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The operating cost of an anaerobic membrane bioreactor (AnMBR) treating sulphate-rich urban wastewater

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ABSTRACT

The objective of this study was to evaluate the operating cost of an anaerobic membrane bioreactor (AnMBR) treating sulphate-rich urban wastewater (UWW) at ambient temperature (ranging from 17 to 33 °C). To this aim, energy consumption, methane production, and sludge handling and recycling to land were evaluated. The results revealed that optimising specific gas demand with respect to permeate volume (SGD_P) and sludge retention time (for given ambient temperature conditions) is essential to maximise energy savings (minimum energy demand: 0.07 kW h m^{-3}). Moreover, low/moderate sludge productions were obtained (minimum value: 0.16 kg TSS kg^{-1} $COD_{Removed}$), which further enhanced the overall operating cost of the plant (minimum value: €0.011 per m^3 of treated water). The sulphate content in the influent UWW significantly affected the final production of methane and thereby the overall operating cost. Indeed, the evaluated AnMBR system presented energy surplus potential when treating low-sulphate UWW.

1. Introduction

Nowadays, a key issue in global sustainable development is the dependency on fossil fuels for electricity production, which represents up to the 80% of the global energy consumption [1]. In this respect, electricity consumption is a key element in the overall environmental performance of a wastewater treatment plant (WWTP) [2]. Hence, it is particularly important to implement new energy-saving technologies that reduce the overall energy balance of the WWTP, such as anaerobic membrane bioreactors (AnMBRs). This technology focuses on the sustainability benefits of anaerobic processes compared to aerobic processes, such as: minimum sludge production due to low biomass yield of anaerobic organisms; low energy demand since no aeration is required; and methane production that can be used to fulfil process energy requirements [3].

Several issues have been recognised elsewhere as potential drawbacks which may affect the sustainability of AnMBR technology treating urban wastewater (UWW). One key issue is the competition between Methanogenic *Archaea* (MA) and Sulphate Reducing Bacteria (SRB) for the available substrate [4] when there is significant sulphate content in the influent, reducing therefore the available COD for methanisation [5]. For urban wastewater, which can easily present low COD/SO_4–S ratio, this competition can critically affect the amount and quality of the biogas produced. Specifically, 2 kg of COD are consumed by SRB in order to reduce 1 kg of influent SO_4–S (see, for instance, [5]). According to the theoretical methane yield under standard temperature and pressure conditions (350 L_{CH4} kg^{-1}COD), SRB reduces the production of approx. 700 L of methane per kg of influent SO_4–S (considering reduction of all sulphate to sulphide). Therefore, higher biogas productions would be achieved when there is little sulphate content in the influent (typical sulphate concentration in UWW fluctuates around 7–17 mg SO_4–S L^{-1} [6]). On the other hand, due to the low-growth rate of anaerobic microorganism, high sludge retention times (SRTs) are required when operating at low temperatures in order to achieve suitable organic matter removal rates, especially for low-strength wastewaters like urban ones (typical COD levels below 1 g L^{-1} [6]). However, as regards filtration process, operating AnMBRs at high SRT may imply operating at high mixed liquor total solid (MLTS) levels. This is considered to be one of the main constraints on membrane operating because it can result in a high membrane fouling propensity and therefore high energy demand for membrane scouring by gas sparging [7].

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The objective of this study was to evaluate the operating cost of an AnMBR system treating sulphate-rich urban wastewater (UWW) at ambient temperature (ranging from 17 to 33 °C). To this aim, power requirements, energy recovery from methane (biogas methane and/or methane dissolved in the effluent), and sludge handling and recycling to land were evaluated at different operating conditions. In order to obtain reliable results that can be extrapolated to full-scale plants, this study was carried out in an AnMBR using industrial-scale hollow-fibre membrane units. This system was operated using effluent from the pre-treatment of the Carraixet WWTP (Valencia, Spain).

2. Materials and methods

2.1. AnMBR plant description

A semi-industrial AnMBR plant was operated using the effluent of a full-scale WWTP pre-treatment. The average AnMBR influent characteristics are shown in Table 1. This influent UWW was characterised by a low COD (around 650 mg L^{-1}) and high sulphate concentration (around 105 mg SO_4–S L^{-1}).

The AnMBR plant consists of an anaerobic reactor with a total volume of 1.3 m^3 connected to two membrane tanks (MT1 and MT2) each one with a total volume of 0.8 m^3. Each membrane tank includes one ultrafiltration hollow-fibre membrane commercial system (PURON®, Koch Membrane Systems, 0.05 μm pore size, 30 m^2 total filtering area). The filtration process was studied from experimental data obtained from MT1 (operated recycling continuously the obtained permeate to the system), whilst the biological process was studied using experimental data obtained from MT2 (operated for the biological process without recycling the obtained permeate). Hence, different 20 °C-standardised transmembrane fluxes (J_{20}) were tested in MT1, without affecting the hydraulic retention time (HRT) of the plant.

In addition to conventional membrane operating stages (filtration, relaxation and back-flushing), two additional stages were considered in the membrane operating mode: degasification and ventilation. Further details on this AnMBR can be found in Giménez et al. [5] and Robles et al. [8].

