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Article

Electricity production by a microbial fuel cell fueled by brewery wastewater and the factors in its membrane deterioration

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ABSTRACT

Electricity production from brewery wastewater using dual-chamber microbial fuel cells (MFCs) with a tin-coated copper mesh in the anode was investigated by changing the hydraulic retention time (HRT). The MFCs were fed with wastewater samples from the inlet (inflow, MFC-1) and outlet (outflow, MFC-2) of an anaerobic digester of a brewery wastewater treatment plant. Both chemical oxygen demand removal and current density were improved by decreasing HRT. The best MFC performance was with an HRT of 0.5 d. The maximum power densities of 8.001 and 1.843 $\mu\text{W}/\text{cm}^2$ were obtained from reactors MFC-1 and MFC-2, respectively. Microbial diversity at different conditions was studied using PCR-DGGE profiling of 16S rRNA fragments of the microorganisms from the biofilm on the anode electrode. The MFC reactor had mainly *Geobacter*, *Shewanella*, and *Clostridium* species, and some bacteria were easily washed out at lower HRTs. The fouling characteristics of the MFC Nafion membrane and the resulting degradation of MFC performance were examined. The ion exchange capacity, conductivity, and diffusivity of the membrane decreased significantly after fouling. The morphology of the Nafion membrane and MFC degradation were studied using scanning electron microscopy and attenuated total reflection-Fourier transform infrared spectroscopy.

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1. Introduction

Present global energy requirements are mostly dependent on fossil fuels, which are predicted to be depleted because of limited fossil energy sources. The combustion of fossil fuels also has serious negative effects on the environment due to CO_2 emission. Climate change, increased global demand for limited oil and natural gas reserves, and energy security have motivated the search for alternatives to fossil fuels [1]. A microbial fuel cell (MFC) is a device to treat wastewater and produce electricity. Microbes attached to the anode of the MFC oxidize

substrates such as brewery wastewater and generate electrons and protons in the process. A MFC is a bioelectrochemical system that exploits the bacterial oxidation of biodegradable organic matter to generate electricity [2–4]. The microbial metabolism generates electrons (e^-) and protons (H^+) by the oxidation of organic substrates, which produces a biopotential. The electrons are transferred to the anode by the bacteria by several mechanisms, such as by a solid transfer matrix or electron shuttling. Electrons are then transferred to the cathode through an external circuit [5]. Brewery wastewater produced in cooling and washing units has a high chemical oxygen de-

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Fig. 1. Schematic of the brewery wastewater treatment plant and MFCs.

mand (COD) but is nontoxic. There are electrochemical limitations on the performance of the MFCs because of the discharge resistance, which results from ohmic, kinetic, and transport limitations [6,7]. A reverse correlation exists between the discharge resistance and power output [8,9]. Electrochemical impedance spectroscopy (EIS) is a technique that measures the resistance of a fuel cell [10]. There has been some research on resistance analysis by EIS using simulated artificial wastewater [11]. However, there are few reports using real wastewater.

In this paper, the possibility of continuous electricity production from brewery wastewater using dual-chamber MFCs was studied. The influences of the hydraulic retention time (HRT) on the voltage and power density and the effect of COD removal efficiency on the MFC performance were investigated. A basic electrochemical model of the MFC was set up using the polarization curve, and an elaborate analysis of the various voltage losses was conducted to obtain the net fuel cell J - V behavior. The surface morphology, dispersion, and functional groups were investigated by scanning electronic microscopy (SEM) and attenuated total reflection-Fourier transform infrared (ATR-FTIR) spectroscopy.

2. Experimental

2.1. MFC construction and operation

Two identical plexiglass dual-chamber MFCs were constructed on the basis of a previous study [12,13]. The reactors comprised a Nafion® 117 (Dupont) proton exchange membrane (PEM) to separate the partitions and tin-coated copper mesh as the anode and cathode electrodes. The PEM and tin-coated copper mesh had an effective area of 7 cm² and were fixed in the middle of the two chambers. The volumes of the anode and cathode chambers were 275 cm³, and the effective volumes were 250 cm³. Nafion® 117 was sequentially pretreated at 85 °C for 1 h in 5% H₂O₂, distilled water, 0.05 mol/L H₂SO₄, and distilled water as described in the literature [7]. The

electrodes were in contact with the PEM and the outer surface of the cathode was exposed to distilled water. The electrodes were connected by a titanium wire across a decade resistance box with 500 Ω external resistance at start-up and 100 Ω thereafter, except during the power density and EIS analysis. The MFCs were fed with wastewater samples obtained from the inlet (called the inflow (MFC-1)) and outlet (called the outflow (MFC-2)) of the anaerobic digester of a brewery wastewater treatment plant (Fig. 1). Brewery wastewater was collected from a local brewing plant in Istanbul, which produces malt from barley. The characteristics of the two types of wastewater are given in Table 1.

