



Biotechnology and Bioengineering

Simultaneously energy production and dairy wastewater treatment using bioelectrochemical cells: In different environmental and hydrodynamic modes



Masoud Hasany, Soheila Yaghmaei *, Mohammad Mahdi Mardanpour, Zahra Ghasemi Naraghi

Department of Chemical and Petroleum Engineering, Sharif University of Technology, Azadi Avenue, P.O. Box 11365-9465, Tehran, Iran

ARTICLE INFO

Article history:

Received 27 November 2016

Received in revised form 4 August 2017

Accepted 4 August 2017

Available online 15 August 2017

Keywords:

Dairy wastewater

Darkness

Light

Microbial electrolysis cell

Microbial fuel cell

Nitrogen

Phosphate

ABSTRACT

A successful design, previously adapted for treatment of complex wastewaters in a microbial fuel cell (MFC), was used to fabricate two MFCs, with a few changes for cost reduction and ease of construction. Performance and electrochemical characteristics of MFCs were evaluated in different environmental conditions (in complete darkness and presence of light), and different flow patterns of batch and continuous in four hydraulic retention times from 8 to 30 h. Changes in chemical oxygen demand, and nitrate and phosphate concentrations were evaluated. In contrast to the microbial fuel cell operated in darkness (D-MFC) with a stable open circuit voltage of 700 mV, presence of light led to growth of other species, and consecutively low and unsteady open circuit voltage. Although the performance of the MFC subjected to light (L-MFC) was quite low and unsteady in dynamic state (internal resistance = 100 Ω , power density = 5.15 $\text{W} \cdot \text{m}^{-3}$), it reached power density of 9.2 $\text{W} \cdot \text{m}^{-3}$ which was close to performance of D-MFC (internal resistance = 50 Ω , power density = 10.3 $\text{W} \cdot \text{m}^{-3}$). Evaluated only for D-MFC, the coulombic efficiency observed in batch mode (30%) was quite higher than the maximum acquired in continuous mode (9.6%) even at the highest hydraulic retention time. In this study, changes in phosphate and different types of nitrogen existing in dairy wastewater were investigated for the first time. At hydraulic retention time of 8 h, the orthophosphate concentration in effluent was 84% higher compared to influent. Total nitrogen and total Kjeldahl nitrogen were reduced 70% and 99% respectively at hydraulic retention time of 30 h, while nitrate and nitrite concentrations increased. The microbial electrolysis cell (MEC), revamped from D-MFC, showed the maximum gas production of 0.2 $\text{m}^3 \text{H}_2 \cdot \text{m}^{-3} \cdot \text{d}^{-1}$ at 700 mV applied voltage.

© 2017 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

1. Introduction

One of the greatest challenges in future world will be about energy, while with its enough sources, most of the world problems such as limited potable water, food scarcity, pollution emissions, to name a few, can be circumvented. Besides, consuming the major energy source which is fossil fuels not only emits various pollutions with very serious consequences at a large scale, but it also is a non-renewable source that can be used for the production of numerous applied materials (e.g. petrochemical products), while other energy sources don't have this advantage. So, with enough renewable energy, preserving of fossil fuel sources for other applications other than combustion is almost certain.

In the last few decades, either electricity or hydrogen, because of the advantages such as no pollutant emission and more efficiency according to Tobin Smith for Billion Dollar Green, has been considered

to be of the best types of renewable energies, and can be someday replaced with fossil fuels. However, to reach this goal, simpler and less expensive methods of production are required. Apart from this, the methods or technologies with simultaneous targets are more appreciated. As exceptional examples, microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) can be adapted because of simultaneous wastewater treatment and inexpensive production of electricity and hydrogen. Therefore, utilizing these technologies, more potable water and renewable energy will be available to human beings [1,2].

There is enough introductory information about these technologies thanks to Logan *et al.* [1,2]. MEC in comparison to MFC is more newly developed, and there are fewer published studies about MEC system characterization. In most of the studies related to MEC, pure or synthetic substrates have been used as fuel cell energy source, whereas one of the advantages of this technology is hydrogen production along wastewater treatment. Of course, there are some articles about treatment of complex substrates in swine [3,4], domestic [3,5–7], refinery [8], municipal [9], industrial and food processing [10], and winery wastewaters [11], and

* Corresponding author. Fax: + 982166166430.

E-mail address: yaghmaei@sharif.edu (S. Yaghmaei).

waste activated sludge [12]. They have also been employed for glycerol [13,14], and heavy metal removal [15], but maybe because of the complexity of dairy wastewater, the study of dairy wastewater treatment in MECs with a detailed examination of different parameters is still lacking. Instead, there are some articles about treating dairy wastewater using MFCs [16].

Dairy is one of the main industries in the upper Midwestern United States [17] and one of the largest sources of industrial effluents in Europe [18]. The wastewater generated in dairy plants, like most other agro-industries, usually contains a high concentration of complex organic compounds such as proteins and organic acids, and consecutively high biological and chemical oxygen demand (BOD and COD) [17,18]. These effluents surely cause serious environmental problems, in terms of high organic loading on local municipal sewage treatment systems and eutrophication of receiving waters due to high levels of phosphorus and nitrogen [17,19,20].

In wastewater treatment plants, adapted bacteria should be able to store polyphosphate as biomass, because in this case, surface waters will be protected from further loading [19]. Although, MFCs are not specially designed for aerobic/anaerobic enhanced biological phosphorus removal (EBPR) process and aerobic/anoxic nitrification/de-nitrification [21], nitrogen and phosphate can still be removed from wastewater by adapted biomass in MFC.

To date, physico-chemical and biological treatment methods have been used for treatment of dairy wastewaters [18,22]. However, because of the high cost of reagents and poor removal of soluble COD in physico-chemical treatment processes, biological processes such as treatment in ponds, activated sludge plants, and anaerobic treatment are usually preferred. Among the different biological approaches, anaerobic methods outperform aerobic ones due to higher energy consumption, larger operational area required, and higher amounts of excess sludge remained in aerobic methods. Among commonly used anaerobic methods, using MFC and MEC leads to more energy recovery [5,23].

Herein, a successful design of MFC [16,24] has been adapted for treatment of dairy wastewater. After evaluation of MFC characteristics, the design was changed to an MEC to be characterized for energy production and treatment of dairy wastewater. The MFCs characteristics were completely evaluated in presence and absence of light, and in batch and continuous operational mode.

2. Materials and Methods

2.1. Systems construction

Two single-chamber MFCs were constructed based on the MFC design in a previous study [16]. Briefly, the body of fuel cells was made from Plexiglas in a cylindrical shape. Graphite-sprayed stainless steel mesh (mesh 300) was prepared for anode electrode. SEM images in the previous study showed that the stainless steel mesh provides a more specific surface area for microorganisms, good bacterial adhesion, and more uniform biofilm which facilitate electron generation and transport [16]. To increase the ratio of available area for microorganisms' attachment to anodic volume, the anode electrode was used in a spiral shape. The annular structure of the MFC can effectively reduce the internal resistance [16]. Despite using carbon cloth in the previous study, the cathode electrode in this study was made of graphite-sprayed stainless steel (mesh 400) because of cost reduction and ease of construction [25]. The cathode electrode was treated according to the procedures reported previously with 10% Pt on carbon (Sigma-Aldrich), 5% Nafion (Nafion® 117 solution, Sigma-Aldrich), and isopropanol [26]. This construction of gas diffusion electrode (GDE) was selected because of high energy efficiency and COD removal reported when using GDE in MFCs [16,24,27]. For MEC evaluation, the cathode chamber of MFC was sealed along with devising a tube for measurement of gas volume.

