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Upflow bio-filter circuit (UBFC): Biocatalyst microbial fuel cell (MFC) configuration and application to biodiesel wastewater treatment

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ABSTRACT

A biodiesel wastewater treatment technology was investigated for neutral alkalinity and COD removal by microbial fuel cell. An upflow bio-filter circuit (UBFC), a kind of biocatalyst MFC was renovated and reinvented. The developed system was combined with a pre-fermented (PF) and an influent adjusted (IA) procedure. The optimal conditions were operated with an organic loading rate (OLR) of 30.0 g COD/L-day, hydraulic retention time (HRT) of 1.04 day, maintained at pH level 6.5–7.5 and aerated at 2.0 L/min. An external resistance of circuit was set at 10 kΩ. The purposed process could improve the quality of the raw wastewater and obtained high efficiency of COD removal of 15.0 g COD/L-day. Moreover, the cost of UBFC system was only US$1775.7/m^3 and the total power consumption was 0.152 kW/kg treated COD. The overall advantages of this invention are suitable for biodiesel wastewater treatment.

1. Introduction

Our technological reliance on petroleum for the last 200 years has created many unintended side effects that will soon impact many aspects of human life. In addition, unmanaged waste production is enormous and increasingly hard to handle. As a partial replacement for fossil fuels, an uncomplicated biodiesel production process has been widely implemented by villagers as a town alternative energy source. However, a strong alkaline (pH 8–11), high COD (>200 g/L) have been generated (Ngamlerdpokin et al., 2011; Siles et al., 2010; Suehara et al., 2005). The biological treatment of biodiesel wastewater is difficult because the composition of such wastewater is not suitable for microbial growth. A growth inhibitor was also present in the biodiesel wastewater, and this growth inhibitor could be detected by measuring the solid content in an aqueous phase. The microorganisms could not grow at solid contents higher than 2.14 g/L (Suehara et al., 2005). To apply the microbiological treatment of biodiesel wastewater, Suehara et al. (2005) using an oil degradable yeast, *Rhodotorula mucilaginosa*, the pH was adjusted to 6.8 and several nutrients such as a nitrogen source to optimize C/N ratio between 17 and 68. To avoid the growth inhibition, the BDF wastewater was diluted with the same volume of water. Recently, Ngamlerdpokin et al. (2011) studied the remediation of biodiesel wastewater using chemical and electrochemical techniques. Initially the fatty acid methyl esters and free fatty acids were chemically removed from the wastewater by three types of mineral acids, H_2SO_4, HNO_3 and HCl, which was costly and harmful to environment.

Microbial fuel cell (MFC), a novel technology which convert complex compounds by sulfate reducing bacteria (SRB), dissimilatory metal-reducing bacteria (DMRB) or iron reducing bacteria into minerals (non degradable). MFCs can be used in wastewater treatment facilities to mineralize organic and inorganic matters and generate electricity as a by-product (Aelterman et al., 2008; Ahn and Logan, 2010; Greenman et al., 2009; Nam et al., 2010; Rabaey et al., 2006; Raghavulu et al., 2009; Rodrigo et al., 2007; Sukkasem et al., 2008; Yi and Harper, 2009). Much recently, it has been studied on biodiesel wastewater treatment by MFCs and MECs (Chignell, 2010; Feng et al., 2011).

The advantages of MFC application in wastewater treatment system is higher COD removal (40–80%) compared to 20–50% COD removal by anaerobic treatment at the same retention time. Biomass is also 68% higher in this system (from 0.07 to 0.22 g

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biomass COD/g SCOD) but it is 45% lower than aerobic system (0.4 g biomass COD/g SCOD (Logan, 2008), which is less sludge disposal (Drapcho et al., 2008).

However, a limitation of MFC development is that the use of expensive materials such as the metal platinum or gold catalyst, proton exchange membranes (PEMs), mediators, and graphite electrodes. Over 50% of the cost is from the metal catalyst alone (Deng et al., 2010). The most recent research has focused on a performance of MFC configurations and a performance of MFC with either mediator-less or membrane-less configurations to increase power generation and reduce the construction and operation costs such as expired mediator or membrane fouling replacement (Behera et al., 2010; Deng et al., 2010; Du et al., 2008; He et al., 2005; Hu, 2008; Jang et al., 2004; Rabaey et al., 2006; Sun et al., 2009). Liu and Logan (2004) examined the power generation in an air cathode MFC containing graphite electrodes in the presence and absence of PEM. It was found that the PEM removal increased 1.9-folds of the maximum power density. Jang et al. (2004), demonstrated that the membrane-less and mediator-less MFC were cost effective compared to previous configurations. Nevertheless, it also had a low electricity generation due to oxygen diffusion back to the anode and the absence of a catalyst in the cathode. Microorganisms can be used as both bio-catalysts and mediators in the cathode by use the cathode as the sole of electron donors (Rismani-Yazdi et al., 2008). Reduction of oxygen was catalyzed directly by the biofilm. Some species of sulfate reducing bacteria can transfer an electron directly between membrane and electrode (Logan and Regan, 2006). A possible approach to enhance the MFC performance would be an immobilization of the electrochemical bacteria on high surface-area electrode materials such as granular activated carbon (GAC) which is nontoxic and cost effective (Jiang and Li, 2009).

