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Treatment of high strength organic wastewater by using an anaerobic membrane bioreactor

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Abstract

Properly managing wastewater with high concentrations of organic compounds is essential to prevent adverse environmental impacts. This study several various values of hydraulic retention times (HRT) to determine the optimal conditions for an anaerobic membrane bioreactor (AnMBR), as well as its performance and membrane fouling. The results indicated that an optimal chemical oxygen demand (COD) removal efficiency of 81.18% was achieved for a 48-hour HRT condition. The organic removal rate (ORR) was found to be 7.90 kg COD/m^3-day, with biogas productivity of 0.224 m^3/kg COD$_{removed}$. The potential operation was optimal for the 48-hour HRT condition compared to the other conditions. Importantly, the study revealed that a longer HRT could mitigate membrane fouling in the AnMBR, which was attributed to the impact of the volumetric organic loading rate.

Keywords: Cassava Starch Wastewater, Hollow Fiber Membrane, Organic Loading Rate, Biogas Productivity, Membrane Fouling

1. Introduction

Wastewater from processed agricultural products and starch-based industries, such as sugar production and alcoholic beverage manufacturing in Thailand, often contains high concentrations of organic substances. These industries generate wastewater with organic matter levels exceeding 4,000 mg/L [1]. Wastewater is often pretreated before entering a biological treatment system to remove organic contaminants. However, biological treatment systems have limitations.

Anaerobic systems, for example, are unsuitable for treating high-strength organic wastewater due to installation costs and microbial proliferation. Furthermore, because of the high organic loading rate, this system may necessitate a final treatment step to address the leftover organic matter [2-5]. Currently, the major approach for treating wastewater from starch-based industries consists of pretreatment to remove suspended solids followed by biological treatment. Anaerobic systems utilize a variety of post-treatment procedures including the Upflow Anaerobic Sludge Blanket (UASB), Anaerobic Fixed Film Reactor (AFFR), Anaerobic Contact Reactor, and Covered Lagoon. Anaerobic membrane bioreactors (AnMBRs) are gaining popularity and have been developed to obtain greater treatment efficiency by combining anaerobic treatment with membrane filtration [6-7].

AnMBR's advantages include its capacity to retain suspended solids in the system, preventing them from escaping. The effluent quality remained stable and excess sludge production was minimal. Additionally, when it comes to organic matter removal and biogas production, AnMBRs outperforms UASB systems by about 40% [8]. A non-aerated biological treatment system can be fed with an organic loading rate (OLR) ranging from 1.1-23 kg/m^3-d and achieve an organic matter removal effectiveness of approximately 80%. AnMBR system, on the other hand, can handle higher organic loading rates up to 4.5-50 kg/m^3-d while achieving over 90% organic matter removal efficiency [9]. Furthermore, AnMBR system requires less space compared to other systems because the system can retain a larger amount of microorganisms, enabling higher organic loading rates and shorter retention times [10]. This study aims to apply AnMBR system for the treatment of high-strength organic wastewater, and investigates the factors affecting the AnMBR operation for providing an optimum condition that can serve as a guidance data for its real application.

2. Materials and methods

2.1 Synthesis of high-strength organic wastewater

Wastewater used in this study is a synthetic high-strength wastewater. It was prepared by using wastewater from the starch-based industry as a representative sample, following the research conducted by [11]. Tapioca starch was used as sole carbon source. NH_4HCO_3 and KH_2PO_4 were added as nutrient to maintain COD:N:P ratio. The wastewater has a chemical oxygen demand (COD) concentration of 20,000 milligrams per liter, and its fully characteristics is shown in Table 1.

Table 1 The characteristics of the wastewater in this study.

Parameter	Unit	Concentration
pH	-	7.5±0.83
Chemical Oxygen Demand, COD	g/l	19.38±0.43
Soluble Chemical Oxygen Demand, SCOD	g/l	2.32±0.62
Biochemical Oxygen Demand, BOD	g/l	14.69±0.28
Soluble Biochemical Oxygen Demand, SBOD	g/l	1.10±0.36
Total Solid, TS	g/l	15.6±0.48
Total Suspended Solids, TSS	g/l	13.6±0.52
TKN	mg/l	950±138
NH_3-N	mg/l	680±71

