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Enhancing simultaneous electricity production and reduction of sewage sludge in two-chamber MFC by aerobic sludge digestion and sludge pretreatments

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ABSTRACT

Batch tests were conducted to enhancing simultaneous electricity production and reduction of sewage sludge in two-chamber MFC by aerobic sludge digestion in cathode chamber and sludge pretreatments (sterilization and base pretreatment) prior to sludge addition to anode chamber, respectively. During the stable stage, The voltage outputs and power densities of MFC increased from 0.28–0.31 V to 17.3–21.2 mW/m^2 to 0.41–0.43 V and 36.8–40.1 mW/m^2, respectively, when aerobic sludge digestion occurred in the cathode chamber. When the sludge added to the anode chamber was sterilized or base pretreated, the voltage outputs and power densities of MFC increased from 0.30–0.32 V and 19.9–22.6 mW/m^2 (raw sludge) to 0.34–0.36 V and 25.5–28.6 mW/m^2 (sterilized sludge), 0.41–0.43 V and 37.1–40.8 mW/m^2 (base pretreated sludge), respectively. At the end of the test, the total suspended solids (TSS) and volatile suspended solids (VSS) reduction of sludge in the anode chambers increased from 33.9% and 36.8% to 34.5% and 38.7% with aerobic sludge digestion in the cathode chamber, respectively; while, those (TSS and VSS reduction) with sludge pretreatments prior to the sludge addition to the anode chambers increased from 25.1% and 22.8% (raw sludge) to 32.8% and 34.6% (sterilized sludge), and 25.5% and 26.7% (base pretreated sludge), respectively. The experimental results illuminated both aerobic sludge digestion in the cathode chamber and sludge pretreatments (sterilization and base pretreatment) prior to sludge addition to the anode chamber could enhance simultaneous electricity production from sludge and sludge reduction.

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1. Introduction

Sewage sludge is an organic by-product of biological wastewater treatment that requires treatment and disposal [1,2]. Due to the wide application of biological wastewater treatment, sewage sludge is mass-produced. For example, in 2007, over 1.43×10^7 tons of dewatered sludge, with 80% water content was generated from the wastewater treatment plants of China [3]. In addition, the quantity of generated sludge has increased annually with the development of sewage treatment systems. As the treatment and disposal of sludge accounts for 25–65% of the total plant operation costs [4], it has become an important problem for many wastewater treatment plants [1,2]. However, Sewage sludge contains high levels of organic matters and is regarded as an available resource [1,2]. Many researches have been done to realize the reclamation of sludge, for example, anaerobic digestion for methane production, anaerobic fermentation for hydrogen production, aerobic compost for fertilizer production, and so on.

Microbial fuel cells (MFCs), which convert the chemical energy in organic matter energy directly into useful electrical energy by the catalytic reaction of microorganisms, have generated considerable worldwide interest in recent years [5–7]. Classic MFCs have two chambers, an anaerobic anode chamber and an aerobic cathode chamber. In the anode chamber, microbes oxidize added substrates (organic matter or biomass) and generate electrons and protons. The electrons are transferred to the cathode through an external circuit and the protons are transferred to the cathode chamber. In the cathode chamber, the electrons and protons are oxidized by an oxidant (normally oxygen). When the organic matters in the wastewater or sewage sludge are used to generate electricity by MFCs, it is possible to lower the treatment cost of wastewater and sewage sludge [5–9]. Accordingly, previous researchers have studied electricity production from wastewater or sewage sludge using various MFCs. For example, Ahn and Logan [10] obtained a maximum power density of 422 mW/m^2 from domestic wastewater and COD removal of 25.8% using single-chamber air-cathode MFC; Jiang et al. [11,12] produced a maximum power density of 8.5 W/m^3 from sewage sludge and obtained a TCOD removal of 46.4% using a two-chambered MFC; Jia et al. [13] and Liu et al. [14] obtained a power density of 40 mW/m^2 and 220.7 mW/m^2 from excess sludge, respectively, using a single chamber floating-

