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Research article

# Performance and design considerations for an anaerobic moving bed biofilm reactor treating brewery wastewater: Impact of surface area loading rate and temperature

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ABSTRACT

Three 4 L anaerobic moving bed biofilm reactors (AMBBR) treated brewery wastewater with AC920 media providing 680 $m^2$ protected surface area per $m^3$ of media. Different hydraulic retention times (HRT; 24, 18, 12, 10, 8 and 6 h) at 40% media fill and 35 °C, as well as different temperatures (15, 25 and 35 °C) at 50% media fill and 18 h HRT were examined. Best performance at 35 °C and 40% media fill was observed when HRT was 18 h, which corresponded with 92% removal of soluble COD (sCOD). Organic loading rates (OLR) above 24 kg-COD $m^{-3}d^{-1}$ decreased performance below 80% sCOD removal at 35 °C and 40% media fill. The reason was confirmed to be that surface area loading rates (SALR) above 50 g-sCOD $m^{-2}d^{-1}$ caused excessive biofilm thickness that filled up internal channels of the media, leading to mass transfer limitations. Temperature had a very significant impact on process performance with 50% media fill and 18 h HRT. Biomass concentrations were significantly higher at lower temperatures. At 15 °C the mass of volatile solids (VS) was more than three times higher than at 35 °C for the same OLR. Biofilms acclimated to 25 °C and 15 °C achieved removal of 80% sCOD at SALR of 10 g-sCOD $m^{-2}d^{-1}$ and 1.0 g-sCOD $m^{-2}d^{-1}$, respectively. Even though biomass concentrations were higher at lower temperature, biofilm acclimated to 25 °C and 15 °C performed significantly slower than that acclimated to 35 °C.



## 1. Introduction

The brewing industry has experienced rapid growth globally over the past decade. The American and European markets have doubled in size since 2010 (Beer Canada, 2016; Brewers Association, 2016; Van de Walle, 2015). Increased brewery wastewater production requires treatment to meet sewer bylaws for maximum allowable concentrations of contaminants. Brewery wastewater can be treated either aerobically or anaerobically. Due to typically high organic content of brewery wastewater, anaerobic pre-treatment followed by aerobic polishing is regarded as the most effective process (Chastain et al., 2011). Several anaerobic technologies have been developed to satisfy industrial requirements for compact reactors working at high volumetric organic loading rates (OLR) and decoupled solids residence times (SRT).

Two general strategies are implemented to satisfy the long anaerobic SRT required: 1) granular biomass used in upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors; and 2) biofilm reactors with high- or low-density particulate carrier materials used in anaerobic fluidized bed reactors and anaerobic moving bed biofilm reactors (AMBBR; Alvarado-Lassman et al., 2008; Cronin and Lo, 1998; Mijaylova Nacheva et al., 2009; Ratanatamskul and Siritiewsri, 2015; Sheli et al., 2014). The UASB and EGSB reactors are the most common pre-treatment of brewery wastewater with more than 1200 full-scale plants world-wide (Brito et al., 2007; Lim and Kim, 2014).

However, conventional UASB may encounter problems in sludge retention while treating complex wastewaters containing high suspended and colloidal particles (e.g., fats and proteins). These conditions lead to fluffier granular sludge, degranulation into flocs, and eventually biomass washout (Lu et al., 2015; Oleszkiewicz and Romanek, 1989). Anaerobic hybrid reactors (AHR) were developed to alleviate these issues by adding material, such as low-density filtration or packing material, to UASB reactors in order to maintain performance in the case of degranulation. (Wahab et al., 2014; Kundu et al., 2013; Sunil Kumar et al., 2007; Tawfik and El-Kamah, 2012). The low-density promoted the establishment of a separate anaerobic biofilm for treatment, as well as work to retain lighter

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flocs resulting from degranulation.

A more reliable process than UASB and AHR would be the AMBBR, which relies on low-density media that facilitate the attachment of bacteria to protected surfaces. Although UASB reactors do not require the capital cost of media, the AMBBR provides a more stable system that could be cheaper under highly variable industrial loads. The AMBBR media, upon which biofilm develops, are physically retained in the system while UASB granules may disintegrate or float under high loads, leading to washout and significant loss in treatment capacity (Lu et al., 2015). Therefore, when treating highly variable influent, especially towards the lower end of wastewater strength (i.e., higher hydraulic load), AMBBR processes could become the cheaper option depending on balancing and equalization requirements to provide UASB granule stability.

The aerobic and anoxic MBBR technology is well established with demonstrated performance in municipal and industrial wastewater, aquaculture, secondary and tertiary treatment, and side stream applications (Ødegaard, 2006; McQuarrie and Boltz, 2011). However, application of AMBBR has been limited to few studies of winery and dairy wastewater (Sheli et al., 2014; Sheli and Moletta, 2007; Wang et al., 2009). There is a demonstrated need to better understand AMBBR performance and operational design parameters for treating wastewater at different loads, hydraulic retention times (HRT), and temperatures. The physical attachment of biofilm to low-density media should facilitate the transition of mesophilic anaerobic digestion processes to temperatures below 20 °C.

