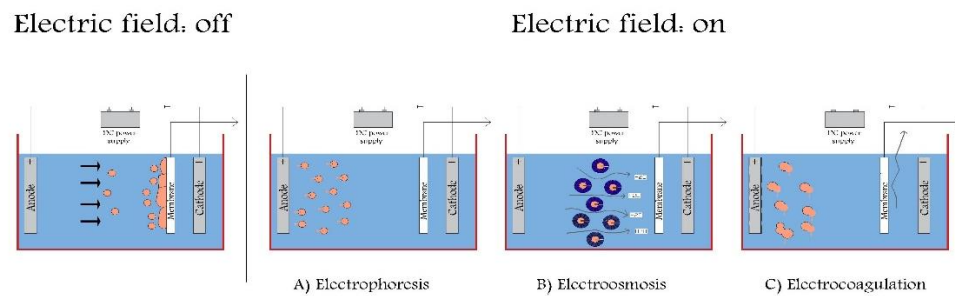


Figure 2.8: Mechanisms of electrochemical reactions involved in the operating of the electro MBR (eMBR): (A) electrophoresis, (B) electroosmosis, (C) electrocoagulation [Adopted from Ensano et al., 2016].

Recently, electrically-assisted processes integrated into AnMBR have been shown to decrease membrane fouling, increase the removal COD, enhance the biogas content and performance of AnMBR systems [Deng et al., 2022], [Liu et al., 2022]. The hybrid system combining AnMBR with the electrochemical process is known as AnEMBR or electro-AnMBR [Chen et al., 2023]. At neutral pH, contaminants in mixed liquor, including sludge flocs and colloids, typically carry a negative charge because of the presence of electronegative functional groups. The principal contributors to membrane fouling are soluble microbial products (SMP) and extracellular polymeric substances (EPS) [Asif et al., 2020]. In AnMBR systems, applying an electric field generates electrophoretic forces that repel negatively charged

particles in the mixed liquor moved from the conductive surface of membrane (as show in **Figure 2.9**). This electrophoresis effect would have the same impact of backwash [**Zhang et al., 2021**]. In the AnEMBR systems, where an electrical bias is introduced to the surface of membrane to create electrochemically supported conditions, it has been stated that the electric field applied promotes the development and metabolic activity of electroactive microorganisms both in the reaction medium and on the electrode surface. It has been reported that these conditions support methane production efficiency by increasing the population of hydrolytic fermentative, methanogenic and acidogenic bacteria [**Li et al., 2022**].

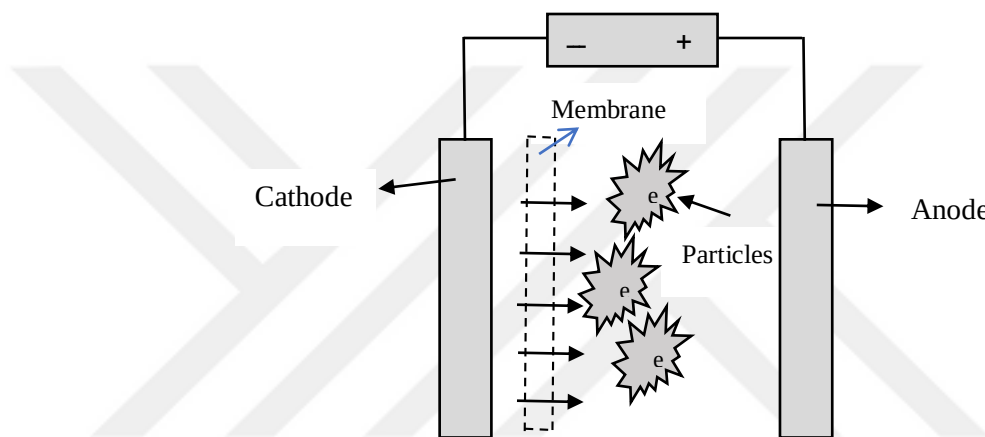


Figure 2.9: Traditional electric membrane technology configuration [**Adopted from Li et al., 2018**].

The first researchers to work on the concept of MBR (Electro-MBR) anaerobically were Katuri et al. (2014), who defined this novel system as an anaerobic electrochemical membrane bioreactor (AnEMBR). This system, utilizing electrically conductive, porous nickel-based hollow-fiber membranes (Ni-HFMs), was designed for the treatment of a solutions with low organic strength wastewater- specifically, a synthetic acetate solution with a COD of 320 mg/L, and recover energy as biogas. The Ni-HFMs served as both membrane and cathode for effluent filtration. The AnEMBR achieved over 95% COD removal across all applied voltages (0.5 V, 0.7 V, 0.9 V). Notably, at 0.7 voltage, the system recovered approximately 71% of the substrate's energy as a form of methane-rich biogas. Moreover, the net energy consumption for operating the AnEMBR at 0.7 voltage (0.27 kWh/m³) was significantly lower compared to typical aerobic membrane bioreactors, which require between 1 and 2 kWh/m³ [**Katuri et al., 2014**].

Choi et al. (2022) investigate the effect of externally applying voltage on the performance of anaerobic DM for high suspended solids status. In their study, they used stainless steel mesh as a support layer of the DM, and filtration experiments were conducted at 13 various voltages (ranging from -1.2 V to $+1.2$ V in 0.2 V intervals). The findings indicated that the TMP increase was delayed in cathodic filtration runs due to electrostatic repulsion and electrochemical reactions. However, applying an excessively (-1.2 V) negative voltage caused substantial fouling due to precipitation and electrochemical corrosion. In anodic filtration, DM formation was enhanced by electrostatic attraction at voltages of $+0.6$ V or lower but was hindered at higher voltages due to the electrocatalytic production of reactive species, with $+1.2$ V resulting in severe chemical fouling from anodic corrosion. Both anodic and cathodic DMs showed high suspended solids rejection (86.4–89.6%) [Choi et al., 2022].

Numerous studies have been conducted on anaerobic electrochemical membrane bioreactors (AnEMBR). Below are summarized some notable works on AnEMBR:

Ding et al. (2015) examined the influence of five different voltages (2.0 V, 1.0 V, 0.8 V, 0.6 V, and 0.4 V) on microbial performance and methane production within an anaerobic microbial electrolysis cell (MEC) treating synthetic wastewater with a COD ranging between 2 to 3 g/L. The study demonstrated that both COD removal efficiency and methane yield improved with increasing voltage up to 0.8 V, whereas further increases beyond this threshold (1.0 V and higher) led to a decline in performance [Ding et al., 2015].

Werner et al. (2016) assessed the operational efficiency and membrane fouling behavior of graphene-coated, electrically conductive hollow-fiber membranes (as cathodes) utilized in the AnEMBRs (anaerobic electrochemical membrane bioreactors). Their study involved comparing a newly developed rectangular reactor design operated at 0.7 , and 0.9 V with a previously used tubular configuration operated at 0.7 V. Findings indicated that the rectangular reactors, particularly at 0.9 V, exhibited significantly reduced and delayed biofouling relative to both the 0.7 V rectangular setup and the tubular system. The maximum transmembrane pressure (TMP) recorded was notably lower in the rectangular reactors (0.10 bar at 0.7 voltage and 0.05 bar at 0.9 voltage) compared to 0.46 bar in the tubular reactor (at 0.7 voltage). Furthermore, the biofilm layer developed on the membrane surfaces in rectangular systems was considerably thinner (approximately 0.4 μm) than that in the tubular

reactor (4 μm). Additionally, the rectangular AnEMBRs achieved superior permeate quality, with total suspended solids (TSS) measured at 0.05 mg/L, in contrast to 17 mg/L in the tubular AnEMBR. This improvement was potentially due to elevated current densities in the rectangular design, which effectively limited microbial cell accumulation in the mixed liquor [Werner et al., 2016].

Hou et al. (2017) explored the integration of microbial electrochemical technology with anaerobic osmotic membrane bioreactors (AnOMBRs). The proposed system incorporates a microbial recovery cell (MRC) into the AnOMBR, demonstrating significant improvements in organic and phosphorus removal, nutrient recovery, and effluent quality. The MRC-AnOMBR system achieved over 93% organic removal and over 99% phosphorus removal, maintaining effluent COD below 20 mg/L. Nutrient recovery was effective, with up to 65% phosphate and 45% ammonium being recovered from the influent. The system achieved 0.19 liters of CH_4 as peak methane yield per gram of COD removed [Hou et al., 2017].

Zhang et al. (2017) explored impact of applying an electric field on the performance of an anaerobic membrane bioreactor (forward osmosis type) integrated with a microbial electrolysis cell (AnOMEBR). Their findings showed that the AnOMEBR exhibited a slower rate of conductivity increase around 0.08 mS/(cm·d) comparing to 0.11 mS/(cm·d) in the system without electrochemical assistance AnOMBR. This indicated a reduced rate of membrane fouling. Additionally, the operational cycle of the AnOMEBR was extended by approximately 1.27 times relative to the AnOMBR. The AnOMEBR also achieved a higher methane yield (0.281 L CH_4 /g COD), marking an increase of roughly 11.07% over the AnOMBR [Zhang et al., 2017].

Ding et al. (2018) investigated how different applied voltages influence membrane fouling and organic pollutant degradation in a hybrid system combining a microbial electrolysis cell (MEC) with an anaerobic membrane bioreactor (osmotic type) AnOMBR. The study proved that the system achieved its highest COD removal efficiency at 0.6 V of approximately 1.2 times greater than that observed under open-circuit conditions (0 V). Furthermore, increasing the applied voltage led to a progressive reducing in membrane fouling rates, with the fouling membrane cycle extending 38 hours (from 60 to 98), indicating improved operational **stability** [Ding et al., 2018].

Yang et al. (2018) studied the impact of various voltages (-0.4 , -0.8 , -1.2 , and -1.4 V) on the filtration efficiency of carbon nanotube hollow-fiber membranes (CNT-HFMs) that were enhanced by electrical stimulation. The study examined antifouling mechanisms by evaluating the removal of sodium alginate (SA), bovine serum albumin (BSA), also the supernatant from an anaerobic bioreactor (SAB). Results indicated that the applied voltage (-1.2 V) was an optimal voltage and effectively mitigated fouling of the membrane by repelling negatively charged particles from the surface of the membrane, impeding gel layer formation, and controlling high-weight molecular pollutant accumulation. At -1.2 V, removal efficiencies of COD for BSA (92.1%), SA (87.3%), and SAB (56.8%) were higher than 3.3, 1.4, and 1.5 times, respectively, compared to membrane filtration alone. Additionally, a 30-day experimental study employing carbon nanotube-coated membranes (type of hollow fiber) CNTs-HFMs as both the filtration medium and cathode in an anaerobic electrochemical membrane bioreactor (AnEMBR) demonstrated a notable reduction in transmembrane pressure (TMP), recording 0.35 bar compared to 0.60 bar in the control system. This outcome indicates that the application of voltage effectively alleviated membrane fouling [Yang et al., 2018].

Yu and Zhang (2019) investigated the fouling resistance of a large-aperture membrane functioning as the anode in an anaerobic membrane bioreactor (AnMBR). The electric potential application was stimulated electrostatic adsorption and the secretion of extracellular polymeric substances (EPS), initially accelerating membrane fouling and causing a rapid rise in transmembrane pressure (TMP), with values reaching -0.3 R at a -0.3 V anode potential and -0.2 R at -0.2 V. Despite this initial increase in fouling, the membrane uses as an anode ultimately mitigated fouling through anodic oxidation and the enrichment of exoelectrogenic bacteria. Over time, this led to a dynamic equilibrium between degradation and fouling accumulation, contributing to stable reactor performance. A mesh-like biofilter layer, consist of microbial cells with reduced EPS content, formed on the surface of membrane, which helped decrease TMP and improve particle retention [Yu and Zhang, 2019].

Xu et al. (2020) explored the application of anaerobic forward osmosis (electro-assisted) membrane bioreactor (AnOMEBR) for treating synthetic municipal wastewater. By applying an external voltage of 0.5 voltage to mitigate fouling of membrane. In this system, a conductive forward osmosis membrane served as both

cathode and the separation unit. The study found that the content of the proteins/polysaccharides (PN/PS) and soluble microbial products (SMP) ratio in AnOMEBR system were 15% and 26%, respectively. It was lower compared to a conventional anaerobic osmosis membrane bioreactor (AnOMBR). Additionally, the absolute Zeta potential of sludge in the AnOMEBR was higher with about 1.2 times than in the AnOMBR. This enhanced interaction between the membrane surface and negatively charged foulants contributed to reducing foulant adsorption during the initial fouling stages of membrane [Xu et al., 2020].

Zhang et al. (2021) investigate the effect of an electric field on membrane fouling evolution, water quality, and production of methane in an anaerobic membrane bioreactor, titanium anodes and cathodes were used. The result indicated that implementing a 0.5 V electric field reduced the fouling rate of the membrane by approximately 23% and decreased organic foulant particles on the membrane by around 10%. Additionally, the study found that electrophoresis was nearly as effective as backwashing, achieving a flux of about 0.56 L/(m²·h). The results also showed that the resistance of filtration for mixed liquor was reduced by the electric field near of 77%. Further analysis like properties of mixed liquor, simulations of electrochemical oxidation, and metagenomics suggested that the electric field could enhance mixed liquor filtration capability through bio-electrochemical oxidation [Zhang et al., 2021].

Zhao et al. (2021) investigated the microbial characterization and antifouling capabilities of an electrochemical anaerobic membrane bioreactor equipped with an iron anode and membrane cathode for sewage treatment. Compared to traditional AnMBRs, the electrically assisted AnMBR (eAnMBR) demonstrated a 24.97% higher average total phosphorus (TP) removal rate and extended the cycle of membrane service expanded by 109.68%. The mixed liquor in eAnMBR exhibited lower EPS concentrations, as well as larger floc sizes, associated with the joint effect of coagulation and the impact of electric field. These factors led to the forming of porous, improving water permeation, hydrophilic cake layer. Additionally, the presence of the electric field and Fe(II) enhanced microbial diversity and enriched the metabolic pathways of methanogens [Zhao et al., 2021].

Li et al. (2021) investigated the influence of varying applied voltage gradients in the range of (0.5–0.9 V) on both antibiotic resistance gene (ARG) propagation and production of biogas in an anaerobic electrochemical membrane bioreactor

(AnEMBR) treating antibiotic-laden wastewater. The study found that the AnEMBR consistently achieved high COD removal efficiencies exceeding 94%, primarily due to improved organic matter degradation and retention by the cathodic biofilm. Methane production was notably enhanced at higher voltages, with optimal yields observed at 0.9 V. However, sustained application of 0.9 V for periods exceeding 30 days led to a decline in methane production and overall reactor performance. Moreover, elevated voltages above 0.7 V were found to stimulate ARG proliferation in both the effluent and supernatant, indicating potential ecological risks associated with high-voltage operation [Li et al., 2021].

Ying et al. (2021) used conductive ceramic membranes for studying the fouling behaviours in electrochemical anaerobic membrane bioreactors (AnEMBR) under various negative voltages (-0.5 V, -1.0 V, and -2.0 V) for synthetic wastewater treatment. The results showed that anti-fouling performance improved by approximately three times for potentials less than -1.0 V compared to control AnMBRs. The scanning electron microscopy and the scanning of confocal laser microscopy revealed that the gel layer porosity at -1.0 V increased for the electricity-conducting membrane, while at -2.0 V, bacterial activity on the membrane surface was inhibited, and the activity of adhering bacteria. However, at -0.5 V, fouling of the membrane increased due to the forming of a dense biofilm. Additionally, methane production was accelerated under potentials below -1.0 V [Ying et al., 2021].

