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Assessment of Anaerobic Membrane Bioreactors in High-Strength Synthetic Wastewater Treatment

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Abstract **-** This study investigates the performance of an Anaerobic Membrane Bioreactor (AnMBR) treating high-strength synthetic wastewater. The system was acclimated using a phased approach, progressively increasing Chemical Oxygen Demand (COD) concentrations from 500 to 2500 mg/L over 120 days under mesophilic conditions (30 ± 1°C). The AnMBR, utilizing a 10L reactor with ceramic microfiltration membranes (pore size: 0.1 µm, area: 0.04 m²), demonstrated exceptional treatment efficiency. Peak COD removal reached 99.26%, while sustained BOD removal efficiencies ranged from 74.59 to 98.79%. Biomass characterization revealed continuous growth, with MLSS and MLVSS increasing from 4.71 to 8.19 g/L and 2.48 to 6.79 g/L, respectively, and the MLVSS/MLSS ratio maintained between 0.53-0.86. Biogas production increased significantly from 0.05 to 2.89 L/day, with methane content rising from 45% to 68%. Effluent VFA concentrations increased from 31.20 to 191 mg/L, indicating efficient organic matter decomposition, while alkalinity remained stable, demonstrating the system's pH buffering capacity. These findings highlight the effectiveness of AnMBR technology for treating high-strength wastewater and its potential for energy recovery through biogas production, but also emphasize the need for fouling mitigation strategies.

Keywords**:** Anaerobic Membrane Bioreactors, Wastewater Treatment, Biogas Production, High Strength Wastewater.

1. Introduction

Membrane bioreactor (MBR) technology has gained considerable attention in recent decades for both municipal and industrial wastewater treatment. This is largely due to its ability to achieve high removal rates of Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), primarily attributed to the maintenance of high Mixed Liquor Suspended Solids (MLSS) concentrations and reduced excess sludge production [1]. Anaerobic MBRs (AnMBRs) offer further advantages over aerobic MBRs, including significantly lower sludge production, a smaller footprint, and high volumetric organic removal rates [2]. These characteristics make AnMBRs a promising alternative for treating a wide range of wastewaters, from industrial streams to domestic sewage [3]. Compared to conventional anaerobic digestion (AD) processes, AnMBRs maintain higher biomass concentrations and longer sludge retention times (SRT) due to the membrane module, which physically retains biomass within the reactor [4]. Moreover, studies have shown that AnMBRs provide improved stability for microbial communities and can efficiently treat wastewater even with short hydraulic retention times (HRT) [5]. These operational advantages, combined with faster start-up times, contribute to the growing potential of AnMBRs in the wastewater treatment industry [6]. The field of wastewater treatment is continuously evolving, with ongoing research exploring various novel technologies and approaches to enhance efficiency, resource recovery, and sustainability [7].

Despite the promise of AnMBR technology for resource recovery, particularly bioenergy in the form of renewable methane, its application to high-strength wastewater presents several operational challenges. Membrane fouling remains the most significant obstacle, leading to increased operational costs and reduced efficiency [8]. While the AnMBR concept was first reported by Grethlein using an external cross-flow membrane to treat septic tank effluent, achieving simultaneous BOD and nitrate removal, the technology has significantly evolved since the late 1980s [9]. Early commercial systems, like the "Membrane Anaerobic Reactor System" and "Anaerobic Digestion Ultrafiltration," were primarily used for industrial wastewater treatment. The Japanese government's "Aqua-Renaissance '90" project further spurred AnMBR development, leading to a variety of systems, mostly based on external membrane configurations [9]. By the 2000s, research began to focus on submerged AnMBR configurations, encouraged by the success of submerged aerobic MBRs. Anaerobic treatment systems offer advantages such as reduced sludge production compared to conventional systems, a factor that can be further optimized in integrated systems, contributing to both economic and environmental benefits [10]. However, despite these advancements, optimizing AnMBR performance for consistent and efficient treatment of high-strength wastewater, particularly concerning the adaptation and performance of the anaerobic microbial community under progressively increasing organic loading conditions, remains a crucial area of research.

