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Palm oil mill effluent treatment using a two-stage microbial fuel cells system integrated with immobilized biological aerated filters

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ABSTRACT

An integrated system of two-stage microbial fuel cells (MFCs) and immobilized biological aerated filters (I-BAFs) was used to treat palm oil mill effluent (POME) at laboratory scale. By replacing the conventional two-stage up-flow anaerobic sludge blanket (UASB) with a newly proposed upflow membrane-less microbial fuel cell (UML-MFC) in the integrated system, significant improvements on NH_3–N removal were observed and direct electricity generation implemented in both MFC1 and MFC2. Moreover, the coupled iron–carbon micro-electrolysis in the cathode of MFC2 further enhanced treatment efficiency of organic compounds. The I-BAFs played a major role in further removal of NH_3–N and COD. For influent COD and NH_3–N of 10,000 and 125 mg/L, respectively, the final effluents COD and NH_3–N were below 350 and 8 mg/L, with removal rates higher than 96.5% and 93.6%. The GC–MS analysis indicated that most of the contaminants were satisfactorily biodegraded by the integrated system.

1. Introduction

Palm oil mill effluent (POME) is generated from the production of palm oil, one of the most prevalent high-yield crop products of tropical countries. During the production of 1 tonne crude palm oil, more than 2.5 tonnes of POME is produced (Ahmad et al., 2003). Typically, the average chemical oxygen demand (COD) and biochemical oxygen demand (BOD) in the POME are about 50,000 and 25,000 mg/L, respectively (Borja et al., 1996). Since POME contains high concentrations of oil and grease, organic matter, suspended solids (SS) and plant nutrients, it can cause considerable environmental problems if discharged without effective treatment. Nowadays, palm oil mills face a huge challenge in meeting increasingly stringent environmental standards.

Over the past decades, several economically viable technological solutions have been utilized for the treatment of POME, including simple skimming devices, land disposal, chemical coagulation and flotation, ultrafiltration, aerobic and anaerobic biological processes and other specialized treatments (Borja et al., 1996). Of these, anaerobic biological processes are most widely used because of their particular advantages, such as energy efficiency, low biomass yield, low nutrient requirement, and high volumetric organic loading. High-rate anaerobic reactors such as the up-flow anaerobic sludge blanket (UASB) presently play an important role in wastewater treatment. The distinct characteristic of these reactors is the existence of granular sludge, which can enhance treatment efficiency. For example, Borja et al. (Borja and Banks, 1994; Borja et al., 1996) obtained satisfactory results using UASB reactors to treat POME. Furthermore, during the anaerobic treatment of POME, methane (Yacob et al., 2005, 2006) and hydrogen (O-Tonga et al., 2007) are generated, which can reduce the demand on energy resources. However, application of anaerobic biological processes is presently limited by their relatively low efficiency regarding biogas collection, purification and utilization. In addition, due to the higher cost, most of the palm oil mills have not equipped the methane recovery and utilization system yet. Usually, the biogas is directly discharged to the atmosphere, thus exacerbating the greenhouse effect.

Bioelectricity is another alternative energy carrier that could be obtained from wastewater in addition to methane and hydrogen (Angenent et al., 2004; He et al., 2005). The microbial fuel cell (MFC) is a device that converts chemical energy stored in the chemical bonds in organic matter to electricity using microorganisms as a catalyst under anaerobic conditions (Back et al., 2004; Du et al., 2007; Li et al., 2008). The organic matter is oxidized by microorganisms, and the resulting electrons transferred to the electrode. The most commonly used MFCs are constructed as a single-chamber or an "H" shape two-chamber. However, such MFCs are difficult to scale-up and to operate in a continuous flow mode. As the anode and the cathode compartments are similar to anaerobic and aerobic reactors, the design of MFCs that integrate these aspects in an upflow reactor could lead to substantial benefits in both electricity generation and removal of organic pollutants.

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MFCs can achieve synchronous pollutant removal and electricity generation, in the context of wastewater treatment. Various wastewaters, such as domestic (Ghangrekar and Shinde, 2007; Min and Logan, 2004; Rabaey et al., 2005), food processing (Oh and Logan, 2005), agricultural (Angenent et al., 2004), hospital (Rabaey et al., 2005), animal (Kim et al., 2008; Min et al., 2005), and brewery (Feng et al., 2008; Jong et al., 2006) wastewaters, have already been used as substrates for MFCs. However, the removal efficiencies of MFCs were limited and an integrated system implementing other technologies was necessary for efficient wastewater treatment.

The immobilized biological aerated filter (I-BAF) is a type of biological reactor usually follows up the UASB system for further degradation of organic pollutants and nutrients. Among other advantages, the I-BAF is well noted for its outstanding characteristics such as high hydraulic loading rates, high processing efficiency, high biomass loadings, and low surplus sludge (Lai et al., 2008).

In this study, an integrated system of two-stage MFCs and I-BAFs was designed for palm oil mill effluent (POME) treatment. A real coupled system of MFC and UASB reactors was established with an upflow membrane-less microbial fuel cell (UML-MFC), which was essentially different from the system of MFC simply connected with the conventional UASB as reported in previous publications (Zhang et al., 2009). The whole system could be optimized by the integrated functions, i.e. MFCs for removal of partial ammonia and major body of organic pollutants companying with simultaneous electricity generation, iron–carbon micro-electrolysis for enhancement of organic removal efficiency and biodegradability, and I-BAFs for removal of major part of ammonia and the surplus organics.