2.2 Anaerobic membrane bioreactor (AnMBR) system

The schematic configuration of AnMBR system for this study is presented in Figure 1. The system consists of a 10-liter wastewater storage tank with a hollow fiber membrane filter made of Polyacrylonitrile (PAN) material that prevents the adsorption of organic substances due to its hydrophilic properties [12]. The filter is widely available on the market and generally used in a common water filtration. It has the surface area of 0.9 m^2 and pore size of 0.4 microns, making it as a microfiltration that efficiently retains microorganisms. The system is equipped with three peristaltic pumps: Pump1 (P1) and pump3 (P3) control the feeding and filtration rates based on the retention time in the system, while pump2 (P2) circulates the water within the system at a flow rate of 60 L/min [13]. A vacuum gauge is installed to monitor the Transmembrane Pressure (TMP). The anaerobic seed sludge was taken from UASB reactor of cassava starch factory. The collected sludge was allowed to settle at 4°C for 24 h and the supernatant was removed, leaving the concentrated sludge at the bottom. Next the thickened sludge was brought to room temperature.

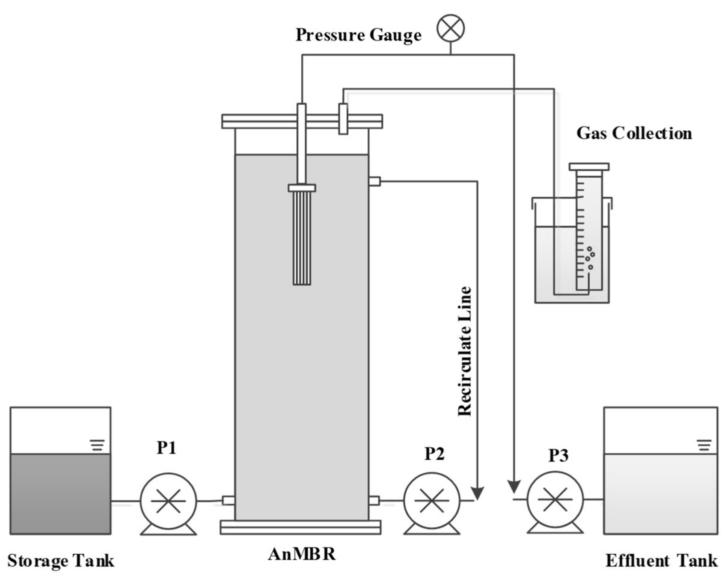

Figure 1 The system used in this study.

2.3 Effect of retention time on AnMBR system performance

This study investigated the effect of Hydraulic Retention Time (HRT) on the performance of an AnMBR system. Three alternative retention times (48 h, 24 h, and 12 h) were tested by continually feeding synthetic wastewater into the system. The pH value was maintained at 7.0±0.2 (adjusted with 1 M HCl and 1 M NaOH), and the effluent was evaluated for COD removal efficiency. The analysis included measuring changes in TMP and membrane fouling resistance to evaluate filtration efficacy. Resistance analysis was used to assess membrane fouling by examining the reduction in flux. Thus, TMP is an important indicator of membrane fouling. Prior to starting the system, an Initial Membrane Resistance (IMR) analysis was performed to determine the membrane's overall resistance. Several methods and tools have been used to establish the relationship between the flux and TMP.

2.4 Analytical methods used in the study

The system was conducted using a continuous-flow experiment by collecting samples at two points: the influent, which is the synthesized organic wastewater entering the system, and the effluent from the reaction tank. Several parameters were analyzed to monitor and control the system's overall performance during the experiments. These parameters included pH, temperature, alkalinity, and methane production. Additionally, parameter related to the assessment of organic removal efficiency was also measured. Samples were collected from both the influent and effluent every two days. This sampling frequency was chosen because it aligns with minimal variations in the organic removal pattern in the system [14]. The analysis of organic content, both total and soluble COD were determined in the effluent after the anaerobic biological treatment system with the method described in [15]. The biogas composition in AnMBR were analyzed separately by gas chromatography equipped with thermal conductive detector (TCD).

3. Results and discussion

3.1 General conditions in the anaerobic membrane bioreactor (AnMBR) system

This study looked at the general operating characteristics of an AnMBR system, including pH and alkalinity control. During the initial stages of the study, a 48 h HRT was used. The system's average pH values were 7.05, 6.88, and 6.85 for HRTs of 48, 24, and 12 h, respectively. The average alkalinity levels in the AnMBR system were 1,990, 2,028, and 1,789 mg/L as $CaCO_3$, at HRTs of 48, 24, and 12 h, respectively (Figure 2). The significant decrease at 12 h was due to higher influent organic matter content. The volumetric organic loading rate (VOLR) for the 12 h HRT showed an average value of 38.95 ± 0.88 kg COD/m^3-day. The average VOLR was 9.79 ± 0.23 kg COD/m^3-day during 48 h of HRT, and 19.36 ± 0.51 kg COD/m^3-day at 24 h of HRT. These changes in alkalinity and VOLR were attributed to the increased quantity of organic matter undergoing decomposition in the AnMBR system without aeration, leading to higher concentrations of organic acids, and required a drop in alkalinity to maintain system stability.

