Biochemical Engineering Journal 97 (2015) 132–141

Contents lists available at ScienceDirect

Biochemical Engineering Journal

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

Anaerobic membrane bioreactors enable high rate treatment of slaughterhouse wastewater

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ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 22 January 2015
Accepted 4 February 2015
Available online 7 February 2015

Keywords:
Anaerobic processes
Biogas
Membrane bioreactors
Slaughterhouse
Resource recovery
Waste-water treatment

ABSTRACT

Anaerobic membrane bioreactors (AnMBRs) enable high space loading by retaining solids selectively through microfiltration membranes. For organic industrial wastewaters, this offers an alternative to lagoons and granule based high-rate anaerobic treatment due to excellent effluent quality, high tolerance to load variations, and ability to produce a solids free effluent for the purposes of reuse. While there has been extensive work on low-strength and low solids effluent, there has been limited application in high-solids, high fats systems such as slaughterhouse wastewater, which are a key application. A 200 L AnMBR pilot plant operated at 2 Australian cattle slaughterhouses consistently removed over 95% of chemical oxygen demand (COD) from the wastewater. Virtually all degradable COD was converted to biogas, 78–90% of nitrogen and 74% of phosphorus in the wastewater were released to the treated permeate as ammonia and phosphate, respectively; which would enable subsequent nutrient capture. The mass loading rate limit of 3–3.5 g COD L^{-1} d^{-1} is imposed by the active biomass inventory, with this in turn limited to 40 g L^{-1} (TS) by the need to manage membrane fouling control.

1. Introduction

Animal slaughterhouses generate large volumes of wastewater rich in organic contaminants and nutrients [1–3], and are therefore strong candidates for treatment processes aimed at recovery of both energy and nutrient resources. The current default treatment methods for removing organic contaminants, indicated by chemical oxygen demand (COD) from slaughterhouse wastewater vary widely. Anaerobic lagoons are commonly used in tropical and equatorial temperate zones and engineered reactor systems (including activated sludge and UASB reactors) are commonly used in polar equatorial temperate zones. Anaerobic lagoons are effective at removing organic material [4]; however, lagoon based processes also have major disadvantages including large footprints, poor gas capture, poor odor control, limited ability to capture nutrients and expensive desludging operations. Daily biogas production from anaerobic lagoons may vary by an order of magnitude depending on temperature or plant operational factors [4]. While the organic solids in slaughterhouse wastewater is highly degradable [3,5] reducing sludge accumulation and expensive desludging events, there are increased risks of scum formation [4] which can reduce methane recovery and damage lagoon covers. Therefore, even in warmer climates, there is an emerging and strong case for reactor based technologies.

High-rate anaerobic treatment (HRAT) is an effective method, with space-loading rates up to 100× that of lagoons, and the ability to manipulate input temperature. The most common is upflow anaerobic sludge blanket (UASB) but UASB and other granule based high-rate anaerobic treatment systems are highly sensitive to fats [6], and moderately sensitive to other organic solids [7], hence require considerable pretreatment (including dissolved air flotation) [8], and still operate relatively poorly, with COD removals on the order of 60%. In the last 5 years, a number of fat and solid tolerant processes have emerged, including the anaerobic baffled

Abbreviations: AnMBR, anaerobic membrane bioreactor; COD, chemical oxygen demand; CSTR, continuous stirred tank reactor; DAF, dissolved air flotation (tank); FOG, fat oils and grease; HRAT, high rate anaerobic technology; HRT, hydraulic residence time; LCFA, long chain fatty acids; OLR, organic loading rate; PLC, process logic controller; RTD, resistance temperature detector; SRT, sludge retention time; TKN, total kjehldahl nitrogen; TMP, transmembrane pressure; TP, total phosphorus; TS, total solids; UASB, upflow anaerobic sludge blanket; VFA, volatile fatty acids; VS, volatile solids; WWTP, waste water treatment plant.