In this study, a membrane-less upflow bioreactor combined with the immobilization of microorganisms on GAC electrode surface as biocatalyst, called an upflow biofilter circuit (UBFC) was renovated and reinvented. The developed system was combined with a pre-fermented (PF) and an influent adjusted (IA) procedure. The biodiesel wastewater treatment was studied in different operational conditions for the performance of UBFC system.

2. Methods

2.1. Bio-filter circuit system construction

A low cost design of upflow bio-filter circuit (UBFC) system was investigated. The combination of pre-fermentation (PF), influent adjustment (IA), up-flow anaerobic filter (UFAF) and bio filter circuit (BFC) was connected in order. The raw biodiesel wastewater (218 ± 30 COD g/L, pH of 10 ± 1) was pretreated by anaerobic pre-fermentation at a ratio of wastewater to tap water 1:1. Then adjusted influent before fed into UBFC at three pH levels. Each PF and AF tank was an 8.0 L plastic bin. The UBFC was consisted two parts. Part 1, two bottles were used as UFAF1 and UFAF2 reactor. Part 2, the two bottles were used as a BFC reactor which was vertically stacked (Fig. 1). All UFAF1, UFAF2 and BFC were 4 L. The bottom bottle of BFC was an anaerobic compartment called "anode", and the top bottle was an aerobic compartment called "cathode". A 14 cm plastic tube-funnel as a membrane replacement was inserted between anaerobic and aerobic compartments to reduce oxygen diffusion into anode. A microorganism immobilized base was prepared by adding 555.0 ± 10 g (1.0 L) of inoculated granular activated carbon (particle size 1.0–10.0 mm) in UFAF1, UFAF2 and BFC anode bottles. The void volume of each bottle was 0.5 L. The BFC cathode chamber was added 333.0 ± 7 g (0.6 L) of inoculated GAC also and purged the air via sparkling-holes at the top of the chamber at rate of 2.0 L/min to induce growth of aerobic bacterial. A total investment of UBFC materials

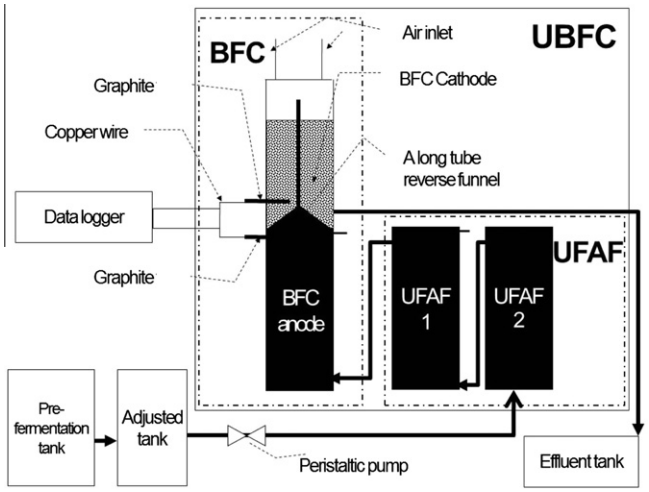

Fig. 1. Schematic of upflow bio-filter circuit (UBFC) System.

was US$1775.7/m^3 and the total power consumption was 2.275 kW/m^3 (Table 1). The comparison based on capital costs, for anaerobic digesters (AD) are on the order of £100,000 ($144,000) per ton of COD treated per day (Pham et al., 2006) while the UBFC is $118,380 per ton of treated COD which was less than AD capital cost.

2.2. Pre-fermentation

Biodiesel wastewater from a tallow biodiesel conversion process with chemical oxygen demand (COD) of 218 ± 30 g/L, sulfate 234.33 ± 23.54 mg SO_4/L, nitrate 83.83 ± 7.69 mg NO_3/L, total solid content (TS) 79.39 g/L and strong alkalinity (pH 10 ± 1) was found. Refer to Suehara and coworker's report (2005), therefore, to avoid the growth inhibition of high TS, the dilution with the tap water was test at various ratios (1:0, 1:1, 1:3, 1:4 and 1:9). It was found that the fermentation could happen at 1:1 rational as Suehara et al. study. To increase the fermentative rate, the dilution was inoculated by 20% (v/v) of activated sludge. After a week, fermented wastewater was sampled and analyzed for COD, volatile fatty acids (VFAs) and pH.