Hu et al. (2022) demonstrated that an electrochemical anaerobic membrane bioreactor (E-AnMBR) outperformed a control anaerobic membrane bioreactor (C-AnMBR) in treating of pesticide wastewater across various hydraulic retention times (HRTs). The E-AnMBR system improved sludge characteristics and effectively mitigated membrane fouling. Specifically, it reduced sludge yield by about 41.2% and lowered the sludge volume index (SVI) by about 32.5%. Methane production ranged from 0.22 to 0.29 L CH₄/g COD_{removed}, which was 1.2 to 1.4 times higher than that of the control system. Volatile fatty acid (VFA) accumulation was also decreased in the E-AnMBR, with an average minimum concentration of 255 mg/L. Additionally, extracellular polymeric substance (EPS) levels in both attached and suspended sludge declined significantly by 41.8% and 77.4%, respectively, contributing to improved sludge settling and reduced membrane fouling. The E-AnMBR delayed fouling of membrane by 31.0–38.5%, with fouling positively correlated to EPS concentration.

However, shorter HRTs negatively affected reactor performance and increased fouling. Overall, the E-AnMBR exhibited enhanced operational stability, greater methane recovery, and reduced sludge disposal challenges compared to the conventional system [Hu et al., 2022].

Liu et al. (2022) conducted a comparative study on the performance and membrane fouling characteristics of an electrochemical anaerobic membrane bioreactor (E-AnMBR, R1) and a conventional anaerobic membrane bioreactor (C-AnMBR, R2) for pesticide wastewater treatment, with reactors of 1.5 m³ active volume. Stainless steel and stainless steel combined with carbon were utilized as cathode and anode materials, respectively. The study evaluated four hydraulic retention times (HRTs): 96, 72, 48, and 24 hours. The E-AnMBR consistently exhibited higher COD removal efficiencies, ranging from 84.7% to 66.3%, compared to 80.1% to 61.1% for the C-AnMBR. Notably, R1 achieved optimal performance at a shorter HRT of 48 hours, whereas R2 required 72 hours. Additionally, R1 reduced colloidal and particulate COD by 60.4%–41.9 and decreased the proportion of COD converting to sludge by 5.0–8.2%, resulting in a 31.0–38.5% mitigation of membrane fouling. The bio-electrochemical processes in R1 also enhanced detoxification rates by 7.8–47.7% relative to R2. Furthermore, the E-AnMBR demonstrated considerable environmental and economic advantages, including a 65.6% reduction in environmental impact, and capital and operating cost savings of 26.3% and 38.9%, respectively [Liu et al., 2022].

2.7. Anaerobic Electro-Dynamic Membrane Bioreactors (AnEDMBRs)

Anaerobic electro-dynamic membrane bioreactors (AnEDMBRs) constitute a novel and developing technology, with research efforts currently limited to a few specialized groups worldwide. The following section reviews the existing literature on this topic. Choi et al. (2022) examined the impact of both negatively and positively applied voltages on the formation and properties of anaerobic dynamic membranes (DMs) in environments with elevated suspended solids levels. Their DM filtration tests were conducted using anaerobic continuously stirred tank reactors (1.7 L working volume). The dynamic membrane module consisted of a 74- μ m stainless steel mesh (dimensions 30 × 50 mm), that functioned both as the DM support and also as the working

electrode. In their study, the membranes were subjected to voltages ranging from -1.2 V to $+1.2$ V to assess the effects of cathodic and anodic polarization. The results showed that the moderate negative voltages (-0.6 V to -1.0 V) delayed fouling through electrostatic repulsion and reactive species generation, while low positive voltages accelerated DM growth via electrostatic attraction. Higher anodic voltages ($+0.8$ V to $+1.0$ V) mitigated fouling by producing oxidative species. However, extreme voltages (± 1.2 V) caused chemical fouling and electrode corrosion. Despite these variations, all tested DMs exhibited high suspended solids rejection efficiencies (86.4–89.6%) [Choi et al., 2022].

Sun et al. (2024) developed an innovative anaerobic cathodic dynamic membrane bioreactor (AnCDMBR) for municipal wastewater (low strength). The system utilized a dynamic membrane (CDM) made from carbon cloth as cathodic with $41\text{ }\mu\text{m}$ pore size, chosen for its affordability and dual role as both a filtration medium and biocathode. This carbon cloth was combined with a titanium (Ti) mesh, which functioned as both the current collector and the structural support for filtration. Two pieces of carbon felts, each with 5 mm thick, served as anodes, and all of electrodes were linked to a direct current (DC) source to maintain a stable electrical field of 1 V. The reactor's working volume was 4 liters. The AnCDMBR system Recorded an average chemical oxygen demand (COD) removal rate above 93%, the effluent COD consistently below 35 mg/L. Additionally, the system enhanced bioenergy recovery, producing methane at a yield of 0.26 liter of CH_4 per gram COD, representing a 1.42-fold increase in contrast with the control group. Methane content exceeded 95%, facilitating the direct use of the biogas [Sun et al., 2024].

Zhou et al. (2025) assessed the operation of an electrochemical anaerobic dynamic membrane bioreactor (electro-AnDMBR) operated at 0.5 V for treating waste activated sludge (WAS) under high-solids conditions ($>50\text{ g/L}$). The study compared an electro-assisted AnDMBR system (EC) with a conventional control AnDMBR (CK). The electro-DM composite membrane module was constructed from titanium (Ti) meshes (pore size: $150\text{ }\mu\text{m}$) and Dacron meshes ($38\text{ }\mu\text{m}$ pore size), bonded with conductive epoxy adhesive. Additional two Ti meshes positioned as anodes on either side, spaced 1.5 cm apart, to enhance electrostatic repulsion. Each system comprised a 3.6 L anaerobic reactor together with external 0.4 L membrane chamber containing the electro-DM module. Hydraulic retention time (HRT) and (SRT) were Kept

constant at 15 and 50 days, respectively, with temperature controlled at 35 ± 2 °C. Results showed that the EC system outperformed the control by exhibiting superior filtration, a more porous and thinner dynamic membrane layer, and significantly reduced fouling. This improvement was attributed to a 27.9% increase in the energy barrier against sludge adhesion to the membrane. Furthermore, the EC system achieved higher volatile solids (VS) reduction, increased biogas production by 22.4%, and elevated methane content from 64.8% to 70.7% [Zhou et al., 2025].

Choi et al. (2025) assessed the operational effectiveness of an anaerobic cathodic dynamic membrane bioreactor (AnCDMBR) designed for treating highly concentrated organic wastewater, characterized by an average chemical oxygen demand (COD) of 22.5 ± 2.1 g/L. The experimental setup comprised 3-liter continuously stirred tank reactors, each integrating a submerged dynamic membrane formed from carbon cloth with a pore diameter of 20 μm . To establish the electrochemical configuration, carbon felt anodes were installed symmetrically 15 mm from the cathodic side of the membrane. The researchers examined four electrochemical scenarios, including a baseline open-circuit condition (0 V) and applying voltages of -0.5 , -0.8 , and -1.2 V. The analysis identified -0.8 V as the most favorable voltage, contributing to a 10% enhancement in methane output and a 21% reduction in the rate of transmembrane pressure accumulation. These improvements underscored better pollutant removal efficiency and reduced membrane fouling. In contrast, the application of -1.2 V had a detrimental effect, accelerating membrane clogging and diminishing methane generation, thus highlighting that excessive voltage can negatively impact system stability [Choi et al., 2025].

3. MATERIAL AND METHOD

3.1. Wastewater Characteristics and Source Sludge

Anaerobic sludge used to seed the proposed reactor was collected from the treatment plant of the PepsiCo Suadiye site in Kocaeli, Türkiye. The treatment plant consists of a physicochemical unit (oil trap, coarse, and fine screens, dissolved air floatation, flocculation and coagulation, primary clarification, neutralization, and equalization) and biological unit (anaerobic system as up-flow anaerobic sludge bed reactor, equalization tank and aerobic reactors with final clarification). WWTP design capacity is 2304 m³/day. The anaerobic seed sludge, in granular form, was collected from the lower part of up-flow anaerobic reactor. The seed sludge after collection stored in the laboratory under controlled conditions, it was kept in a cooling room at approximately 4 °C in a sealed, airtight container to minimize oxygen exposure and maintain anaerobic conditions. The initial parameters of the seed sludge were: pH 6.9, TSS of 83,000 mg/L, and VSS of 54,000 mg/L.

The studies were carried out with two different types of wastewater: synthetic wastewater and the real leachate. The main components of the synthetic wastewater solution as well as macro- and micronutrient components are slightly revised from the recipes described in the studies by [Londoño et al., 2012] and [Ozgun et al., 2013], respectively. The synthetic wastewater characteristics throughout the experimental period are summarized in **Table 3.1** The feeding of concentrated synthetic wastewater solution was kept at 4°C and diluted daily with water before feeding. The reactor was supplied with wastewater having average soluble COD of 11.4±1 g COD/L.

Table 3.1: Synthetic wastewater formulation.

Chemical	Amount (g/L)	Note
Glucose	9.6	Main component
Starch	0.8	
Peptone	0.8	
Urea	0.88	
Monopotassium phosphate	0.08	
Sodium bicarbonate	8	
Calcium chloride dihydrate	0.05	Macro nutrients stock solution. 1 mL for each L of feeding solution
Ammonium chloride	1.4	
Magnesium sulfate heptahydrate	0.5	
Yeast extract	0.5	
Sodium carbonate	2	
Boric acid	0.05	Micro nutrients stock solution. 1 mL for each L of feeding solution
Zinc chloride	0.05	
Copper(ii) chloride dihydrate	0.03	
Ferrous chloride tetrahydrate	1	
Manganese(ii) chloride tetrahydrate	0.25	
Cobalt(ii) chloride hexahydrate	1	
Ammonium molybdate tetrahydrate	0.05	
Aluminium sulfate	0.09	
Sodium thiosulfate pentahydrate	0.1	
EDTA	0.1	
Resazurin	0.1	
Nickel(ii) chloride hexahydrate	0.05	
Hydrochloric acid	-	pH adjustment

The leachate was obtained from a landfill (IZAYDAŞ) in Kocaeli, Türkiye. Sixty liters of landfill leachate were collected for the experimental processes, stored at 4°C. **Table 3.2** shows the real leachate characteristics.

Table 3.2: Real leachate characteristics.

Parameters	Average Value
pH	7.78
Electrical conductivity, EC (mS/cm)	20.89
Total alkalinity, TA (mg CaCO ₃ /L)	9,300
Dissolved Oxygen (DO) (mg/L)	1.77
Total solid, TS (mg/L)	25,890
Total volatile solid, TVS (mg/L)	9,575
Total suspended solid, TSS (mg/L)	2,135
Volatile suspended solid, VSS (mg/L)	400
Soluble chemical oxygen demand, sCOD (mg/L)	10,280
Total chemical oxygen demand, tCOD (mg/L)	14,000
Biological oxygen demand, BOD ₅ (mg/L)	5,600
Total Kjeldahl nitrogen, TKN (mg/L)	1,670
Ammonium nitrogen, NH ₄ ⁺ (mg/L)	1,496
Phosphate-Phosphorus, PO ₄ -P (mg/L)	7.34

3.2. Experimental Setup

Experiments were conducted in the AnDMBR and AnEDMBR system comprised of a glass reactor, membrane module, a direct current (DC) electrical power supply unit, pumps, sensors, and a control system for process automation (**Figure 3.1**). The glass reactor has a 5 L effective working volume and is equipped with a heating water jacket. A circulating water bath (Grant GD120, England) was used to maintain the temperature of both systems (AnDMBR and AnEDMBR) under mesophilic conditions ($35 \pm 1^\circ\text{C}$). Two independent peristaltic pumps were utilized (Longer BT101, China) to feed wastewater into the reactor and collect membrane permeate, where the negative pressure was monitored using a pressure transducer. Biogas generated in the system was recirculated from the reactor base using a diaphragm-type pump (KNF, N86 KTDCB, Germany) at a flow rate of 1 L/min, regulated by a rotameter (Gentek, 1 to 5 L/min, Turkey). This recirculation provided a shearing influence on the membrane surfaces, helping to reduce formation of cake layer on the membrane.

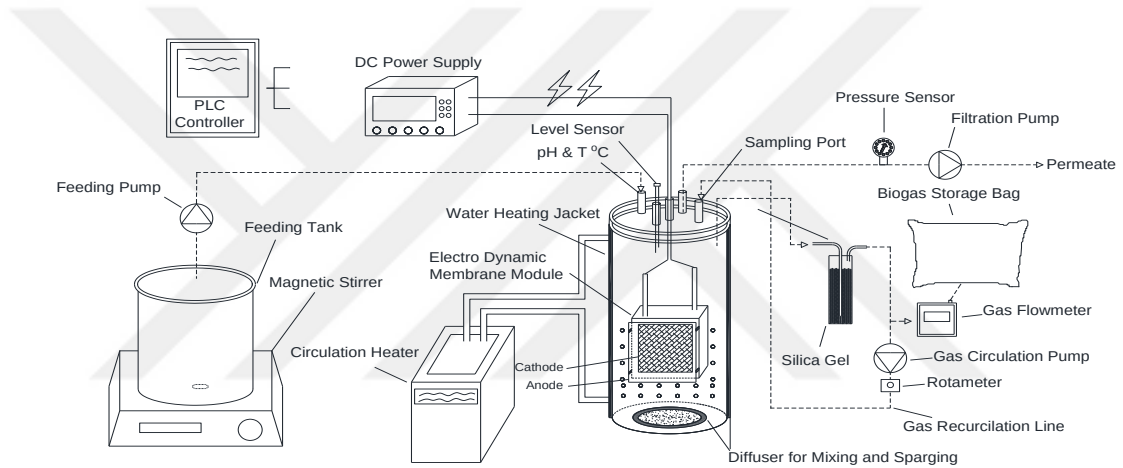
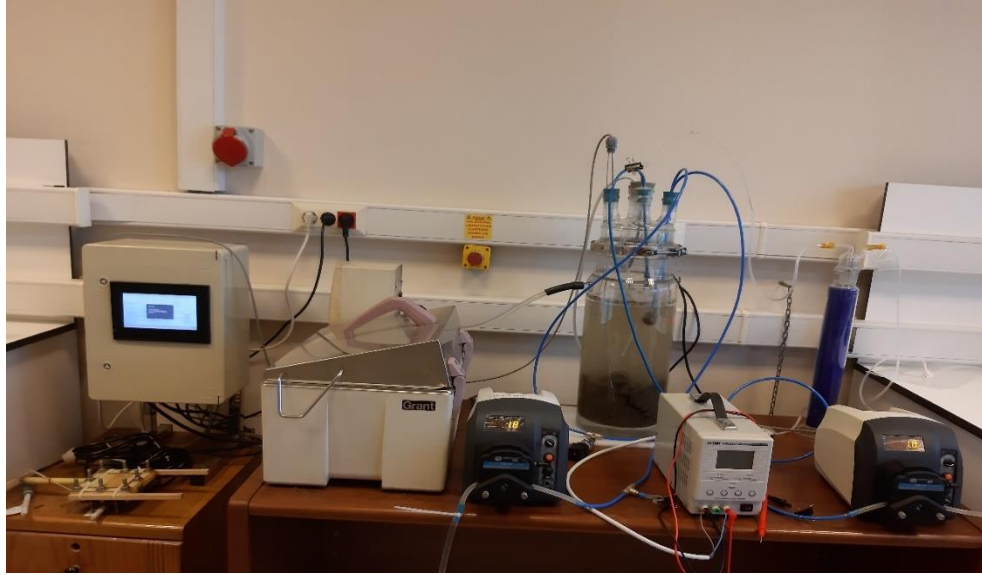


Figure 3.1: Photograph and schematic diagram of AnEDMBR setup.