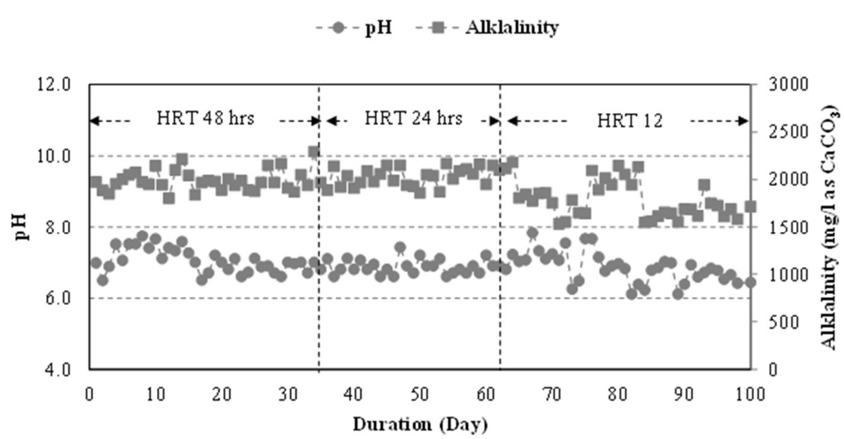

Figure 2 pH values and system alkalinity of the AnMBR system.

3.2 Removal efficiency of organic matter in the anaerobic membrane bioreactor (AnMBR) system

The efficiency of organic matter removal in high-strength wastewater is assessed using COD. Wastewater contains both soluble and particulate organic compounds. This study focused on the ratio of soluble COD to total COD (SCOD/COD). A low SCOD/COD ratio suggests that most organic matter is particulate, which is the focus of this study (Table 1). The influent wastewater had an average COD concentration of 19,436 ± 458 mg/L. Upon entering the AnMBR system, COD concentrations decreased to average values of 3,658 ± 280, 4,228 ± 389, and 5,780 ± 658 mg/L at HRTs of 48, 24, and 12 h, respectively (Figure 3). The remaining COD concentration increased as the HRT decreased. The highest removal efficiency was at an HRT of 48 h with the lowest effluent COD concentration. The COD removal efficiencies at HRTs of 48 h, 24 h, and 12 h were 81.18%, 78.24%, and 70.26%, respectively (Figure 4).

When assessing the removal of organic matter in high-strength wastewater, considering the Organic Removal Rate (ORR), it was observed that as the HRT decreased, the rate of organic degradation increased. The AnMBR system exhibited ORR values of 7.90, 15.13, and 27.39 kg COD/m^3-day at HRTs of 48, 24, and 12 hours, respectively. This observation corresponds with the VOLR, which increased as HRT decreased. The average VOLR values for HRTs of 24 and 12 hours were 19.36 ± 0.51 and 38.95 ± 0.88 kg COD/m^3-day, respectively. This effect was attributed to increased volumetric organic loading, resulting in higher organic degradation rates. It aligns with research by [11], which studied the efficiency of organic matter removal in a Two-Stage TAnMBR system and found removal efficiencies ranging from 84% to 92% for VOLR values in the range of 6 to 12 kg COD/m^3-day, with organic degradation rates of 5.3 to 10.1 kg COD/m^3-day. The AnMBR serves to separate biomass from treated water, allowing for the retention of microorganisms within the reactor. This configuration enhances the treatment efficiency and ensures a high level of organic matter removal from the wastewater.