2.3. Adjusted influent

The supernatant (skimmed out) from pre-fermented process was adjusted to the designable COD concentration and pH level as shown in an experimental design (Table 2) in order to control the influent condition before fed into the UBFC.

2.4. UBFC inoculation

The biocatalytic electrode preparation, GAC was inoculated in activated sludge obtained from an industrial treatment plant (Songkhla, Thailand) at ratio of 1:1 (v/v) for three days to immobilize the microorganisms on electrode surface as a biocatalyst producer instead of metal catalysts or mediators. Afterwards, the immobilized GAC was added into the UBFC. For start-up process, 6.0 gCOD/L of wastewater influent was continuously fed into the UBFC at 1.0 mL/min. The BFC cathode was aerated at 2.0 L/min to simulate aerobic microorganisms on GAC surface. The UBFC was operated until output voltage stabilized at >0.6 V in open circuit mode for a week. Then, the circuit was closed by external resistance of 10 kΩ. All experiments were operated at an ambient temperature of 30 ± 3 °C.

Table 1
Materials cost of UBFC system.

Materials	Cost/4.0 L reactor (US$)	Cost (US$/m^3)	Power consumption (kW/m^3)
Materials	Cost/4.0 L reactor (US$)	Cost (US$/m^3)	Power consumption (kW/m^3)
Two of 8.0 L bin	1.0	250–30% = 175	–
Four of 1.0 L bottles	1.48	370–30% = 259	–
A funnel	0.15	37.5–30% = 26.25	–
4.0 L of GAC	1.06	265–30% = 185.5	–
Others e.g. joint, glue, tape, plastic tube	1.52	380–30% = 266	–
Pump (*Peristaltic pump 30 W, 4 heads)	1.270*	674.0 (www.plumbersurplus.com)	1.875[a]
Aerator (*3.2 W, two heads, double speed rate)	8.48*	189.95 (www.marineandreef.com)	0.4[a]
Total		1775.7	2.275[a]

[a] Laboratory scale.

Table 2
Experimental designs.

Set of experiment	External load (kΩ)	OLR (gCOD/L-day)	HRT (day)	pH	Aeration (L/min)
External load	1–30	30	1.04	5.6–6.5	2.0
OLR	⇩	15–45.0	1.04	5.6–6.5	2.0
HRT		⇩	0.21–1.04	5.6–6.5	2.0
pH level			⇩	4.5–7.5	2.0
Aeration rate				⇩	0 (open cathode), 1.0, 2.0

2.5. UBFC operation

The UBFC system was stepwise conducted to determine the optimum condition (Table 2). First, five external resistances (1.0, 5.0, 10.0, 20.0 and 30.0 kΩ) were test at control condition: organic loading rate (OLR) 30.0 gCOD/L-day of neutral pH influent, hydraulic retention time (HRT) 1.04 day and aerated at 2.0 L/min. Second, three OLRs (15.0, 30.0 and 45.0 g COD/L-day) were test at selected resistance in control condition from the first test. Third, three HRTs (1.04, 0.35 and 0.21 day) were determined at selected resistance and OLR at control condition from the second test. Forth, three pH levels of influent (6.5–7.5, 5.5–6.5 and 4.5–5.5) were test at selected resistance, OLR and HRT at control condition from the third test. Finally, three aeration rates (2.0, 1.0 and 0 (open cathode) L/min) were test at selected conditions from the forth test. Each experiment was operated for three days. The COD concentration of UBFC influent and BFC anode and BFC cathode effluent were analyzed. The UBFC voltage across the external resistor was measured and automatically recorded by a data logger computer program (National Instrument, 2008). All operations were done in triplicate.

2.6. Analysis and calculations

Current (I) and power (P) was calculated as Eq. (1) and (2);

$$I = V/R \quad (1)$$

$$P = V^2/R \quad (2)$$

where V is a cell voltage (V), R is an external resistance (Ω). Volumetric current or power is calculated by divided the current or power by an anode volume. HRT and OLR were calculated as described in Eqs. (3) and (4);

$$\text{HRT (day)} = [\text{reactor volume (L)}]/[\text{influent flow rate (L/day)}] \quad (3)$$

$$\text{OLR (gCOD/L-day)} = [\text{CODconcentration (gCOD/L)}]/[\text{HRT (day)}] \quad (4)$$

The COD concentration was analyzed using Standard method (APHA, 1995), and volatile fatty acid (VFAs) was analyzed by GC-FID (HP 6850) (Thanakoses et al., 2003). A complete block design (CBD) and Duncan test were used for statistical analysis. DGGE genetic analysis was used to identify microbial communities in both BFC anode and cathode chambers (Muyzer et al., 1993).