DC power supply (Netes, GW Instek GPD-3303D, China) was used to provide constant voltage. Two identical carbon fabric fiber membrane modules (Norm Technology Company, Istanbul, Turkey) having 2100 m²/g surface area with 67.28 cm² total effective filtration area were used in an AnDMBR and AnEDMBR. The carbon fabric fiber membrane and iron plates (120 mm × 120 mm) were employed as the cathode and the anode, respectively. The gap between the cathode and anode was 9 mm. The water level within the reactor was monitored using a conductive level sensor. A gas flowmeter type (Bioprocess, BPC, Sweden) was used to measure the produced biogas. An online pressure detector (ATEK 4 to 20 mA; − 1 to 0 bar, Turkey) was employed to detect transmembrane pressure (TMP). The AnDMBR and AnEDMBR systems were operated via an automated control system built on a PLC unit. A Raspberry Pi single-board computer, running the Linux operating system,

served as the core of the control system. The control software was developed in C++ using the QT application framework. The automation device tracked and recorded the TMP.

3.3. Experimental Operation Conditions

For synthetic wastewater, the acclimation was carried out over 66 days and consisted of two phases: batch mode followed by a short continuous mode. In the batch phase, the reactor was inoculated with 5 liters of seed sludge and fed with synthetic wastewater. This phase started at a COD level similar to that of the real wastewater from the Suadiye Pepsico factory (the source of the seed sludge) and continued until COD removal efficiency stabilized over multiple feeding cycles, indicating successful microbial adaptation. Subsequently, the system was transitioned to continuous mode at the final acclimated COD level, as the biomass was already well-adapted. Following the acclimation, experiments continued with three operational stages, first and second stages the system were fed with synthetic wastewater, while in the third stage the system was fed with real leachate obtained from a landfill leachate treatment facility operated by IZAYDAŞ in Kocaeli, Türkiye. **Figure 3.2** illustrates the experimental operation stages applied in the experiments of the thesis. In the first stage, the system was operated for 80 days as an AnDMBR without any electrical field (0 V) at two HRT of 8 and 5 days (40 days for each HRT). The second stage, the system was operated for 80 days as an AnEDMBR under the effect of electrical field at also under two HRT of 8 and 5 days (40 days for each HRT). In the third stage, the system was operated as an AnEDMBR for 40 days under the effect of an electrical field at HRT of 5 days. Two membranes were operated simultaneously: one at 0.8 V and the other at 1.2 V. The temperature of the reactor was stable throughout the operation time at 35 ± 1 °C that was sustained by a water bath circulation system. Membrane filtration and wastewater feeding were conducted continuously. The operation was conducted at an average volatile mixed liquor suspended solids (MLVSS) concentrations of 14848 ± 498 mg/L and 14700 ± 541 mg/L in AnDMBR and AnEDMBR, respectively. The reactor's pH was monitored daily, with adjustments made whenever it fell outside of 6.8 to 7.4 (optimal range). The TMP was regularly monitored using a manometer connected between the permeate collection tube and the suction pump. The electric field of 0.8 V and 1.2 V for every membrane in AnEDMBR system was applied by

DC power supply. The self-circulation biogas is recycled to the base of reactor by a pump, providing a shear impact on the module of membrane and reducing cake formation and mixing. The level of water in the reactor was maintained near a constant using a sensor linked to the PLC automation system, which regulated the permeate pump to maintain a steady flux during the operation period. For the two systems (AnDMBR and AnEDMBR) nitrogen gas was injected after membrane replacement to sustain the anaerobic environment of anaerobic microbial activity.

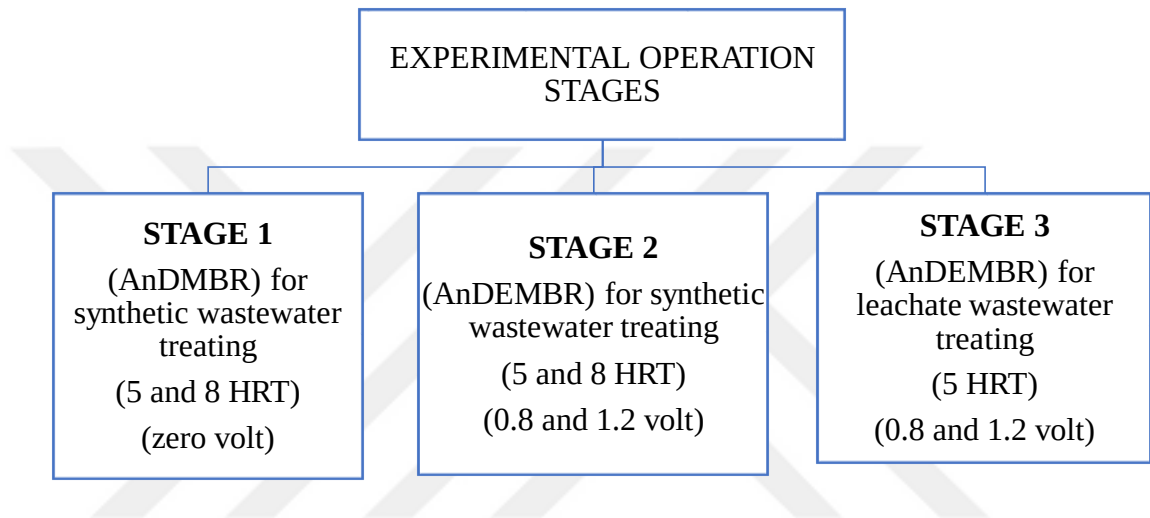


Figure 3.2: Experimental operation stages.

3.4. Analytical Methods

3.4.1. Physio-Chemical Analyses

Total suspended solids (TSS), volatile suspended solids (VSS), chemical oxygen demand (COD), ammonium nitrogen, and total phosphorus (TP) were analyzed following the Standard Methods [APHA, 2008]. The reactor pH was measured daily using a portable meter (HACH HQ40d, USA). Samples were pre-filtered using 0.45 μm membranes before conducting soluble COD analysis.

3.4.2. Membran Fouling Analysis

Protein and carbohydrate concentrations for the SMP (Soluble Microbial Products) and EPS (extracellular polymeric substances) were identified using methods described

by Lowry et al. (2014) [**Lowry and Rosebrough, 2014**] and Dubois et al. (1956) [**Dubois et al., 1956**], respectively.

Scanning electron microscopy (SEM) (Philips XL30 SFEG SEM) was used to observe the surface morphology of the membranes before and after the filtration experiments. Prior to SEM observation, the samples were dehydrated using ethanol (95%) and then allowed to dry at room temperature, also gold coating was applied to the samples. Energy dispersive X-ray spectroscopy (EDX) (Philips, XL-30S FEG) analysis was also performed in order to identify the elemental composition of inorganic species present on the surface of the used membranes. The chemical composition of the pollutants on the surface of membrane was analyzed using Attenuated Total Reaction-Fourier infrared spectrometer (ATR-FTIR, Perkin Elmer, USA).

3.4.3. GC Method for Biogas Analysis

Biogas samples were analysed by gas chromatography combined with flame ionisation detector with-methanizer system. An Agilent 6890N gas chromatograph (GC) equipped with a flame ionization detector (FID) was employed to quantify methane (CH_4) concentrations, utilizing a Molsieve capillary column ($60 \text{ m} \times 530 \text{ }\mu\text{m I.D.} \times 50 \text{ }\mu\text{m}$ film thickness). For carbon dioxide (CO_2) analysis, a methanizer (part number: G1580-61020, Agilent, USA) containing a nickel-based catalyst was integrated with the FID. The methanizer catalytically converts CO_2 into CH_4 , enabling simultaneous detection of both gases using a single chromatographic column and detector system through the FID-methanizer configuration [**Almeida et al., 2020**], [**Pascale et al., 2017**], [**Wilson et al., 2017**]. The oven program was run in isothermal mode at 60°C for 10 minutes. The carrier gas for the column was high purity Argon, and the column flow rate was 9.9 mL/min . Temperatures of the detector and the methanizer were 250°C and 375°C , respectively. The inlet temperature of the gas chromatograph was maintained at 150°C , with a split ratio set to 0.5:1. The flow rates for the flame ionization detector (FID) gases were controlled at 300 mL/min for air and 30 mL/min for hydrogen (H_2). For calibration purposes, a standard gas mixture containing 70% methane (CH_4) and 30% carbon dioxide (CO_2) by volume was utilized.

4. RESULTS AND DISCUSSION

4.1. COD removal performance

4.1.1 Acclimation stage

The acclimation of microorganisms was conducted in two main phases to ensure effective adaptation to the high-strength synthetic wastewater conditions. More than 5 liters of seed sludge were used (TSS = 83,000 mg/L, VSS = 54,000 mg/L), with an original COD concentration (C_0) of 1,435 mg/L. The process began with a fed-batch mode operation, where the reactor was inoculated and fed with synthetic wastewater at a COD concentration close to that of the real wastewater from the Suadiye Pepsico factory, and then gradually increased. During this initial acclimation phase, the influent (COD_{inf}) and effluent (COD_{eff}) COD concentrations were measured daily, along with regular monitoring of microbial activity indicators such as pH and gas production. This phase continued for 66 days (as shown in **Figure 4.1**), until the COD removal efficiency stabilized over several consecutive cycles, confirming the establishment of an active and adapted microbial community. The peaks in **Figure 4.1** represent the feeding cycles.

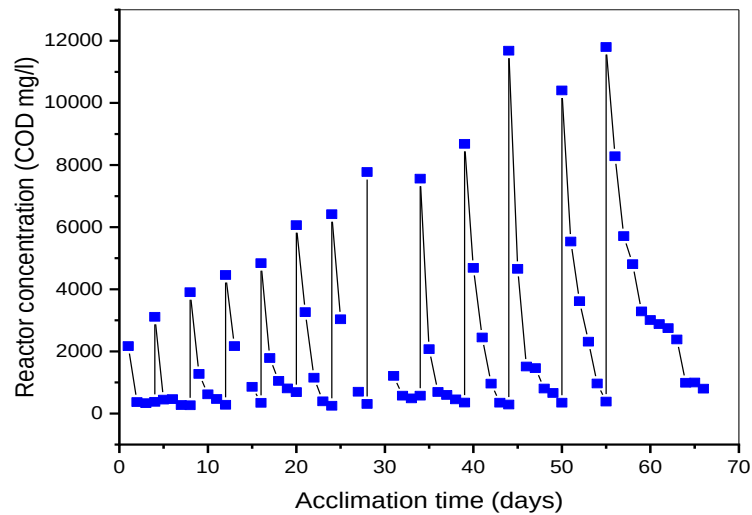


Figure 4.1: Concentrations of COD in the reactor during the acclimation period.

After achieving stable performance in fed-batch mode, the system was transitioned to continuous operation at the final acclimated COD level (over 11,000 mg/L). This transition phase was intentionally kept short, lasting only a few days, as the biomass was already well-adapted. During continuous operation, HRT was gradually adjusted to optimize treatment efficiency, while COD removal, system performance, and microbial population stability were continuously monitored.

4.1.2 COD removal performance of AnDMBR and AnEDMBR systems

The concentrations of both influent and permeate COD of the AnDMBR systems (synthetic wastewater) with operation time are presented in **Figure 4.2**. The average influent COD concentrations (**Figure 4.2 a**) were 12359 ± 972 mg/L during the 8 day HRT stage and 11310 ± 895 mg/L during the 5 day HRT stage. The average permeate COD concentrations were 140 ± 39 mg/l for the 8 day HRT and 173 ± 61 mg/l for the 5 day HRT stage. The average COD removal efficiencies (**Figure 4.2 b**) were $99 \pm 0.4\%$, for the 8 day HRT and $98 \pm 0.6\%$ for the 5 day HRT stage.

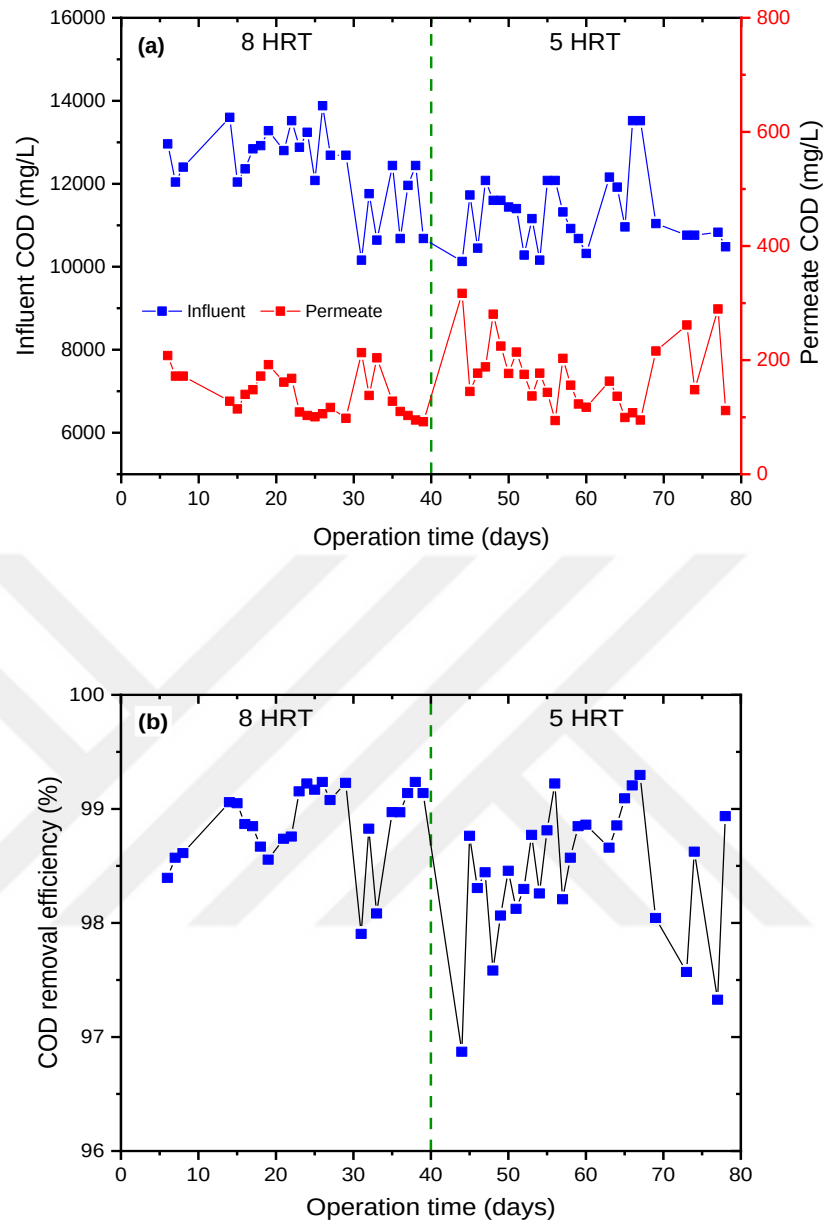


Figure 4.2: (a) Concentrations of COD influent and permeate for AnDMBR system. (b) COD removal efficiency for AnDMBR system during the operation time.