2.2. Inoculation of the systems

Dairy wastewater (2000–2100 mg·L⁻¹ COD, pH 7–8, 185–190 NTU Turbidity, 13.6 mg·L⁻¹ orthophosphate, 75.93 mg·L⁻¹ Total Kjeldahl Nitrogen (TKN), 46.5 mg·L⁻¹ ammonium, and 86.18 mg·L⁻¹ total nitrogen) was collected from Pegah-Tehran Dairy Industrial Corporation and used for MFC experiments with two times dilution. Because of the vast range of organic materials in complex wastewaters and to provide higher efficiency, use of mixed culture is prior to pure culture [28]. Microbial diversity existing in mixed cultures leads to functional redundancy crucial to wastewater treatment plants [19]. Every wastewater contains a distribution of microorganisms which is suitable for treatment of the same wastewater. Therefore, the inoculum used in most MEC and MFC studies has been taken from wastewater treatment plants [24,28–33]. In the present study, the MFCs were inoculated with 10 ml of activated sludge taken from Pegah Corporation. However, the microbial community existing in activated sludge, when used in anodic part of MEC, is not able to donate electrons at a significant rate [32]. Thus, after evaluation of MFC characteristics (4 months), 10 ml of anaerobic sludge taken from Pegah Corporation was injected to the MEC. Then, the voltage of 500 mV was applied to MEC electrodes using an adjustable DC power supply for one month prior to logging the characteristic data.

2.3. Different modes

Right after inoculation, one of the MFCs was subjected to light (L-MFC) using a light source (SMD MR16, 1000 Lux), and another one placed in complete darkness (D-MFC). After recording required data in batch mode, the MFCs were operated in continuous mode using a peristaltic pump (BVP Standard, Ismatec Laboratory Pumps). However, the high growth of algae and microalgae caused the exit flow of L-MFC to clog several times, and finally the cathode was ruptured. This drawback of running MFC in presence of light should be considered in future works. As previously mentioned, after finishing MFC tests, D-MFC was revamped to MEC for more investigations.

2.4. Analysis and calculation

The COD was quantified using HACH COD system after sample pre-treatment according to Standard Method [34]. In the continuous mode, COD, phosphorus, nitrogen, and turbidity change were evaluated based on Standard Method [34]. The electrochemical characteristics of the MFC were acquired, in which voltage monitoring was conducted with a data acquisition device, at a scan rate of 0.1 mV·s⁻¹. Current and power densities were calculated with Ohm's law ($I = V / R$) and $P = VI$ respectively, and then normalized with the anodic volume (70 ml). So far, different methods have been presented to measure internal resistance [35,36]. In this study, polarization curve and current interrupt methods were used for this purpose.

Coulombic efficiencies in batch and continuous mode were calculated as below:

$$C_E = \frac{8 \int_0^{t_b} I dt}{F V_{MFC} \Delta COD} \quad (1)$$

$$C_E = \frac{8I}{F Q \Delta COD} \quad (2)$$

In which ΔCOD depicts changes in COD over a cycle and between inlet–outlet in batch and continuous mode respectively. F is Faraday's constant, I is the output current. In batch mode (1), V_{MFC} is the liquid volume of anodic compartment, while Q is volumetric flow rate in continuous mode (2).

3. Results and Discussion

3.1. Microbial enrichment

Firstly, both MFCs were operated at open circuit condition for a more uniform enrichment of microbial community on anode electrode surface [16,37]. Whenever voltage decreased, some of the anodic liquid was changed with fresh wastewater for about six weeks. Fig. 1a shows open circuit voltage (OCV) of L-MFC versus time in which arrows depict the injections. After two feed injections (12 days), the voltage increased to 550 mV. Despite more injections after this peak in voltage, OCV was limited to below 200 mV. This result might be related to algae, microalgae and photosynthetic bacteria growth confirmed by the color change of grown biofilm on the anodic surface from brownish to orange and green during this period and also the microscopic images taken

by a light microscope, $1000\times$ (Fig. 2). High dissolved oxygen and consecutively the electron consumption in the anodic compartment are established by these species [38,39].

OCV of D-MFC, as can be seen from Fig. 1b, reached 620 mV on the 4th day after inoculation and became steady on 700 mV after four batch cycles (about 36 days). In contrast to OCV of L-MFC [Fig. 1(a)], what stands out in this figure is the rapid increase of voltage and longer voltage plateau at peaks which are referred to complete enrichment in the latter cycles.

3.2. Performance of the MFCs in batch mode

3.2.1. MFC operation in dark environment

The performance of D-MFC was evaluated by applying different resistances ($10\text{--}2500\ \Omega$) and measuring voltages in which resistances were changed after reaching two succeeding steady peaks in output

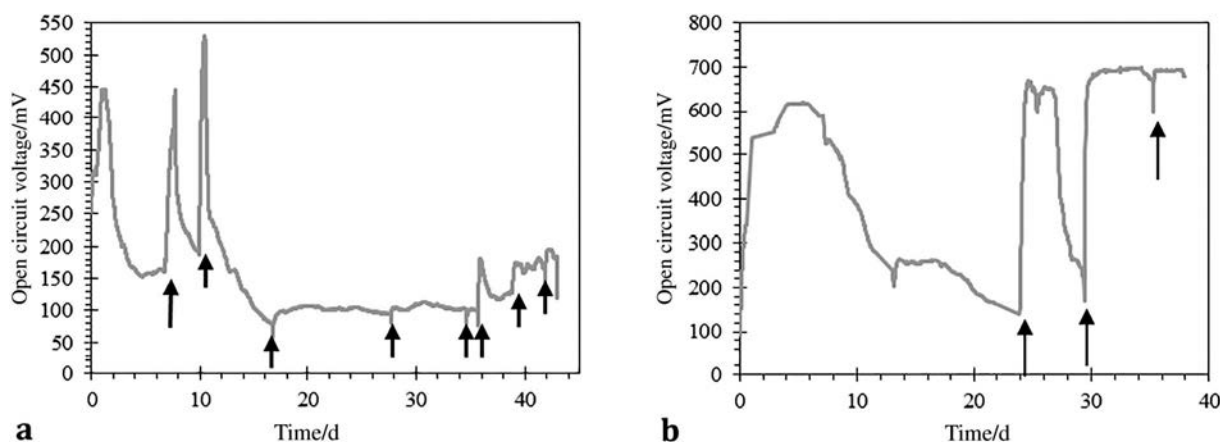


Fig. 1. OCV versus time in (a) L-MFC and (b) D-MFC.

