Bioresource Technology 169 (2014) 581–587

Contents lists available at ScienceDirect

Bioresource Technology

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

Power generation and oil sands process-affected water treatment in microbial fuel cells

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HIGHLIGHTS

- Voltage generation and OSPW treatment were examined in a single chamber air–cathode MFC.
- AS-MFC produced higher voltage than MFT-MFC.
- The addition of a carbon source (acetate) improved voltage generation.
- Mesophilic temperature improved the OSPW treatment efficiency and the voltage generation.
- The AS-MFC contained a higher microbial community diversity than the MFT-MFC.

ARTICLE INFO

Article history:
Received 8 May 2014
Received in revised form 30 June 2014
Accepted 4 July 2014
Available online 11 July 2014

Keywords:
Microbial fuel cell
Oil sands process-affected water
Mature fine tailings
Electricity
Pyrosequencing

ABSTRACT

Oil sands process-affected water (OSPW), a product of bitumen isolation in the oil sands industry, is a source of pollution if not properly treated. In present study, OSPW treatment and voltage generation were examined in a single chamber air–cathode microbial fuel cell (MFC) under the effect of inoculated carbon source and temperature. OSPW treatment with an anaerobic sludge-inoculated MFC (AS-MFC) generated 0.55 ± 0.025 V, whereas an MFC inoculated with mature-fine tailings (MFT-MFC) generated 0.41 ± 0.01 V. An additional carbon source (acetate) significantly improved generated voltage. The voltage detected increased to 20–23% in MFCs when the condition was switched from ambient to mesophilic. The mesophilic condition increased OSPW treatment efficiency in terms of lowering the chemical oxygen demand and acid-extractable organics. Pyrosequencing analysis of microbial consortia revealed that *Proteobacteria* were the most abundant in MFCs and microbial communities in the AS-MFC were more diverse than those in the MFT-MFC.

1. Introduction

The oil sands industry in northern Alberta, Canada, has been developed rapidly during the last few decades. In the oil sands field, the mined bitumen is separated from sands and clays using water-based extraction, for which approximately 2–2.5 cubic meters of fresh water is required to produce one cubic meter of crude oil (Kim et al., 2011). The water used in bitumen extraction collects clay and particulates and is discarded in large tailings ponds. The clay and large particulates settle and the clarified water at the top is reused for bitumen extraction to reduce freshwater withdrawal. When the recycled water has accumulated a high quantity of dissolved inorganic (e.g., sulfates, chlorates) and organic (e.g., naphthenic acids, polycyclic aromatic hydrocarbons) compounds, it is discarded in tailings ponds and referred to as oil sands process-affected water (OSPW). Remediation of OSPW through physicochemical and biological means (Hwang et al., 2013; Islam et al., 2014) is an active research topic.

As bacteria oxidize organic matter and directly convert chemical energy into electrical energy, microbial fuel cells (MFCs) have been suggested as promising devices for wastewater treatment. MFCs have reportedly treated domestic wastewater (Choi and Ahn, 2013), animal wastewater (Zhao et al., 2012), and activated sludge (Ge et al., 2013). Moreover, the simultaneous removal of organic matter and recalcitrant compounds and the generation of electricity has been reported. For example, biological Cr (VI) reduction at the biocathode by putative Cr (VI) reducing microorganisms in MFCs was demonstrated when acetate was provided to the anode compartment (Tandukar et al., 2009). Reductive dechlorination and mineralization of pentachlorophenol were reported in a two-chamber biocathode MFC with voltage generation (Huang

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http://dx.doi.org/10.1016/j.biortech.2014.07.029
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et al., 2012). Jiang et al. (2013) demonstrated the feasibility of MFCs to simultaneously generate electricity and treat oil sands tailings, producing a maximum electrical potential of 0.726 V and a maximum power density of 392 mW/m^2 in dual chamber MFCs.

The extension of the Athabasca oil sands industry requires new means to reduce its operating cost and to improve OSPW treatment. The use of MFCs would contribute a new method of OSPW treatment with an energy generation bonus. Mature fine tailings (MFT) deposited oil sands tailings reservoirs can be a good source of indigenous microorganisms, including *Proteobacteria*, *Firmicutes*, *Bacteroidetes*, and *Chloroflexi* (Penner and Foght, 2010), that could act as seed biomass. Voltage generation in a dual-chamber MFC inoculated with MFT has been demonstrated (Jiang et al., 2013), but as yet there has been no study of OSPW treatment with an MFC inoculated with anaerobic sludge. A carbon source that supplements the MFC inoculant is a crucial factor in increasing the level of electricity generation. Acetate has been widely used rather than complex organics because its simple structure resists hydrolysis. Temperature is another important operating parameter in biological wastewater treatment, as well as in MFC performance. A mesophilic condition yielded higher (12%) voltage generation than an ambient condition when treating domestic wastewater (Ahn and Logan, 2010).

This study investigated the effects of various environmental parameters that can influence the performance of MFCs in OSPW pollutant removal (hereafter referred to as “treatment”). Sludge and MFT inoculants were tested and their potentials to assist MFC treatment of OSPW were compared. The addition of carbon source and different temperatures were tested for their effects on voltage generation and pollutant removal efficiency. Microbial communities in the MFC were analyzed using high throughput pyrosequencing.