The MFCs were continuously operated at room temperature (25 ± 2 °C) for approximately 87 d. N₂ was sparged to maintain anaerobic conditions in the anodic chamber. The wastewater in the MFC reactors was initially inoculated with a sediment sample obtained from the Golden Horn in Istanbul at a ratio of 1:10. The enrichment of microorganisms was carried out using a 250-mL serum bottle under anaerobic conditions. The enrichment medium was a composition of synthetic wastewater constituents with the following compounds (amount in 1 L deionized water): 9 g glucose, 4 g yeast extract, 4 g NaHCO₃, 0.6 g NH₄Cl, 9.3 g NaH₂PO₄·H₂O, 3.2 g Na₂H₂PO₄, 0.125 g K₂HPO₄·3H₂O, 0.1 g MgCl₂·6H₂O, 0.11 g CaCl₂·2H₂O, 3.92 g NaHCO₃, and trace amounts of metal ions (Fe, Zn, Co, Cu, and Ni) and vitamins [14]. The pH of the medium was 6.7. Cysteine (0.5 g/L) was included in order to keep the medium in an anaerobic condition. The medium (100 mL) was put into the bottle and flushed with nitrogen gas for 5 min to remove the air inside. Then the bottle was capped with a rubber stopper and stirred at 150 rpm with a magnetic stirrer. Each enrichment

Table 1
Characteristics of the brewery wastewater.

Stage	COD (mg/L)	BOD ₅ (mg/L)	TN (mg/L)	TP (mg/L)
MFC-1	2250 ± 80	650 ± 50	35 ± 2	33 ± 2
MFC-2	480 ± 20	250 ± 20	10 ± 2	12 ± 4

cycle continued for 2 d at room temperature (25 °C). After the second transfer, the enriched culture was inoculated into the anode chamber. As discussed in previous studies, the external resistance in the MFCs affected bacterial diversity and intermediate metabolism [1]. Therefore, the anode was enriched with a 500 Ω external resistance. After 5 d, the anode solution was removed and replaced with fresh wastewater, and the external resistance was gradually decreased to 100 Ω . The cathode chamber was filled with distilled water and aerated continuously at 10 cm³/min at 20 °C and 101 kPa. The MFC reactors were operated in continuous mode. They were fed by a peristaltic pump (Watson Marlow, Belgium) and refilled every time the OCV dropped below 200 mV.

2.2. Analysis

The voltage (*V*) across the load was monitored at 5 min intervals in real time using a computer-based data logging system (Agilent 34970A). The current (*I*) and power ($P = IV$) were calculated as described in a previous study [7] and normalized to the effective surface area of the anode (7 cm²). MFC performance was analyzed by EIS using the Ludre L02/V01 software (produced by Ludre Software, Istanbul, Turkey) electrochemical interface connected to a computer equipped with ZsimpWin 3.22 software [7,15]. Polarization and power density curves were obtained automatically for the range of external resistance of 10–20 k Ω . The current and potential were normalized to the effective surface area of the electrode (7 cm²).

EIS was performed over the frequency range of 1 mHz to 100 kHz. The amplitude of the modulating sinusoidal voltage was 10 mV using a Ludre potentiostat. By fitting and simulating the experimental data with equivalent circuits, the internal resistance distributions were calculated using ZsimpWin 3.22. All chemical analyses were done using the standard APHA-AWWA-WEF methods [16]. Microstructural changes in the Nafion were determined using the attenuated total reflection (ATR) method with an IR spectrometer with a Watson 1000 FTIR apparatus. Spectra were acquired using 100 scans between 400 and 4000 cm⁻¹ at a resolution of 16 cm⁻¹. A CamScan Apollo-300 scanning electron microscope (SEM) with energy dispersive X-ray analysis (EDX) was used to investigate the membrane morphology. The film surface was sputter coated with gold (Polaron Range). SEM pictures were taken at 2000 $\times$ magnification.