For AnEDMBR systems (synthetic wastewater) (**Figure 4.3**), the average influent COD concentrations were 11678 ± 1147 mg/L during the 8 day HRT stage and 11443 ± 1108 mg/L during the 5 day HRT stage. The average permeate COD concentrations were 117 ± 44 mg/L for 0.8 V and 107 ± 34 mg/L for 1.2 V for the 8 day HRT, and the average permeate COD concentrations were 120 ± 65 mg/L for 0.8 V and 117 ± 61 mg/L for 1.2 V for the 5 day HRT stage (**Figure 4.3 a**). The average COD

removal efficiencies (**Figure 4.3 b**), were $98.98 \pm 0.38\%$ for 0.8 V and $99.07 \pm 0.29\%$ for 1.2 V for the 8 day HRT and $98.97 \pm 0.53\%$ for 0.8 V and $98.99 \pm 0.49\%$ for 1.2 V for the 5 day HRT stage.

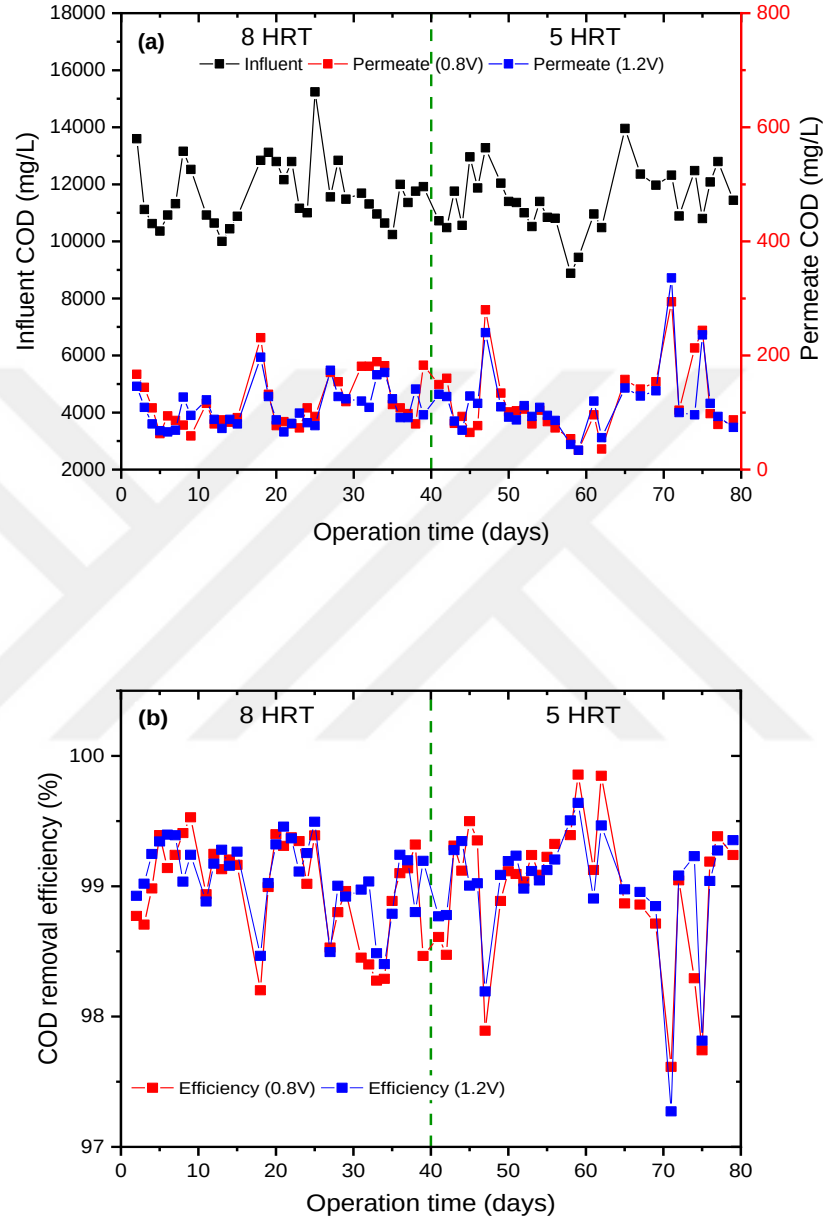


Figure 4.3: (a) Concentrations of COD influent and permeate for AnEDMBR system. (b) COD removal efficiency for AnEDMBR system (for synthetic wastewater) during the operation time.

For real leachate wastewater feeding to the AnEDMBR stage (**Figure 4.4**), the average influent COD concentration (**Figure 4.4 a**) was 9756 ± 935 mg/L. The average permeate COD concentrations were 2098 ± 363 mg/L for 0.8 V and 2076 ± 383 mg/L for

1.2 V. The average COD removal efficiencies (**Figure 4.4 b**) were $78.21 \pm 4.54\%$ for 0.8 V and $78.49 \pm 4.51\%$ for 1.2 V.

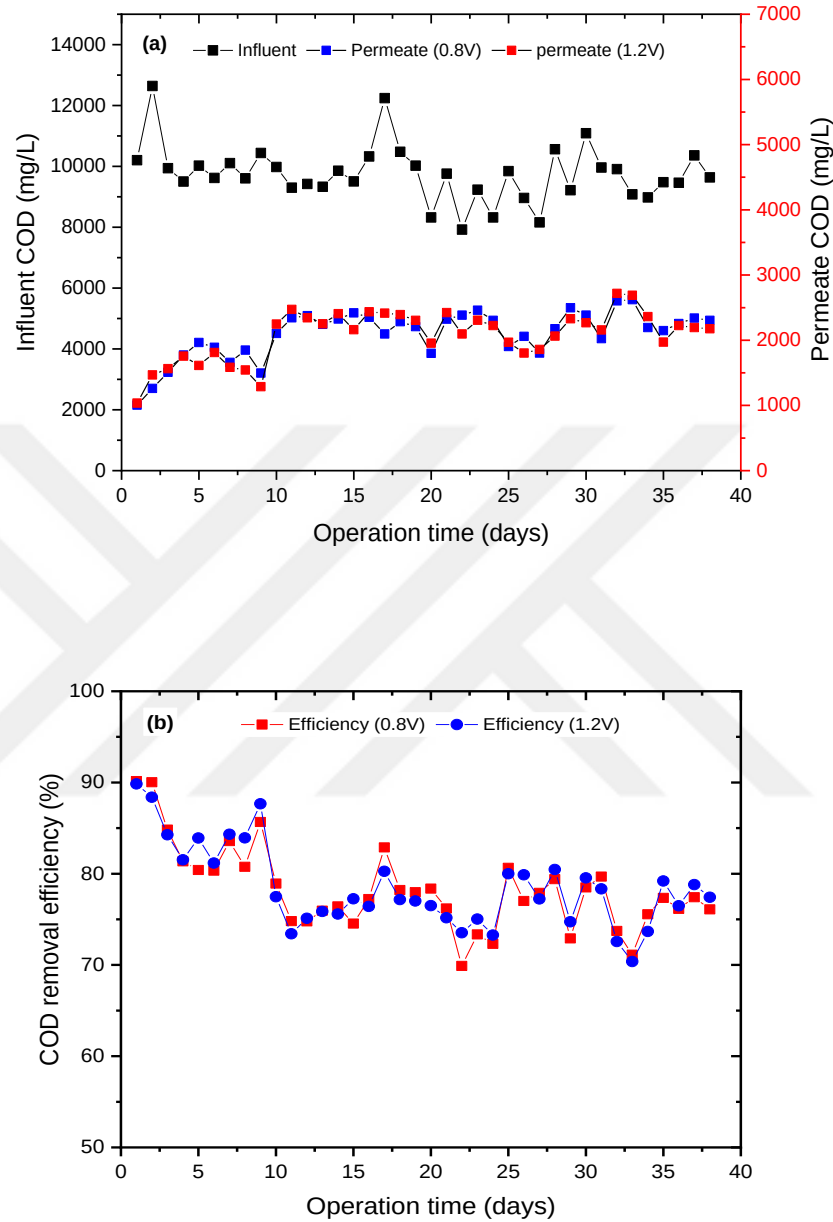


Figure 4.4: (a) Concentrations of influent and permeate COD for AnEDMBR system. (b) COD removal efficiency for AnEDMBR system (for real leachate wastewater) during the operation time.

For the AnEDMBR system, the average COD removal efficiencies at the 8 day HRT stage ($98.98 \pm 0.38\%$ at 0.8 V and $99.07 \pm 0.29\%$ at 1.2 V) were comparable to those achieved by the AnDMBR system ($99 \pm 0.4\%$). However, at the 5 day HRT stage, the AnEDMBR system exhibited slightly higher COD removal efficiencies

($98.97 \pm 0.53\%$ at 0.8 V and $98.99 \pm 0.49\%$ at 1.2 V) than the AnDMBR system ($98 \pm 0.6\%$). In contrast, for real leachate wastewater, the AnEDMBR system exhibited significantly low efficiencies ($78.21 \pm 4.54\%$ for 0.8 V and $78.49 \pm 4.51\%$ for 1.2 V) compared to its removal with synthetic wastewater under the same operating conditions (5 day HRT).

For synthetic wastewater at the 8 day HRT stage, the average permeates COD concentrations in the AnEDMBR system (117 ± 44 mg/L at 0.8 V and 107 ± 34 mg/L at 1.2 V) were lower than those in the AnDMBR system (140 ± 39 mg/L), representing reductions of over 19% and 30%, respectively. Similarly, at the 5 day HRT stage, the AnEDMBR system (120 ± 65 mg/L at 0.8 V and 117 ± 61 mg/L at 1.2 V) also exhibited lower permeate COD concentrations compared to the AnDMBR system (173 ± 61 mg/L), corresponding to reductions of more than 44% and 47%, respectively. For the synthetic wastewater AnEDMBR system at both HRTs (8 and 5 day), the average permeate COD concentration at 1.2 V was slightly lower than that at 0.8 V. In contrast, when treating real leachate wastewater, the AnEDMBR system exhibited significantly higher permeate COD concentrations (2098 ± 363 mg/L at 0.8 V and 2076 ± 383 mg/L at 1.2 V) compared to its performance with synthetic wastewater under the same operating conditions (5 day HRT).

The reductions in permeate COD concentrations in the AnEDMBR system compared to the conventional AnDMBR at both HRT stages (8 and 5 day) can be attributed to several factors related to enhanced membrane performance and electrochemical effects. The application of an external electric field in the AnEDMBR plays a significant role in improving both removal and filtration efficiency. The electric field promotes electrostatic repulsion between the negatively charged organic pollutants and the membrane surface. This leads to more effective separation of organic matter from the treated effluent. Additionally, the electrochemical conditions at the cathode may have enhanced microbial activity and substrate degradation, especially by stimulating the activity of electroactive bacteria. This microbial enhancement contributed to better COD removal before the permeate passed through the membrane layer, resulting in improved effluent quality. Furthermore, the stable dynamic membrane layer under the influence of the electric field may contributed to reduced resistance and more efficient pollutant retention.

In contrast to synthetic wastewater, the AnEDMBR system treating real leachate wastewater produced significantly higher permeate COD concentrations, indicating reduced treatment efficiency. Despite operating under the same conditions (5 day HRT and applied voltages of 0.8 V and 1.2 V), the effluent quality deteriorated when real leachate was used, suggesting a greater treatment challenge associated with the complex composition of leachate and presence of refractory organic substances in mature landfill leachate.

The performance and COD removal efficiencies from this study were compared to those reported in the literature. Our findings are consistent with those of Choi et al. (2025), who reported comparable organic removal performances across all tested reactors for the treatment of high-strength organic wastewater with a COD concentration of 24 g/L. The study employed an anaerobic cathodic dynamic membrane bioreactor (AnCDMBR) equipped with a carbon cloth dynamic membrane (pore size: 20 μm) operated under externally applied negative voltages ranging from 0 to -1.2 V. The average COD removal efficiencies observed were $81.3 \pm 1.9\%$ (0 V), $81.2 \pm 1.0\%$ (-0.5 V), $83.1 \pm 2.3\%$ (-0.8 V), and $77.2 \pm 1.9\%$ (-1.2 V), indicating that moderate electrochemical stimulation (particularly at -0.8 V) slightly enhanced treatment efficiency, while higher voltage levels may have adversely affected performance [Choi et al., 2025]. Yang et al. (2018) evaluated the performance of electro-enhanced carbon nanotube hollow-fiber membrane (CNTs-HFMs) using three types of wastewater: sodium alginate (SA), bovine serum albumin (BSA), and supernatant from an anaerobic bioreactor (SAB). They demonstrated COD removal efficiencies of 92.1% for BSA, 87.3% for SA, and 56.8% for SAB at an applied voltage of -1.2 V. These efficiency values correspond to an increase of 3.3-fold, 1.4-fold, and 1.5-fold, respectively, when compared to membrane filtration without an applied voltage [Yang et al., 2018]. Similarly, Deng et al. (2022) investigated novel electro-AnMBR systems (AnMBR-PVDF and AnMBR-Ceram) using a Fe anode and Ti membrane cathode, applying different voltages (0, -0.6 , and -1.2 V). These systems were designed to treat simulated kitchen wastewater with three COD levels (5,000, 12,000, and 20,000 mg/L) at various organic loading rates (0.66, 1.58, and 2.63 kg COD/ $\text{m}^3\cdot\text{d}$). The electro-AnMBR showed superior pollutant removal compared to traditional AnMBRs, with effluent COD concentrations stabilizing between 200 and 550 mg/L and achieving over 96% COD removal. As the OLR rose to 2.63 kg

COD/m³·d, initially the reactors showed a temporary spike in effluent COD, but levels eventually stabilized within the range 200 and 700 mg/L, maintaining a removal efficiency of over 95% [Deng et al., 2022]. In contrast, Zhang et al. (2021) discovered that both the electro-AnMBR (with 0.5 V electric field) and the control AnMBR treating synthetic municipal wastewater (comprising starch at 100 mg/L and glucose at 400 mg/L) maintained COD removal efficiencies above 90% throughout the long-term duration operation. The application of the electric field did not considerably affect the COD removal performance of either system [Zhang et al., 2021]. Xie et al. (2014) investigated the application of an anaerobic dynamic membrane bioreactor (AnDMBR) for landfill leachate treatment, reporting an average COD removal efficiency of 62.2%. The reactor was fed with raw leachate characterized by high total ammonium concentrations (>3000 mg/L) and COD levels exceeding 13,000 mg/L. The authors attributed the relatively low removal efficiency to the high concentration of refractory organic compounds commonly present in mature landfill leachate, which are resistant to biological degradation [Xie et al., 2014].