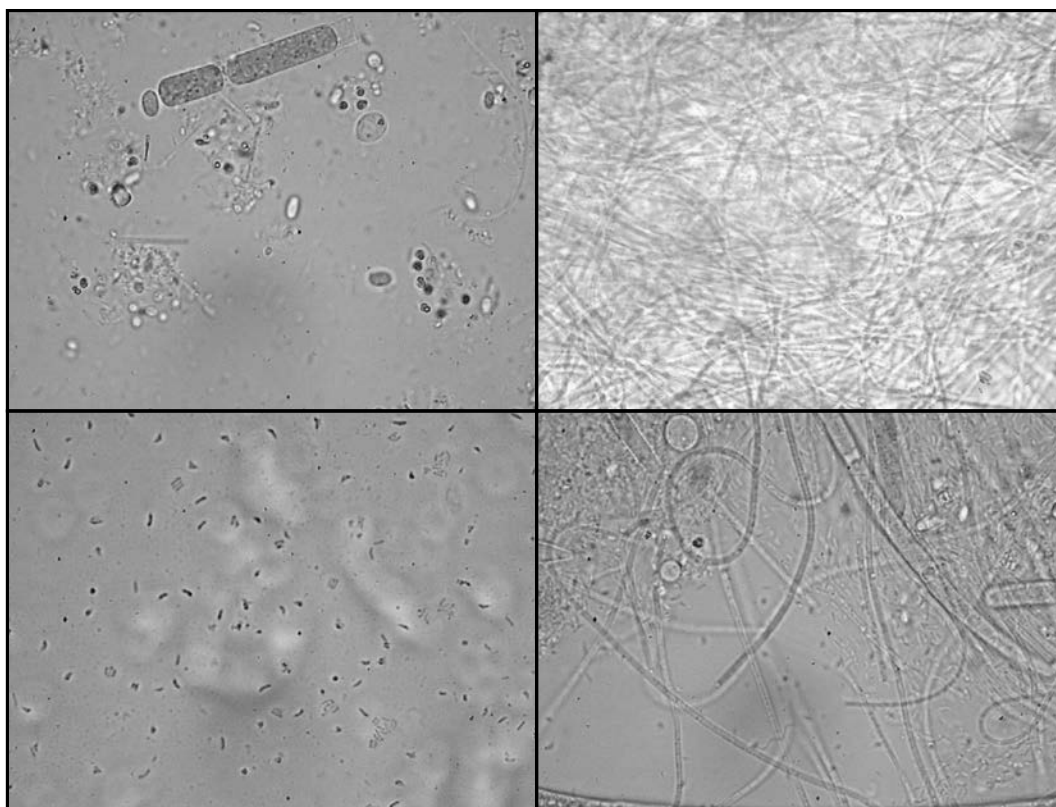


Fig. 2. Taken images showing the grown species in L-MFC.

voltage [16]. Fig. 3 provides polarization and power density curves indicating $10.3 \text{ W} \cdot \text{m}^{-3}$ and 35Ω respectively as maximum power density and power overshoot. The internal resistance of 45Ω evaluated by current interrupt method confirmed 50Ω resistance of D-MFC in maximum power density.

3.2.2. MFC operation in presence of light

Up to now, the shift from open circuit to a resistance, in all of the researches on MFCs, led to a decrease in output voltage [16,40,41]. Surprisingly, in this study, the voltage increased to 230 mV and

470 mV (from below 200 mV in open circuit mode) respectively when the circuit closed with $5 \text{ k}\Omega$ and $2.5 \text{ k}\Omega$ resistances (Fig. 4 a and b). However, voltage decreased after changing to $1 \text{ k}\Omega$ and so on (Fig. 4 c and d). At this stage, maximum power density and internal resistance were $5.15 \text{ W} \cdot \text{m}^{-3}$ and 100Ω respectively. The unexpected observation can be referred to symbiosis of various microorganisms existing in biofilm and anodic solution, their interactions, substrate consumption and production of byproducts, and electron generation, consumption and its transportation pathways. Moreover, it might be possible that the electron transfer through

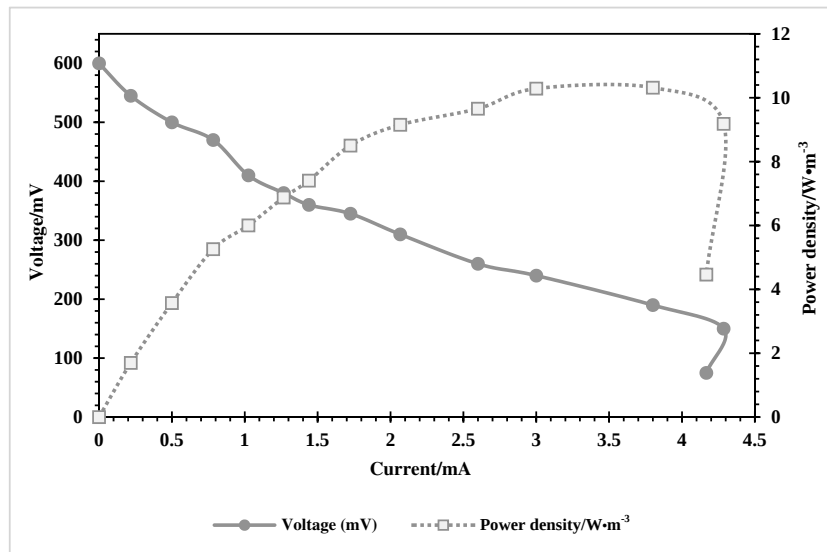


Fig. 3. Polarization and power density curves of D-MFC.