3. Results and discussion

3.1. Pre-fermentation

In the anaerobic fermentation pretreatment, pH dropped from 10 ± 1 to 5.5 ± 1 without chemical treatment because of VFAs production, which decreased 42.02 ± 5.0% of initial COD concentration (218 ± 30 g/L to 126.4 ± 10 g/L) in a form of skim. Most of grease and oil could be recovered as biodiesel oil by heat curing (Gerpen and Menges, 2004). The main VFAs in fermented effluent were propionic acid (70.0%), valeric acid (13.2%), acetic acid (10.1%) and butyric acid (6%), respectively.

3.2. UBFC performance

3.2.1. Start-up period

The open circuit voltage at start-up period was 0.6 ± 0.1 V. The efficiency of COD removal and pH from each bottle (Fig 1), UFAF1, UFAF2, BFC anode and BFC cathode, was shown in Table 3. The results illustrate that the UBFC has a potential to treat COD 10% higher in a closed circuit mode than an open circuit mode (normal process). At the end of this process, the effluent of this system was neutral pH which is benefit in downstream process.

3.2.2. Effect of external load on %COD removal and volumetric power

After the circuit was connected, an aqueous phase from the pre-fermentation process was then neutralized and fed into the UBFC at a control condition of an OLR of 30 gCOD/L-day (composted of COD 30.0 ± 2.2 g/L, NO_3^-–N 83.21 ± 7 mg/L, SO_4^{2-} 49.00 ± 4.5 mg/L and TS 3.18 g/L), HRT of 1.04 d and aeration rate of 2.0 mL/min. The advantage, this UBFC was able to treat this wastewater without nitrogen source added, while anaerobic treatment required urea or yeast extract to reach the optimum C:N ratio (Suehara et al., 2005).

An effect of external loads was investigated at 1.0, 5.0, 10.0, 20.0 and 30.0 kΩ. The results show that the percentage of COD removal increased about 10% from open circuit mode and obtained highest efficiency up to 70% at an exterior resistance of 10 kΩ (Fig 2A). This

Table 3
Percentage of COD removal and pH of open circuit and close circuit mode of UBFC at OLR 30 g COD/L-day, HRT 1.04 day, pH 5.6–6.5, high aeration 2.0 L/min.

External load (kΩ)	%COD removal					pH			
	UFAF1	UFAF2	BFC anode	BFC cathode	Input	UFAF1	UFAF2	BFC anode	BFC cathode
Open circuit	25.62 ± 0.15	39.34 ± 0.18	44.24 ± 0.20	61.15 ± 0.08	6.5–7.0	6.0	5.5–6.0	5.5–6.0	6.5
10	27.53 ± 0.14	40.18 ± 0.23	49.59 ± 0.27	69.94 ± 0.13	6.5–7.0	6.0	5.5	5.5–6.0	7.0

corresponds to a peak of power on the polarization curve (Fig 2B). Maximum volumetric power is achieved when the internal resistance (R_{int}) equals external resistance (R_{ext}) (Aelterman et al., 2008). The voltage across a circuit of UFAF1/cathode and UFAF2/cathode were negligibly (<0.01 V), and the BFC generated electricity quite low (35.62 mW/m^3 of BFC anode volume). It is because of a large internal resistance (10 kΩ) caused by a low biodegradation degree or a long distance between electrodes or material sensitivity, which needs to be addressed further.

3.2.3. Effect of OLR on COD removal

The UBFC was operated at various OLR (15.0, 30.0 and 45.0 g COD/L-day) at selected resistance from 3.2.2 (10 kΩ) and controlled other factors as pH of influent 6.5–7.5, HRT 1.04 day and aerated cathode flow rate 2.0 L/min. The purpose system can be loaded the organic wastewater successfully up to 45.0 g COD/L-day. However, the 30.0 gCOD/L-day loading rate was selected because it can generate highest electricity (Fig. 3A). The OLR was only one significant effect on cathode efficiency, which means the anode had a limiting biodegradation of 30% and the cathode required optimum COD input. Obviously, the COD removal efficiency was downwards from startup about 20% with a drop of open circuit potential from 0.8 to 0.5 V after three months operation. Moreover, the colloidal particles and biofilm development caused the reactor clogging rapidly. At the end of each following experiment, the reactor was cleaned by back washing using tapped water.