4.2. Biomass Concentration Variation

The AnDMBR and AnEDMBR systems for both synthetic and real leachate wastewaters were operated at approximately the same TSS and VSS concentrations to allow for a comparative performance assessment. **Figure 4.5** illustrates the TSS and VSS concentrations in the reactors over time for both systems. To sustain a stable concentration of anaerobic microorganisms throughout the experimental procedure, no sludge was extracted from the reactors, and the SRT was assumed to be nearly infinite. For synthetic wastewater, in the AnDMBR system (**Figure 4.5 a**), the average concentrations of MLSS and MLVSS during both HRT stages were 24800±900 mg/L and 14600±500 mg/L, respectively. For the AnEDMBR system (**Figure 4.5 b**), these concentrations were 24102±1153 mg/L and 15039±700 mg/L, respectively. For leachate wastewater, the MLSS and MLVSS concentrations in the AnEDMBR system (**Figure 4.5 c**) were 23745±514 mg/L and 13675±526 mg/L, respectively.

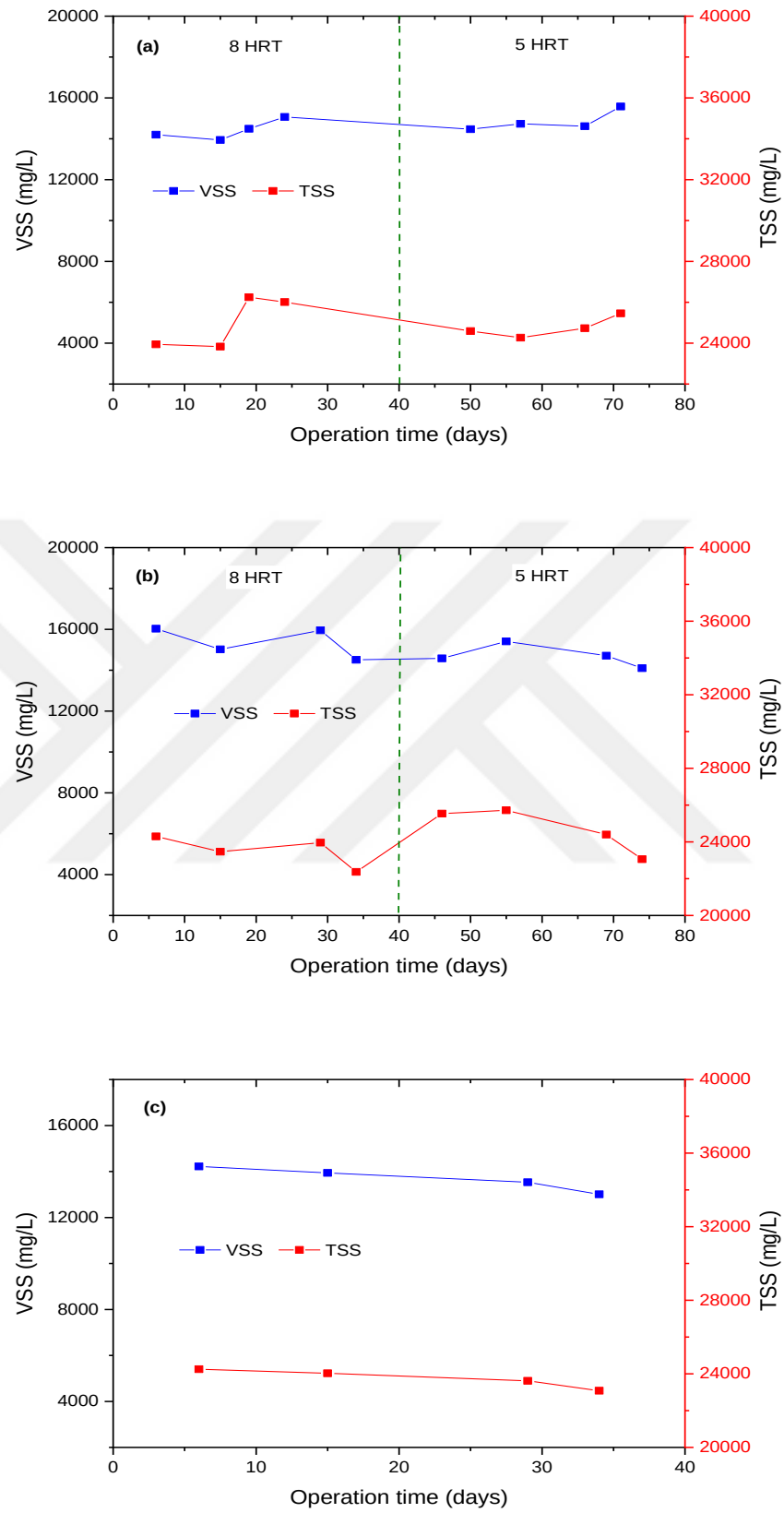


Figure 4.5: Concentrations of TSS and VSS for (a) AnDMBR system for synthetic wastewater, (b) AnEDMBR system for synthetic wastewater, (c) AnEDMBR system for real leachate treatment during the operation times.

In our study, The MLSS concentrations were intentionally elevated to optimize treatment efficiency for high-strength wastewater. Similarly, Mutamim et al., (2012) suggested that higher MLSS levels further improve the degradation process [Mutamim et al., 2012].

4.3 Biogas Production

The high concentration of organic matter in wastewater makes it suitable for anaerobic conversion, leading to energy-rich biogas producing. **Figure 4.6** illustrates the variations of biogas yield from the synthetic wastewater in the AnDMBR and AnEDMBR, and real leachate wastewater in AnEDMBR system respectively. For the treatment of synthetic wastewater in AnDMBR (**Figure 4.6 a**), the average biogas productions were 3.50 ± 0.52 L/day at 8 day HRT and 4.35 ± 0.51 L/day at 5 day HRT. For the treatment of synthetic wastewater in AnEDMBR (**Figure 4.6 b**), the average biogas productions were 3.66 ± 0.82 L/day at 8 HRT and 4.79 ± 0.87 L/day at 5 day HRT. For the real leachate wastewater treatment in AnEDMBR (**Figure 4.6 c**), the average production of biogas was 3.06 ± 0.72 L/day at 5 day HRT.

Biogas production from synthetic wastewater in the AnEDMBR system exceeded that of the AnDMBR system by around 4.5% for 8 day HRT and 10% for 5 day HRT. In our study, the observed increase in biogas production in the AnEDMBR system compared to the AnDMBR system can be attributed to the beneficial effects of the applied electric field. The electrochemical stimulation in AnEDMBR likely enhanced microbial activity, particularly for electroactive microorganisms involved in methanogens. This improvement in biological activity may have contributed to more efficient substrate degradation and gas production, especially under higher organic loading at the shorter HRT.

In contrast, when real leachate wastewater was treated under the same AnEDMBR conditions (5 day HRT), biogas production decreased by approximately 36%. This reduction is likely due to the complex and inhibitory nature of real leachate, which typically contains a high concentration of refractory organic compounds, heavy metals, and toxic substances that are more resistant to anaerobic degradation and can inhibit the metabolic activity of methanogenic, leading to reduction in biogas yield.

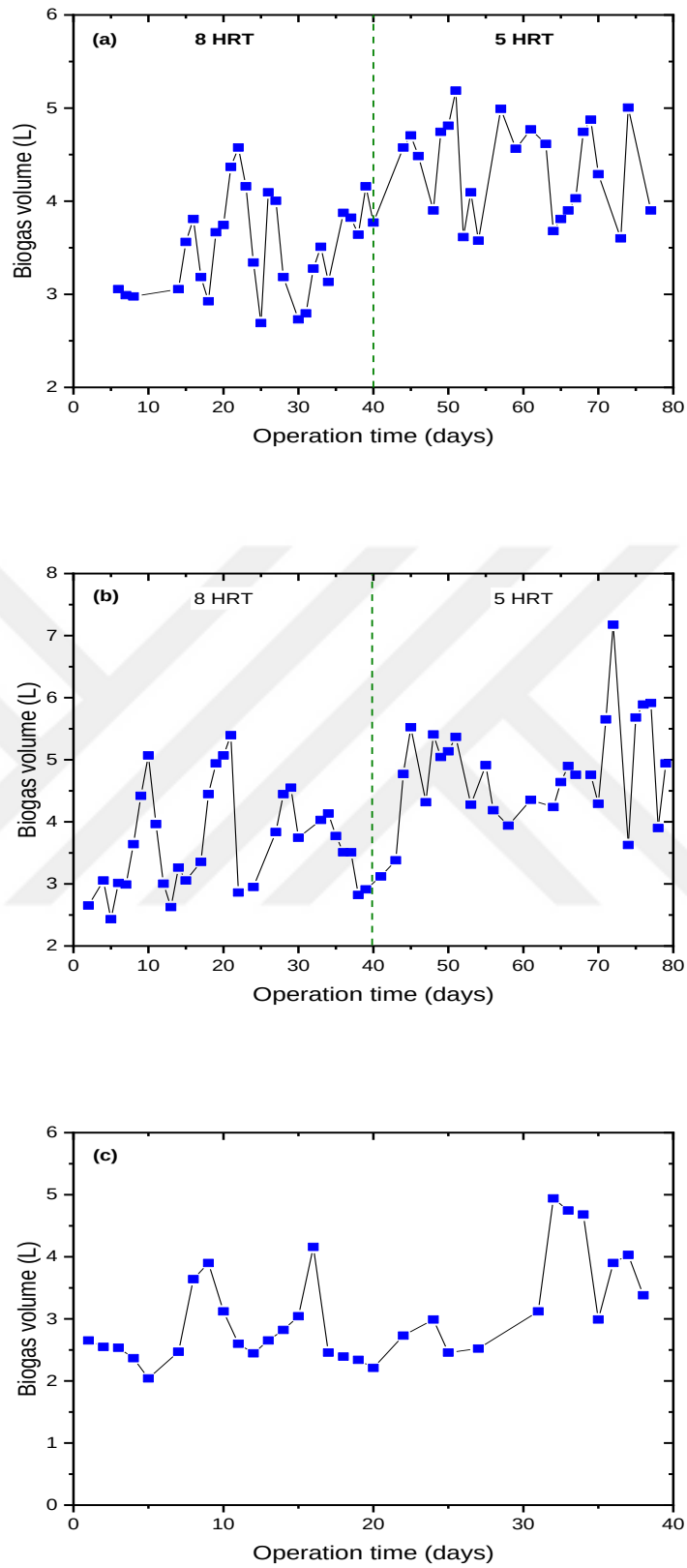


Figure 4.6: (a) Biogas production from synthetic wastewater in AnDMBR , (b) biogas production from synthetic wastewater in AnEDMBR, (c) biogas production from real leachate in AnEDMBR during the operation times.

The biogas production in this study were compared to those reported in the literature. Our findings are consistent with those of Zhou et al. (2025), who explored the performance of electrochemical anaerobic dynamic membrane bioreactor (electro-AnDMBR) at 0.5 V for waste activated sludge (WAS) under high-solids conditions (>50 g/L). The study consists of an electro-assisted AnDMBR system (EC) and a control AnDMBR (CK). The hydraulic and solids retention times (HRT and SRT) were maintained at 15 days and 50 days, respectively. The EC system achieved a 22.4% increase in biogas yield than the CK system [Zhou et al., 2025]. Zhen et al. (2023) also reported an increase in biogas production upon the application of an external voltage in their study using an electrochemical anaerobic membrane bioreactor (EC-AnMBR) for the treatment of mixed wastewater composed of sewage sludge and food waste. In their experiments, the average rate of biogas production during Stage I (0 V) was 0.12 ± 0.01 L/L·day, which increased to 0.17 ± 0.02 L/L·day and 0.18 ± 0.12 L/L·day in Stage II (0.4 V) and Stage III (0.8 V), respectively. These findings support the enhancing effect of electrochemical stimulation on anaerobic digestion performance and biogas generation [Zhen et al., 2023].

Figure 4.7 (a), (b), and (c) illustrate the variations in methane (CH_4) and carbon dioxide (CO_2) content in the biogas produced during the treatment of synthetic wastewater in the AnDMBR and AnEDMBR systems, as well as real leachate wastewater in the AnEDMBR system, respectively.

For synthetic wastewater treatment in the AnDMBR system (**Figure 4.7 a**), the average CH_4 concentration at 8 day HRT was $66.75 \pm 3.11\%$, which increased slightly to $67.77 \pm 2.88\%$ at 5 day HRT. Correspondingly, the average CO_2 concentration decreased from $27.43 \pm 3.05\%$ at 8 day HRT to $26.00 \pm 2.62\%$ at 5 day HRT.

In the AnEDMBR treating synthetic wastewater (**Figure 4.7 b**), the average CH_4 concentration increased from $65.84 \pm 3.87\%$ at 8 day HRT to $68.04 \pm 2.65\%$ at 5 day HRT. Similarly, CO_2 concentrations declined from $28.52 \pm 3.90\%$ at 8 day HRT to $25.50 \pm 2.71\%$ at 5 day HRT stage.

For the treatment of real leachate wastewater in the AnEDMBR system (**Figure 4.7 c**), operated at a 5 day HRT, the average CH_4 and CO_2 concentrations in the biogas were $69.09 \pm 1.72\%$ and $25.54 \pm 1.86\%$, respectively.

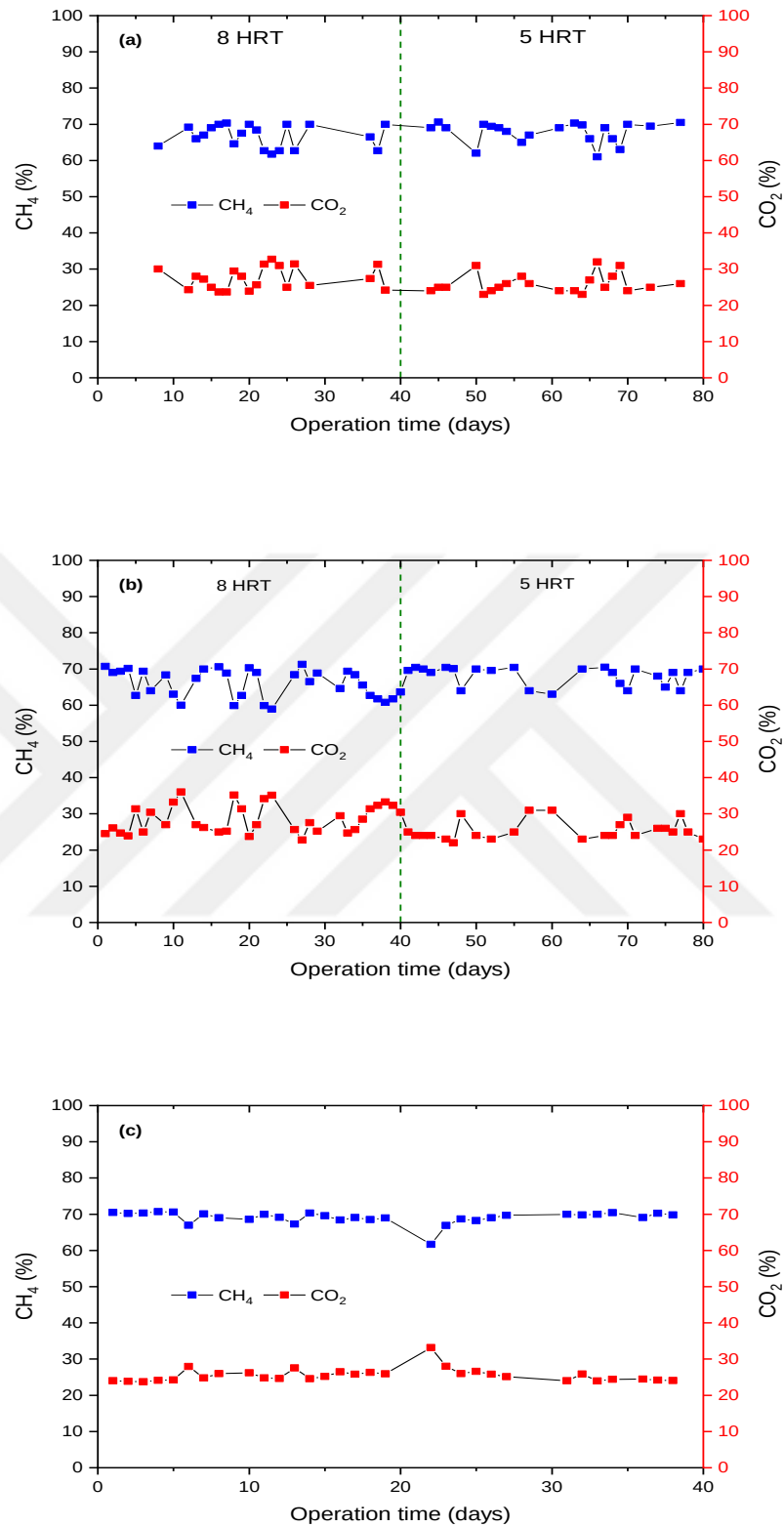


Figure 4.7: Methane-carbon dioxide percentages in the biogas of: (a) AnDMBR (synthetic wastewater), (b) AnEDMBR (synthetic wastewater), (c) AnEDMBR (real leachate wastewater) systems during the operation times.