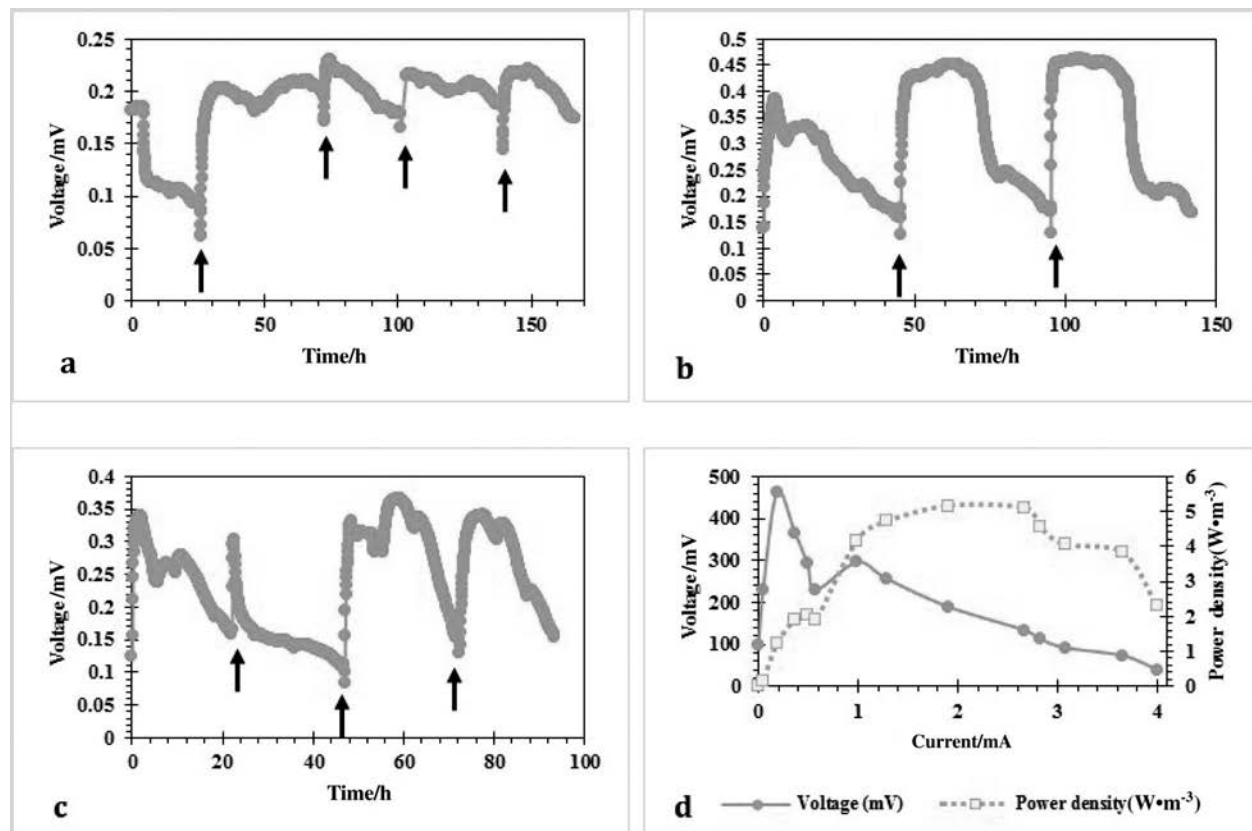


Fig. 4. The output voltages from L-MFC for the external resistance of (a) $5 \text{ k}\Omega$ (b) $2.5 \text{ k}\Omega$, and (c) $1 \text{ k}\Omega$. (d) Polarization and power density curves of the MFC in the light.

the circuit is faster than its consumption by existing microorganisms, and consecutively can lead to the decrease of electron scavenger species. However, this observation should be more investigated in future studies through analysis of microbial community.

After this dynamic state, polarization was repeated by putting the MFC to open circuit mode again in which resistances were changed in a faster way after observing a steady voltage and current for some minutes, but not after reaching equal voltage plateau sequentially. Latter polarization revealed different results in which maximum voltage and power density increased to 570 mV (in OCV mode) and $9.2 \text{ W} \cdot \text{m}^{-3}$ respectively (Fig. 5). Internal resistance evaluated by power density curve and current interrupt reached 50Ω . This dynamic behavior of MFC should be more investigated by considering governing mechanisms, dominant species and metabolic pathways in presence of light.

Far apart from these observations, it should be noted that power densities in all of these experiments were much higher than other similar studies [42–45]. It can be related to the annular design of anode, its high surface to volume ratio available for microorganisms, and the better bacterial attachment to stainless steel surface [16].

3.3. Performance of D-MFC in continuous mode

Fig. 6a and b shows the polarization and power density curves related to D-MFC in continuous mode at different hydraulic retention times (HRTs). As confirmed by COD removal in different HRTs (Fig. 7), maximum power density and OCV decreased in lower HRTs because of the lower time given to microorganisms to catabolize complex molecules. The maximum power density in continuous mode ($2.2 \text{ W} \cdot \text{m}^{-3}$) was two-fold higher in comparison to a similar study [43].

The coulombic efficiencies in continuous mode, 9.6, 3, 1.5 and 0.29% respectively in HRTs of 30, 20, 12 and 8 h, were highly lower than 30% observed in batch mode. However, 9.6% was much higher than that of previously reported coulombic efficiency in similar studies operated in batch mode [14,45].

3.3.1. Nitrate and phosphate change

Microorganisms play a crucial role in preserving the balance between different types of phosphorus by scavenging phosphorus even at nanomolar concentrations, binding it up into biomass, liberating it from complex organic matters, and altering its reductive potential which results in different solubilities [19]. Dairy wastewater includes

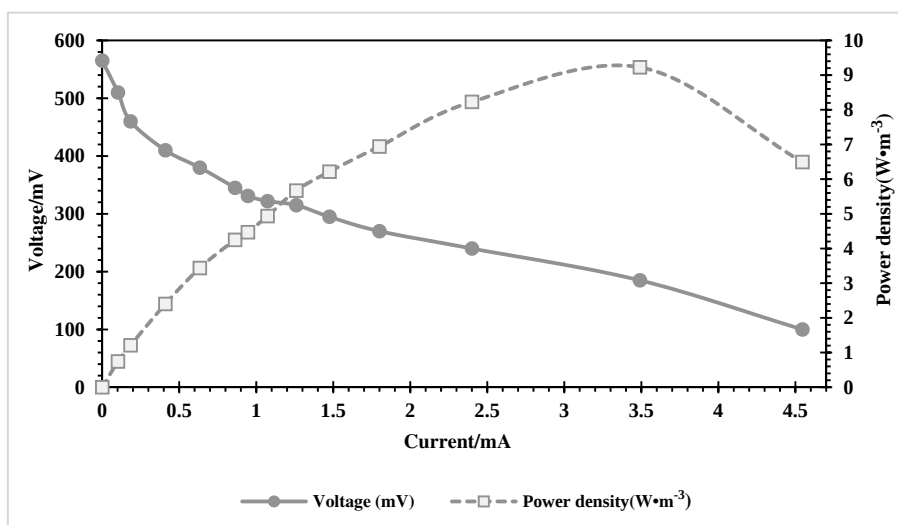


Fig. 5. Latter polarization and power density curves of L-MFC.

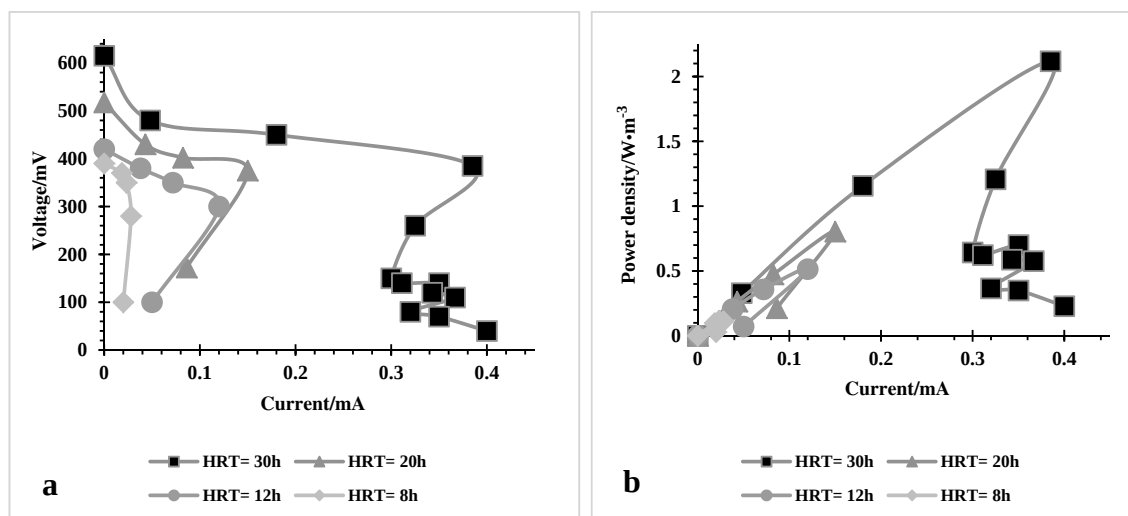


Fig. 6. (a) Polarization and (b) power density curves for D-MFC in continuous mode at HRT of 30, 20, 12 and 8 h.