3.2.4. Effect of HRT on COD removal

The various HRTs (1.04, 0.35 and 0.21 day) were determined at the selected OLR (30 g COD/L-day) and resistance (10 kΩ) from Section 3.2.3 at control condition (pH of influent 6.5–7.5 and aerated cathode flow rate 2.0 L/min). The optimum performance was obtained at HRT of 1.04 days with the maximum COD removal (>50%) (Fig. 3B). This indicates that longer digestion time allowed bacteria to completely mineralize the organic matters.

3.2.5. Effect of pH on COD removal

The COD removal was examined at three pH ranges (4.5–5.5, 5.6–6.5 and 6.6–7.5) at the selected OLR (30 g COD/L-day), resistance (10 kΩ) and HRT (1.04 day) from Section 3.2.4 and aerated cathode flow rate 2.0 L/min. The result shows that neutral pH gave the maximum COD removal more than 55% (Fig. 3C). The result is agreed with literature values (Raghavulu et al., 2009) that substrate degradation was highest at neutral pH. It is possible that neutral pH maximizes the biodegradation by microbial diversities in the symbiotic biofilm.

3.2.6. Effect of aeration rate on COD removal and volumetric power

The effect of aeration rate was investigated at three levels: high aeration (2.0 L/min), low aeration (1.0 mL/min) and no aeration (open cathode chamber) at selected conditions from Section 3.2.5: OLR (30 g COD/L-day), resistance (10 kΩ), HRT (1.04 day) and pH (6.5–7.5). The maximum COD removal, approx. to 60%, (Fig. 3D) was obtained at the highest aeration rate of 2.0 L/min while aeration at 1.0 mL/min was not different from the open cathode mode, significantly. In addition, treating COD without aeration shows a good performance of the system which is possible to cut off the aeration cost.

3.2.7. DGGE analysis

Fig 4 elucidates the microbial populations represented in the anode chamber (AN), which were dominated by *Camamonas denitrificans*, unidentified Rhodospirillaceae species and *Heliobacterium modesticaldum*. The DGGE result of the anode communities in the UBFC is similar to Chae et al. (2009) which reported the MFC fed with propionic acid were populated with propionate fermentative bacteria, specifically α,β-proteobacteria. Surprisingly, the cathode chamber (CT) was dominated by an unidentified *Clostridium* species which is well known as obligatory anaerobic bacteria. However, Kawasaki et al. (1998) reported that *Clostridium butyricum*, the type species of the genus Clostridium, possesses the ability to consume oxygen in amounts proportional to the size of the inoculum. As scavengers for involved oxygen species, the activities of NADH/NADPH peroxidase were detected in *C. butyricum*. Furthermore, the activities of these enzymes are distributed widely in the genus Clostridium. This genus is possible to be a biocatalyst producer in MFC which needs to further investigation for the efficiency enhancement.

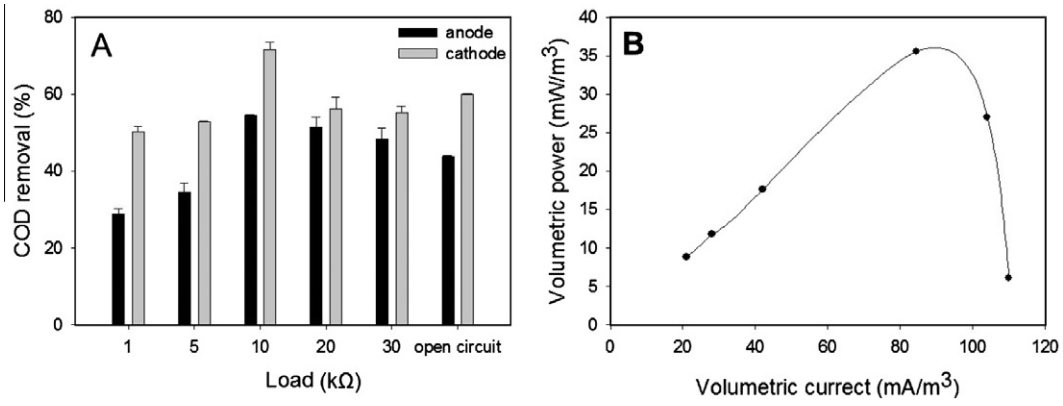

Fig. 2. Effect of external load on %COD removal (top) and volumetric power (bottom) and at OLR 30 g COD/L-day, HRT 1.04 day, pH 5.6–6.5, high aerated 2.0 L/min.