This study investigates the performance of an AnMBR system treating high-strength synthetic wastewater, with a specific focus on elucidating the gradual adaptation and response of the anaerobic microbial community to increasing COD loading. By employing a stepwise increase in COD concentrations from 500 to 2500 mg/L, we aim to optimize the AnMBR's performance for high-strength wastewater treatment, providing valuable insights into biomass characteristics, biogas production dynamics, and membrane fouling behavior under these challenging conditions. The anaerobic bacterial inoculum utilized in this study was sourced from the anaerobic digesters at the Gabal Al-Asfar Wastewater Treatment Plant. This study serves as a precursor to evaluating the reactor's treatment efficiency for various inhibitory substances, including lipids, pharmaceutically active compounds, and select pesticides, which inherently generate high COD concentrations. To determine AnMBR efficiency, essential water quality parameters, biogas production, and biomass characteristics were thoroughly investigated.

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2. Material and Methods

2.1 Wastewater Feed and Seed Sludge

High-strength synthetic wastewater (SWW) was used to simulate wastewater and maintain consistent influent conditions throughout the study. The SWW was fed in three phases, with increasing Chemical Oxygen Demand (COD) concentrations. Phase 1 had a COD of approximately 500 mg/L, Phase 2 increased to 1500 mg/L, and Phase 3 further increased to 2500 mg/L. The reactor was inoculated with anaerobic digester sludge obtained from the Gabal Al-Asfar Wastewater Treatment Plant (WWTP). The inoculum volume was calculated to achieve a target Total Suspended Solids (TSS) concentration of 5-6 g/L in the reactor. The total solids (TS) content of the sludge was determined to be 33.44 g/L, requiring a dilution ratio of 4.18 to reach the desired TSS.

2.2 Experimental Protocol

The reactor was operated under mesophilic conditions (30 ± 1 °C). Sodium bicarbonate was added as needed to maintain the pH of the mixed liquor between 6.5 and 7.8. The oxidation-reduction potential (ORP) was maintained at −150 ± 20 mV by ensuring all pipelines were well-sealed to prevent oxygen intrusion. Nitrogen gas was also sparged twice a week to maintain anaerobic conditions. The hydraulic retention time (HRT) was set at 2 days, and the sludge retention time (SRT) was maintained in the range of 80–100 days. The experiment was divided into three phases (Phase I, Phase II, and Phase III), corresponding to the stepwise increases in COD concentrations (500, 1500, and 2500 mg/L, respectively). Each phase lasted for 60, 30, and 30 days, respectively.

2.3 Experimental Set-up

The AnMBR system consisted of a conical 10 L transparent fiberglass reactor with an internal ceramic membrane module (Figure 1). The membrane module comprised four flat-sheet silicon carbide (ceramic) microfiltration membranes with a pore size of 0.1 µm, providing a total effective filtration area of 0.04 m². The membranes were positioned on either side of the reactor to accommodate a central mixer. A heating unit maintained the mixed liquor temperature at 30 ± 1 °C, and insulation foam was used to minimize heat loss. A conductive level controller with two float switches regulated the water level within the reactor. The first float switch controlled the influent feed pump to maintain a working volume of 10 L, while the second served as an emergency overflow prevention mechanism. The mixed liquor was mechanically stirred at 60 rpm/min, based on previous studies, to avoid negative impacts on biomass [11]. Peristaltic pumps (BT600FC, Chuang Rui, China) were used for feeding, recirculation, and permeate extraction.

The wastewater was circulated to the membrane for 14 minutes, followed by a 1-minute relaxation period. Biogas production was measured using a water displacement method, and biogas was collected in Tedlar bags for composition analysis. Biogas recirculation was used for membrane cleaning, with a 12 L/min biogas pump distributing 3 L/min to each of the two diffusers located beneath the membranes. The recirculation pump operated for 1 minute every 10 minutes. Transmembrane pressure (TMP) was continuously monitored using a high-resolution (±0.1 kPa) pressure sensor (HG-808XB, Ho Asia, China).