2. Methods

2.1. Source of inoculated biomass and OSPW

Anaerobic sludge and mature fine tailings (MFT) were used as inoculants in separate MFCs. Anaerobic sludge was collected from the Gold Bar wastewater treatment plant in Edmonton, Alberta. MFT samples were collected from Syncrude’s Mildred Lake tailings pond. Samples of OSPW were collected into 200 L polyvinyl chloride containers from the West In-pit water pumping station at the Syncrude Canada Ltd. site in Fort McMurray, Alberta, and were stored in a cold room (4 ± 0.1 °C) prior to use. Table 1 shows the characteristics of OSPW: chemical oxygen demand (COD), 208.0 ± 0.5 mg/L; pH, 8.43 ± 0.05; sulfate, 350 ± 15 mg/L; ammonia, 3.1 ± 0.2 mg NH_3-N/L; nitrate, 11.0 ± 0.3 mg/L NO_3-N; phosphorus, 0.5 ± 0.05 mg PO_4-P mg/L; total organic carbon, 82 ± 3 mg/L; acid extractable organics (AEO), 56.0 ± 4.6 mg/L.

Table 1
Characteristics of OSPW.

Parameter	Average value
pH	8.43 ± 0.05
Chemical oxygen demand (mg/L)	208.0 ± 0.5
Turbidity (NTU)	89.0 ± 1.6
Conductivity (mS/cm)	4.22 ± 0.03
Sulfate (mg/L)	350 ± 15
Ammonia nitrogen (mg/L)	3.1 ± 0.2
Nitrate nitrogen (mg/L)	11.0 ± 0.3
Phosphorus (mg/L)	0.5 ± 0.05
Total organic carbon (mg/L)	82 ± 3
Acid extractable organics (AEO) (mg/L)	56.0 ± 4.6

2.2. MFC construction and operation

Single chamber air–cathode MFCs were constructed with 4 cm length and 28 mL liquid volume. The anode was made of brush electrode pretreated by immersion in acetone overnight and heated at 450 °C for 30 min as previously described (Wang et al., 2009). The air–cathode was a 30% wet-proof carbon cloth containing 0.5 mg/cm^2 of Pt catalyst. The MFCs were inoculated with anaerobic sludge or MFT (10% v/v). First, two anaerobic sludge-inoculated MFCs (hereafter called AS-MFCs) and two MFT-inoculated MFCs (hereafter called MFT-MFCs) were used to test the effect of seed biomass on MFC purified OSPW amended with acetate (400 mg/L). Second, OSPW without acetate was added into duplicate reactors (AS-MFC only) to investigate the effect of an external carbon source on the generated voltage. Third, duplicate AS-MFCs and MFT-MFCs treating only OSPW were tested for their ability to generate an electrical potential under ambient (18 ± 0.5 °C) and mesophilic conditions (36 ± 0.1 °C) in a temperature-controlled room.

2.3. Electrical potential

The MFC voltage was recorded every 20 min by a digital multimeter (2700, Keithley Instruments, Inc., Cleveland, OH, USA). Substrates (OSPW amended with acetate or OSPW alone) were replaced when the voltage reached almost zero. After the reactors were stabilized (two weeks after the start of reactor operation), different external resistances (1000–10 Ω) were used to obtain the polarization curve that characterizes the cell voltage as a function of current density. Current (I) was calculated by $I = V/R_{ex}$, where V is voltage and R_{ex} is external resistance. Power was calculated by $P = V \cdot I$. Power density and current density were determined by the normalized cathode surface area. The projected surface area of cathode is 7 cm^2 (Choi and Ahn, 2013).

2.4. COD and AEO analysis

Chemical oxygen demand (COD) was measured by a colorimetric method according to the manufacturer’s instructions (HACH DR-3900, HACH, Loveland, CO). A dual channel bench meter (SympHony, B40PCID, VWR) was used to measure pH and conductivity.

Total acid-extractable organics (AEO) were extracted from acidified samples (50 mL, pH 2.0) into dichloromethane (DCM) using a separation funnel. After separation, AEO were stored in a container. The AEO were reconstituted with a known volume of DCM and subjected to Fourier transform infrared spectroscopy (FT-IR) (Clemente and Fedorak, 2005; Hwang et al., 2013; Pourrezaei et al., 2011). Carboxylic acid absorbance was measured at wave lengths of 1743 and 1706 cm^{-1} and AEO concentrations were determined using a calibration curve.

2.5. High throughput pyrosequencing

2.5.1. DNA extraction

Samples were collected from the MFCs after two months of operation. Before DNA extraction, the samples were centrifuged at 7000×g to concentrate biomass and a 0.25 g pellet was used for DNA extraction. Genomic DNA was extracted using a Soil DNA isolation Kit (MoBioLaboratories, Inc., CA) according to the manufacturer’s protocol. Extracted DNA was quantified and qualified by measuring the absorbance at 260 and 280 nm (Nanodrop 2000, Thermo Scientific).

2.5.2. 454 High-throughput 16S rRNA gene pyrosequencing

All DNA samples were diluted to 100 ng/μL. A 100 ng aliquot of each DNA sample was used for a 10 μL step PCR reaction. Amplicon