Biochemical Engineering Journal 105 (2016) 321–331

Contents lists available at ScienceDirect

Biochemical Engineering Journal

journal homepage: www.elsevier.com/locate/bej

Brewery wastewater treatment using an anaerobic membrane bioreactor

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ARTICLE INFO

Article history:
Received 23 March 2015
Received in revised form 22 August 2015
Accepted 5 October 2015

Keywords:
Anaerobic processes
Membrane bioreactor
Waste-water treatment
Biogas
Brewery wastewater
Water reuse

ABSTRACT

Anaerobic digestion technology plays an important role in the treatment of high strength wastewater. This study investigated the treatment of brewery wastewater using an advanced anaerobic membrane reactor (AnMBR). The results suggest that the AnMBR can achieve a COD removal higher than 98% when treating brewery wastewater, with a biogas yield of $0.53 \pm 0.015\ m^3$ biogas/kgCOD at 35 °C. It was found that the 0.04-μm UF membrane played an important role in reducing COD concentrations in the AnMBR effluent. The observed specific MLVSS growth rate and yield for the AnMBR system tested were determined as 0.022 ± 0.001 gVSS/gVSS/d and 0.029 ± 0.001 gVSS/gCOD, respectively. The critical flux for the membrane filtration with the AnMBR system tested was in the range of $8.64 \pm 0.69\ L/m^2/h$, and the results showed that chemical recovery cleaning is necessary to maintain a stable, long-termoperation at a filtration flux of $8\ L/m^2/h$ when treating brewery wastewater. The size fraction analysis of the EPS showed that particulate proteins and polysaccharides were the dominant forms of EPS in the AnMBR, which could exert a critical influence on the filtration behavior of the membrane process under the sub-critical flux condition in AnMBRs.

1. Introduction

The brewing industry typically generates 3–10 L of wastewater per liter of beer production. The main wastewater constituents include sugars, soluble starch, ethanol, VFAs and total suspended solids [1]. High-rate anaerobic reactors, such as the upflow anaerobic sludge blanket (UASB) reactor, have been proven to be effective technologies for brewery wastewater treatment. Compared to aerobic treatment, the anaerobic treatment offers many advantages, including energy recovery, no aeration requirement, no oxygen transfer limit at high organic load rates and a low sludge production rate [2].

An anaerobic membrane bioreactor (AnMBR) is an integrated anaerobic digestion and membrane filtration process, where the membrane can completely retain all suspended solids, including slow-growing methanogens, to achieve a complete separation of solid retention time (SRT) from hydraulic retention time (HRT). Additional benefits of AnMBR include the elimination of the risk of biomass washout and the improvement of effluent quality, which results from the retention of suspended solids by the membrane filtration [3]. AnMBRs have demonstrated excellent performances for the treatment of wastewater, which was generated from a wide range of sources [2,4,5]. Anderson et al. [6] reported that an AnMBR achieved 99% COD removal for brewery wastewater treatment at an organic loading rate (OLR) higher than 20 gCOD/L/d. Ince et al. [7] showed successful treatment of synthetic brewery wastewater using a conventional cross-flow ultrafiltration membrane anaerobic reactor (CUMAR) at a mixed liquor suspended solid concentration between 10 and 50 g/L. They reported that average effluent COD concentrations of 220, 440 and 660 mg/L were achieved at organic loading rates of 7.5, 11.5 and 17.3 gCOD/L/d, respectively. Ince et al. [8] also reported that the energy recovered from the biogas production was able to supplement approximately 75% of the operation energy requirement of the CUMAR system. Although many studies have shown that the AnMBR is an effective technology for high strength wastewater treatment, its practical applications have been limited by the availability of effective membrane modules and operation strategies for full-scale anaerobic wastewater treatment.

Increasingly restrictive environmental regulations and municipal by-laws can result in enormous wastewater surcharges related to the direct discharge of brewery wastewater into municipal

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http://dx.doi.org/10.1016/j.bej.2015.10.006
1369-703X/

sewers. Thus, the development of effective wastewater treatment technologies is critical for the sustainable growth of the brewery industry. Recent successes using aerobic membrane bioreactor (MBR) technology have substantially advanced the membrane module design and the operation strategies for full-scale wastewater treatment [9,10]. These changes potentially provide an opportunity to revitalize AnMBR technology for brewery wastewater treatment. However, to the best of our knowledge, AnMBR systems equipped with a state of the art submerged membrane module have not been assessed so far for the treatment of brewery wastewater for the COD removal, biogas production, and membrane filtration in any previously published literature.

The objective of this study is to systematically assess the applications of advanced AnMBR technology for brewery wastewater treatment in terms of the COD removal, biogas production and membrane filtration performance by using an AnMBR with the advanced submerged membrane module and filtration operation design. The AnMBR system used in this study was characterized by a submerged hollow fiber membrane module, the utilization of biogas scouring for membrane fouling control and a programmable logic controller (PLC) controlled permeation/relaxing filtration operation. Therefore, the results produced from this study, which include the COD removal efficiency, biogas production, biomass growth rate, alkalinity consumption, and long-term stability of the membrane filtration, can shed light on the treatment performance and membrane filtration behavior of the advanced AnMBR systems in the treatment of high strength brewery wastewater.