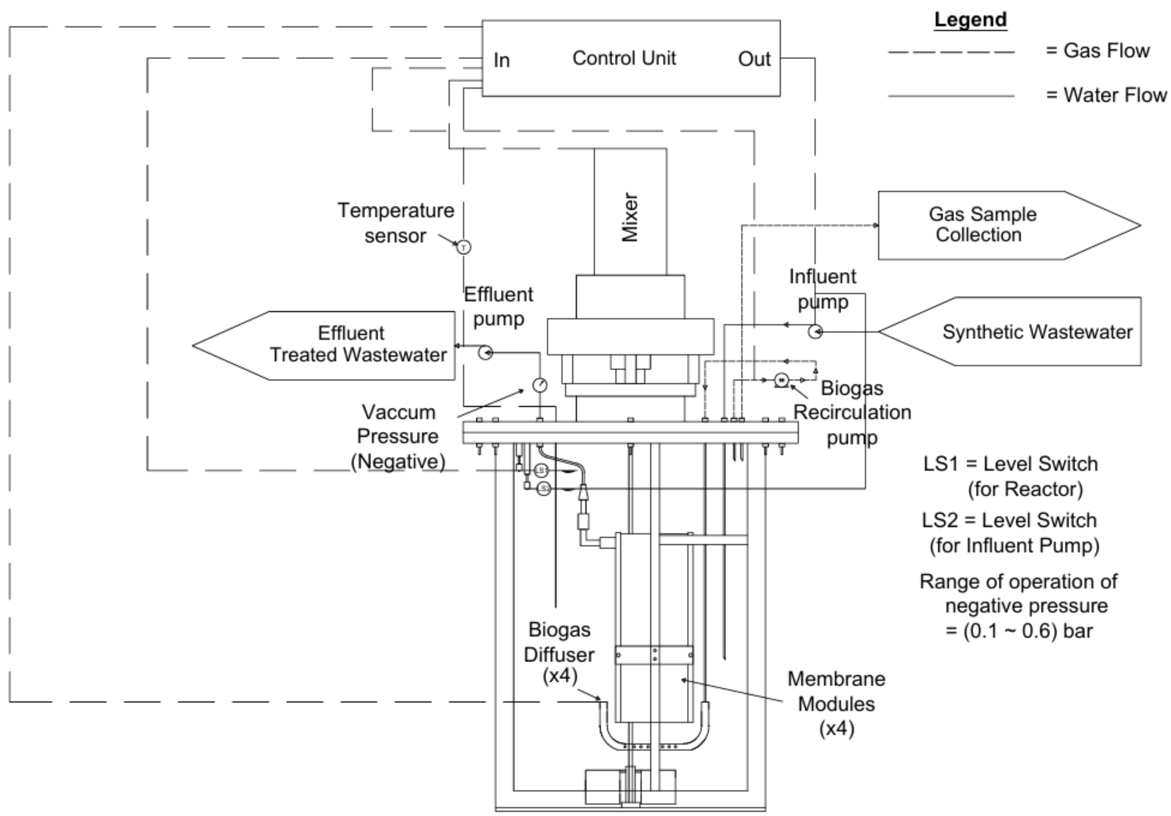

Fig. 1: Lab-scale AnMBR set-up

2.4 Analytical Methods

Chemical Oxygen Demand (COD) was measured using the colorimetric closed reflux (high range) method, and five-day Biological Oxygen Demand (BOD5) was measured using a dissolved oxygen meter. Both methods followed the Standard Methods for the Examination of Water and Wastewater. Total Nitrogen (TN) was measured using the Brucine method, according to the Environmental Protection Agency guidelines. Alkalinity was determined as carbonate and bicarbonate anions using a titrimetric method with standardized sulfuric acid, and Volatile Fatty Acids (VFAs) were measured using a conventional titration method (acidification and back titration). Both methods adhered to the Standard Methods for the Examination of Water and Wastewater. Total Solids (TS) and Volatile Solids (VS) were also measured according to the Standard Methods for the Examination of Water and Wastewater.