2.3. Microbial community analysis

The diversity and changes in the bacterial population of the inflow and outflow were profiled by DNA extraction and the PCR-DGGE of partial 16S rRNA genes followed by their sequencing. The extraction of DNA from the samples was performed using a PowerSoil DNA isolation kit (MO BIO Laboratories, Inc., USA) using the manufacturer's instructions. Universal GC-BacV3f (5'-CGC CCG CCG CGC GCG GCG GGC GGG GCG GGG GCA CGG GGG GCC TAC GGG AGG CAG CAG-3') and 907R (5'-CCG TCA ATT CMT TTG AGT TT-3') primers were used for amplifying the bacterial 16S rRNA genes for DGGE analysis [1,17,18].

Each PCR reaction mixture was prepared with a total volume of 50 μ L containing 2 μ L of each DNA extract to 0.25 μ L of 100 μ mol/L primers, 5 μ L combination of 10 $\times$ reaction buffer (TriseHCl, pH 8.8), 0.125 μ L of 40 mmol/L dNTPs, 0.75 μ L Taq DNA polymerase, 1 μ L bovine serum albumin, and 40.63 μ L sterile purified water. The PCR amplification of 16S rRNA was performed with a BIO-RAD Mycycler Thermal Cycler System using the protocol: initial denaturation at 95 °C for 5 min, followed by 30 cycles of denaturing at 94 °C for 0.5 min, annealing at 50 °C for 1 min and extension at 72 °C for 2 min, and the final extension at 72 °C for 10 min and end at 4 °C.

The DGGE profiling of bacterial populations was performed using a Bio-Rad Dcode system (Bio-Rad, USA). Electrophoresis was carried out in 8% acrylamide gels with a denaturing gradient from 25% to 65% (7 mol/L urea plus 40% formamide). Gels were run at 60 °C and 60 V for 30 min, and at 120 V for 8 h, then stained with SYBRs Gold and the bands were observed under blue light. The dominant bands were eluted using sterile water overnight. The sequences were compared with the data in GenBank (<http://www.ncbi.nlm.nih.gov/blast/>).

3. Results and discussion

3.1. Polarization measurements

The HRT is an important parameter in wastewater treatment and it directly affects the design and operation of the equipment. Research has shown that the HRT has a significant effect on the electricity production characteristics of a continuous-flow MFC [19]. The type and quantity of bacteria can be controlled by regulating the HRT. When the HRT is decreased, the strength of the substrate is increased, resulting in an increase in the total rate of substrate consumption (by bacteria), and power generation will increase [10]. To understand the effects of the HRT on the power output, MFC-1 and MFC-2 were operated continuously at three different HRTs (0.5, 0.75, and 1 d).

Fig. 2 illustrates the results of the effect of HRT on polarization diagram and power density. At high HRT, there was a rapid drop in voltage, which was followed by a linear decrease. The ideal polarization curve can be divided into three regions: activation polarization at high current density, concentration polarization at low current density, and ohmic polarization in the intermediate linear region. In this study, the internal resistance was determined from the sum of all the resistances obtained from the simulation results. Fig. 2(a) shows that a maximum power density of 8.001 μ W/cm² was produced from MFC-1 at an HRT of 0.5 d with 100 Ω external resistance and 79.58 Ω internal resistance. The stepwise increase of HRT from 0.5 to 1 d gave a smaller power output relative to that at 0.5 d. The power density was decreased to 1.069 μ W/cm² by increasing HRT to 1 d for MFC-1.

For MFC-2, the maximum power density was not negatively affected by increasing the HRT. The power decreased from 1.843 to 1.235 μ W/cm² as a result of changing HRT from 0.5 to 0.75 d and it increased again to 1.731 μ W/cm² for the HRT of 1 d. The internal resistance was increased from 10.59 to 200.15

Fig. 2. Polarization and power density curves for MFC-1 (a) and MFC-2 (b) at different HRTs.

Ω by increasing the HRT. A similar power output from the HRT values of 1 and 0.5 d could be explained by the internal resistance. However, a sustainable and higher power output was obtained from MFC-2 when the external resistance was close to the internal resistance.

The results demonstrated that the performance of MFC-1 was better than that of MFC-2 as a consequence of the organic loading rates. The internal resistance results also showed a good relationship with the external resistance. There was sustainable power output from the MFCs. The higher power output obtained at low HRTs confirmed that a continuous supply of brewery wastewater was rapidly converted to energy.

3.2. Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy measurements were performed for MFC-1 and MFC-2 at the optimum HRT of 0.5 d using a potentiostat (Ludre Software, Istanbul, Turkey). The Nyquist impedance plots for both MFCs are shown in Fig. 3.