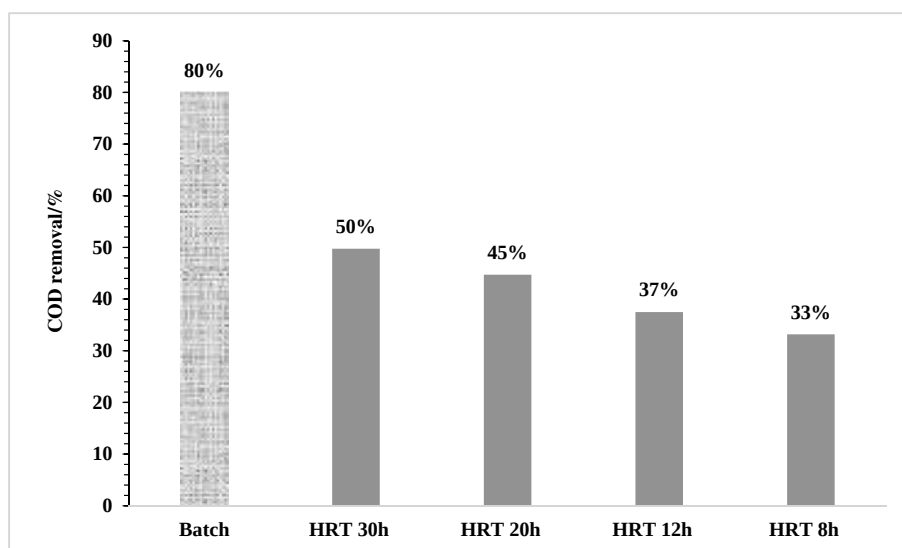


Fig. 7. Comparison of COD removal between batch and continuous operational modes.

high concentrations of ammonia–nitrogen, organic–nitrogen, and phosphorus whose removal or change has been examined in some study [21, 46–48]. Puig *et al.* [48] reported that pH could influence on conversion between different types of phosphorus which is a chemical mechanism without microorganisms intervention. Under anaerobic condition, organic phosphorus and polyphosphate are transformed into orthophosphate [19]. This could be because of low redox potential in MFCs that stimulates the increase of orthophosphate [47]. In order to investigate the performance of D-MFC in the treatment of dairy wastewater, changes in concentration of these substances were examined. Orthophosphate concentration was changed through D-MFC from 6.8 at influent to 12.55 $\text{mg}\cdot\text{ml}^{-1}$ at effluent (HRT = 8 h) which confirms the above argument.

Regarding nitrogen removal, some studies investigated this issue in different places such as cathodic chamber [49–53], anodic chamber [21,47,48] and even accompanied by supplementary processes [50], in continuous [21,48,50–53] and batch mode [47,49]. In this study, changes in concentration of all nitrogen types were analyzed (Fig. 8) and resulted in higher removal efficiency than previous studies. Most of the TKN content was converted to N_2 by sequential processes of ammonification, nitrification, and denitrification, and to some amount

to nitrate and nitrite by nitrification step. As can be realized from Fig. 8, nitrate and nitrite concentrations were higher than that at the influent. The performance of D-MFC was probably influenced by denitrification mechanism in which many electrons and protons were scavenged by denitrifying species [28].

Study of phosphorus and nitrogen removal in different external resistances is suggested in future works because the metabolic pathways of microorganisms can be very influenced by different rates of electron consumption through an external circuit. This can be investigated precisely and in a faster way using high throughput microfluidic MFCs. Besides, different temperature ranges might be another parameter influencing on the removal of these materials. To design a system suitable for phosphorus removal from wastewaters, separated successive parts should be devised. One in anaerobic condition for conversion of organic phosphate to orthophosphate and the next one in aerobic condition for reduction of orthophosphate to biomass [19]. A two-chamber MFC with an anodic part in anaerobic condition and a cathodic part including algal or other polyphosphate accumulating organisms (PAOs) in aerobic condition can be designed for this study. The next idea is the integration between MFCs and photo-bioreactors for better removal and energy production. The study of formed biofilm

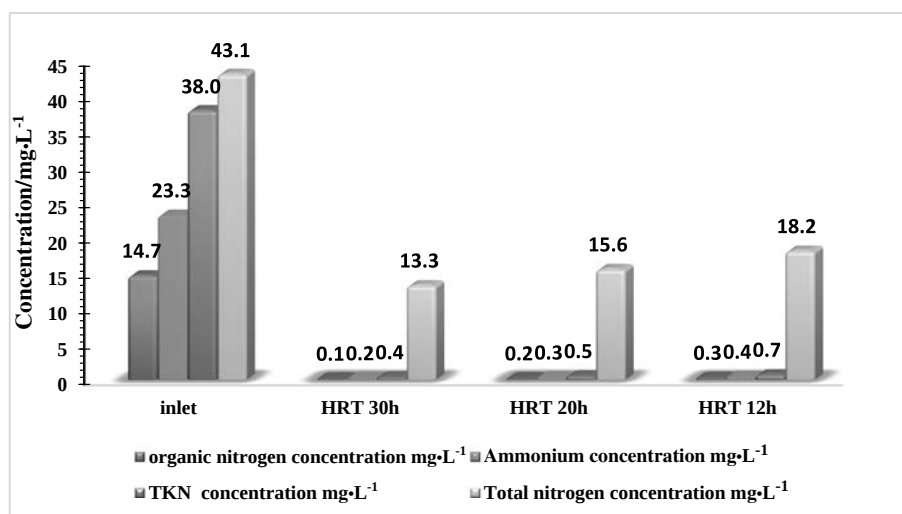


Fig. 8. Concentration of different nitrogen types in D-MFC influent and effluent in different HRTs.

on cathode and anode electrodes should reveal valuable information about the dominant nitrification and denitrification pathways such as anammox, etc. [20,54]. A preliminary hypothesis is that the nitrifying and denitrifying species are dominant respectively on cathode and anodic electrodes because of different oxygen level presenting in these parts.

3.4. MEC performance

After accomplishment of MFC tests, the MFC was converted to MEC to be characterized in batch mode. Applying voltage of 500 mV to the MEC was continued for about one month. Then, it was set to 300 mV and data logging started. The performance of the MEC was assessed in applied voltages of 300, 400, 600, 700, 800 and 1000 mV.

