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Evaluating the effects of scaling up on the performance of bioelectrochemical systems using a technical scale microbial electrolysis cell

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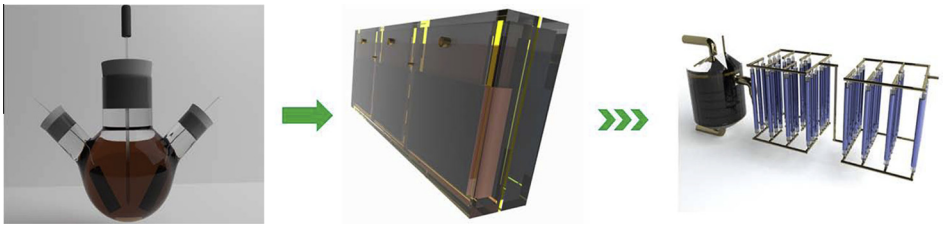
HIGHLIGHTS

- An example of BES scaling up is shown on a technical scale microbial electrolysis cell.
- Efficient COD removal and current production is achieved.
- A multitude of parameters influences the scaling-up.
- A model for system comparison is introduced.

GRAPHICAL ABSTRACT

Scaling up: from labscale to technical scale to pilot and beyond. Requirements and performance assesment.



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ABSTRACT

This study focuses on the challenges of the scaling up process of bioelectrochemical systems on the example of a technical scale microbial electrolysis cell referred to as the "prototype". Anodically treating real wastewater and operated in continuous mode at a hydraulic retention time of 1.23 d with an average chemical oxygen demand (COD)-loading rate of 0.5 g O_2 d^{-1} $L_{Reactor}^{-1}$ the prototype on average showed COD removal efficiency of 67% with effluent concentrations of 210 mg O_2 L^{-1} and an ammonium elimination rate of 17.8 ± 3.9 mg N d^{-1} $L_{Reactor}^{-1}$ resulting in effluent concentrations of 30.7 ± 3.7 mg N L^{-1} with a removal efficiency of 40% at a current generation of 72 μA cm^{-2} and Coulomb efficiency of 11%. A model is described as a method for comparing conventional and BES based technology using the above mentioned criteria and balancing them against the respective loading rates.

1. Introduction

While bioelectrochemical systems (BES) have been constantly improving in its widespread types microbial fuel cells (MFC) and microbial electrolysis cells (MEC) (Schröder et al., 2003; Oliveira et al., 2013), there are only few studies that focus on technical operating parameters and scaling-up. Examples of operational parameters that have been studied are the effects of pH (Patil et al., 2011) or temperature (Patil et al., 2010) on current generation and of substrate loading on Coulombic efficiency (Sleutels et al., 2011). Furthermore, a plethora of studies devoted to the investigation and engineering of single components of BES exists in an ever increasing number, e.g., on electrode materials and architecture (Chen et al., 2011) or ion exchange membranes (Harnisch et al., 2008). However, the majority of the publically available experimental studies were performed on a lab-scale;

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with reactors of less than 1L-reactor volume and often using synthetic or well defined wastewater (Pant et al., 2010) for an overview. The process of scaling up BESs has been the subject of several studies and is one of the critical research areas for the success, especially, of BES in the field of wastewater treatment (Logan, 2010; Kim et al., 2012). As scaling up BES from the lab-scale via the technical to pilot and even larger scales is a truly multidisciplinary endeavor, and detailed information on all the relevant operating parameters is required, especially those allowing benchmarking BES to conventional technologies.

For this study a MEC was chosen, as these in comparison to MFCs (i) presently allow a more precise electrochemical control and (ii) are potentially an economically more promising solution (Foley et al., 2010). An underperforming reactor was purposefully used to begin with in order to gauge the effects of technical improvements such as dead space reduction or improving the flow regime on the performance of a technical scale MEC while also determining the effects of decreasing hydraulic retention times while increasing COD loading rates. Using the data gained from laboratory, literature, technical scale MEC and the local WWTP a comprehensive model for accessing the performance of BESs in comparison to one another and to aerobic treatment systems was developed.

2. Methods

This study incorporates results from experiments performed in small laboratory reactors and a technical scale reactor, which will be referred to in the following as the "prototype".

2.1. Chemicals

All chemicals were obtained from Sigma–Aldrich, Germany or Carl Roth, Germany and were of analytical grade. Nitrogen gas (99.99%) was obtained from Linde Gas, Germany.

2.2. Wastewater, inoculum and buffer solution

Primary effluent, effluent after primary settling tank (EAPS) and treatment plant effluent (TPE) wastewater were derived from the wastewater treatment plant (WWTP) "Steinhof" (KWS), Braunschweig, Germany. The wastewater used in the prototype was filtered with a 1.5 mm household sieve to remove particles which could cause clogging in the tubing or pumps.