2. Material and methods

2.1. AnMBR system

As shown in Fig. 1, the laboratory-scale AnMBR used in this study consisted of a mechanically mixed anaerobic digester and a membrane tank. The mixed liquor was recirculated from the anaerobic reactor to the bottom of the membrane tank and overflowed from the top portion of the membrane tank back to the reactor. A submerged hollow fiber membrane module, with a total surface area of 0.047 m^2 and a normalized membrane pore size of 0.04 μm (GE Water and Process Technologies, Oakville ON), was used in this study. A peristaltic pump (Miniplus 3, Gilson) was installed to extract the permeate at a constant flux, and the biogas was recirculated to the membrane tank for membrane scouring. Pressure sensors (Cerabar T, Endress Hauser) were installed on the digester tank and the permeate line to monitor the system and transmembrane pressure (TMP). Level sensors were used to control the feed pump to maintain a working volume of 15 L in the system. The bioreactor temperature was maintained by recirculating hot water through the water jacket of the reactor. The pH of the reactor was controlled by dosing sodium bicarbonate using a diaphragm metering pump (Stepdos 08, KNF). Biogas production was measured on-line by a mass flow meter (Burkert 8700). A programmable logic controller (PLC) system was used for the AnMBR operation control and data collection.

2.2. Wastewater characteristics

The synthetic and brewery wastewater was fed to the AnMBR in different stages of this study. The recipe of synthetic brewery wastewater was slightly modified from the one used by Scampini [11]. The composition of the synthetic wastewater at 10 gCOD/L/d was 27.54 g/L beer (Sleeman, ON, Canada), 11.50 g/L glacial acetic acid, 1.50 g/L yeast extract, 0.38 g/L NH_4Cl, 0.24 g/L K_2HPO_4, 0.11 g/L $MgSO_4$ and 51.4 mL of the trace element solution. The trace element solution contained 11.66 mg/L $FeCl_2{\cdot}4H_2O$, 2.92 mg/L $MnCl_2{\cdot}4H_2O$, 11.66 mg/L $CoCl_2{\cdot}6H_2O$, 0.83 mg/L $NiCl_2{\cdot}6H_2O$, 0.29 mg/L $ZnCl_2$, 0.72 mg/L Na_2SeO_3, 0.29 mg/L H_3BO_3, 0.01 mg/L HCl and 5.83 mg/L EDTA. The wastewater had a COD of 17,000 ± 600 mg/L, total nitrogen (TN) of 268 ± 18 mg/L, NH_4-N of 101.0 ± 5.0 mg/L, total phosphorus (TP) of 66.0 ± 2.0 mg/L and PO_4-P of 55.0 ± 2.0 mg/L.

The brewery wastewater tested in this study was taken from a local craft brewery on a weekly basis. A 20-L wastewater container was placed in a bar refrigerator (6 °C) to feed the reactor using a feeding pump connected to the refrigerator. The main wastewater characteristic parameters of each batch, including COD, TN, NH_4-N, NO_2-N, NO_3-N, TP and PO_4-P, were tested prior to feeding it to the reactor. The characteristics of the real wastewater varied from time to time and will be discussed in detail in Section 3.1.

2.3. AnMBR operation

The reactor was started in an inactive state, which was described in a previous study [12]. It had initial MLSS and MLVSS concentrations of 2.8 g/L and 1.8 g/L, respectively. The operational phases involved in this study included the synthetic wastewater and brewery wastewater treatment stages.

The duration of the synthetic wastewater operation was 140 days, which included a 20-day start-up period by batch feeding at an OLR of 2.0 gCOD/L/d. The continuous feeding operation included OLRs at 2.0, 5.0, 7.5 and 10.0 gCOD/L/d for 12, 25, 15 and 68 days, respectively. To accelerate biomass build-up, there was no sludge wasting during the OLR 2.0, 5.0 and 7.5 gCOD/L/d operation periods. The sludge wasting started on the 16th day of the 10.0 gCOD/L/d OLR operation or day 87 of the AnMBR operation by wasting an average of 500 mL sludge per day. This stabilized the MLSS concentration at 11.0 ± 1.0 g/L and resulted in an SRT of approximately 30 days for the synthetic wastewater treatment. The pH of the reactor was controlled at 6.8–7.3 using an online alkalinity dosing system. The temperature was controlled at 35 °C by circulating the hot water through the water jacket of the reactor. The membrane operation flux was set at 8 $L/m^2/h$ (LMH) and the operation cycle involved 10 min of permeation and 1 min relaxation throughout the entire study. The biogas was injected into the bottom of the membrane module at a scouring intensity of 15.3 $m^3/h/m^2$ (membrane area).

The brewery wastewater operation lasted 90 days and started immediately after ending the synthetic wastewater operation. The initial MLSS concentration for the brewery wastewater operation was 11.8 g/L. However, it was reduced to 7.0 g/L MLSS and maintained at this level by adjusting daily sludge wasting volume throughout the operation period. The hydraulic operation time (HRT) was maintained at 44 h throughout the entire operation. The OLR varied from 3.5 to 11.5 gCOD/L/d, which was due to COD fluctuations in the brewery wastewater.

A maintenance cleaning protocol, using citric acid (2000 mg/L) and sodium hypochlorite (2000 mg/L effective chlorine) as the cleaning reagents, was initialized on day 87 when an increased TMP rate was observed at the OLR of 10.0 gCOD/L/d, and carried out for the rest of operation in a frequency of once a week. The maintenance cleaning operation involved backwash at a flux of 8 LMH using citric acid for 15 min, followed with sodium hypochlorite for 15 min and deionized water for 10 min.

2.4. Sampling and analytical methods

Samples were regularly taken from the reactor, the membrane tank and the membrane permeate for analysis. For the mixed liquid samples, the supernatant of mixed liquor was obtained using a centrifugation/filtration procedure. The centrifugation (Thermo Scientific) was conducted at 8000 rpm for 15 min at 4 °C and followed by filtration through a 1.5-μm filter paper (Whatman, GE