3. Results and Discussions

3.1 Treatment Performance

The AnMBR system demonstrated high efficiency in removing COD from the synthetic wastewater across all three phases of organic loading. In Phase I, with influent COD concentrations ranging from 400 to 600 mg/L (Figure 2a), the system achieved COD removal rates exceeding 78%. Notably, effluent COD concentrations were as low as 5 mg/L, indicating effective initial microbial acclimation and proper system operation, consistent with previous research on AnMBR stability during startup [12]. In Phase II, despite a significant increase in influent COD to 1500-1600 mg/L (Figure 2a), removal efficiencies further improved to 90-99%, demonstrating the system's resilience and adaptability to higher organic loads. This aligns with the ability of AnMBRs to retain slow-growing anaerobic microorganisms, enabling effective treatment of high-strength wastewater [13]. In Phase III, with the highest influent COD concentrations (2300-2600 mg/L, Figure 2a), the AnMBR maintained exceptional performance, achieving peak COD removal efficiencies of 99.26% and consistently low effluent COD levels (11-86 mg/L). While minor fluctuations were observed in this phase, potentially due to membrane fouling or the presence of recalcitrant compounds, these results highlight the importance of operational adjustments for sustained performance under high-stress conditions [14]. These findings collectively demonstrate the AnMBR's robust capacity for treating high-strength wastewater, even with significant variations in organic loading.

BOD removal efficiency also exhibited variability throughout the 120-day operational period, with removal rates ranging from 74.59% to 98.79% (Figure 2b). The system achieved an overall average BOD removal efficiency of approximately 87%. Lower removal efficiencies observed during the initial days of operation are typical of AnMBR startup, as microbial communities adapt to the specific characteristics of the synthetic wastewater [15]. As the system progressed, BOD removal efficiencies increased, exceeding 90% on days 48, 56, and 61 (Figure 2b), indicating successful microbial acclimation and stabilization. However, fluctuations persisted throughout the experiment, with removal efficiencies dropping below 80% on days 9, 19, and 44 (Figure 2b). These variations may be attributed to changes in influent composition, such as increased organic load or the presence of inhibitory substances known to affect microbial degradation [16]. Despite these fluctuations, the consistently high overall BOD removal underscores the AnMBR's ability to handle variations in influent characteristics, making it a viable option for treating organic-rich wastewater. Further investigation into the specific causes of these fluctuations could lead to improved operational control strategies.