3.4.1. Current assessment

By applying a 20 Ω resistor in series with the MEC, current flow through the MEC was measured. Fig. 9 shows the current flow through the MEC in applied voltage of 700 mV for the course of 140 h. For every

applied voltage, it was observed that the current had a peak after about 2 h past wastewater refreshment, followed by an almost stable phase of current (Fig. 9, inset), and then the phase of current decrease started. It can be argued that the peaks were related to biodegradation of simpler nutrients. The stable phase was because of converting complex substances to smaller ones (such as acetate) and their consumption by microorganisms. It was continued until the complex substances suitable for microorganisms were removed to a little extent. This stability was completely obvious in lower applied voltages because the phase of voltage decrease started earlier when higher voltages was being applied. It is, as explained by Karimi *et al.* [55], because of higher rates of bio electrochemical reactions in higher voltages. It was also observed that, as the current was decreasing, the rate of gas production would become lower.

Fig. 10 shows the stable current density and average rate of gas production at every applied voltage among which the highest current density ($60 \text{ A} \cdot \text{m}^{-3}$) and gas production rate ($0.2 \text{ m}^3 \text{ H}_2 \cdot \text{m}^{-3} \cdot \text{d}^{-1}$) were produced in applied voltage of 700 mV. In this voltage, percentage of COD removal and the coulombic efficiency were 92% and 24%,

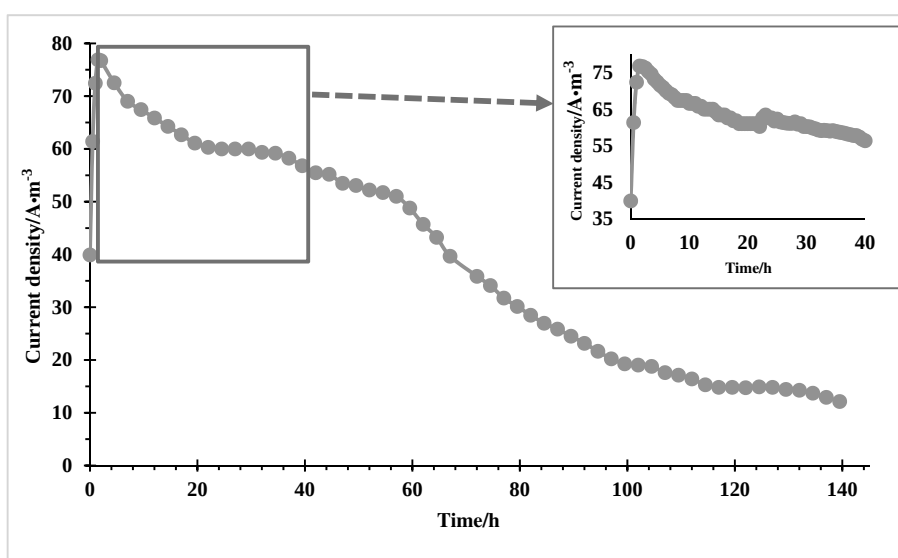


Fig. 9. Current density versus time in applied voltage of 700 mV. The inset shows the stable phase.

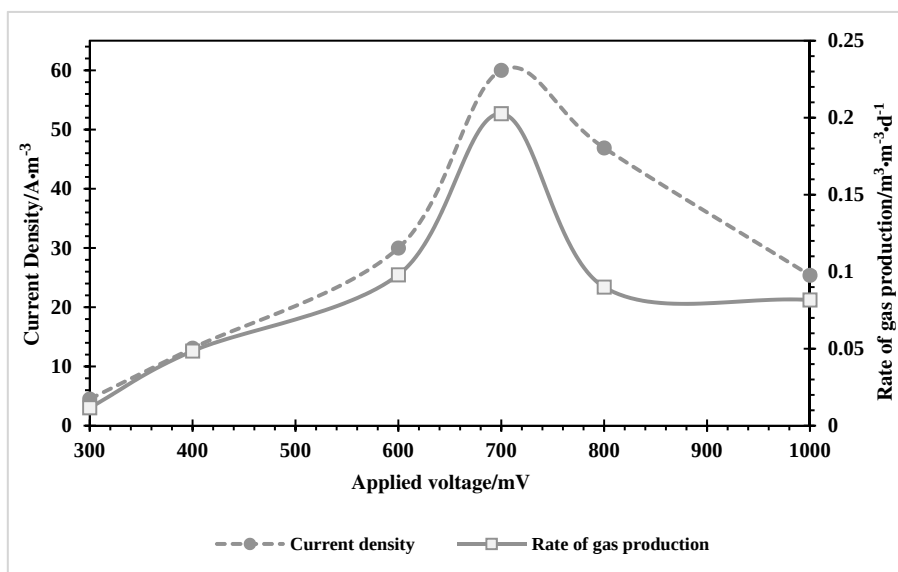


Fig. 10. Gas production rate and steady current density at each applied voltage.

respectively. COD removal in this system was significantly higher in comparison to other similar studies related to treatment of complex wastewater using MEC [4,56,57].

4. Conclusions

In this study, energy production with simultaneously dairy wastewater treatment was investigated in different systems and modes (microbial fuel cell, in presence of light and dark environment, batch and continuous and microbial electrolysis cell) using a successful design for treating complex wastewaters. This design showed better bioelectrochemical performance, and COD and nitrogen removal in comparison to similar studies. Change in phosphate and different types of nitrogen were investigated for the first time. The higher performance in these systems can be related to the annular design of the anode, its high surface to volume ratio available for microorganisms, and better bacterial attachment to stainless steel surface.

While L-MFC Performance in dynamic state (internal resistance = 100 Ω , power density = 5.15 $\text{W} \cdot \text{m}^{-3}$) was quite low and unsteady, it reached power density of 9.2 $\text{W} \cdot \text{m}^{-3}$ which was close to D-MFC performance (internal resistance = 50 Ω , power density = 10.3 $\text{W} \cdot \text{m}^{-3}$). From batch to continuous mode, and in lower HRTs, because of the lower time given to microorganisms to catabolize biomolecules in the wastewater, power density, COD removal and coulombic efficiency were reduced. Through processes such as ammonification, nitrification, and denitrification, most of the TKN content was converted to N_2 . However, the observed nitrate and nitrite were higher in effluent. Among different voltages applied to the MEC, the highest current density and gas production were observed in applied voltage of 700 mV in which percentage of COD removal and coulombic efficiency were 92% and 24%, respectively.

Some results revealed in this study should be more investigated in future studies for a better grasp of governing mechanisms, and reaching better performances in energy production and removal of water pollutions.

Acknowledgements

The authors are indebted to Zahra Ghobadi, Sharif University of Technology, for their valuable help in the study. This research was supported by Sharif University of Technology, Vice President for Research Grant G930111.