In our study, both AnDMBR and AnEDMBR systems treating synthetic wastewater, a slight increase in methane concentration was observed when the HRT was reduced from 8 days to 5 days. This improvement in methane percent at shorter HRTs may be attributed to the increased organic loading rate, which can stimulate microbial activity and promote higher methanogenesis efficiency under optimal conditions. Additionally, the corresponding decrease in CO₂ concentrations suggests a shift toward more efficient substrate conversion to methane. The AnEDMBR system demonstrated slightly higher methane content at 5 day HRT compared to the AnDMBR system under the same conditions. This can be explained by the positive influence of the applied electric field. Interestingly, when real leachate wastewater was treated in the AnEDMBR system, the methane concentration remained relatively high, comparable to that obtained with synthetic wastewater. This suggests that the AnEDMBR was capable of maintaining stable methanogenic activity even under more complex and potentially inhibitory conditions, such as those found in mature landfill leachate.

Our findings are consistent with those of Choi et al. (2025), who reported relatively stable methane content across all tested reactors treating high-strength organic wastewater with a COD concentration (24 g/L), under various negative voltages ranging from 0 to −1.2 V. The average methane concentrations observed were $64.7 \pm 0.7\%$ at 0 V, increased to $66.8 \pm 1.1\%$ at −0.5 V, $66.6 \pm 1.8\%$ at −0.8 V, and $66 \pm 1\%$ at −1.2 V, indicating that moderate electrochemical stimulation slightly enhanced methane yield [Choi et al., 2025]. Zhen et al. (2023) demonstrated that applying an external voltage in an electrochemical anaerobic membrane bioreactor (EC-AnMBR) treating mixed sewage sludge and food waste enhanced methane (CH₄) production. The CH₄ production rate increased from 0.04 ± 0.00 L/L·reactor/day at 0 V (Stage I) to 0.09 ± 0.01 L/L·reactor/day at 0.4 V (Stage II), and further to 0.12 ± 0.02 L/L·reactor/day at 0.8 V (Stage III), showing a clear voltage-dependent improvement in methane generation [Zhen et al., 2023]. Katuri et al. (2014) reported that applying an appropriate external voltage can enhance methanogenesis and increase methane (CH₄) content in an anaerobic electrochemical membrane bioreactor (AnEMBR). The reactor, operated with a synthetic acetate solution (COD 320 mg/L), was tested under three voltages—0.5, 0.7, and 0.9 V—to evaluate the effects of electrochemical stimulation on performance [Katuri et al., 2014].

Figure 4.8 illustrates the variations in the average methane production (L) per g of COD removed during the treatment of synthetic wastewater in the AnDMBR and AnEDMBR systems, as well as real leachate wastewater in the AnEDMBR system. For synthetic wastewater treatment in the AnDMBR (**Figure 4.8 a**), the average methane yields were 0.31 ± 0.05 and 0.26 ± 0.04 L CH₄/g COD at 8 day and 5 day HRT stages, respectively. In the AnEDMBR system (**Figure 4.8 b**), the corresponding values for the same HRT stages increased to 0.34 ± 0.08 and 0.28 ± 0.05 L CH₄/g COD. For real leachate wastewater treatment in the AnEDMBR at the 5 day HRT stage (**Figure 4.8 c**), the average methane yield was 0.28 ± 0.09 L CH₄/g COD.

The results presented in this section of thesis reveal clear differences in methane yield across the AnDMBR and AnEDMBR systems when treating synthetic wastewater, as well as between synthetic and real leachate wastewater in the AnEDMBR. The methane yield from synthetic wastewater was higher in the AnEDMBR system than in the AnDMBR by approximately 9.6% at 8 day HRT and 7.6% at 5 day HRT. This improvement can be attributed to the application of an external electric field in the AnEDMBR, which likely enhanced microbial activity, particularly methanogenic microorganisms, thereby enhancing methanogenesis efficiency.

Interestingly, the methane yield for real leachate treatment in the AnEDMBR at 5 day HRT stage was comparable (0.28 ± 0.09 L CH₄/g COD) to that obtained from synthetic wastewater (0.28 ± 0.05 L CH₄/g COD), despite the complex and potentially inhibitory composition of real leachate. This outcome suggests that the AnEDMBR system exhibits robust performance even under more challenging wastewater. The comparable yield also indicates that the AnEDMBR can maintain methanogenic activity without significant inhibition from leachate constituents, such as heavy metals, ammonia, or refractory organics, which typically reduce biogas production in conventional anaerobic systems. Furthermore, the general trend of higher methane yields at longer HRTs (8 days) in both systems supports the notion that extended contact time allows for more complete biodegradation of organics and subsequent methane formation.

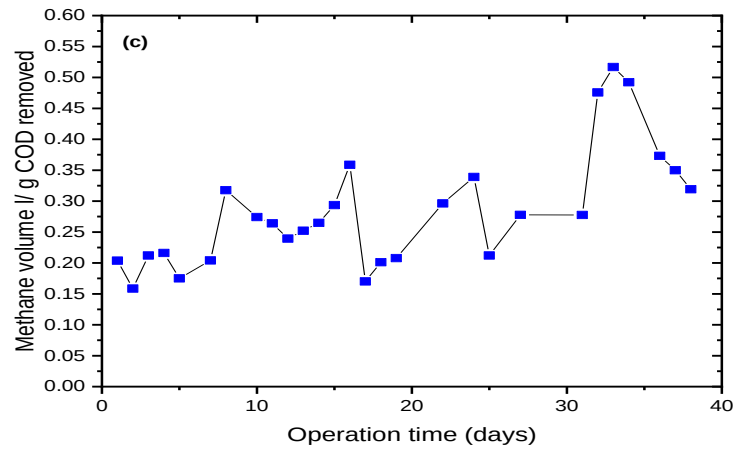
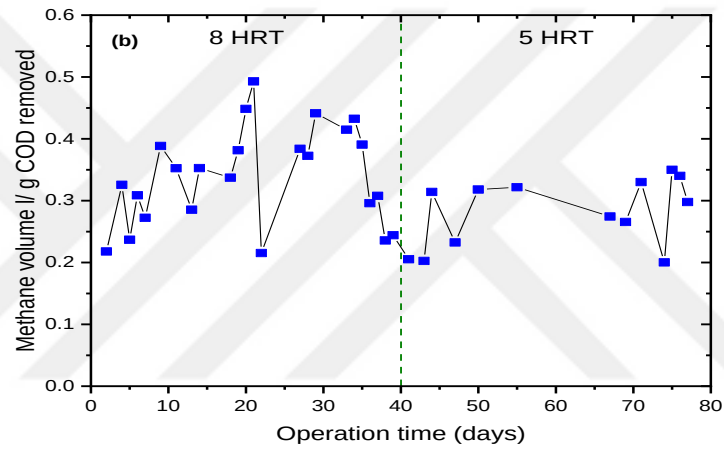
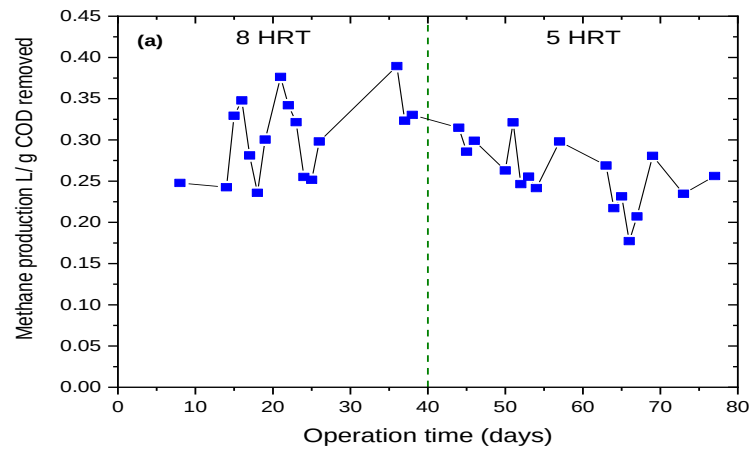


Figure 4.8: Methane production yields (L CH₄/g COD) from: (a) AnDMBR (synthetic wastewater), (b) AnEDMBR (synthetic wastewater), (c) AnEDMBR (real leachate wastewater) systems during the operation times.

The results of this thesis align with the findings of Sun et al. (2024), who demonstrated that an AnCDMBR system treating synthetic wastewater (9.2 g/L COD) at a hydraulic retention time (HRT) of 12 hours utilizing carbon cloth as the dynamic membrane achieved a methane yield of 0.26 L CH₄/g COD with methane content exceeding 95%. This yield was 1.42 times higher than that of the control reactor, which was attributed to enhanced microbial metabolic activity and upregulated expression of key methanogenesis-related enzymes [Sun et al., 2024]. Choi et al. (2025) evaluated an electrochemically enhanced anaerobic dynamic membrane bioreactor (e-AnDMBR) for the treatment of high-strength organic wastewater, characterized by a chemical oxygen demand (COD) of 24 g/L. The system was operated under a hydraulic retention time (HRT) of 7.5 days and an organic loading rate of 3 g COD/L·day. A series of negative voltages (0 to -1.2 V) were applied to the cathodic dynamic membrane, with the optimal performance observed at -0.8 V, which led to a 10% improvement in methane generation [Choi et al., 2025]. In this study, the average methane yield was less than theoretical value of 0.35 L/g COD removed [McCarty, 1964]. Zhang et al. (2021) observed that the average methane production for both the electrochemical anaerobic membrane bioreactor (EF-AnMBR) operated at 0.5 V and the control reactor (CK-AnMBR) without applied voltage (0 V) was marginally below the theoretical yield of 0.35 L CH₄ per gram of COD removed, with measured values averaging around 0.32 L CH₄/(g COD removed) [Zhang et al., 2021].

4.4. SMP and EPS Concentrations

Figure 4.9 (a), (b), and (c) illustrates the variations of SMP and EPS (protein and carbohydrate) for the treatment of synthetic wastewater in the AnDMBR and AnEDMBR systems, and the treatment of real leachate wastewater in the AnEDMBR, respectively. Throughout the operation of the AnDMBR system treating synthetic wastewater, the concentrations of SMP and EPS, including both proteins and carbohydrates, remained relatively stable without notable fluctuations (**Figure 4.9 a**). The averages of SMP protein concentrations were 33.8 and 36.1 mg/L, and average SMP carbohydrates were 40.2 and 33.9 mg/L, while average EPS protein concentrations were 195.9 and 172.7 mg/L, and EPS carbohydrates were 139.5 and 137.7 mg/L for 8 days HRT and 5 days HRT, respectively.

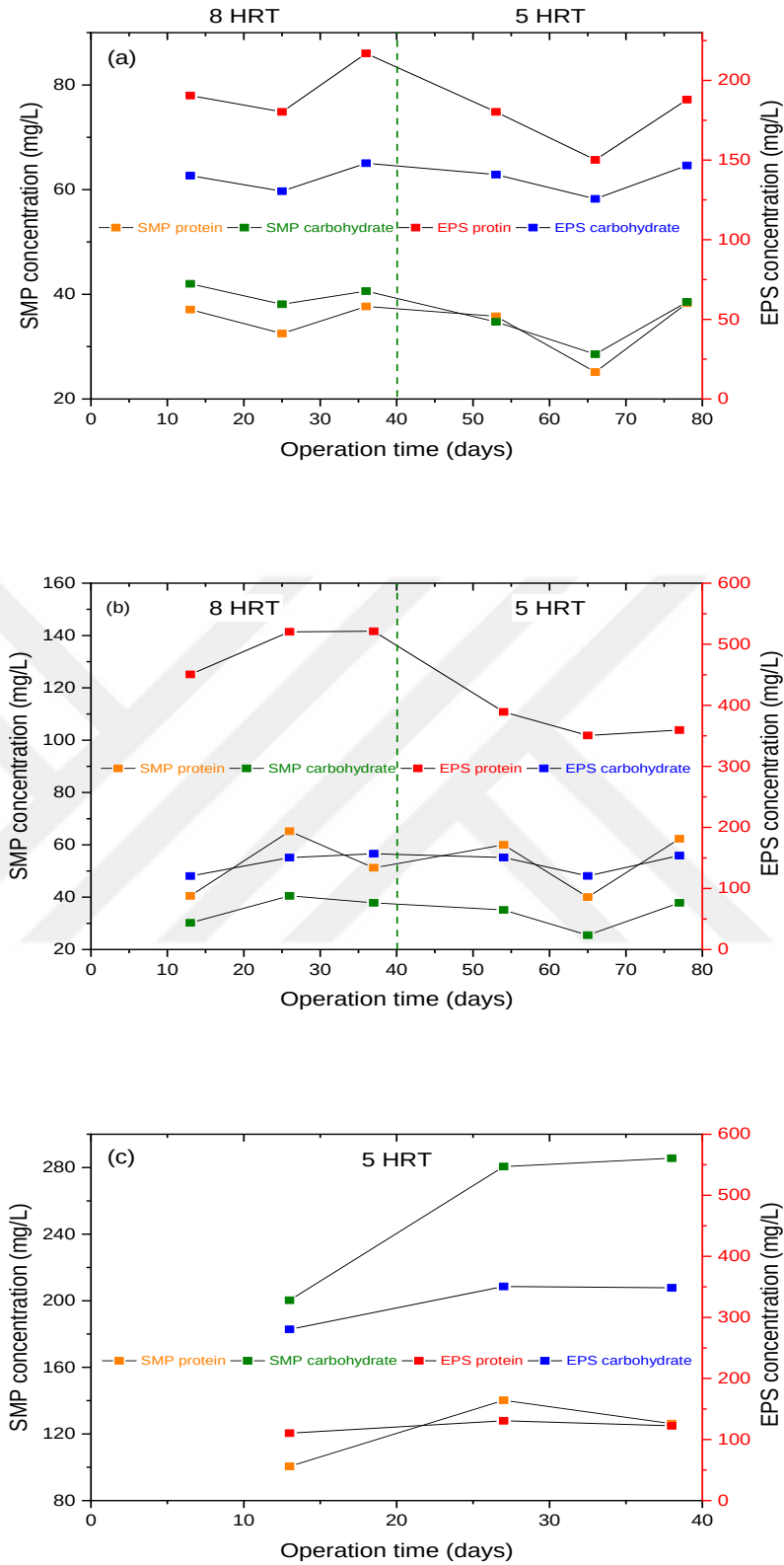


Figure 4.9: The average SMP and EPS concentration in: (a) AnDMBR (synthetic wastewater), (b) AnEDMBR (synthetic wastewater), (c) AnEDMBR (real leachate wastewater) systems during the operation time.