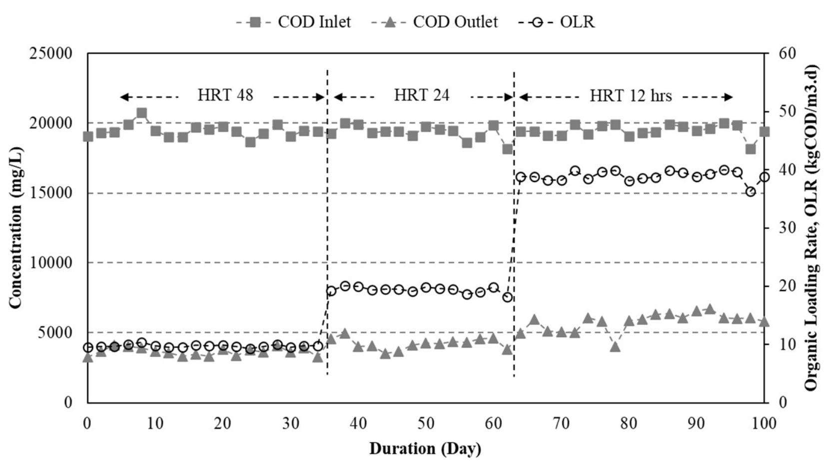

Figure 3 Influent and effluent COD concentrations of the AnMBR system.

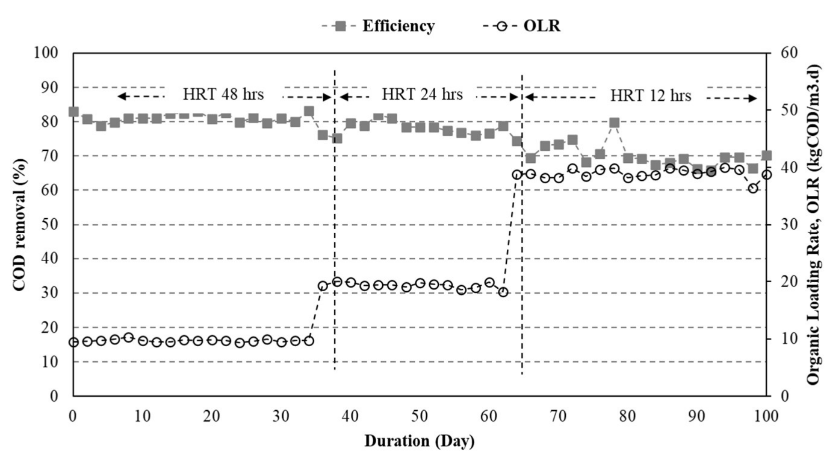

Figure 4 Removal efficiency of COD in the AnMBR system.

3.3 Biogas Generation Rate in the Anaerobic Membrane Bioreactor (AnMBR) System

Under different conditions, the AnMBR system outperformed the other systems in terms of organic matter removal efficiency. When considering biogas generation, it was found that the average biogas production rate was 32.22, 42.64, and 53.58 L/d at HRTs of 48, 24, and 12 h, respectively, as shown in Figure 5. The highest biogas production was observed at a 12 h HRT, primarily due to the higher influent organic content (38.95 ± 0.88 kg COD/m3-day). This higher organic content allowed anaerobic microorganisms in the AnMBR system to degrade organic matter efficiently, resulting in increased biogas production compared with other systems. The AnMBR system produced an average of 0.224, 0.127, and 0.092 m^3methane/kg COD removed at HRTs of 48, 24, and 12 h, respectively. AnMBRs produce methane through a series of microbial transformations. The anaerobic process in an AnMBR is effective for treating high-strength organic wastewater and has several advantages, including energy recovery in the form of biogas. The utilization of methane produced in anaerobic systems is consistent with sustainable practices as it harnesses energy from organic waste, contributing to waste treatment and renewable energy generation.

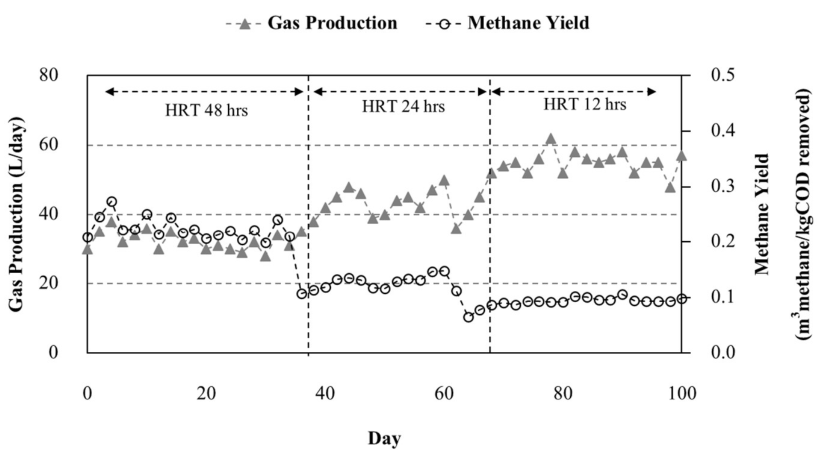

Figure 5 Biogas volume and biogas production rate of the AnMBR system.