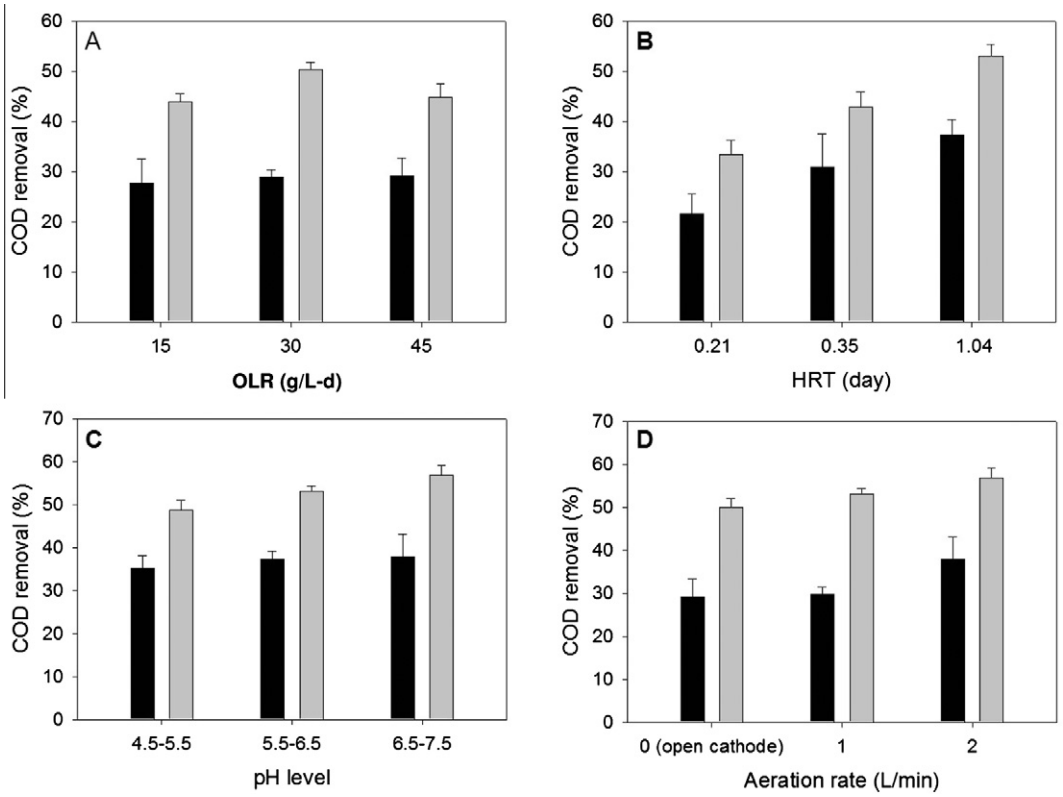

Fig. 3. Effect of OLR (A), HRT (B), pH (C) and aeration rate (D) on COD removal of MFC from anode chamber (black bar) and cathode chamber (gray bar).