In this study different hydraulic residence times were applied to three 4 L AMBBR at 35 °C and 40% media fill. Process performance at increasing surface area loading rates (SALR) was evaluated and loading conditions adverse to mass transfer were observed. After identifying SALR with the best performance at 35 °C and 40% media fill, the pre-established media was subjected to different temperatures (35 °C, 25 °C, and 15 °C) at constant HRT of 18 h and 50% media fill. The specific objectives of the study were: 1) to determine process performance at different HRT of 24, 18, 12, 8, and 6 h; 2) to evaluate performance at different temperatures of 15 °C, 25 °C and 35 °C; and 3) to define key design parameters of SALR and methane yields at the various operating temperatures.

## 2. Material and methods

### 2.1. Experimental setup

Three identical 4 L sealed acrylic reactors were used with biomass acclimated to brewery wastewater in a previous study (di Biase et al., 2016). The reactors were filled with 40% media during the HRT study and 50% media for the temperature study. Mechanical mixing at 65 rpm with a double paddle mixer. Media were AC920 (Headworks BIO, Victoria BC, Canada) with a total surface area of 920 $m^2$ $m^{-3}$ and protected surface area of 680 $m^2$ $m^{-3}$. The internal channels of the media, which contain the protected surface area, is the space where biofilm can develop without being mechanically sloughed off by contact with other media, reactor walls, or the mechanical mixer. Wastewater from a local brewery (Winnipeg, Canada) was used to prepare the feedstock. Fermenter underflow (150 ± 10 g-COD $L^{-1}$) was used as substrate because it is the main source of organics in brewery wastewater (Chastain et al., 2011). The collected fermenter underflow was diluted to a COD concentration of 3.5 g-COD $L^{-1}$. Real wastewater was not collected due to the variable nature of end-of-pipe effluent and the lack of composite autosampler for the project. Alkalinity of 1.5–2.0 g-$CaCO_3$ $L^{-1}$ was provided as calcium bicarbonate in order to maintain pH in the reactors above the methanogenesis inhibition threshold of pH 6 (Kleerebezem et al., 2015).

#### 2.1.1. Hydraulic retention time study

The three parallel reactors were allowed two months acclimation to brewery wastewater at 35 °C before commencing the study. A 200 L tank was used to store the brewery wastewater at 4 °C and a heat exchanger raised the temperature to 35 °C during continuous pumping into the three reactors. The protected surface area of 680 $m^2$ $m^{-3}$ at 40% media fill resulted in approximately 1.1 $m^2$ for biofilm development in each reactor. The initial HRT was 24 h and then decreased stepwise to 18, 12, 10, 8 and 6 h. The reactors were operated for 150 days and each step of HRT was maintained for at least three weeks before decreasing.

Periodic kinetic tests were performed on the mixed liquor suspended solids to evaluate their contribution to the total organic removal capability of the system. The kinetic tests were carried out at the end of each distinct HRT period immediately before transition to the next, lower HRT. Mixed liquor was withdrawn from each reactor and transferred to 0.5 L flasks and as much as 5 g-sCOD $L^{-1}$ was supplied as glucose (Sigma-Aldrich Canada Co.). The kinetic tests were performed over 24 h. Maximum suspended biomass activity as g-sCOD $d^{-1}$ was quantified by linear regression of sCOD concentrations over time. As a conservative estimate, the maximum suspended biomass activity was compared to entire reactor removal rates in order to estimate the maximum contribution from suspended biomass.

#### 2.1.2. Temperature study

The previously described reactors were placed in individual incubators at 15, 25, and 35 °C. The media filling was increased from 40% to 50% by volume, therefore 10% by reactor volume of uncolonized new AC920 media were added resulting in 650 ± 50 media units per reactor. The reactors, now at 50% media fill, were acclimated for three months in order to reach steady state removal at each temperature. The concentrations in the influent averaged 3.9 ± 0.1 g-sCOD $L^{-1}$ during this time. Total and volatile suspended solids on the media were determined in triplicate (20 media each for each quantification) by mechanical removal of biofilm from the media into 2 L of deionized water (APHA, 2012). After achieving steady state, three 24 h sets of batch experiments per reactor were designed to evaluated performance of both suspended and attached biomass.

The first set of batch experiments, performed with 4 replicates in 0.5 L septum bottles each containing 60 media, was used to quantify biogas production rates of attached biomass in a AER-800 Research Respirometer (Challenge Technology, USA). Gas composition was quantified at the end of the test in each replicate by gas chromatography (490 Micro GC, Agilent Technologies, Santa Clara, CA). The second set of batch experiments, performed with 4 replicates in 0.5 L septum bottles each containing 60 media, was used to determine COD removal rates by the attached biofilm through kinetic tests. The third and final set of batch experiments, performed in triplicate in 0.5 L septum bottles filled with mixed liquor, was used to estimate the suspended biomass contribution to overall sCOD removal. The substrate used for all the three sets of batch experiments was brewery wastewater at concentrations of 4.0 ± 0.5 g sCOD $L^{-1}$.

### 2.2. Analytical methods and calculations

Total chemical oxygen demand (COD) and sCOD were filtered through medium porosity Q5 filter paper (Fisher Scientific, CA) and analyzed spectrophotometrically as per Standard Methods (APHA, 2012). Biochemical oxygen demand (BOD) was determined using Oxitop bottles (model IS 12, Xylem, CA). Alkalinity, TS and VS were

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