2.2. AnMBR operating conditions

The AnMBR plant was operated for around 920 days within a wide range of operating conditions for both filtration and biological process.

2.2.1. Filtration process

Five operating scenarios related to filtration process (FP1-FP5) were considered to evaluate the energy consumption of the AnMBR plant (see Table 2). As Table 2 shows, the main operating conditions in these five scenarios were as follows: transmembrane pressure (TMP) during filtration: from 0.09 to 0.35 bar; J_{20} from 9 to 20 LMH; MLTS entering the membrane tank: from 12.5 to 32.5 g L^{-1}; sludge recycling flow in anaerobic reactor and membrane tank (SRF_{MT} and SRF_{AnR} respectively): 2.7 and 1 m^3 h^{-1} respectively; specific gas demand per square metre of membrane area (SGD_m): controlled at 0.17 and 0.23 m^3 h^{-1} m^{-2}; and biogas recycling flow to the anaerobic reactor (BRF_{AnR}): 1.5 m^3 h^{-1}.

Table 1
Average characteristics of AnMBR influent.

Parameter	Mean ± SD
Treatment flow rate (m^3 day^{-1})	3.2 ± 0.7
TSS (mg L^{-1})	313 ± 45
VSS (mg L^{-1})	257 ± 46
COD (mg L^{-1})	650 ± 147
SO_4–S (mg L^{-1})	105 ± 13
NH_4–N (mg L^{-1})	35 ± 3
PO_4–P (mg L^{-1})	4 ± 1

2.2.2. Biological process

Variations in SRT and seasonal temperature were studied to account for the dynamics in methane and sludge productions over time. During the 920-day experimental period the plant was operated at ambient temperature ranging from 17 to 33 °C and SRT varied from 30 to 70 days. Three different experimental scenarios related to biological process ($BP_{33\,°C,\ SRT\ 70\ days}$, $BP_{22\,°C,\ SRT\ 38\ days}$ and $BP_{17\,°C,\ SRT\ 30\ days}$) were considered to evaluate the energy consumption of the AnMBR plant (see Table 3): (1) a summer period of 2 months of operation resulting in high methane and low sludge productions ($BP_{33\,°C,\ SRT\ 70\ days}$) due to operating at high temperature (33 °C in average) and high SRT (70 days); (2) one year of operation resulting in moderate methane and sludge productions ($BP_{22°\,C,\ SRT\ 38\ days}$) due to operating at variable temperature (22 °C in average) and moderate SRT (38 days); and (3) a winter period of 2 months of operation resulting in low methane and moderate sludge productions ($BP_{17\,°C,\ SRT\ 30\ days}$) due to operating at relatively low temperature (17.1 °C in average) and moderate SRT (30 days). These three scenarios represent boundary ($BP_{33\,°C,\ SRT\ 70\ days}$: best conditions; and $BP_{17\,°C,\ SRT\ 30\ days}$: worst conditions) and average ($BP_{22\,°C,\ SRT\ 38\ days}$) of the operating conditions evaluated in the plant.

In addition, several simulation scenarios were calculated in order to assess the AnMBR performance within the whole range of temperature (17–33 °C) and SRT (30–70 days) evaluated in this study. Simulation results were obtained using the WWTP simulating software DESASS [9]. This simulation software features the mathematical model BNRM2 [10], which was previously validated using experimental data obtained in the AnMBR plant. Fig. 1 shows the resulting effluent COD without including dissolved methane concentration (see Fig. 1a); total methane production (see Fig. 1b); and sludge production (Fig. 1c) for the different temperature and SRT conditions simulated.

2.2.2.1. Influent sulphate concentration. The effect of the influent sulphate on the AnMBR operating cost was also evaluated. As mentioned before, the UWW fed to the AnMBR plant was characterised by relatively low COD and high sulphate concentrations (see Table 1). Therefore, an important fraction of the influent COD was consumed by SRB. To be precise, the sulphate content in the influent was approx. 105 mg S–SO_4 L^{-1}, from which approx. 98% was reduced to hydrogen sulphide (around 103 mg S–SO_4 L^{-1}). Therefore, about 206 mg L^{-1} of influent COD were consumed by SRB.

The results obtained in this study were compared to the theoretical results obtained in an AnMBR system treating low-sulphate UWW (10 mg S–SO_4 L^{-1}). To this aim, the methane production when treating low-sulphate UWW was calculated on the basis of the theoretical methane yield under standard temperature and pressure conditions: 350 L_{CH4} kg^{-1} COD. Table 4 shows the theoretical methane production (including both biogas methane and methane dissolved in the effluent) obtained for cases $BP_{33\,°C,\ SRT\ 70\ days}$, $BP_{22\,°C,\ SRT\ 38\ days}$ and $BP_{17\,°C,\ SRT\ 30\ days}$ when treating low-sulphate UWW (10 mg S–SO_4 L^{-1}). The distribution between gas and liquid phase of the produced methane was established on the basis of the experimental distribution obtained in the AnMBR plant.

2.3. Analytical monitoring

The following parameters were analysed in mixed liquor and influent stream according to Standard Methods [11]: total solids (TS); total suspended solids (TSS); volatile suspended solids