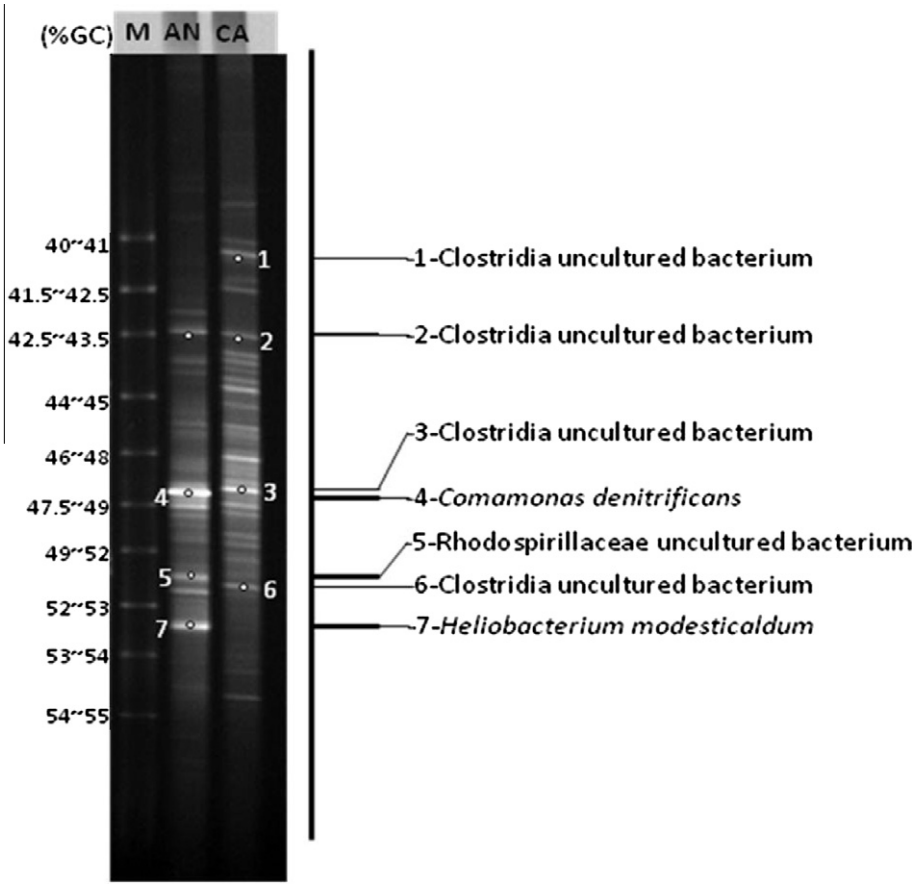

Fig. 4. DGGE negative image of anode (AN) and cathode (CA).

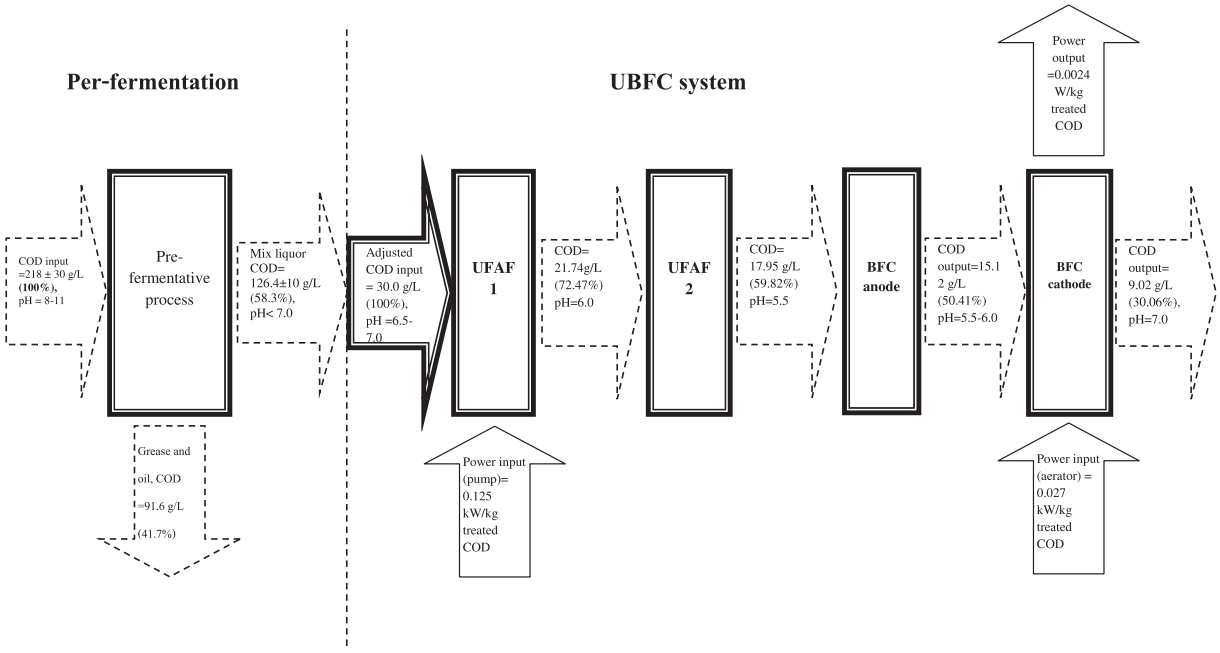

Fig. 5. The UBFC systematic diagram.

Table 4
Comparison of MFC combination system for wastewater treatment.

Waste water treatment systems	Volume (L)	Micro-organisms	Membrane	Catalyst	Substrates	Crude waste-water COD (g/L)	OLR (g/L-day)	HRT (day)	COD removal (g/L-day)	References
Pre-fermentation & UBFC	UBFC 4.0	Sludge	No	Biocatalyst	Biodiesel wastewater	216 ± 30	30.0	1.04	UBFC > 15.0	This study
MFC & UASB[b]	MFC 2.36	Sludge	No	Biocatalyst	Palm oil mill	50	4–5.25	2.0	5.0	Cheng et al. (2010)
Single chamber MFC	0.028	Sludge	No	Platinum	Domestic wastewater	182	54	0.009	13.93	Ahn and Logan (2010)
Double chamber MFC	1.15	Sludge	No	$KMnO_4$	Artificial wastewater	NA[a]	6.0	0.5	2.42–3.71	Behera and Ghangrekar (2009)
Single chamber MFC	0.25	Active electro-Chemical bacteria	No	Platinum	Fermented wastewater	25.9	3.84	1.04	3.57	Nam et al. (2010)
Single chamber MFC	0.25	Sludge	Yes	Platinum	Domestic wastewater	0.2	12.0–18.0	3.0	0.89–1.34	Jiang and Li (2009)

Some data calculated or modified from original data.
[a] NA = no data from original data.
[b] UASB = Upflow Anaerobic Sludge Blanket.