3.4 Filtration Performance

The filtration performance of the AnMBR system was compared between the filtration and fouling conditions byconsidering the state of fouling when a constant TMP was maintained and permeate flux decreased. Afterward, appropriate cleaning was conducted using chemical solutions. Sodium hydroxide (NaOH) was employed to remove hydrolyzed molecules and substances that adhered to the membrane surface due to its high hydrolyzing power. Nitric acid (HNO_3) was used to manage organic fouling.

As shown in Figure 6, there were variations in TMP when HRT changed. The AnMBR system at an HRT of 48 hours was capable of longer operational periods compared to the system with an HRT of 24 hours, with a factor of 1.29, and even longer when compared to a 12-hour HRT, with a factor of 1.50. As the HRT decreased, the increased organic loading, measured as VOLR, had values of 9.79 ± 0.23, 19.36 ± 0.51, and 38.95 ± 0.88 kg COD/m^3-day for HRTs of 48, 24, and 12 hours, respectively. These higher organic loadings led to the proliferation of microorganisms and the release of enzymes for organic degradation [12]. This resulted in having an increased fouling, as well as an elevated permeate flux, leading to cake layer accumulation on the membrane surface, causing faster fouling at shorter HRTs.

When considering the fouling rate of the filtration system, the potential for filtration was evaluated by comparing the AnMBR system at three different HRTs. The fouling rates were found to be 20.20, 26.21, and 30.20 mbar/day at HRTs of 48, 24, and 12 hours, respectively. As the HRT decreased, the increased inflow of organic matter and filtration rates into the system resulted in a higher fouling rate. This was because a reduced HRT was directly associated with an increased permeate flux rate. Consequently, rapid cake layer accumulation on the membrane surface occurred, leading to a form of filtration called "dead-end filtration," where cake layers accumulate more significantly than "cross-flow filtration," ultimately reducing the system's operational duration. In summary, the observed increase in permeate flux with a decrease in HRT underscores the significance of hydraulic conditions in influencing the overall performance of the system. Further elucidation on this relationship enhances our understanding of the dynamic interactions within the AnMBR and contributes valuable insights to the optimization of wastewater treatment processes.

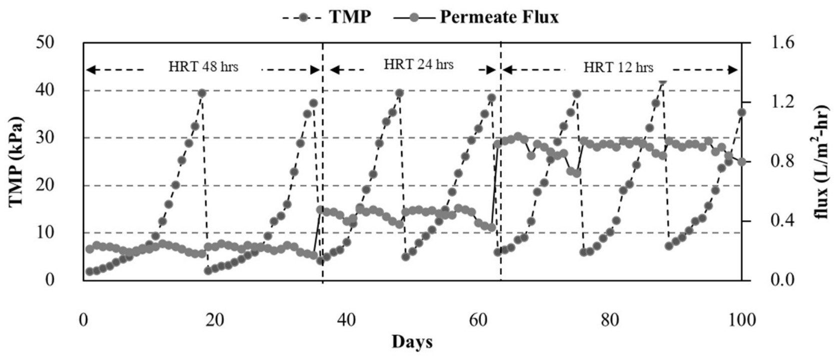

Figure 6 Transmembrane pressure and permeate flux values of the AnMBR system.

4. Conclusion

The study found that the AnMBR system had the highest efficiency in COD removal at a HRT of 48 h with an efficiency of 81.18%. The efficiency decreased to 78.24% and 70.26% at HRTs of 24 and 12 hours, respectively. When considering the ORR, the AnMBR system showed higher efficiency as HRT decreased, with values of 7.90, 15.13, and 27.39 kgCOD/m^3-d at HRTs of 48, 24, and 12 hours, respectively. This increase in ORR was due to an increase in the VOLR which, in turn, led to a higher organic degradation rate. However, the methane yield (biogas production) showed a decreasing trend with a lower HRT. The methane yield values were 0.224, 0.127, and 0.092 $m^3_{methane}$/kg $COD_{removed}$ at HRTs of 48, 24, and 12 hours, respectively. Furthermore, the AnMBR system at an HRT of 48 h exhibited the longest operational duration, 1.29 and 1.50 times longer than at 24 and 12 h, respectively.

5. Acknowledgments

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