Performance parameters such as the solution resistance (R_s ,

ohmic resistance), anodic (R_a) and cathodic (R_c) polarization resistances, and constant phase element (CPE) were determined by fitting the impedance data to an equivalent circuit of the system, which is shown in Fig. 4. The equivalent circuit was defined using the best fit for the EIS data. Observed differences

Fig. 3. Nyquist plots for MFC-1 and MFC-2.

Fig. 4. Equivalent circuit for the two MFCs.

in the values of R_s , R_a , and R_c are given in Table 2. Variations in the composition and concentration of the ions in the electrolytes changed the resistance of the solution, thus causing ohmic losses in the MFCs during the operation with an HRT of 0.5 d. As seen in Table 2, R_c (inverse of the cathodic reaction rate), R_s , and R_a were higher in MFC-1 compared to MFC-2. The reasons for this were the different wastewater compositions and the concentrations of the ions in the wastewater.

The internal resistance was determined from the sum of all the resistances obtained from the simulation results. The main resistance was found to be the anodic charge transfer resistance (50% and 62.4% in MFC-1 and MFC-2, respectively), which was inversely proportional to the chemical reaction rate in all runs. In this study, the reactors were inoculated with a mixed culture. However, it has been suggested that the use of more active microorganisms will decrease the anodic charge transfer resistance [20].

3.3. Experimental results

The average TN removal was similar for both MFCs: 47% for MFC-1 and 41% for MFC-2, while the TP removal efficiencies were 65% and 55%, respectively. After stabilization, the highest COD removal efficiency was 82% in both systems. This was because readily available organics were supplied to the MFCs in sufficient quantity and were rapidly converted to electricity by the anode biofilm with the increase of the influent concentration. This result is in agreement with previous findings that the anodic reactions are determined by the available carbon fuel in the influent COD [21].

3.4. Changes in microbial population

The changes in the DGGE profile of the microbial population in the MFCs are presented in Fig. 5. The closest relatives of each band are given in Table 3. The first two lanes represent the microbial diversity in the influent brewery wastewater, while the last two show the bacterial population in the effluent brewery wastewater. Uncultured *Clostridium* sp. (band 8) was only present in the inflow brewery wastewater. Similarly, uncultured *Firmicutes* bacterium (band 4) was present only in the

Table 2
Impedance parameters of MFC-1 and MFC-2.

Stage	R_a/Ω	R_c/Ω	R_s/Ω	R_{in}/Ω
MFC-1	65 (50%)	45 (34.6%)	20 (15.4%)	130
MFC-2	28.26 (62.4%)	15 (33.2%)	2 (4.4%)	45.26

Fig. 5. DGGE profile of the bacterial diversity in brewery wastewater.

outflow brewery wastewater. Uncultured *Geobacter* sp. (bands 2 and 7) was identified in the MFC reactors operated with both influent and effluent brewery wastewater.

Uncultured *Geobacter* sp. was dominant in both MFC reactors. Uncultured bacterium sp. (bands 1, 3, 5, and 6) also played an important role in the treatment of brewery wastewater by the MFC reactors [22,23].

The distribution of the bacterial population indicated that MFC-1 and MFC-2 were dominated by *Geobacter* and *Clostridium* species. *Clostridium*, *Geobacter*, *Firmicutes*, and *Shewanella* species have been commonly reported as having the capability to generate electricity [23].

3.5. Properties of clean Nafion 117 membrane

ATR-FTIR, SEM and EDX, and TGA/DSC analysis were performed on the clean membranes. The ATR-FTIR spectra of the clean membrane are shown in Fig. 6. The bands in the spectra are given in Table 4.

Table 3
Closest relatives of the DGGE bands.

Band No.	Bacteria	Accession No.	Similarity (%)	Ref.
1	Uncultured bacterium	EF515697	99	[24]
2	Uncultured <i>Geobacter</i> sp.	JF817834	93	[20]
3	Uncultured bacterium	FR823624	92	[25]
4	Uncultured <i>Firmicutes</i> bacterium	HE856474	88	[26]
5	Uncultured bacterium	FR823540	92	[25]
6	Uncultured bacterium	EF515517	99	[24]
7	Uncultured <i>Geobacter</i> sp.	JF817745	82	[20]
8	Uncultured <i>Clostridium</i> sp.	JQ724353	93	[27]

Fig. 6. ATR-FTIR spectra of a clean Nafion 117 membrane.