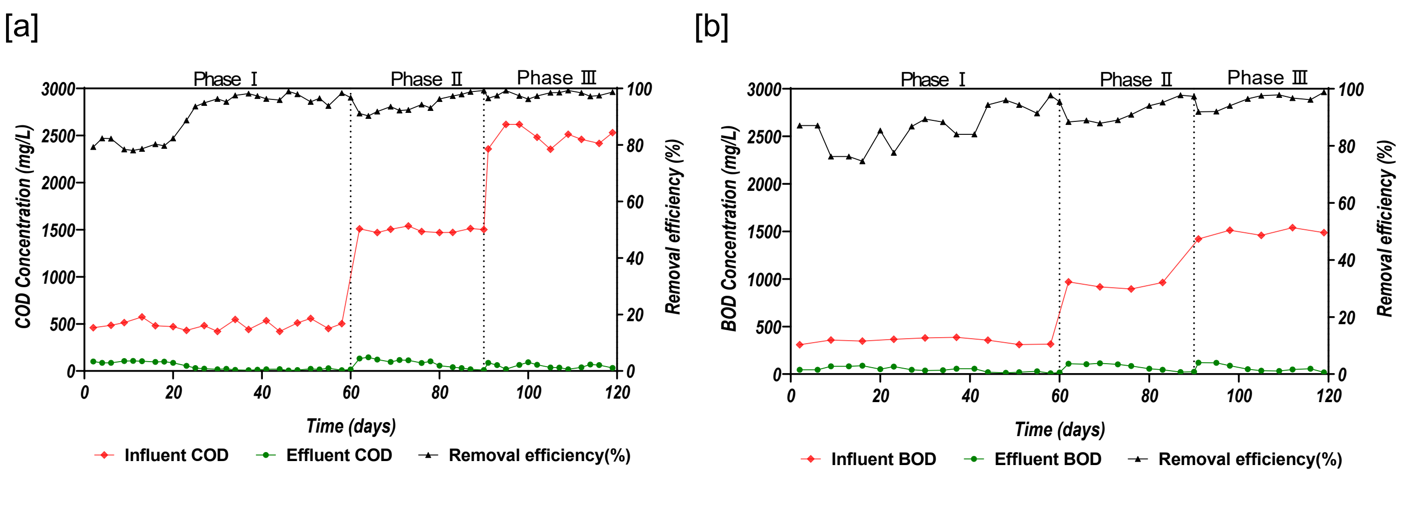

Fig. 2: Carbon removal performance over time: [a] COD influent, COD effluent, and COD removal efficiency; [b] BOD influent, BOD effluent, and BOD removal efficiency. Phase I, II, and III indicated the COD concentration at 500,1500, and 2500 mg/L, respectively.

The AnMBR system exhibited a clear trend of increasing microbial biomass over the 120-day period. MLSS values gradually increased from 4.71 g/L on day 2 to 8.19 g/L on day 119, reflecting the growth of the total biomass concentration. Similarly, MLVSS, representing the active microbial fraction, increased from 2.48 g/L to 6.79 g/L, indicating a growing and active microbial population crucial for organic pollutant degradation. The consistent increase in both MLSS and MLVSS suggests that the system effectively supported an active and growing microbial community capable of treating wastewater [15], [17].

3.2 Biogas Production

Biogas production and methane yield consistently increased over the 120-day period (Figure 3a), indicating a gradual gradual enhancement in anaerobic microbial activity. Biogas production rose from 0.05 L/day on day 2 to 2.89 L/day on day 120, demonstrating the system's increasing capacity to degrade organic matter and generate biogas. This steady increase suggests that the microbial community adapted to the synthetic wastewater, optimizing organic material degradation over time. Methane yield also showed an upward trend, increasing from 0.026 L/day to 0.228 L/day (Figure 3a). The relatively high methane yield, particularly in the later stages, indicates efficient methanogenic activity, which is vital for biogas production in anaerobic digestion systems [18].

The biogas composition shifted favorably over time, with methane content increasing from 45% on day 16 to 68% on day 118, while carbon dioxide content decreased from 35% to 19% (Figure 3b). This change indicates that the anaerobic microbial community became more efficient at converting organic substrates into methane, the desired product of anaerobic digestion. The increasing methane content and decreasing CO2 content are positive indicators of system performance, suggesting that methanogens were effectively utilizing the available organic matter and that the system was optimizing the conversion process while minimizing non-methane gas production. The consistent improvement in biogas production and methane yield, coupled with the favorable shift in gas composition, demonstrates the AnMBR system's success in treating synthetic wastewater and its potential for energy recovery through biogas production.

