Bioresource Technology 155 (2014) 84–90

Contents lists available at ScienceDirect

Bioresource Technology

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

Effect of presence of cellulose in the freshwater sediment on the performance of sediment microbial fuel cell

T.K. Sajana [a], M.M. Ghangrekar [b,*], A. Mitra [a]

[a] Department of Agricultural and Food Engineering, Indian Institute of Technology, Kharagpur 721 302, India
[b] Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721 302, India

HIGHLIGHTS

- In situ remediation of aquaculture pond sediment and water was tried using SMFC.
- Effective reduction of COD and nitrogen from water occurred in presence of SMFC.
- Up to 2% addition of cellulose the performance of SMFC improved.
- At higher cellulose concentration, performance of SMFC decreased.
- This decrease in performance is attributed to the higher acetic acid accumulation.

ARTICLE INFO

Article history:
Received 13 October 2013
Received in revised form 16 December 2013
Accepted 21 December 2013
Available online 30 December 2013

Keywords:
Aquaculture water remediation
Cellulose degradation
Freshwater sediment
Sediment microbial fuel cell

ABSTRACT

The performance of sediment microbial fuel cells (SMFCs) was evaluated in the presence of cellulose in the aquaculture pond sediment as 2% (w/w) in SMFC-2, 4% in SMFC-3 and without adding cellulose in SMFC-1. From aquaculture water, average chemical oxygen demand (COD) and total nitrogen (TN) removal efficiencies of 80.6 ± 0.3% and 83.0 ± 0.01% were obtained in SMFC-1, 88.2 ± 0.5% and 89.6 ± 0.8% in SMFC-2 and 83.1 ± 0.3% and 64.5 ± 1.6% in SMFC-3, respectively. During the complete experimental period, acetic acid was the only short chain fatty acid detected in all three SMFCs. Sediment organic matter removal in SMFC-1, SMFC-2 and SMFC-3 were 16%, 22% and 18.6%, respectively. SMFCs demonstrated effective cellulose degradation from aquaculture pond sediment and maintained the oxidized sediment top layer favourable for aquaculture.

1. Introduction

Aquaculture is the farming of aquatic organisms including fish, crustaceans, molluscs and aquatic plants (macrophytes/microphytes). The combination of raising fish, crustaceans, molluscs including pearl oysters and giant clams with cultivation of aquatic plants are getting more importance now a day. The aquatic plants are used as the food for these organisms. Aquatic plants include macrophytes and microphytes (phytoplankton or micro algae). Aquatic plants density varies from pond to pond. The dead aquatic plants are getting deposited at the pond bottom. In addition, tree leaves are falling in the practicing aquaculture ponds and decomposed matter is being settled in the bottom sediments. The dead aquatic plants and leaves, aquatic weeds, higher plants containing cellulose contribute to the organic matter in the pond bottom sediment.

Cellulose ($(C_6H_{10}O_5)_n$) is the structural component of the primary cell wall of green plants and many forms of algae and it is a linear homopolymer, consisting of glucose units joined by β-1, 4 glucosidic bonds. The saccharification of cellulose is a complex and poorly understood process done by cellulase enzyme which have three components mainly exo glucanases, endo glucanases, and cellobiase (Singh and Jain, 1985; Leschine, 1995). Acetate, propionate and butyrate are the common end products from cellulose degradation (Singh and Jain, 1985; Rezaei et al., 2008; Ren et al., 2009). The end product from cellulose is used as the substrate for the production of different energy carrier such as ethanol (Ingram and Doran, 1995) and used at the anode of microbial fuel cell (MFC) for converting it to electricity (Rismani-Yazdi et al., 2007; Rezaei et al., 2009; Hassan et al., 2012).