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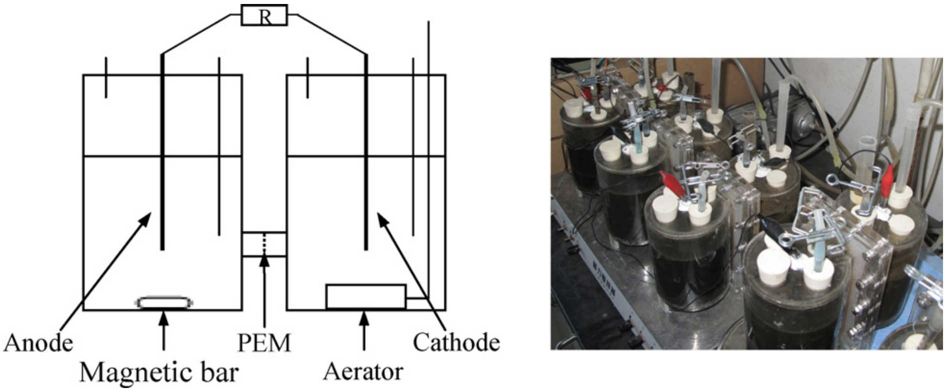

Fig. 1. Schematic diagram of the MFCs used in this study.

cathode MFC. During electricity production of MFCs from sludge, the sludge is hydrolyzed, converted and reduced. Previous studies suggested that the power density of the MFC using sewage sludge as substrate was usually lower that of wastewater [9–14]. Therefore, additional studies need to be conducted to enhance the power density of MFC using sewage sludge as substrate.

As most organic matters in sludge are microbial and enclosed within microbial cell walls [1,2], it is thought that electricity production of sludge is similar to other sludge treatment, such as anaerobic digestion, and would be impacted by the hydrolysis of sludge. The results of previous studies suggest that sterilization and base pretreatment are effective to accelerate the hydrolysis of sludge by releasing the microbial organic matters to water [15,16]. Consequently, it is possible to enhance the electricity production from sludge by the two pretreatments. However, few studies have addressed this problem. Furthermore, the cathode chamber of MFC is usually used oxygen as oxidant and biocathodes could improve sustainability of MFCs [17]. When sludge is addition into the cathode chamber of MFC, aerobic digestion of the sludge would occur. Aerobic digestion of sludge can produce certain ions (like NH_4^+, NO_3^-, PO_4^{3-}) [18,19], which could replace the traditional cathode electrolytes (like phosphate buffered saline) [20,21]. The replacement would make MFC more environmentally friendly since the addition of phosphate buffered saline in the cathode chamber both wastes phosphorus and increases the pollution of MFC. Additionally, bacteria in the aerobic digestion of sludge may accelerate oxygen reduction by functioning as a biocathode. It is, therefore, possible that sludge could be used to replace the buffer solution in the cathode chamber. Similarly, however, few studies have directed their attention to the above problem.

Thus, this study was conducted to investigate the effects of aerobic sludge digestion in the cathode chamber and sludge pretreatments on simultaneous electricity production and sludge reduction.

2. Materials and methods

2.1. Sludge samples

Sewage sludge (raw sludge, RS) was obtained from a municipal wastewater treatment plant in Beijing (China) that treats 400,000 t of wastewater daily by activated sludge process. The pH of the sludge was 6.9 (±0.1) and its total suspended solids (TSS), volatile suspended solids (VSS), total chemical oxygen demand (TCOD), and soluble chemical oxygen demand (SCOD) were 2.60 g/L, 1.92 g/L, 11,380 mg/L (±100 mg/L), and 24.7 mg/L (±2 mg/L), respectively. The inoculum, anaerobic sludge (AS), was obtained from the anaerobic sludge digester of another municipal wastewater treatment plant in Beijing (China). The pH, TSS, VSS, TCOD, and SCOD of the anaerobic sludge was 7.1 (±0.1), 3.40 g/L, 1.83 g/L, 6900 mg/L (±50 mg/L), and 365 mg/L (±10 mg/L), respectively. The collected sludge samples were gravitationally settled and condensed to appropriate density and the sediments were stored at 4 °C until use.

2.2. MFCs construction and operation

The MFCs consisted of two identical chambers separated by a proton exchange membrane (PEM, Nafion^{TM} 117, Dupont Co., USA) (Fig. 1). Each chamber had a volume of 500 mL and the net volumes of the anode chamber and cathode chamber were 390 mL and 350 mL, respectively. All electrodes were made of Toray carbon paper without wet proofing (Toray Co., Japan). The two electrodes were $L \times W \times T = 6.0\,\text{cm} \times 4.0\,\text{cm} \times 0.03\,\text{cm}$ in size and their distances were 14 cm. For each MFC, an aerator with a volume of 40 mL was fixed at the bottom of the cathode chamber and the anode chamber was mixed using a magnetic bar.