Figure 4.9 b illustrate the average SMP and EPS (protein and carbohydrate) concentrations during the operation time of the treatment of synthetic wastewater in AnEDMBR. The SMP protein concentrations were 52.3 and 51.7 mg/L, and average SMP carbohydrates were 36.1 and 32.8 mg/L, while average EPS protein concentrations were 497.3 and 366.3 mg/L, and EPS carbohydrate concentrations were 142.5 and 141.6 mg/L for 8 days HRT and 5 days HRT, respectively. **Figure 4.9 c** illustrate the average SMP and EPS (protein and carbohydrate) concentrations during the operation time for the treatment of real leachate wastewater by 5 day HRT applied in AnEDMBR, the SMP protein concentration was 122.3 mg/L and average SMP carbohydrate concentration was 255.5 mg/L, while average EPS protein concentration was 121.2 mg/L, and EPS carbohydrate concentration was 326 mg/L.

In this study, the concentration of EPS was significantly more than that of SMP for both protein and carbohydrate, given that EPS was trapped by the membrane due to its colloidal form, it tended to collect in the reactor [Chen et al., 2017]. In contrast, SMP, being more soluble, can more easily pass through membrane pores [Balcioglu et al., 2021]. Also the concentrations of SMP and EPS (both protein and carbohydrate) in AnEDMBR system more than in AnDMBR system (for synthetic wastewater). This observance aligns with the findings of Yang et al. (2019), who noted that an increase in the EPS amount in the biomass within the reactor occurred when a voltage was utilized to the system [Yang et al., 2019].

The observed reduction in SMP and EPS concentrations at the 5 day HRT stage compared to the 8 day HRT stage can be attributed to the shorter hydraulic retention time. These findings are consistent with the studies by [Chen et al., 2017] and [Ding et al., 2018], which demonstrated that EPS components tend to accumulate under longer retention times and decrease with increased washout or reduced biofilm maturity. Additionally, Jiang et al. (2024) reported that EPS content in the LDH (layered double hydroxide)-AnMBR was lower than in the LDH-eAnMBR, suggesting that the electric field in the latter system enhanced the degradation of organic matter, including complex substrates such as EPS [Jiang et al., 2024].

4.5. TMP profiles of membrane

To assess the membranes fouling characteristics of the both AnDMBR and AnEDMBR systems, transmembrane pressure (TMP) variations were observed at constant flux. The membrane was replaced with the new ones when TMP increased substantially. Backwashing was intentionally avoided in this study to prevent possible damage to the membrane material (carbon fabric fiber). Generally, membrane fouling is characterized by raise in TMP and leads to higher operation costs and lower efficiency [Jiang et al., 2024], [Zhang et al., 2021]. **Figure 4.10 (a), (b,) and (c)** illustrates the TMP profiles for each membrane used throughout the operational period during the treatment of synthetic wastewater in AnDMBR and AnEDMBR systems, and real leachate wastewater in the AnEDMBR system, respectively.

The application of 8-day HRT in AnDMBR exhibited better antifouling performance, requiring only four membrane replacements with an average operational lifespan of 10 days per membrane. In comparison, the AnEDMBR underwent five membrane replacements, with each membrane lasting an average of 8 days under the same operational conditions. At the 5 day HRT stage, however, the AnEDMBR demonstrated superior antifouling performance relative to the AnDMBR. Specifically, the AnDMBR required seven membrane replacements, with an average operational period of 5.14 days per membrane, whereas the AnEDMBR required six replacements with an average duration of 6.66 days per membrane. For the AnEDMBR system treating synthetic wastewater, the TMP at both 0.8 V and 1.2 V was comparable, indicating similar membrane filtration resistance under these applied voltages. This suggests that increasing the voltage from 0.8 V to 1.2 V did not significantly impact membrane fouling behavior. For the treatment of real leachate wastewater in the AnEDMBR at a 5 day HRT stage, five membrane replacements were necessary over the course of the operational period.

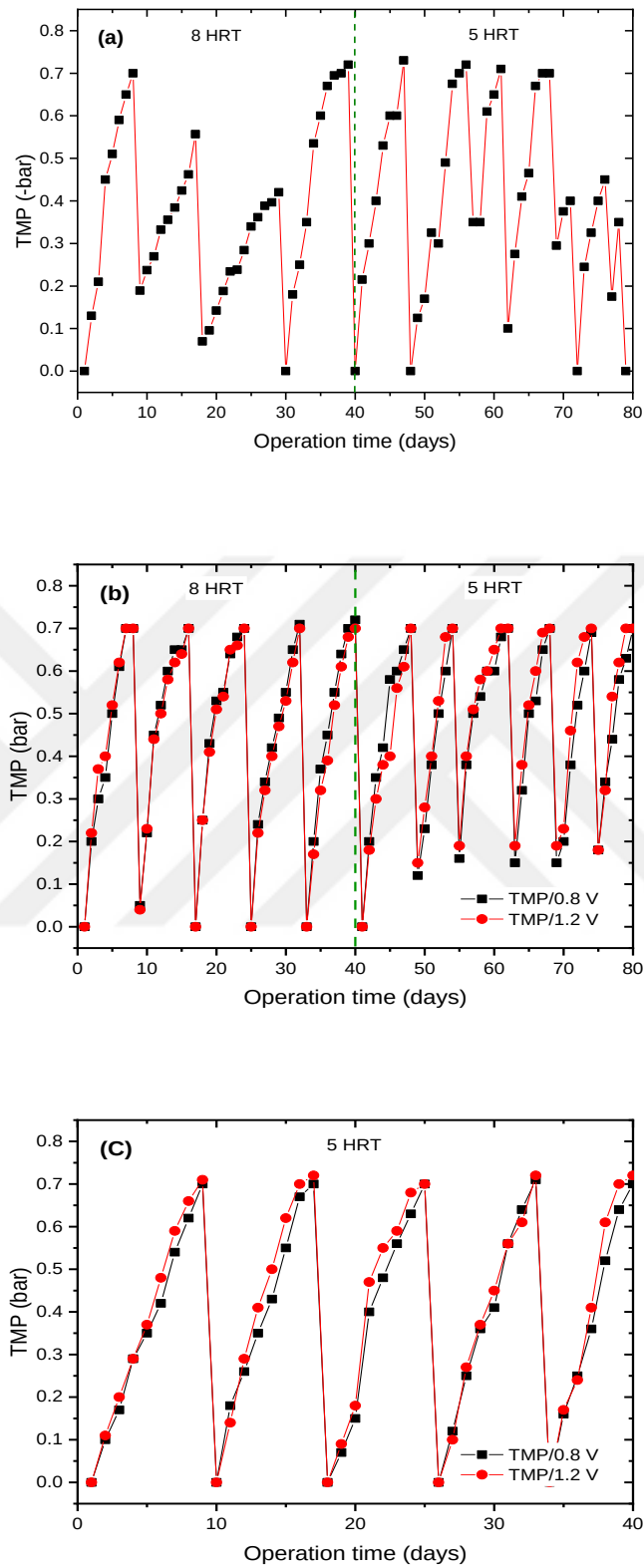


Figure 4.10: TMP of membranes for the treatment of: (a) AnDMBR (synthetic wastewater) (TMP represents the average value of two membranes), (b) AnEDMBR (synthetic wastewater), (c) AnEDMBR (real leachate wastewater) during the operation time.

During the 8 day HRT stage, the AnDMBR system demonstrated superior antifouling performance compared to the AnEDMBR, as evidenced by fewer membrane replacements and an extended average membrane lifespan. This suggests that under lower organic loading conditions and extended HRT, the electrochemical enhancement in AnEDMBR may have contributed to accelerated fouling, possibly due to increased microbial activity, which can promote cake layer formation. Conversely, at the 5-day HRT stage, the AnEDMBR perform better than the AnDMBR system in terms of antifouling performance. The reduction in membrane replacement frequency and extended membrane lifespan in the AnEDMBR under higher organic loading conditions suggests that the applied electric field likely played a role in mitigating membrane fouling. This effect can be attributed to the inhibition of biofilm development and the enhancement of electrostatic repulsion between foulants and the membrane surface. These findings align with many studies [Xu et al., 2020], [Yang et al., 2018], [Zhang et al., 2021]. Implying that the applied voltage contributed to the resistance against fouling and enhanced electric repulsion effect to inhibiting cake formation, also indicating that electrochemical assistance can reduce fouling by altering the electrochemical properties of foulants and membrane surfaces. For the treatment of real leachate wastewater in the AnEDMBR at 5-day HRT, the requirement of five membrane replacements over the operational period demonstrates that the system maintained a comparable level of antifouling performance to that observed with synthetic wastewater. Despite the complex and recalcitrant nature of leachate, the AnEDMBR maintained operational stability. This result highlights the robustness of the AnEDMBR system under real wastewater conditions and supports its potential application for the treating of complex high-strength wastewaters. The above results demonstrated that the membrane separation performance in the AnMBR system was enhanced with electro-assistance [Deng et al., 2022], [Jiang et al., 2024], [Yang et al., 2018].

Membrane fouling in the AnDMBR and AnEDMBR processes can be explained by the following mechanisms. As seen in **Figure 4.11 a**, anaerobic bacteria and other pollutants accumulate over time on AnDMBR operated without an electric field and form a biofilm layer on the membrane surface. In the AnDMBR system, sufficient biogas may not be produced to strip the biofilm from the membrane surface. In addition, activated carbon fabric may have adsorbed organic substances in the mixed

liquor. On the contrary, when electric current was applied to the AnEDMBR system, the biogas volume in the system increased (see **Figure 4.11 a**) and created a stripping effect on the biofilm accumulated on the membrane surface (**Figure 4.11 b**). Additionally, increasing the voltage may have increased the electrostatic repulsion between the membrane surface and negatively charged contaminants. Another reason is that the iron electrode used as the anode in the AnEDMBR system may have reduced protein-induced membrane fouling by dissolving and forming a complex with negatively charged proteins. In addition, some organic pollutants adsorbed on the activated carbon fabric from the mixed liquor may have been desorbed under the electric field. This can be another factor that reduced membrane fouling in the AnEDMBR system.

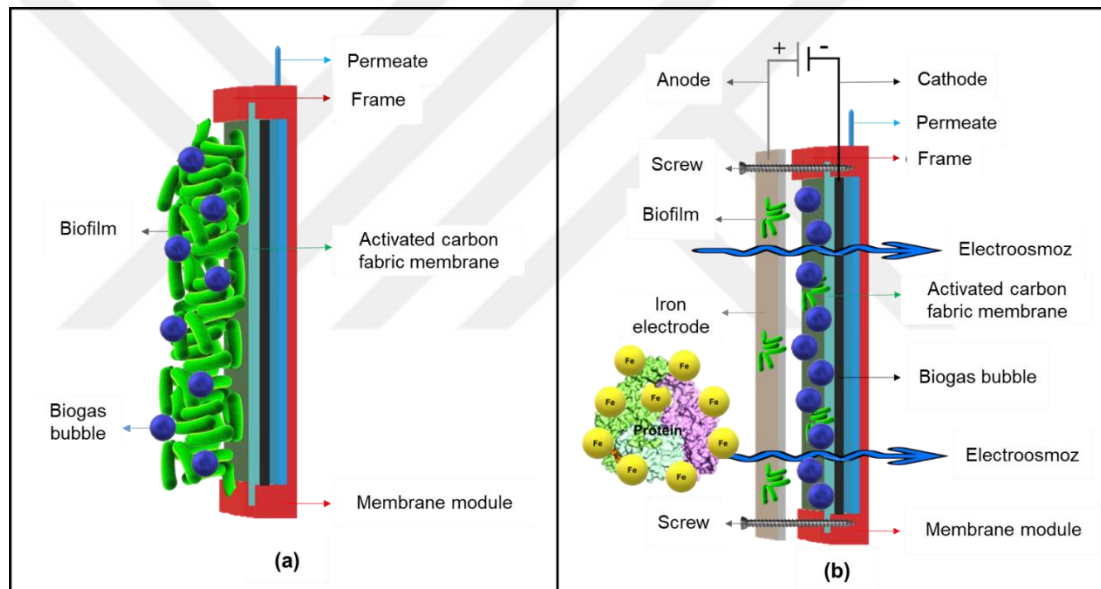


Figure 4.11: Proposed fouling mechanism for (a) AnDMBR, and (b) AnEDMBR systems during the operation time.

4.6 The membrane morphology

The membrane morphologies were observed with SEM to evaluate the effect of applied voltage on mitigating the membrane fouling. The membrane modules were removed from each system's reactor, and the SEM images were presented in Figure 21. According to **Figure 4.12 a**, it was seen that the pristine membrane fibers had almost equal thickness. However, SEM images of the membrane in the AnDMBR

system (**Figure 4.12 b**) showed that pollutants accumulated on the membrane surface with the deposit accumulation is less network structure, while images of the membrane in the AnEDMBR system (**Figure 4.12 c, 4.12 d**) demonstrate that applying voltage reduces the amount of pollutants accumulated on the membrane surface. This reduction can likely be attributed to the increased electrostatic repulsion between the membrane surface and negatively charged contaminants under the influence of an electric field [Grossman et al., 2024], [Yang et al., 2018].

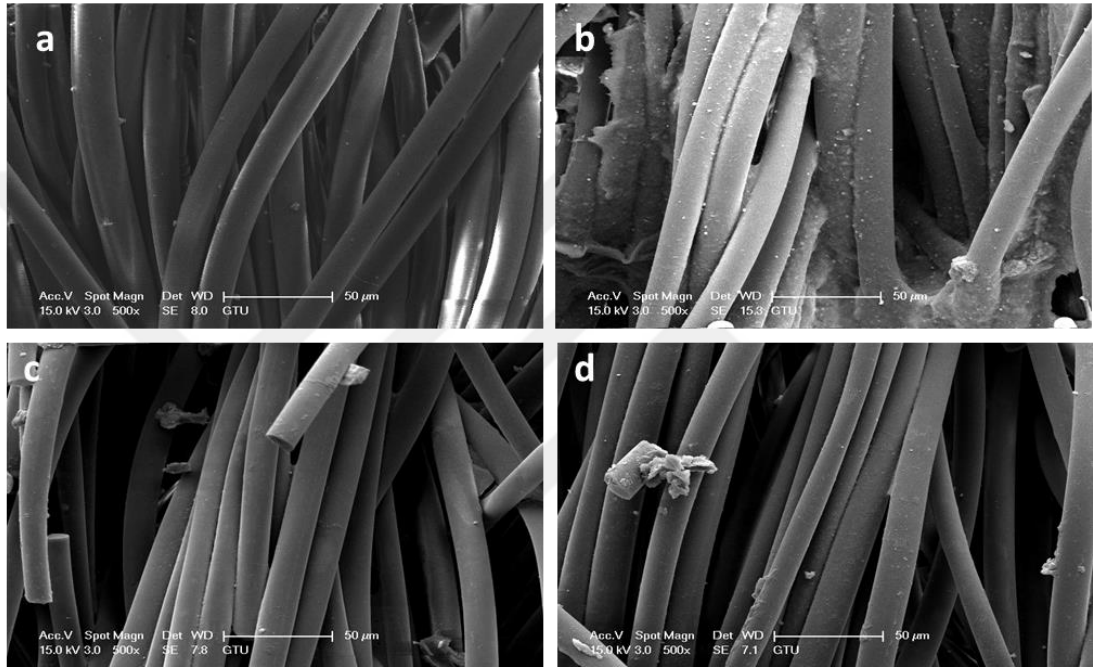


Figure 4.12: SEM images of membranes surface (a) pristine membrane, (b) AnDMBR membrane, (c) AnEDMBR membrane 0.8 V, and (d) AnEDMBR membrane 1.2 V.