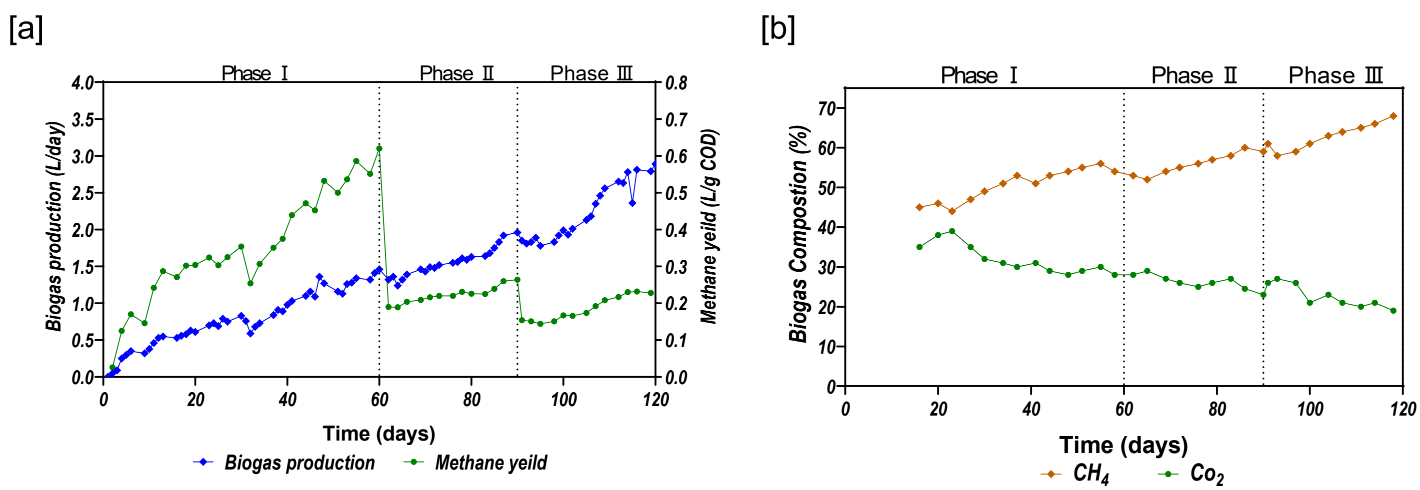

Fig. 3: Effect of COD concentration on [a] biogas production and [b] biogas components during AnMBR operation.

3.5 VFA and Alkalinity Analysis

The study revealed dynamic changes in both VFA and alkalinity concentrations throughout the 120-day operational period, providing insights into the performance of the anaerobic digestion process within the AnMBR system. Effluent VFA concentrations exhibited a gradual increase, rising from an initial 31.20 mg/L to a peak of 191 mg/L by day 116. This trend indicates effective microbial conversion of organic substrates in the influent into VFAs, key intermediates in anaerobic digestion. The consistently higher effluent VFA concentrations compared to influent values demonstrate the system's capacity for organic matter decomposition, aligning with the typical behavior of anaerobic environments where microbial populations degrade complex organic substances into VFAs [12]. The continuous rise in VFA concentrations suggests a maturing microbial community adapting to the specific conditions and organic loads, leading to enhanced substrate breakdown and VFA production, consistent with observations in similar anaerobic systems treating organic-rich wastewater [5] and [19].

Concurrently, alkalinity measurements provided further evidence of a well-functioning anaerobic digestion process. While influent alkalinity fluctuated between 180 mg/L and 235 mg/L, influenced by variations in the organic matter of the influent wastewater [20], effluent alkalinity exhibited a steady decrease from 375 mg/L on day 4 to 260 mg/L on 120. This decline suggests a stabilization period in the AnMBR system, where the microbial community became more efficient in breaking down organic waste, and the system approached its buffering capacity. The observed reduction in alkalinity production after an initial increase is typical in anaerobic digestion as microbial communities adapt to available carbon sources and the system reaches equilibrium [17]. The consistent reduction in effluent alkalinity, coupled with initially higher values compared to influent, indicates efficient microbial activity and a well-functioning buffering system within the AnMBR. This pattern aligns with previous studies on long-term anaerobic systems, demonstrating that microbial adaptation and stability lead to reduced total alkalinity production as the system matures [17].

4. Conclusion

This study demonstrated the effectiveness of an AnMBR system for treating high-strength synthetic wastewater and highlighted its potential for energy recovery. The system exhibited exceptional stability and performance, achieving COD removal efficiencies exceeding 99% and average BOD removal rates of 87% throughout the 120-day operational period, even under high and progressively increasing organic loading conditions. The significant growth in biomass, evidenced by a 73.8% increase in MLSS and a 173.8% increase in MLVSS, coupled with a stable MLVSS/MLSS ratio (0.53-0.86), indicated successful microbial adaptation to the high-strength wastewater. Furthermore, the substantial increase in biogas production (from 0.05 to 2.89 L/day) and methane concentration (from 45% to 68%) underscores the system's potential for energy recovery. The consistent VFA production and stable alkalinity profiles further confirmed the system's robust performance in organic matter decomposition and pH buffering. These findings support the feasibility of AnMBR technology as a viable option for high-strength wastewater treatment. However, to facilitate its successful commercial-scale implementation, future research should prioritize the development of advanced membrane fouling mitigation strategies, optimization of operational parameters to maximize energy recovery, and long-term stability assessments under varying influent conditions. This includes further investigation into the microbial community dynamics under high organic loading to refine operational control strategies for enhanced performance.

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