Two types of water, free and bound, were found in the membrane. Free water is usually shown in the 3700–3080 cm^{-1} zone as monomeric H_2O molecules (Fig. 6). Bound water is present in the porous structure and it is difficult to remove [14,35].

This band was directly related to the increase in the hydrophilic and conductive properties of the membrane and corresponded to the stretching of H–O in the free SO_3H group [16,28]. In Nafion membranes, the 1410 and 910 cm^{-1} bands are attributed to the S=O and S–OH vibrations of the stretching band of SO_3H [16]. The membrane showed two peaks at 1056 and 1300 cm^{-1} , which were the $-\text{SO}_3^-$ asymmetric and symmetric stretching bands, respectively. The asymmetric $-\text{SO}_3^-$ band can be obscured by strong C–F absorption. However, the moisture sensitivity can be affected by proton transfer [16]. In Fig. 6, this band was observed as a shoulder at 1316 and 1304 cm^{-1} , which supported this conclusion. Also, the vibrations of the $-\text{SO}_3^-$ and SO_3H groups gave information about proton transfer, the proton transport mechanism, and coordination events [16]. In Fig. 6, strong peaks of CF bands were observed in the region between 1300 and 1100 cm^{-1} . For the Nafion membrane, two bands appeared in the region between 1000 and 900 cm^{-1} , which are C–O–C bonds directly connected to the main and side chains.

3.6. Properties of the used membrane

The MFC-1 and MFC-2 membranes were assessed in two

different ways. A comparison of the membranes taken from the reactors is shown in Fig. 7. In Fig. 7, the MFC-2 data are not shown because of the overlap of the signals, but there were some differences in the peaks. The OH stretching band of the MFC-2 membrane was shifted to the lower frequencies, and the intensity decreased compared with MFC-1. In fuel cell systems, a decrease in the intensity of this band means that the OH groups on the membrane surface were decreased, and this is directly proportional to a reduction in membrane conductivity [16]. This shift in the band can be due to microbial contamination on the surface of the membrane [28]. The shift amount of the anode was 877 cm^{-1} . This was also referred to as a N–H stretching vibration band (amide band of protein) [16]. In addition, more obviously seen on the anode side, a new peak at 2921 cm^{-1} was observed. This peak was not present for the cathode. When the $-\text{SO}_3^-$ asymmetric and symmetric stretching bands of MFC-2 and MFC-1 membranes are compared, it can be seen that the intensity of these bands was very low for the anode side and it had disappeared for the cathode. Similarly, for both the anode and cathode, the CF symmetric band had disappeared, and the intensity of the asymmetric band was significantly reduced (for the anode at 1212 cm^{-1} and for the cathode at 1216 cm^{-1}). As shown in Fig. 7, the symmetric C–F and C–O–C bands of the sulfone group formed a broad spectrum band (1060 cm^{-1}) in the region between 1181 and 842 cm^{-1} for the anode. In microbial fuel cells, a visible biofilm forms on the surface of the membrane layer. The analysis showed that the

Table 4
Bands in the ATR-FTIR spectrum of a clean Nafion 117 membrane.

Wavenumber (cm^{-1})	Bands
3453	OH stretching of water molecule [28–30]
2713	CH_2 asymmetric aliphatic stretching [30]
2379	CH_3 symmetric aliphatic stretching [30]
1316	Asymmetric stretching vibration of sulfone group [31]
1199	CF_2 asymmetric stretching [32]
1142	CF_2 symmetric stretching [32]
1056	Symmetric stretching vibration of sulfone group [31]
979	C–O–C connected to the main chain [32,33]
969	C–O–C connected to the main chain [32,33]
716	C=O bending [34]
626	$-\text{SO}_3^-$ in clean Nafion membrane [34]

Fig. 7. ATR-FTIR spectra of the membranes.

biofilm layer comprised organic substances. These substances contain carbon (C), oxygen (O), sulfur (S), thiol (S–H) groups, and disulfide (S–S) groups. In Fig. 7, a sharp peak at 1627 cm^{-1} was observed, which corresponded to the protein from amide-I [6]. This peak also indicated the contamination of the membrane surface over time.

3.7. SEM of the membranes

An SEM image of a clean membrane is shown in Fig. 8(a). The surface of the membrane was smooth and clean. The pores can be observed on close examination.

SEM images taken at different places of the MFC-1 membrane surface are shown in Fig. 8(b,c). When the images of the clean Nafion and MFC-1 membrane surfaces are compared, a physical increase in biocontamination can be observed. After the experimental study in the reactor, it was observed that a biofilm containing S anions and Cu, Fe, and Ca cations was formed. The EDX, ATR-FTIR, and electrical data further supported this.