Elemental composition analysis via EDX (**Figure 4.13**) provided further insights into membrane surface characteristics. As anticipated, the pristine membrane (**Figure 4.13 a**) exhibited only carbon (C) and oxygen (O) signals, indicative of its clean and unmodified state. In contrast, the membrane retrieved from the AnDMBR system (**Figure 4.13 b**) displayed additional elemental signals including sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), calcium (Ca), phosphorus (P), sulfur (S), potassium (K), and iron (Fe), suggesting the adsorption of inorganic constituents from the synthetic wastewater. Similar elemental profiles were observed for the AnEDMBR membranes operated under 0.8 V (**Figure 4.13 c**) and 1.2 V (**Figure 4.13 d**), with a notably higher accumulation of Fe, Ca, Mg, Al, Si, S, and P on their surfaces.

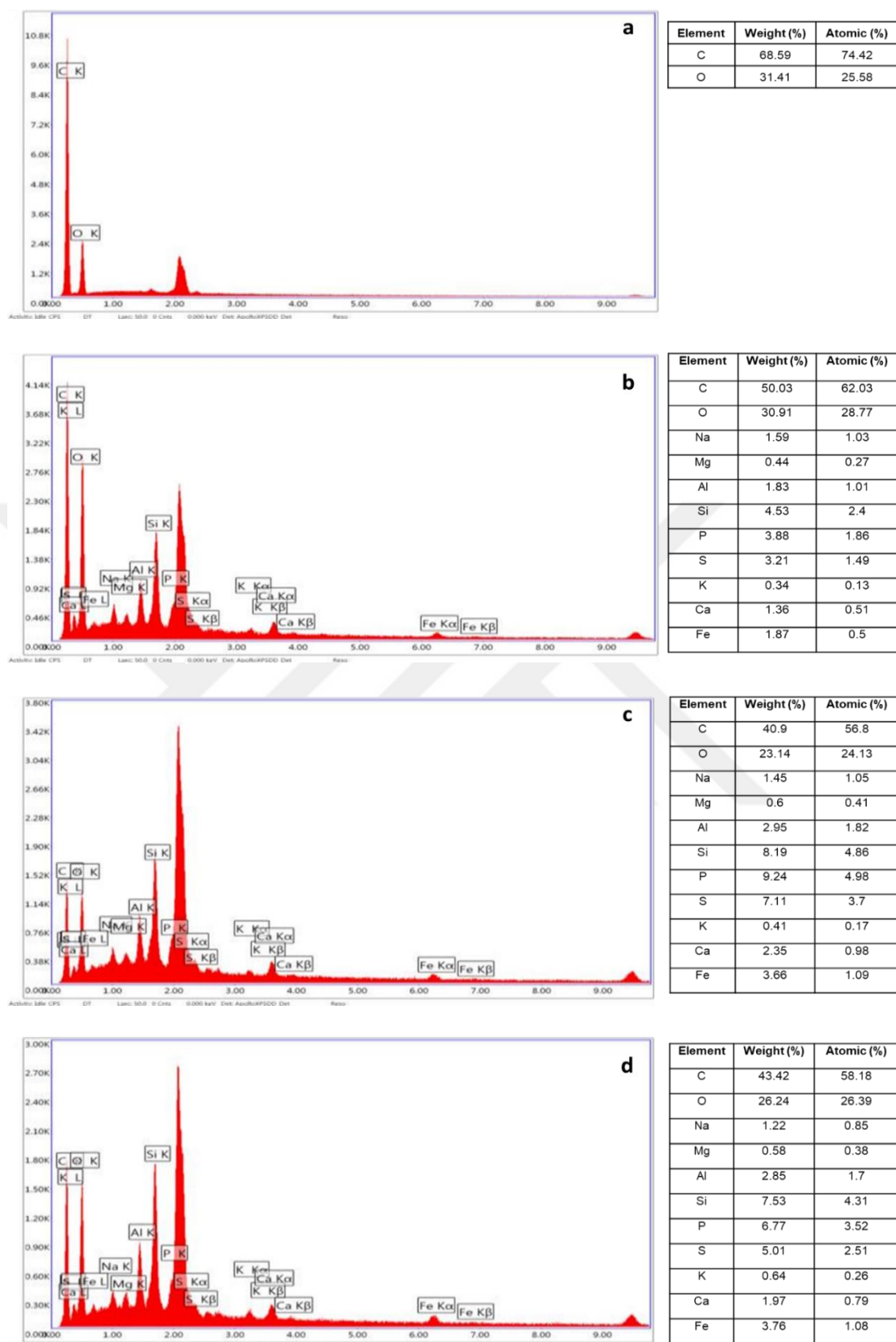


Figure 4.13: EDX images of membranes surface (a) pristine membrane, (b) AnDMBR membrane, (c) AnEDMBR membrane 0.8 V, and (d) AnEDMBR membrane 1.2 V.

This increased deposition under electrochemical conditions is likely due to the formation of metal complexes on the cathodic surface. The applied electric field promotes the migration of cations toward the cathode via electromigration and hydraulic transport. Once at the cathode, these cations can interact with anions such as S, Si, and P, resulting in the formation of sparingly soluble metal complexes. The subsequent accumulation of these complexes on the membrane surface contributes to the observed increase in elemental concentrations, highlighting a potential mechanism of membrane fouling under electro-assisted operation.

Fourier Transform Infrared (FTIR) spectral analysis revealed characteristic peaks on the surfaces of both pristine and used membranes in both the AnDMBR system and AnEDMBR system (at 0.8 V and 1.2 V). As shown in **Figure 4.14**, similar absorption peaks were detected at 1598 cm^{-1} (pristine), 1593 cm^{-1} (0 V), 1591 cm^{-1} (0.8 V), and 1598 cm^{-1} (1.2 V). These peaks within the 1591–1598 cm^{-1} range are attributed to protein secondary structures, specifically C=N stretching in amide II and N–H deformation [Deng et al., 2022]. In the pristine membrane, absorption bands observed at 1250 and 750 cm^{-1} corresponded to C–H bending. However, the intensity of the 750 cm^{-1} peak significantly increased in the membrane used in the AnDMBR, likely due to microbial accumulation on the membrane surface. Upon applying voltage up to 1.2 V, these bands (1250 and 750 cm^{-1}) gradually diminished and eventually disappeared. Additionally, a reduction in the transmittance at 3500 cm^{-1} , related to N–H stretching, was associated with N–H depolarization. The key difference between the 0.8 V and 1.2 V membranes lies in the enhanced polarization of amide groups observed at 1.2 V, indicating a greater electron storage capacity within the sludge matrix. Furthermore, membranes operated under applied potential, particularly at 1.2 V, exhibited more pronounced alterations in amide group intensity compared to the non-electrified membranes. This suggests the persistence of residual polarization in the amide groups, which may no longer be electrochemically active [Yu and Zhang, 2019]. These spectral shifts support the hypothesis that proteins containing amide functional groups were the primary contributors to these observed bands.

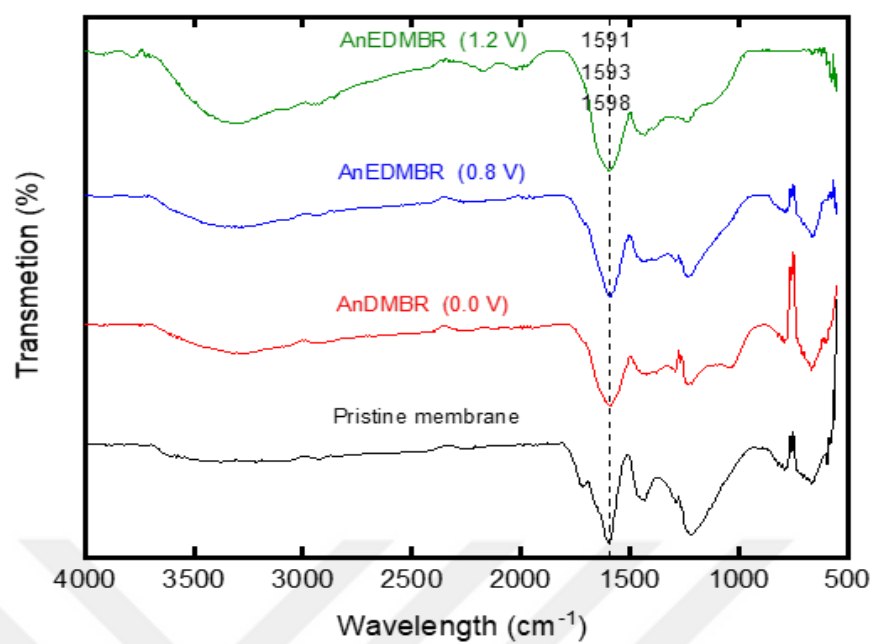


Figure 4.14: Infrared spectra of the pristine and used membranes.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This study evaluated and compared the performance of two systems: Anaerobic Dynamic Membrane Bioreactor (AnDMBR) and Anaerobic Electro-Dynamic Membrane Bioreactor (AnEDMBR) systems for treatment of high-strength wastewater (both synthetic wastewater and real leachate). The analysis focused on COD removal efficiency, biogas production, and fouling occurrence. Both the AnDMBR and AnEDMBR systems demonstrated high COD removal efficiencies when treating synthetic wastewater, achieving over 98% COD removal under various conditions. The AnEDMBR system showed a slight improvement in COD removal performance compared to AnDMBR, likely due to the electric field enhancing microbial degradation. However, the treating of real leachate wastewater was less efficient, with COD removal rates at around 78%, attributable to the refractory organic substances present in leachate.

In our study, AnDMBR was evaluated at different HRTs (8 and 5 days). The results demonstrated that: at 8-days HRT, COD removal was higher due to increased contact time. While at 5-days HRT, the system maintained efficient COD removal, indicating its robustness under reduced retention times. These findings confirm that AnDMBRs can effectively handle high organic loads while offering operational flexibility. In contrast, AnEDMBR was tested at 0.8 V and 1.2 V to evaluate its efficiency compared to AnDMBR. The key findings include higher COD removal efficiency of AnEDMBR outperformed AnDMBR, particularly at 1.2 V, achieving COD removal >98%.

Biogas production rates were slightly higher in the AnEDMBR than in the AnDMBR when treating synthetic wastewater, with an increase of approximately 4.5% for 8 days HRT and 10% for 5 days HRT. While for real leachate wastewater treatment, the biogas production was about 36% lower than that of synthetic wastewater at the same 5 days HRT application. However, for leachate, biogas production decreased due to the elevated concentration of recalcitrant organics. Methane content in the biogas was comparable between the systems, suggesting that applied voltage in the AnEDMBR

system may not significantly affect methane composition but could improve overall biogas yield due to enhanced organic matter degradation. Biomass concentrations (MLSS and MLVSS) were maintained at high levels across both systems. The AnEDMBR also exhibited lower transmembrane pressure (TMP) increases, suggesting better resistance to fouling compared to the AnDMBR, specially at 5-days HRT, the AnEDMBR showed better antifouling performance than the AnDMBR: The AnDMBR needed 7 membrane replacements (average 5.14 days), while the AnEDMBR required only 6 replacements (average 6.66 days). This is attributed to the electric field's role in reducing EPS accumulation on the membrane surface. EPS concentrations were notably higher than SMP in both systems, with the AnEDMBR displaying greater EPS protein concentrations, potentially due to the electrochemical environment encouraging EPS production. SMP levels were lower in the AnEDMBR due to the system's enhanced ability to filter soluble microbial products. These results highlight that the electro-assisted system effectively mitigates fouling.

In summary, the AnEDMBR system shows promise for high-strength wastewater treatment with slightly better COD removal, biogas production, and antifouling performance compared to the AnDMBR system. However, for real mature leachate, its effectiveness is limited. This comparative study provides a basis for future research on optimizing AnEDMBR systems, particularly in addressing fouling and enhancing treatment efficiency for complex wastewater types.

5.2 Recommendation for Future Work

1. Future studies should investigate the effects of different voltages other than 0.8 and 1.2 volt, and electrode materials on the AnEDMBR system to determine optimal conditions that maximize COD removal efficiency, biogas production, and membrane fouling resistance, particularly for complex wastewaters like leachate.
2. Exploration of Alternative Wastewater Types: While this study focused on synthetic and leachate wastewaters, testing the AnEDMBR with various high-strength industrial wastewaters (e.g., food, pharmaceutical, and textile effluents) could provide insights into its broader applicability.
3. Since biogas production is a valuable by-product, research on integrating biogas upgrading techniques or energy recovery systems (e.g., fuel cells) within the AnEDMBR could improve the system's economic and environmental viability.

4. Investigating the integration of AnEDMBR with additional treatment technologies, like advanced oxidation or nutrient recovery units, could offer a complete treatment solution that meets stricter discharge standards and enhances resource recovery.
5. Conducting a detailed cost-benefit and energy analysis of the AnEDMBR at pilot and full scale will be crucial for assessing the feasibility of large-scale implementation. This would include evaluating operating costs, maintenance requirements, and the potential return on investment in commercial applications.
6. Conducting a long-term operational study of two systems (AnDMBR and AnEDMBR), carried out to reduce HRT from 5 days to 2-3 days.
7. The performance of AnDMBR and AnEDMBR systems can be evaluated by using alternative reactor configurations (externally submerged or cross-flow configurations) and different membrane materials.

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BIOGRAPHY

Mohammed Sameer Ghanim GHANIM earned his B.Sc. in Civil and Environmental Engineering at Mosul University, IRAQ in 2004. GHANIM joined an environmental engineering master's program at Mosul University, IRAQ in 2006, studied the comparison of mesophilic and thermophilic in dairy wastewater treatment. GHANIM received his MSc in June 2009. In 2020, GHANIM started his PhD. research at Gebze Technical University, School of Engineering in the Department of Environmental Engineering. GHANIM's graduate work focused on the investigation of the treatability of high-strength wastewater by using an anaerobic electro-dynamic membrane bioreactor (AnEDMBR) system. Based on GHANIM PhD. research, he published one Sci. Expanded index journals.



PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

Ghanim M. S., Soydemir G., Yılmaz F., Perendeci N. A., Karagündüz A., Alazaiza M. Y. D., (2025), “Anaerobic Dynamic Membrane Bioreactors (AnDMBRs): Are They an Efficient Way to Treat High-Strength Wastewater?”, *Water*, 17(6), 787.