2. Methods

2.1. Experimental equipment and techniques

The UML-MFCs coupled with MFC and UASB reactors (Fig. 1) were fabricated as 9 cm internal diameter and 36.5 cm effective height polymethyl methacrylate cylinders (5 mm wall thickness) with a total volume of 2.36 L. The anode compartment of MFC1 was filled with 3–5 mm diameter graphite granules as the anode, and a 5 mm diameter graphite rod as the current collector, while MFC2 used carbon fiber felt as the anode and a copper wire as the current collector. Prior to use, the graphite granules and carbon fiber felt were washed several times with water to remove impurities. In the present study, lead dioxide was used as an alternative cathode catalyst to platinum due to its superior performance (Morris et al., 2007) and lower cost ($0.5/cm^2 in present study). The PbO_2 electrode (3 cm × 5 cm) was fabricated following Kong et al. (2007). A copper wire that served as the current collector was pressed on the PbO_2 electrode and sealed with electrical tape and nonconductive epoxy. Then, the anode and cathode electrodes were connected via copper wires to form a circuit with an external resistor. The aeration rates of the cathode compartments were controlled by aquarium air pumps. A 20 cm spacing was set between the anode and cathode compartment to minimize the effect of oxygen diffusion and retain the advantages of UASB reactors in wastewater treatment as much as possible. The I-BAFs were filled with Functional Polyurethane Foams (FPUFS) developed at Peking University (Zhao et al., 2006).

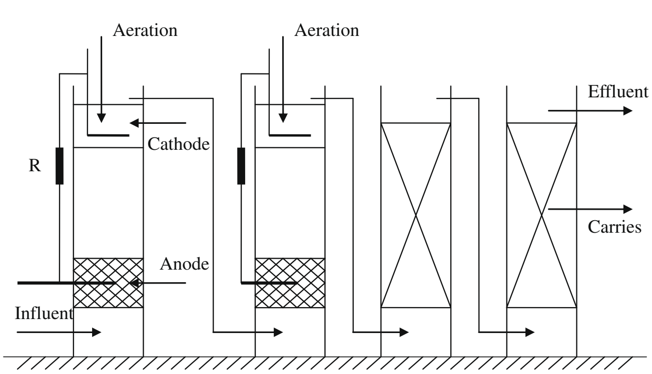

Fig. 1. Schematic diagram of experimental apparatus for MFC and I-BAF stages.

Two conventional UASB reactors were constructed from polymethyl methacrylate cylinders, each with a gas–biomass–liquid separator at the top. All interfaces were airproofed. Unlike the UML-MFCs, in order to provide a higher upflow speed in the reactors and improve the formation process of granular sludge, the height per diameter ratio of UASB reactors was set within the range of 5–10. Furthermore, the hydraulic retention time (HRT) was stringently controlled for both the acidogenic and methanogenic stages in order to provide the best growth environment for the acidogens and methanogens.

2.2. Wastewater and inoculation

Wastewater used in this study was supplied by a palm oil mill in Malaysia. Raw POME was diluted by tap water before feeding into the reactors, and the pH of the initial feed was adjusted to about 6.0 using sodium bicarbonate. The dilution rate of raw POME for the main text was about six.

Anaerobic digestion and activated sludge taken from Gaopeidian sewage treatment plant (China) were used as inoculation in the integrated system. The anodes of UML-MFCs were inoculated with both anaerobic digestion and activated sludge (2:1) to enrich microorganism species, whereas the I-BAFs were inoculated solely with activated sludge. To enhance the treatment efficiency, both UASB reactors were inoculated with anaerobic sludge taken from a starch factory, which had already been partially granulated (i.e. black globular and ellipsoidal granules were visible to the naked eye). The MFCs, I-BAFs and UASBs were all inoculated with samples from different sources in order to achieve their optimal performance due to the pre-experiment.

2.3. Operating conditions

The MFC stage and UASB system were both operated in a continuous flow mode with a total hydraulic retention time (HRT) of 48 h. During the start-up period, the influent chemical oxygen demand (COD) was increased gradually to about 8000 mg/L. Then, the influent COD was controlled at about 8000–10,500 mg/L for the main test. Metered pumps (Iwaki Pumps Co. Ltd., Japan) controlled the flow rates. Intensified electric agitators ensured the influent was uniformly mixed. Phosphate buffer solution (PBS) was not added to enhance the electricity generation of MFC stage, because PBS might have led to a high concentration of phosphorus in effluent.

The HRTs of the acidogenic and methanogenic UASB reactors were set at 8 and 40 h, respectively, so that the ratio of $HRT_{methanogenic}$: $HRT_{acidogenic}$ = 5:1. The HRTs of the UML-MFCs were both set at 24 h to prevent acidogens and methanogens from restraining the growth and activity of electricigens. Finally, the HRTs of the integrated I-BAFs were also set at 24 h.

It has previously been reported that the operating temperature has a relatively small effect on the performance of MFCs (Feng et al., 2008; Liu et al., 2005). In the present study, the UML-MFCs were operated at room temperature, while the operating temperature of UASB reactors was controlled at 35 ± 1 °C.