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http://dx.doi.org/10.1016/j.bej.2015.02.009
1369-703X/

reactor [9], the anaerobic sequencing batch reactor [10], anaerobic membrane bioreactors (AnMBR) [11,12] and the anaerobic flotation reactor [13]. The AnMBR combines high rate anaerobic digestion with a membrane biomass retention system that is independent of sludge settleability [14]. AnMBRs in particular are probably the most appropriate HRAT technology suitable for slaughterhouse wastewater, particularly high-strength streams, due to excellent effluent quality, high tolerance to load variations, and ability to produce a solids free effluent for the purposes of final treatment an reuse [15]. However, they have most widely been applied to domestic and soluble industrial wastewaters, with a number of potential risk factors as outlined below.

Slaughterhouse waste risks include high proteins, causing release of ammonia (NH_3), and fats, causing release of long chain fatty acids (LCFA), both potential inhibitors of methanogenic activity [16]. Ammonia inhibition is related to its capacity to diffuse into microbial cells and disruption of cellular homeostasis [17], whereas LCFAs may exert a surface proportional toxicity to anaerobic biomass, similar to toxicity exhibited by surfactants and resulting in cell lysis [18]; or may suppress the sludge activity by adsorbing on to the anaerobic biomass and limiting transfer of substrate and nutrients across the cell membrane, interfering with membrane functionality [19,20]. Release of ammonia and/or LCFA is a particular risk at high-strength and in high rate or intensified processes such as AnMBRs where increased OLR and shorter HRT may result in accumulation of substrate and/or inhibitory intermediates within the reactor volume. AnMBRs have been used successfully to treat raw snack food wastewater with high fat, oil and grease (FOG) concentrations (4–6 g L^{-1}) reporting removal efficiencies of 97% in COD and 100% in FOG at a loading rate of 5.1 kg COD m^{-3} d^{-1}, without any biomass separation problems or toxic effects [21]. This suggests AnMBRs could be applied successfully to treat slaughterhouse wastewater.

The accumulation of particulates in the AnMBR vessel can increase membrane fouling due to cake accumulation [22]. Membrane fouling rate, and the ability to operate at an effective critical flux (the flux below at which the system can be operated without periodic cake dispersal) is the primary factor influencing economic feasibility of membrane processes [23], with membrane costs in the range of 72% of capital investment [24]. Fouling is potentially more severe in slaughterhouse applications due to the high protein content in the waste and the fouling propensity of mixtures with a high protein to polysaccharide ratio [25,26].

While AnMBR systems have been widely applied to low strength, and soluble industrial wastewaters, particularly in the laboratory, risks around higher solids wastewater, which should be a key application, are not well known. The aim of the present study is to evaluate loading rates, retention times, and membrane performance for intensified anaerobic treatment of combined slaughterhouse wastewater through a longer term study, associated to achievable performance through biochemical methane potential (BMP) testing.

2. Materials and methods

2.1. Biomethane potential tests

Batch digestions were performed according to Angelidaki et al. [27] in 160 mL non-stirred glass serum vials (100 mL working volume) at 38 °C. Inoculum was collected from mesophilic anaerobic digesters operating at 37 °C and treating a mixture of primary and waste activated sludge at a domestic WWTP (Queensland, Australia). The average inoculum composition was 28.6 g L^{-1} COD, 26.1 g L^{-1} TS and 69% VS (as a fraction of TS). Specific methanogenic activity of the inoculum was 0.2 g COD g VS^{-1} d^{-1}. The inoculum to substrate ratio (ISR) in the BMP tests was set at 2 (volatile solids basis) according to Jensen et al. [28]. Bottles were flushed with 100% N_2 gas for 3 min (1 L min^{-1}), sealed with a rubber stopper retained with an aluminum crimp seal and stored in temperature-controlled incubators (38 ± 1 °C). Tests were mixed by inverting once per day. Blanks containing inoculum without the substrate were used to correct for background methane. Separate positive controls were conducted using α-cellulose, casein or olive oil at 1 g L^{-1} resulting in biochemical methane potential (B_0) values of 373 L kg^{-1} VS, 537 L kg^{-1} VS and 1012 L kg^{-1} VS, respectively (data not presented).

Fig. 1. Anaerobic membrane bioreactor pilot plant installed at an Australia beef processing facility (left) and hollow fiber membrane module (right).