3.3. Discussion

The fermentative, anaerobic and aerobic processes were combined to UBFC system. The complex organic compounds were digested to simple organic forms such as volatile fatty acid (VFA) via fermentation process by aerobic and anaerobic heterotrophic microorganisms. Heterotrophs consume organic carbon for the formation of new biomass (Jantrania and Gross, 2006).

The assumption of the biodiesel wastewater degradation in UBFC system could be shown as;

3.3.1. Pre-fermentative process

$$\mathrm{BiodieselwastewaterOrganiccompounds(CHONS)} \times \overset{\mathrm{Heterotrophicbacteria}}{\rightarrow} \mathrm{greaseandoil} + \mathrm{Mixliquor\ (highcarbonVFAs} + \mathrm{CO_2} + \mathrm{H2O} + \mathrm{newcell} + \mathrm{residuals})$$

3.3.2. UFAF1/ UFAF2 anaerobic process

$$\mathrm{Mixliquor\ (highcarbonVFAs} + \mathrm{H_2O} + \mathrm{cellmass} + \mathrm{residuals}) \overset{\mathrm{Anaerobicbacteria}}{\rightarrow} \mathrm{lowcarbonVFAs} + \mathrm{H_2} + \mathrm{CO_2} + \mathrm{HCO_3^-(see\ Logan,\ 2008)} + \mathit{residuals} + \mathrm{CH_4(see\ Jordening\ and\ Winter,\ 2005)}$$

3.3.3. BFC anode MFC anaerobic compartment

In biochemical operation, when the H_2 partial pressure was kept low enough (10^4 atm (60 Pa) or less), the production of acetic and H_2 as the end products of acidogenesis was allowed. These molecules were simple and provided high rate of biodegradation (Jantrania and Gross, 2006; Logan, 2008). The H_2 partial pressure of UBFC always keeps lower by electrons and protons transferred

through the metal wire and electrolyte from anode to cathode. Consequently, high efficiency was presented.

$$\text{lowcarbonVFAs} + H_2 + CO_2 + HCO_3^- + CH_4 + \text{residuals} \xrightarrow{\text{Acetogenicbacteria}} CH_3COOH(\text{see Logan, 2008}) + H_2 + CO_2 + \textit{residuals}$$

3.3.4. BFC cathode MFC aerobic compartment

Through the process of respiration, aerobic microorganisms in cathodic compartment can further transform VFAs (and other bioavailable organic compounds) into carbon dioxide, water (Lehninger, 1973). Aerobic microbes can readily convert organic carbon into inorganic carbon and aerobic systems can provide high-rate wastewater treatment.

$$CH_3COOH + H_2 + CO_2 + O_2 \xrightarrow{\text{Aerobicbacteria}} CO_2 + H_2O + H_2O_2(\text{see Logan, 2008}) + \text{newcell} + \text{residuals}$$

The UBFC systematic diagram (Fig 5) showed the input and output COD (g/L, % removal), pH and power (kW per kg treated COD). The power consumption to destroy 15.0 kg COD was 2.275 kW/m^3 or 0.152 kW/kg treated COD which closed to aerated lagoon operational cost 0.1625 kW/kg treated COD (Baz et al., 2008). By the way, the system generated small amount of electric power of 0.0024 W/kg treated COD caused by the reason as described above (see Section 3.2.1).

The summary of water recycling guidelines and mandatory standards in the United States and other countries (Saidi, 2006) presented that the discharge should has BOD 5–30 mg/L (<50 mgCOD/L), TSS 3–30 mg/L and pH 6–9. To comply with standard, the mix liquor from pre-fermentative process has to be diluted to 30.0 g/L and adjusted to neutral pH before fed into the UBFC at HRT 1.04 d. Four rounds recycling, is suggested to provide the biodiesel discharge allowance.

4. Conclusion

The UBFC system, a combination of biocatalyst MFC with PF and IA process is able to treat biodiesel wastewater without chemical treatment or nutrient supplementation. A maximum COD removal was obtained 15.0 g/L-day which higher than conventional technologies (Table 4). The capital cost was $118,380 per ton of treated COD, less than AD capital cost and the power consumption was 0.152 kW/kg treated COD, closed to aerated lagoon operational cost. To comply with standard, four rounds recycling, is suggested to provide the biodiesel discharge allowance. Further development is needed at pilot and industrial scale for wastewater treatment.

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