Sediment microbial fuel cells (SMFCs) or benthic microbial fuel cells (BMFCs) produce electricity by placing an anode into organic rich sediment and a cathode in overlying water. Electrogenic bacteria degrade organic compounds present in the sediment and wastewater, generating electrons and protons. Electrons reduce the anode and are transferred to the cathode through an external

* Corresponding author. Tel.: +91 3222 283440; fax: +91 3222 282254.
E-mail address: ghangrekar@civil.iitkgp.ernet.in (M.M. Ghangrekar).

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http://dx.doi.org/10.1016/j.biortech.2013.12.094

circuit. Protons move from sediment to the cathode side and combine with oxygen and electrons on cathode to produce water. SMFC can perform *in situ* bioremediation of organic rich sediment and wastewater, and it could offer very good option for *in situ* remediation of water quality in aquaculture ponds (Sajana et al., 2013). Reimers et al. (2001) successfully demonstrated first SMFC by employing platinum mesh electrodes to produce current from both salt marsh and estuarine sediments.

Substrates used in the microbial fuel cell (MFC) are important because they serve as carbon and energy source for the bacterial community in the anode biofilm, and also influences MFC performance like power density (PD) and Coulombic efficiency (CE) (Chae et al., 2009). Simple substrates like acetate (Bond et al., 2002), glucose (Chae et al., 2009) and complex substrates such as paper recycling wastewater (Huang and Logan, 2008); food processing wastewater (Oh and Logan, 2005), cellulose (Ren et al., 2007; Rezaei et al., 2009; Rismani-Yazdi et al., 2011; Hassan et al., 2012) are used as substrates in MFC.

Niessen et al. (2005) did the first study that used cellulose as a substrate in MFC. Rismani-Yazdi et al. (2007) found that when anode chamber of MFC was inoculated with rumen microorganisms and cellulose as substrates, simultaneous hydrolysis of cellulose occurred to produce a maximum power density of 55 mW m^{-2}. Ishii et al. (2007) inoculated the anode chamber of MFC with the rice paddy field soil and supplemented with cellulose as well as *Geobacter sulfurreducens*, to produce a maximum current of 0.31 mA and power density of 10 mW m^{-2}. When Chitin 20, Chitin 80 and cellulose powder was added in the sediment the maximum power densities of 76 ± 25 mW m^{-2}, 84 ± 10 mW m^{-2} and 83 ± 3 mW m^{-2}, respectively, were observed (Rezaei et al., 2007). When the anodic chamber of MFCs were filled with cellulose and *Enterobacter cloacae* ATCC 13047 T and *E. cloacae* FR, maximum power density of 1.6 ± 0.01 mW m^{-2} was produced from *E. cloacae* ATCC 13047 T and 1.8 ± 0.02 mW m^{-2} from *E. cloacae* FR. Further, the power density increased to 5.5 ± 0.03 mW m^{-2}, when the mixed culture of these two bacteria was used (Rezaei et al., 2009). Rismani-Yazdi et al. (2011) studied the effect of various external resistances on power output and CE of cellulose fed MFCs. A maximum power density of 66 mW m^{-2} was achieved by MFCs with 20 Ω external resistance, while MFCs with 249, 480 and 1000 Ω external resistances produced power density of 57.5, 53 and 47 mW m^{-2}, respectively. Hassan et al. (2012) reported that for cellulose-fed MFC inoculated with the mixed culture of cellulose-degrading bacteria and cellulose as the substrate, a stable power density of 190.2 mW m^{-2} was observed.

In aquaculture ponds, the dead aquatic plants and decomposed tree leaves are getting deposited at the pond bottom. They contain cellulose and contribute to the organic matter in the pond bottom sediment. Accumulation of higher concentration of organic matter in the sediment leads to loss in the oxidized layer. This layer prevents diffusion of most toxic metabolites from sediment to the pond water (Boyd et al., 2002). Hence, this study was aimed at investigating the effect of cellulose content in the aquaculture pond bottom sediment on performance of SMFC employed for *in situ* remediation of aquaculture water, for maintaining the desired water quality to support higher fish yield. Performance of SMFC was evaluated in terms of wastewater treatment efficiency and power output.