In order to study the effects of aerobic sludge digestion in the cathode chamber of MFC, a total of 340 mL raw sludge and 45 mL anaerobic sludge were added into the anode chambers of MFCs (MFC1 and MFC2 in Table 1). Raw sludge or sludge supernatant was added into the cathode chambers of two MFCs, respectively (MFC1 and MFC2 in Table 1).

In order to study the effects of sludge pretreatments, the sludge were sterilized or base pretreated before being added into the anode chambers of MFCs. The methods of two pretreatments were same as the previous study [16] and the detailed methods were as follows. Sterilization: the sludge was autoclaved at 121 °C and 1.2 kgf/cm^2 (VARIOKLAV steam sterilizer, 300/400/500 EP) for 30 min. Base pretreatment: the pH of sludge was adjusted to 12.0 ± 0.1 with 6 M sodium hydroxide and stabilized for 5 min under stirring. Raw sludge or pretreated sludge (sterilized sludge, SS, and base pretreated sludge, BS) (340 mL) and anaerobic sludge (45 mL) were added into the anode chambers of MFCs, respectively (MFC3–MFC5 in Table 1). The raw sludge was added into the cathode chambers of three MFCs (MFC3–MFC5 in Table 1).

The dissolved oxygen (DO) in the cathode chambers was kept at approximately 5.0 mg/L to maintain a sufficient level of dissolved oxygen in the mixed liquid [22]. Because the water in the cathode chambers would volatilize by aeration, deionized water was supplied periodically to maintain the volume of the mixed liquid. Additionally, 5 mL of trace elements solution [23] was added to each chamber. The pH of the mixed liquid in the two chambers was adjusted to 7.0 ± 0.1 with 6 M NaOH and 6 M HCl. The MFCs were connected with an external resistance ($R_{\text{ext,}}$ 1000 Ω) using copper wires and operated at room temperature (19–27 °C). Tests of each MFC were conducted in triplicate and all results were the means of replicate analyses.

Table 1
The substrates in the two chambers of MFCs.

Item	MFC1	MFC2	MFC3	MFC4	MFC5
Anode chamber	RS + AS	RS + AS	RS + AS	SS + AS	BS + AS
Cathode chamber	RS	Supernatant of RS	RS	RS	RS

RS: raw sludge; AS: anaerobic sludge; SS: sterilized sludge; BS: base pretreated sludge.

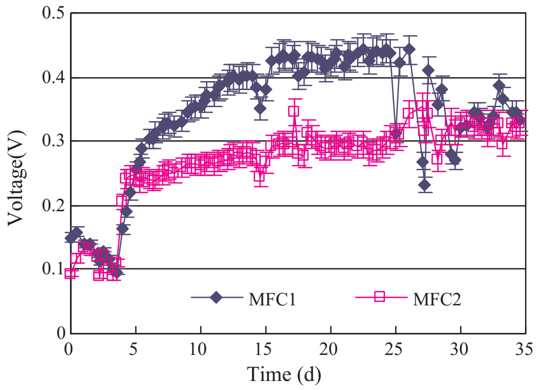

Fig. 2. Voltage outputs of MFC1 and MFC2 during the test.

2.3. *Analytical methods and calculations of electrical parameters*

The TCOD and SCOD of the sludge were quantified using a HACH COD measurement system and kit (HACH Co., USA). The sludge was filtered through a 0.45 μm membrane prior to SCOD determination. The pH of the sludge was measured with a pH meter (PHS-3C, China). The TSS and VSS of the sludge were measured according to the standard methods [24].

The voltages of the MFCs (V) were recorded using a precision digital-multimeter and a data acquisition system (Ruibohua Co., China) connected to a computer. The power densities of MFCs (P) are calculated as [6]

$$P = \frac{V^2}{A_{an} \cdot R_{ext}} \quad (1)$$

where V is the voltage of the MFCs, A_{an} is the area of anode and R_{ext} is the external resistance.

