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Using a tubular photosynthetic microbial fuel cell to treat anaerobically digested effluent from kitchen waste: Mechanisms of organics and ammonium removal

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ABSTRACT

Anaerobically digested effluent from kitchen waste (ADE-KW) was used herein as the substrate of a tubular photosynthetic microbial fuel cell (PMFC) for power production, and also, after being diluted, as a medium for cultivation of algae in the cathodic chamber. Adding 3 mg/L phosphorus to the catholyte could efficiently enhance the algal growth and the PMFC performance. About 0.94 g/L algal biomass and 0.57 kWh/m^3-ADE-KW bioelectricity were obtained from the PMFC. Soluble microbial byproduct-like material and aromatic proteins were the dominant organics in the ADE-KW, which were readily degradable in the system. About 79% of the 1550 mg/L ammonium in the anolyte transferred to the catholyte through the cation exchange membrane. The ammonium was removed mainly as electron acceptors at the cathode after being oxidized by oxygen, whereas algal assimilation only account for about 14.6% of the overall nitrogen.

1. Introduction

Kitchen waste constitutes a large component (30–50%) of municipal solid wastes (Shin et al., 2015; Levis and Barlaz, 2011). Anaerobic digestion has been proved to be an effective technology to manage kitchen waste and also produce abundant energy resources like methane (Huang et al., 2015). Nonetheless, anaerobically digested effluent from kitchen waste (ADE-KW) is still of severe environmental concern for its high content of nutrients (Shin et al., 2015). Microbial fuel cells (MFCs) are bioelectrochemical systems that have been recommended to complement anaerobic digestion for ADE-KW treatment (Li et al., 2013a; Li et al., 2013b). However, some disadvantages limit the practical application of MFC, such as incapable of ammonium removal and energy-intensive (*e.g.* aeration).

A tubular photosynthetic microbial fuel cell (PMFC) system, using an algae-assisted cathode, is a promising technology that can not only convert chemical energy stored in organic matter to electric energy but also recover nutrients using microalgal technology. The oxygen produced by the photosynthesis of algae will save the additional energy that would otherwise be needed for aeration. Previous studies demonstrated that it is feasible to cultivate algae in wastewater, such as diluted ADE-KW, to produce biodiesel (Shin et al., 2015; Vasconcelos Fernandes et al., 2015; Pei et al., 2017). Thus, using diluted ADE-KW as algal culture medium, which also functions as the catholyte, can simultaneously achieve organics removal, nutrient removal and bioenergy production. Additionally, the tubular PMFC that a MFC was installed in a photosynthetic bioreactor (PBR) allows the algae to grow in the "U" shape sector so that the light is more accessible (Xiao et al., 2012; Ma et al., 2017). Furthermore, the large effective area of cation exchange membrane (CEM) can reduce the internal resistance of the PMFC markedly, which was beneficial for power generation (You et al., 2006).

ADE-KW was characterized with high nutrients (ammonium) and salinity (Pei et al., 2017). Thus, recovery of nitrogen from ammonium-rich ADE-KW was a goal of this study. It is notable that the ammonium could transfer from the anodic chamber to the cathodic chamber through the CEM, especially in the tubular PMFC, in which the CEM has a large specific surface area of about 23 m^2 CEM m^{-3} anolyte. The effect of current generation is a driving force for ammonium transportation from an anodic chamber to a cathodic chamber. Diffusion is another reason for ammonium transportation, especially in ammonium-rich anolyte (Haddadi et al., 2013). Thus, it is expected that vast amounts of ammonium would transfer into the catholyte which could function as the nutrient for algal growth. The ammonium in the

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catholyte can also be oxidized and then removed as electron acceptors on the cathode. To the best of our knowledge, the study was the first attempt to study the ammonium migration effect in an algae-assisted bioelectrochemical system.

It is estimated that the N/P (molar) ratio of ADE-KW was more than 100 which much higher than the ideal N/P ratio for algal growth (Chisti, 2007). Phosphorus (P) is the second most frequent macronutrient that limits algal growth after nitrogen (Solovchenko et al., 2016) Therefore, it is necessary to introduce additional phosphorus to the diluted ADE-KW to regulate the N/P ratio of the culture. In this study, anaerobically digested effluent from kitchen waste (ADE-KW) was used as the substrate for bioelectricity generation in the anodic chamber of a tubular PMFC. Diluted ADE-KW was used as the microalgal culture, and also functioned as the catholyte. The objectives of this study were to: (1) optimize the performance of PMFC by varying phosphorus concentration; (2) reveal the mechanisms of organics removal in the PMFC with a substrate of ADE-KW; (3) study the ammonium removal processes in an algae-assisted bioelectrochemical system.

2. Materials and methods

2.1. Experimental set-up

The tubular *Plexiglas* anode chamber of the PMFC had a working volume of 350 mL (height 200 mm, diameter 60 mm) and ten rectangular holes (height 160 mm, width 5 mm) on the anode chamber for cation exchange between anolyte and catholyte. The cathode chamber (working volume 1500 mL) consisted of a cylindrical section (height 200 mm, diameter 13 mm) joined to a conical section, and also functioned as an algal bioreactor (Fig. 1). A cation exchange membrane (CEM) was wrapped around the tubular anodic chamber to separate the anodic and cathodic chambers, and then a layer of carbon cloth was wrapped around the CEM to function as the cathode. The anode was a piece of carbon cloth (height 160 mm, width 40 mm) interwoven with titanium wires. Prior to use, the carbon cloth and CEM were pretreated to remove possible trace metal and microbial contamination (Ma et al., 2014). The CEM was pretreated by immersion in the 3% H_2SO_4 for 4 h at room temperature and then washed with deionized water. The carbon cloth was pretreated by immersion in the 1 M HCl and 1 M NaOH for 24 h, respectively. After that, they were washed with deionized water as previously described (Hou et al., 2016). The anode and cathode were connected by titanium wires with an external resistance of 200 Ω.