2. Methods

2.1. Sediment sampling

Sediment samples were collected from a depth of 0–10 cm below the sediment surface from the existing 15-year-old operating freshwater aquaculture pond of IIT Kharagpur, exposed to natural climatic conditions and having a dimension of $14 \times 10 \times 1.5$ m. Stocking density of 7 fish/m^2 was cultured in the pond. Fishes reared in this pond were Silver Carp, *Rohu*, *Catla* and *Mrigal* in the ratio of 1:2:2:2.

2.2. SMFC construction and operation

Three experimental SMFCs were constructed from a PVC cylinder having internal diameter of 13 cm. Three graphite plates were used as anode and cathode having a total projected surface area of 1418 cm^2 for each anode and cathode. Anode was placed in the sediment zone. Cellulose was added at the rate of 2% (w/w) in SMFC-2 and 4% in SMFC-3 in the collected sediment to evaluate the effect of presence of cellulose in the sediment on performance of SMFC. Cellulose was mixed with sediments and filled in the experimental column up to a height of 50 cm from bottom. Cellulose was not added in SMFC-1. SMFC-1, SMFC-2 and SMFC-3 were operated at feed pH of 8.5 and the shortest distance between electrodes was maintained at 90 cm. The anode and cathode were short-circuited (0 Ω external resistance). After addition of the sediment, the remaining volume was filled with used water collected from the practicing aquaculture pond up to a total height (including sediment zone) of 1.66 m for all these three SMFCs. Three ports were provided to the cylinder at a distance of 25 cm center to center between them from top for collection of water samples along the depth. The cathode was placed 6 cm below the top water level in these SMFCs. Aeration was provided near to the cathode through commercially available aquarium aerator (Zhongshan RISHENG Electrical Product Co. Ltd) at a depth of 25 cm from the top liquid level in all these SMFCs.

Experiments were performed in a batch mode. Performance of these SMFCs was monitored for 45 days covering nine feed cycles. Fresh feeding was given at interval of 5 days after achieving the water quality suitable for aquaculture. The chemical oxygen demand (COD, 170–185 mg L^{-1}) and ammonium nitrogen concentration (4–6 mg L^{-1}) were maintained by adding 158–167 mg L^{-1} sucrose and 13–18 mg L^{-1} NH_4Cl during feeding these SMFCs. Feed water pH of 8.5 was maintained by using 10 mM phosphate buffer. The performance of these SMFCs was evaluated at ambient temperature ranging from 28 to 31 °C.

The Total Kjeldahl Nitrogen (TKN) concentration in the feed aquaculture used water was in the range of 7–9 mg L^{-1}. The dissolved oxygen (DO) concentration in the aquaculture water was in the range of 5.5–6.0 mg L^{-1}. The conductivity of the feed water was 1.75–1.8 mS cm^{-1} after correcting the pH to 8.5.

2.3. Analyses and calculation

Analysis of the parameters such as DO, COD, TKN, inorganic nitrogen (ammonium nitrogen, nitrite nitrogen and nitrate nitrogen) was performed regularly according to APHA et al. (1998). The percent weight of organic matter in sediments was determined by the loss on ignition (LOI) method, which is based on sequential heating of the samples in a muffle furnace (Song et al., 2011).

The voltage and current were measured using a digital multimeter (RISH Multi 15S, India) and converted to power according to Ohm's law, $P = IV$, where, P = power (W), I = current (A), and V = voltage (V). Power density (mW m^{-2}) and current density (mA m^{-2}) were calculated by dividing the power and current by the projected anode surface area (m^2). Polarization studies were carried out by varying the external resistance from 30 KΩ to 100 Ω after allowing the circuit to stabilize for 5–10 min at each resistance. Internal resistance of the MFC was measured from the slope of the line from the plot of voltage versus current density (Sajana et al., 2013).