Bioresource Technology 195 (2015) 89–95

Contents lists available at ScienceDirect

Bioresource Technology

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

Evaluation of an integrated continuous stirred microbial electrochemical reactor: Wastewater treatment, energy recovery and microbial community

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HIGHLIGHTS

- A novel integrated system CSMER was developed.
- COD removal of CSMER was 1.6 times higher than CSTR at OLR of 12 kg COD m^{-3} d^{-1}.
- Energy recovery efficiency was improved by 2.5 times in CSMER.
- CSMER exhibited a greater level of phylogenetic diversity compared with CSTR.

ARTICLE INFO

Article history:
Received 10 April 2015
Received in revised form 6 June 2015
Accepted 8 June 2015
Available online 12 June 2015

Keywords:
Continuous stirred microbial electrochemical reactor (CSMER)
Continuous stirred tank reactor (CSTR)
COD removal
Energy recovery
Community analysis

ABSTRACT

A continuous stirred microbial electrochemical reactor (CSMER) was developed by integrating anaerobic digestion (AD) and microbial electrochemical system (MES). The system was capable of treating high strength artificial wastewater and simultaneously recovering electric and methane energy. Maximum power density of 583 ± 9, 562 ± 7, 533 ± 10 and 572 ± 6 mW m^{-2} were obtained by each cell in a four-independent circuit mode operation at an OLR of 12 kg COD m^{-3} d^{-1}. COD removal and energy recovery efficiency were 87.1% and 32.1%, which were 1.6 and 2.5 times higher than that of a continuous stirred tank reactor (CSTR). Larger amount of *Deltaproteobacteria* (5.3%) and hydrogenotrophic methanogens (47%) can account for the better performance of CSMER, since syntrophic associations among them provided more degradation pathways compared to the CSTR. Results demonstrate the CSMER holds great promise for efficient wastewater treatment and energy recovery.

1. Introduction

Wastewater is increasingly being recognized as a resource rather than a waste, due to its substantial energy and resources potential, including the organic fraction, measured as chemical oxygen demand (COD). However, the energy contained in wastewater is currently not being used and the widely applied traditional aerobic activated sludge technology is still a net energy input process. So, technologies characterized by energy-efficient or energy-recovery have attracted more attention in recent years (Li et al., 2014).

Anaerobic digestion (AD) is an efficient process for extracting energy from organic matter in the form of biogas (methane and hydrogen). Both single-phase and two-phase AD processes hold distinct advantages in dealing with high-strength wastewater. However, requirements for thermophilic temperatures and suboptimal quality of the biogas hinder its application on wider scope (Pham et al., 2006). Moreover, low energy harvest efficiency is still one of the barriers of AD and makes the effluent COD cannot meet the discharge standards (McCarty et al., 2011).

Microbial electrochemical system (MES) is regarded as a promising technology for energy production from organic matter contained in wastewater (Rozendal et al., 2008). In the MES, electrochemically active microorganisms acclimated in the anode are capable of oxidizing organic matter and generating electrical current, the current can be captured for electricity generation or used for valuable chemicals production (such as hydrogen production) (Wang and Ren, 2013). Typical maximum power densities in MESs can reach to 17–19 W m^{-2} of projected cathode if the internal resistance is minimal enough (Logan and Rabaey, 2012). Other benefits of using MES in wastewater treatment are its good effluent

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http://dx.doi.org/10.1016/j.biortech.2015.06.039

quality and low biomass production, which might be caused by a cooperation of biological and electrochemical effects.

Based on the complementary synergy of AD and MES, combining AD with MES for wastewater treatment and energy recovery has attracted interests recently. However, some studies just connect two individual reactors in sequence without truly integrating them, consequently, increasing the operation complexity (Zhang et al., 2009). In addition, platinum-coated carbon cloth cathode was used in some MES-ABR integrated systems, which increased the capital cost (Feng et al., 2010a). Moreover, some MES-AFB integrated systems were constructed with carbon granules and porous polymer as carriers, which were not suitable for treating high-strength wastewaters (Huang et al., 2011; Kong et al., 2011). Toward practical application of MES for real wastewater treatment, maximizing biomass and reducing capital cost were of great importance. In view of the advantage of continuous stirred tank reactor (CSTR), such as high mass transfer efficiency, high rate of hydrolysis and acidification, sufficient amount of biomass because of three-phase separator (Cheng et al., 2012), integrating CSTR into MES is a solution for enhancing biomass. In addition, avoid using separator materials and expensive electrodes will reduce capital costs of MES to some extent.

An integrated system CSMER (continuous stirred microbial electrochemical reactor) was developed by combining CSTR and MES. The CSMER was mainly comprised of a complete mixing zone (CMZ) at the bottom and a microbial electrochemical zone (MEZ) on the top. The incoming organic matter was firstly expected to be hydrolyzed and fermented in the CMZ and its end-products would be consumed by the electrochemically active microorganisms in the MEZ. The performance of CSMER in terms of wastewater treatment and energy recovery was compared with that of a parallelized operating CSTR. Microbial diversity in the two systems were analyzed to determine if or to what extent operation as an integrated system had an impact on the community ecology.