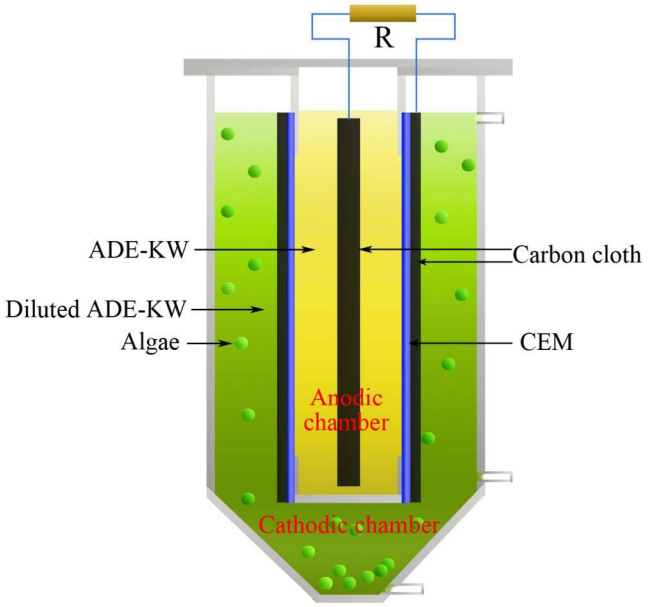

Fig. 1. Schematic of tubular photosynthetic microbial fuel cell (PMFC) for ADE-KW treatment.

The anode chambers were fed with ADE-KW (Shandong Shifang Environmental Protection and Bio-Energy Co.) that had been filtered through eight layers of gauze to remove insoluble solids before being used. The pore size of the gauze is 0.6 mm (diameter). The concentrations of pollutants in the ADE-KW were as follows: 4530 ± 108 mg/L COD, 1550 ± 20 mg/L NH_4^+-N, 15.0 ± 4.8 mg/L NO_3^--N, 2.5 ± 0.6 mg/L NO_2^--N and 26.7 ± 3.2 mg/L TP. The green algae *Golenkinia* sp. SDEC-16 (Accession No.: KT180320) was cultivated in the cathodic chambers with diluted ADE-KW. Before the experiment, the ADE-KW was firstly centrifuged (5000*g*, 10 min) to reduce the dark colour of ADE-KW, and a concentration of 4% (v/v) ADE-KW diluted with deionized water was specified as the medium for algae.

In order to enhance the algal growth, extra P was added into the catholyte. The P levels were boosted by 1, 3, 6 and 9 mg/L through addition of K_2HPO_4 to the catholyte of the relevant systems. The diluted ADE-KW (with a P concentration of about 0.7 mg/L) without extra P addition was set as the control system. Before the experiment, 0.1 M KCl and 0.1 M HCl were used to maintain similar pH and conductivity levels of the catholytes in different systems. The initial values of the pH of anolyte and catholyte were about 8.1 and 7.8, respectively. The initial values of conductivity of the anolyte and catholyte were about 0.56 mS/cm and 1.25 mS/cm, respectively. An initial algal biomass concentration of 0.15 ± 0.1 g/L was inoculated into the cathodic chambers. The anodic chamber was inoculated with 20 mL anaerobic sludge collected from a municipal wastewater treatment plant in Jinan, China. A continuous illumination of 100 μmol m^{-2} s^{-1} was provided by a row of fluorescents lamps during the experiment. Room temperature was control at 25 ± 1 °C. Continuous mixing (300 rpm) was provided in the cathodic chamber using a magnetic stirrer.

2.2. Analytical methods

2.2.1. Bioenergy analysis

The voltage across the external resistance was recorded with a data acquisition system (Keithley Instruments 2700, USA). The volumetric power density (W/m^3) normalized to the anolyte volume was calculated by dividing the power (W) by working volume of the anodic chamber (m^3). The Coulombic efficiency (CE) was calculated from the equation:

$$CE = \frac{8\int_0^t Idt}{FV_A\Delta COD}$$

where V_A is the effective anode volume, I is the current, ΔCOD is the change of COD over time t, and F is the Faraday constant (96,485 C/mol). The lipid contents of the algae were measured using a chloroform/methanol mixture (2:1, v/v) (Pei et al., 2017). Energy embedded in lipids was estimated based on a conversion efficiency of 30% from lipid (energy of lipid is about 37,800 J/g) to electricity excluding the energy produced from biomass (Xiao et al., 2012). The total energy (kWh) produced in the form of electricity and lipid was normalized to the volume of consumed ADE-KW (m^3).

2.2.2. Ion transfer

When current is generated, ion transfer to satisfy charge neutrality would cause cations to migrate from the anodic chamber to the cathodic chamber through the CEM. Hence, the total ion transfer driven by current generation can be expressed by the following equation (Haddadi et al., 2013):

$$\frac{dQ}{F} = \sum_i^n Z_i M_i$$

in which, Q is cumulative coulombs (C), F is the Faraday constant