References

- [1] B.E. Logan, D. Call, S. Cheng, H.V.M. Hamelers, T.H.J.A. Sleutels, A.W. Jeremiasse, R.A. Rozendal, Microbial electrolysis cells for high yield hydrogen gas production from organic matter, *Environ. Sci. Technol.* 42 (23) (2008) 8630–8640.
- [2] B.E. Logan, B. Hamelers, R. Rozendal, U. Schröder, J. Keller, S. Freguia, P. Aelterman, W. Verstraete, K. Rabaey, Microbial fuel cells: methodology and technology, *Environ. Sci. Technol.* 40 (17) (2006) 5181–5192.
- [3] R.C. Wagner, J.M. Regan, S.E. Oh, Y. Zuo, B.E. Logan, Hydrogen and methane production from swine wastewater using microbial electrolysis cells, *Water Res.* 43 (5) (2009) 1480–1488.
- [4] Y.H. Jia, J.Y. Choi, J.H. Ryu, C.H. Kim, W.K. Lee, H.T. Tran, R.H. Zhang, D.H. Ahn, Hydrogen production from wastewater using a microbial electrolysis cell, *Korean J. Chem. Eng.* 27 (6) (2010) 1854–1859.
- [5] S. Cheng, B.E. Logan, High hydrogen production rate of microbial electrolysis cell (MEC) with reduced electrode spacing, *Bioresour. Technol.* 102 (3) (2011) 3571–3574.
- [6] N. Wrana, R. Sparling, N. Cicek, D.B. Levin, Hydrogen gas production in a microbial electrolysis cell by electrohydrogenesis, *J. Clean. Prod.* 18 (2010) S105–S111.
- [7] L. Gil-Carrera, A. Escapa, P. Mehta, G. Santoyo, S.R. Guiot, A. Moran, B. Tartakovsky, Microbial electrolysis cell scale-up for combined wastewater treatment and hydrogen production, *Bioresour. Technol.* 130 (2013) 584–591.
- [8] L. Ren, M. Siegert, I. Ivanov, J.M. Pisciotta, B.E. Logan, Treatability studies on different refinery wastewater samples using high-throughput microbial electrolysis cells (MECs), *Bioresour. Technol.* 136 (2013) 322–328.
- [9] A. Wang, W. Liu, N. Ren, H. Cheng, D.-J. Lee, Reduced internal resistance of microbial electrolysis cell (MEC) as factors of configuration and stuffing with granular activated carbon, *Int. J. Hydrog. Energy* 35 (24) (2010) 13488–13492.
- [10] A. Tenca, R.D. Cusick, A. Schievano, R. Oberti, B.E. Logan, Evaluation of low cost cathode materials for treatment of industrial and food processing wastewater using microbial electrolysis cells, *Int. J. Hydrog. Energy* 38 (4) (2013) 1859–1865.
- [11] R.D. Cusick, B. Bryan, D.S. Parker, M.D. Merrill, M. Mehanna, P.D. Kiely, G. Liu, B.E. Logan, Performance of a pilot-scale continuous flow microbial electrolysis cell fed winery wastewater, *Appl. Microbiol. Biotechnol.* 89 (6) (2011) 2053–2063.
- [12] W. Liu, S. Huang, A. Zhou, G. Zhou, N. Ren, A. Wang, G. Zhuang, Hydrogen generation in microbial electrolysis cell feeding with fermentation liquid of waste activated sludge, *Int. J. Hydrog. Energy* 37 (18) (2012) 13859–13864.
- [13] P.A. Selembo, J.M. Perez, W.A. Lloyd, B.E. Logan, High hydrogen production from glycerol or glucose by electrohydrogenesis using microbial electrolysis cells, *Int. J. Hydrog. Energy* 34 (13) (2009) 5373–5381.
- [14] N. Montpart, L. Rago, J.A. Baeza, A. Guisasola, Hydrogen production in single chamber microbial electrolysis cells with different complex substrates, *Water Res.* 68 (2015) 601–615.
- [15] B. Qin, H. Luo, G. Liu, R. Zhang, S. Chen, Y. Hou, Y. Luo, Nickel ion removal from wastewater using the microbial electrolysis cell, *Bioresour. Technol.* 121 (2012) 458–461.
- [16] M.M. Mardanpour, M. Nasr Esfahany, T. Behzad, R. Sedaqatvand, Single chamber microbial fuel cell with spiral anode for dairy wastewater treatment, *Biosens. Bioelectron.* 38 (1) (2012) 264–269.
- [17] J. Danalewicz, T. Papagiannis, R. Belyea, M. Tumbleson, L. Raskin, Characterization of dairy waste streams, current treatment practices, and potential for biological nutrient removal, *Water Res.* 32 (12) (1998) 3555–3568.
- [18] B. Demirel, O. Yenigun, T.T. Onay, Anaerobic treatment of dairy wastewaters: a review, *Process Biochem.* 40 (8) (2005) 2583–2595.
- [19] K.D. McMahon, E.K. Read, Microbial contributions to phosphorus cycling in Eutrophic Lakes and wastewater, *Annu. Rev. Microbiol.* 67 (1) (2013) 199–219.
- [20] G.Z. Breisha, J. Winter, Bio-removal of nitrogen from wastewaters—A review, *J. Am. Sci.* 6 (12) (2010) 508–528.
- [21] D. Jiang, M. Curtis, E. Troop, K. Scheible, J. McGrath, B. Hu, S. Suib, D. Raymond, B. Li, A pilot-scale study on utilizing multi-anode/cathode microbial fuel cells (MAC MFCs) to enhance the power production in wastewater treatment, *Int. J. Hydrog. Energy* 36 (1) (2011) 876–884.
- [22] T.J. Britz, C. van Schalkwyk, Y.-T. Hung, Treatment of Dairy Processing Wastewaters, Waste Treatment in the Food Processing Industry, CRC Press, Taylor and Francis Group, UK, 2006 1–28.
- [23] D. Call, B.E. Logan, Hydrogen production in a single chamber microbial electrolysis cell lacking a membrane, *Environmental Science & Technology* 42 (9) (2008) 3401–3406.
- [24] Z.G. Naraghi, S. Yaghmaei, M.M. Mardanpour, M. Hasany, Produced water treatment with simultaneous bioenergy production using novel bioelectrochemical systems, *Electrochim. Acta* 180 (2015) 535–544.
- [25] G.G. Kumar, V.G.S. Sarathi, K.S. Nahm, Recent advances and challenges in the anode architecture and their modifications for the applications of microbial fuel cells, *Biosens. Bioelectron.* 43 (2013) 461–475.
- [26] S. Cheng, H. Liu, B.E. Logan, Increased performance of single-chamber microbial fuel cells using an improved cathode structure, *Electrochem. Commun.* 8 (3) (2006) 489–494.
- [27] R.A. Rozendal, H.V. Hamelers, R.J. Molenkamp, C.J. Buisman, Performance of single chamber biocatalyzed electrolysis with different types of ion exchange membranes, *Water Res.* 41 (9) (2007) 1984–1994.
- [28] M. Hasany, M.M. Mardanpour, S. Yaghmaei, Biocatalysts in microbial electrolysis cells: a review, *Int. J. Hydrog. Energy* 41 (3) (2016) 1477–1493.
- [29] A. Wang, W. Liu, S. Cheng, D. Xing, J. Zhou, B.E. Logan, Source of methane and methods to control its formation in single chamber microbial electrolysis cells, *Int. J. Hydrog. Energy* 34 (9) (2009) 3653–3658.
- [30] W.-Z. Liu, A.-J. Wang, N.-Q. Ren, X.-Y. Zhao, L.-H. Liu, Z.-G. Yu, D.-J. Lee, Electrochemically assisted biohydrogen production from acetate, *Energy Fuel* 22 (1) (2007) 159–163.
- [31] A. Wang, W. Liu, N. Ren, J. Zhou, S. Cheng, Key factors affecting microbial anode potential in a microbial electrolysis cell for H_2 production, *Int. J. Hydrog. Energy* 35 (24) (2010) 13481–13487.
- [32] P.D. Kiely, R. Cusick, D.F. Call, P.A. Selembo, J.M. Regan, B.E. Logan, Anode microbial communities produced by changing from microbial fuel cell to microbial electrolysis cell operation using two different wastewaters, *Bioresour. Technol.* 102 (1) (2011) 388–394.
- [33] L. Lu, N. Ren, X. Zhao, H. Wang, D. Wu, D. Xing, Hydrogen production, methanogen inhibition and microbial community structures in psychrophilic single-chamber microbial electrolysis cells, *Energy Environ. Sci.* 4 (4) (2011) 1329–1336.
- [34] L.S. Clesceri, A.D. Eaton, A.E. Greenberg, A.P.H. Association, A.W.W. Association, W.E. Federation, Standard Methods for the Examination of Water and Wastewater, American Public Health Association, The University of California, United States, 1998.
- [35] B.E. Logan, Microbial Fuel Cells, John Wiley & Sons, Hoboken, New Jersey, 2008.
- [36] J. Larminie, A. Dicks, M.S. McDonald, Fuel Cell Systems Explained, Wiley New York, 2003.
- [37] L. Zhang, X. Zhu, J. Li, Q. Liao, D. Ye, Biofilm formation and electricity generation of a microbial fuel cell started up under different external resistances, *J. Power Sources* 196 (15) (2011) 6029–6035.
- [38] Y. Zou, J. Pisciotta, R.B. Billmyre, I.V. Baskakov, Photosynthetic microbial fuel cells with positive light response, *Biotechnol. Bioeng.* 104 (5) (2009) 939–946.
- [39] C.-C. Fu, T.-C. Hung, W.-T. Wu, T.-C. Wen, C.-H. Su, Current and voltage responses in instant photosynthetic microbial cells with *Spirulina platensis*, *Biochem. Eng. J.* 52 (2) (2010) 175–180.
- [40] T. Jafari, M. Rahimnejad, A.A. Ghoreyshi, G. Najafpour, F. Hghparast, W.R.W. Daud, Assessment of bioelectricity production in microbial fuel cells through series and parallel connections, *Energy Convers. Manag.* 75 (2013) 256–262.