2. Materials and methods

2.1. Configuration of CSMER

The CSMER was comprised of a cylindrical complete mixing zone (CMZ) (ID 175 mm × H 94 mm) at the bottom and a rectangular microbial electrochemical zone (MEZ) (H 125 mm × 175 mm × 175 mm) on the top, with the working volume of 4 L (Fig. 1). Continuous mixing was supplied by a micro-motor, which was installed on the top of the reactor and controlled by a transducer at a fixed speed of 200 r min^{-1}. A three-phase separator was used for solid–liquid–gas separation and gas collection. Twelve carbon fiber brushes (40 mm diameter, 100 mm length) pretreated as previously described (Feng et al., 2010b) were used as anode, which were fixed on the upper portion of the MEZ. Four rolling-pressed activated carbon cathodes (55 mm × 105 mm) (Dong et al., 2012), one on each face of the quadrangle, were used as cathode. The system was operated in four-independent circuit mode (each circuit was composed of a three-carbon fiber brush-anode and a piece of rolling-pressed activated carbon cathode) during start-up period. During stable operation period, it was switched to single-whole circuit mode (the twelve carbon fiber brushes were connected in series, and four rolling-pressed activated carbon cathodes were also in series connection) to investigate which operation mode was suitable for power generation. The distance between the anode and cathode was set as 2 cm. The anode and cathode of each cell was connected to an external resistance of 10 Ω during steady running period.

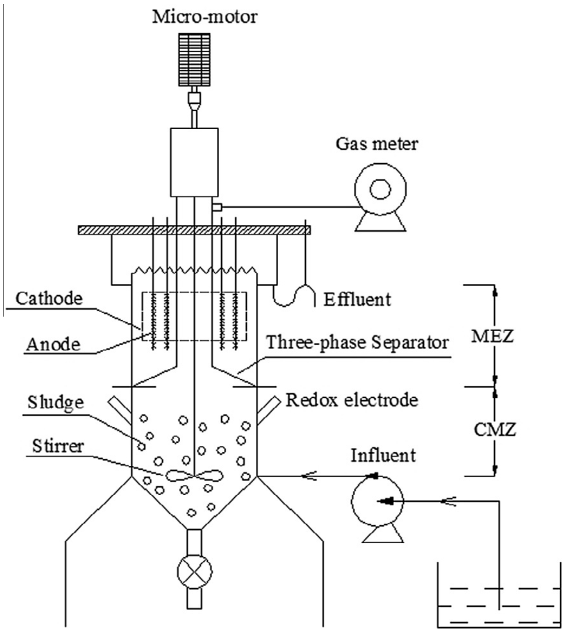

Fig. 1. Schematic diagram of the CSMER (CSMER: continuous stirred microbial electrochemical reactor, CMZ: complete mixing zone, MEZ: microbial electrochemical zone).

A continuous stirred tank reactor (CSTR) with the same configuration and working volume of CSMER was designed as control reactor, except that the microbial electrochemical zone was replaced by a closed chamber manufactured with rectangular plexiglas.

2.2. Inoculation and operation

Both CSMER and CSTR were inoculated with 1 L of anaerobic activated sludge collected from a continuous stirred-tank reactor in our Lab, which has been operated over one year for treating cellulosic ethanol wastewater. Synthetic wastewater containing 0.9 g L^{-1} sucrose as the carbon source and also consisted of (per liter of water): KCl, 0.13 g; NH_4Cl, 0.31 g; $NaH_2PO_4 \cdot 2H_2O$, 3.32 g; $Na_2HPO_4 \cdot 12\ H_2O$, 10.32 g; trace metals (1 mL) and vitamin mixture (1 mL) (Angelidaki and Sanders, 2004).

In the start-up period, the four independent cells were acclimated at external resistance of 500 Ω for 150 h firstly, and then the external resistance was consistently switched to 100 Ω and 10 Ω in the following 350 h. The operation period was divided into two stages by changing HRT and influent COD level with increased OLRs. Firstly, three lower OLRs of 1, 1.3 and 2 kg COD m^{-3} d^{-1} were tested by fixing the influent COD of 1 g L^{-1} with varied HRT of 24, 18 and 12 h by using a peristaltic pump at a flow rate of 2.8, 3.7 and 5.6 mL min^{-1}. Furthermore, three higher OLRs of 4, 8 and 12 kg COD m^{-3} d^{-1} were conducted by varying the influent COD of 2, 4 and 6 g L^{-1} at a constant HRT of 12 h. The systems were operated for 20 days at each experimental condition to ensure steady performance. After stable voltage and COD removal were achieved, analysis was conducted to investigate the performance of the CSMER and CSTR with respect to wastewater treatment and energy recovery, including COD removal, end-liquid fermentation products, power density, biogas, et al. The two systems were operated at an ambient temperature of 25 ± 2 °C.

2.3. Measurements and calculations

The output voltage (U) across the external resistance was recorded every 30 min by a data acquisition system PISO-813 (32 Channel ICP DAS Co., Ltd.). Polarization curves were obtained by