SEM images taken at different places of the MFC-2 membrane surface are shown in Fig. 8(d,e). When the images of the MFC-2 membrane and the MFC-1 membrane surface (Fig. 8(b,c)) are compared, a physical increase in biocontamination on the surface of membrane can be observed. After the experimental study in the reactor, it is observed that a biofilm containing Fe and Ca cations has been formed on the surface of the MFC-1 membrane. EDX, ATR-FTIR, and electrical data also supported this.

3.8. EDX of a clean membrane

The quantitative data of EDX spectra of a clean membrane

are given in Table 5. It can be seen that the membrane is composed of C and F. Au atoms were also present because the SEM-EDX images were obtained after coating the surface of the membrane with gold. As there were no other elements apart from these three, it can be concluded that the surface was smooth.

The data of EDX spectra of the MFC-1 membrane are also given in Table 5. A comparison of the clean Nafion membrane and MFC-1 membrane showed that Ca, Na, Cu, and Fe cations were present on the surface of the membrane. The EDX data of the MFC-2 membrane in Table 5 showed that Ca, Mg, and Fe cations were found on the surface of the MFC-2 membrane.

4. Conclusions

The effects of the organic loading rate on the MFCs were investigated versus the HRT and COD concentration. Up to an HRT of 0.5 d, COD removal and current density increased. At an HRT of 0.5 d, the highest COD removal efficiency and voltage were 82% and 0.31 V, respectively. At the HRT of 0.5 d, the maximum power densities of 8.001 and $1.843\text{ }\mu\text{W}/\text{cm}^2$ were obtained with reactors MFC-1 and MFC-2, respectively. For the MFC-1 reactor, the maximum power density decreased from 8.001 to $1.069\text{ }\mu\text{W}/\text{cm}^2$ on increasing the HRT from 0.5 to 1 d. The microbial population in the MFC was dominated by *Geobacter*, *Shewanella*, and *Clostridium* species, and some bacteria were easily washed out at lower HRTs. The Nafion membrane became fouled by microorganisms, extracellular polymers, and inorganic salts during the MFC operation, which will disrupt the MFC performance. After fouling of the Nafion membrane, the properties of the membrane were negatively influenced. In addition, physical blockage of cation transfer can also cause the decay of the current.

Fig. 8. SEM images of a clean Nafion membrane surface (a), MFC-1 membrane surface (b,c), the MFC-2 membrane surface (d,e).

Table 5

Quantitative data of the EDX spectra of the clean Nafion membrane, MFC-1 membrane, and MFC-2 membrane.

Element	Clean Nafion membrane			MFC-1 membrane			MFC-2 membrane		
	Intensity	Wt%	At%	Intensity	Wt%	At%	Intensity	Wt%	At%
C	2.0040	18.27	58.54	—	—	—	1.8431	53.22	67.97
F	1.2711	13.93	28.22	0.6270	1.40	2.22	0.8817	2.42	1.95
Au	0.7849	67.80	13.25	—	—	—	—	—	—
O	—	—	—	1.6934	32.86	61.67	1.9172	22.19	21.28
Na	—	—	—	1.0462	0.09	0.12	—	—	—
Si	—	—	—	1.0092	2.10	2.24	1.0786	5.71	3.12
Ca	—	—	—	1.1011	12.15	9.11	0.8986	6.00	2.30
Fe	—	—	—	0.6018	5.50	2.95	0.6252	9.03	2.48
Cu	—	—	—	0.6452	45.90	21.69	—	—	—
Mg	—	—	—	—	—	—	1.2366	1.43	0.90
Total		100.00			100.00			100.00	

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Graphical Abstract*Chin. J. Catal.*, 2015, 36: 1068–1076 doi: 10.1016/S1872-2067(15)60833-6**Electricity production by a microbial fuel cell fueled by brewery wastewater and the factors in its membrane deterioration**

Afşin Y. Çetinkaya *, Emre Oğuz Köroğlu, Neslihan Manav Demir, Derya Yılmaz Baysoy, Bestamin Özkaya, Mehmet Çakmakçı
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Electricity production by microbial fuel cells (MFCs) using wastewater from a brewing plant and the influence of the hydraulic retention time (HRT) and effect of chemical oxygen demand (COD) removal on MFC performance, the microbial population, surface morphology, and functional groups were investigated.

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