- [41] H. Liu, Microbial Fuel Cell: Novel Anaerobic Biotechnology for Energy Generation from Wastewater, *Anaerobic Biotechnology for Bioenergy Production: Principles and Applications*, John Wiley & Sons, Hoboken, New Jersey, 2009 221–246.
- [42] E. Elakkiya, M. Matheswaran, Comparison of anodic metabolisms in bioelectricity production during treatment of dairy wastewater in microbial fuel cell, *Bioresour. Technol.* 136 (2013) 407–412.
- [43] S.V. Mohan, G. Mohanakrishna, G. Velvizhi, V.L. Babu, P. Sarma, Bio-catalyzed electrochemical treatment of real field dairy wastewater with simultaneous power generation, *Biochem. Eng. J.* 51 (1) (2010) 32–39.
- [44] A.S. Mathuriya, V. Sharma, Bioelectricity production from various wastewaters through microbial fuel cell technology, *J. Biochem. Technol.* 2 (1) (2010) 133–137.
- [45] S. Velasquez-Orta, I. Head, T. Curtis, K. Scott, Factors affecting current production in microbial fuel cells using different industrial wastewaters, *Bioresour. Technol.* 102 (8) (2011) 5105–5112.
- [46] O. Ichihashi, K. Hirooka, Removal and recovery of phosphorus as struvite from swine wastewater using microbial fuel cell, *Bioresour. Technol.* 114 (2012) 303–307.
- [47] B. Min, J. Kim, S. Oh, J.M. Regan, B.E. Logan, Electricity generation from swine wastewater using microbial fuel cells, *Water Res.* 39 (20) (2005) 4961–4968.
- [48] S. Puig, M. Serra, M. Coma, M. Cabre, M.D. Balaguer, J. Colprim, Effect of pH on nutrient dynamics and electricity production using microbial fuel cells, *Bioresour. Technol.* 101 (24) (2010) 9594–9599.
- [49] P. Clauwaert, K. Rabaey, P. Aelterman, L. De Schamphelaire, T.H. Pham, P. Boeckx, N. Boon, W. Verstraete, Biological denitrification in microbial fuel cells, *Environ. Sci. Technol.* 41 (9) (2007) 3354–3360.
- [50] B. Virdis, K. Rabaey, Z. Yuan, J. Keller, Microbial fuel cells for simultaneous carbon and nitrogen removal, *Water Res.* 42 (12) (2008) 3013–3024.
- [51] B. Virdis, K. Rabaey, R.A. Rozendal, Z. Yuan, J. Keller, Simultaneous nitrification, denitrification and carbon removal in microbial fuel cells, *Water Res.* 44 (9) (2010) 2970–2980.
- [52] Y.H. Jia, H.T. Tran, D.H. Kim, S.J. Oh, D.H. Park, R.H. Zhang, D.H. Ahn, Simultaneous organics removal and bio-electrochemical denitrification in microbial fuel cells, *Bioprocess Biosyst. Eng.* 31 (4) (2008) 315–321.
- [53] B. Virdis, K. Rabaey, Z. Yuan, R.A. Rozendal, J.R. Keller, Electron fluxes in a microbial fuel cell performing carbon and nitrogen removal, *Environ. Sci. Technol.* 43 (13) (2009) 5144–5149.
- [54] H.O. Den Camp, B. Kartal, D. Guven, L. Van Niftrik, S. Haaijer, W. Van Der Star, K. Van De Pas-Schoonen, A. Cabezas, Z. Ying, M. Schmid, Global impact and application of the anaerobic ammonium-oxidizing (anammox) bacteria, *Biochem. Soc. Trans.* 34 (1) (2006) 174–178.
- [55] M.K. Alavijeh, M.M. Mardanpour, S. Yaghmaei, A generalized model for complex wastewater treatment with simultaneous bioenergy production using the microbial electrochemical cell, *Electrochim. Acta* 167 (2015) 84–96.
- [56] B. Logan, R. Wagner, R. Cusick, P. Selembo, Using microbial electrolysis cells (MECs) for wastewater treatment, *Proc. Water Environ. Fed.* (17) (2009) 536–541.
- [57] E. Lalaurette, S. Thammannagowda, A. Mohagheghi, P.-C. Maness, B.E. Logan, Hydrogen production from cellulose in a two-stage process combining fermentation and electrohydrogenesis, *Int. J. Hydrog. Energy* 34 (15) (2009) 6201–6210.