The synthetic wastewater used in the prototype experiments was a standard growth medium according to Kim et al. (2005), supplemented with sodium acetate (10 mM or 20 mM) and a vitamin and trace metal solution prepared according to Balch et al. (1979). Primary effluent served as the inoculum at a volumetric ratio of 1:20 in the first cycle of each batch. Two biologically independent replicates with 4 closed-loop batch cycles were conducted whereby the prototype was completely cleaned and restarted between the sets. The formation of an electrochemically active biofilm was recognized by a significant increase of a current flow, see Fig. 1.

EAPS was used in laboratory batch experiments and prototype trials in closed-loop fed-batch experiments. The prototype reactor was not cleaned and the biofilm was the one grown on acetate during the synthetic wastewater experiments. In the first and third phase of the continuous mode trials the prototype was operated on EAPS. For the second phase of continuous mode operation EAPS was replaced by TPE spiked with sodium acetate solution to a concentration corresponding to 650–1250 mg O_2 L^{-1} equivalents of chemical oxygen demand (COD). The final COD concentration was measured after 30 min of mixing after spiking.

Wastewater in the storage tank was purged with nitrogen for at least 30 min after each refilling of the storage tank in order to remove oxygen and establish anaerobic conditions.

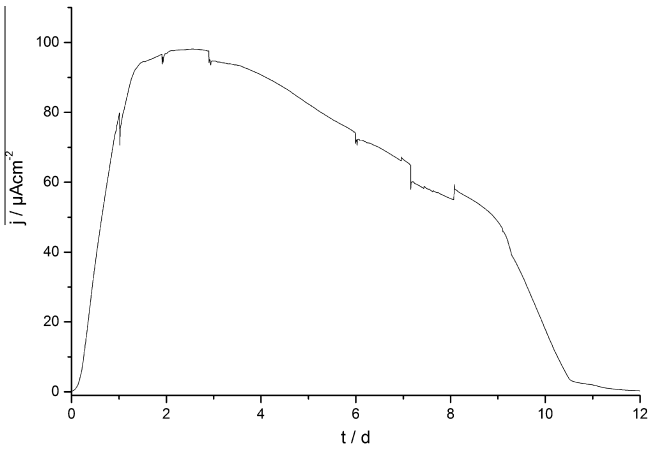

Fig. 1. Example of the development of the current density over time in growth cycle using synthetic wastewater supplemented with 10 mM acetate and operated at a temperature of 25 °C.

For batch operation a phosphate buffer solution (0.5 M NaH_2PO_4 and 0.5 M Na_2HPO_4, pH 7) was used as the catholyte solution. After switching to continuous mode operation carbonate buffer (0.5 M $NaHCO_3$ and 0.5 M Na_2CO_3, pH 10) was used.

2.3. Sample preparation and analysis

Collected wastewater samples that were not filtered are denoted by the index O for original fraction. To analysze the solute fraction, aliquots of the sample were filtered; this fraction is denoted by the index F, using glass fiber pre-filters (Sartorius, Germany) over 0.45 µm filters (cellulose nitrate, Sartorius, Germany). COD_O and COD_F, the concentration of sulfate, total phosphor (PO_4-P_O) and phosphate (PO_4-P_F) were determined using cuvette tests (LCK Series, Hach Lange, Germany) and a spectral photometer (Cadas 50, Hach Lange, Germany). Total Kjeldahl nitrogen (TKN as NH_4-N_O) and ammonium (NH_4-N_F) were measured using an ammonia selective electrode (NH_3-gas sensitive ion selective electrode, Metrohm, Germany). Here, for determination of TKN in the sample the nitrogen was converted to NH_4^+ in concentrated sulfuric acid with K_2SO_4 and $HgSO_4$ added as catalysts in excess for the test range of 5–50 mg N L^{-1} in this modified potentiometric method (based on ISO 5663: 1984).

The acetate consumption was monitored using a HPLC system (Spectrasystem P4000, Thermo Fischer Scientific, USA) equipped with refractive index detector (Finnigan Surveyor RI Plus, Thermo Fischer Scientific, USA) and "HyperREZ XP Carbohydrate" column (H+8 µm, S/N: 026/H/012-227, Thermo Fischer Scientific, USA) using 0.005 N sulfuric acid at 0.5 mL min^{-1} as the eluent. Before injection the samples were filtered using 0.2 µm filters (Phenex™-RC membrane filters, Phenomenex, USA).

Coulomb efficiencies in this study refer to the amount of charge which passed through the anodes versus the theoretical amount of charged which could be gained by the amount of consumed acetate or COD, in synthetic wastewater or real wastewater experiments, respectively.

2.4. Electrochemical operation

The electrochemical performance of the prototype was monitored using a potentiostat (SP-150, BioLogic, France), connected to a VMP3B amplifier (20 V/20 A), (BioLogic, France). For the laboratory wastewater screening a multi-channel potentiostat (MPG2,