During the test, the polarization curves were detected by verifying external resistances from 50,000 Ω to 30 Ω with an interval of 2 min to gain stable voltages. The open circuit voltage, internal resistance, and maximum power density were obtained by analyzing the polarization curves [25].

3. Results and discussion

3.1. *Effect of aerobic sludge digestion on electricity production*

Since the cathode chamber was aerobic and some studies have shown that the growth of bacteria in the cathode chamber could enhance MFC electricity production [17], batch tests were conducted to study the effects of aerobic sludge digestion in the cathode chamber on electricity production using the sludge supernatant as a control (MFC1 and MFC2 in Table 1). The voltage outputs of the two MFCs are summarized in Fig. 2.

During the first stage of the tests (0–3.5 d), the voltage outputs of the two MFCs were about 0.09 V. This was the lag stage, during which the exoelectrogenic bacteria acclimatized to the new environment. After 3.5 d, however, the voltage outputs rapidly increased from about 0.09 V to 0.25 V (at 5 d). After the fifth day, the voltage outputs of the two MFCs differed. Specifically, the voltage outputs of the MFC that employed aerobic sludge digestion (MFC1) in the cathode chamber increased to 0.41–0.43 V at 15.5–26 d, while that of the MFC with the supernatant cathode (MFC2, the control) only increased to 0.28–0.30 V. During the later stable stage, the voltage outputs of MFC1 decreased to 0.34–0.35 V, while that of MFC2 increased to 0.32–0.34 V. The voltage outputs of the two MFCs clearly decreased around 14th d (Fig. 2) due to power failure. When the power continued, the voltage outputs of the two MFCs increased at 15th d. During the last stage, the decrease in MFC1's voltage outputs fluctuated remarkably, which may be due to the consumption rate of soluble organic matters was faster than the hydrolysis rate of insoluble matters and the exoelectrogenic bacteria needed to adapt to the new conditions.

The power densities of the two MFCs could be got based on their voltage outputs. During the stable stage, the power densities of MFC1 were 36.8–40.1 mW/m^2 and of MFC2 were 17.3–21.2 mW/m^2. As the only difference between the two MFCs evaluated in this study was the cathode mixed liquid, the above results show that aerobic digestion of sludge in the cathode chamber could enhance the electricity production from sewage sludge. The reason for this enhancement may be that the bacteria involved in the aerobic sludge digestion in the cathode chamber may accelerate the reduction of oxygen and the product of aerobic sludge digestion (like NH_4^+, NO_3^-, PO_4^{3-}) may act as the electrolyte.

Polarization curves were regularly detected during the test (data not shown) and three parameters (open circuit voltage, internal resistance, and maximum power density) were obtained from the curves (Table 2). The open circuit voltages and maximum power densities of the two MFCs increased with the operation of MFCs, with those of MFC1 higher than those of MFC2. The internal resistances of the two MFCs decreased with MFCs operation, however, with those of MFC1 lower than those of MFC2. The higher internal resistances of MFC2 may be one reason for its lower electricity production. These results show that aerobic sludge digestion in the cathode chamber could increase the open circuit voltages and the maximum power densities while decreasing the internal resistances.

3.2. *Effect of sludge pretreatments on electricity production*

Two pretreated sludge samples (sterilized sludge and base pretreated sludge) were added to the anode chambers of MFCs to produce electricity with aerobic sludge digestion in the cathode chambers (MFC4 and MFC5 in Table 1). In addition, the pretreated sludge was replaced with raw sludge as a control (MFC3 in Table 1). The electricity production processes were similar to those of MFC1 and MFC2 and the experimental results are summarized in Fig. 3. The electricity production (voltage outputs and power densities) from base pretreated sludge was the highest, while that from raw sludge was the lowest. During the stable stage (10–25 d), the voltage outputs from the three sludge samples were 0.41–0.43 V (base pretreated sludge), 0.34–0.36 V (sterilized sludge), and 0.30–0.32 V (raw sludge). In addition, the power densities from the three sludge samples were 37.1–40.8 mW/m^2 (base pretreated sludge), 25.5–28.6 mW/m^2 (sterilized sludge), and 19.9–22.6 mW/m^2 (raw sludge), respectively. During the last stage of the test (after 25 d), the electricity produced from base pretreated sludge decreased to 0.28 V, while that from raw sludge decreased to 0.24 V and that from sterilized sludge remained stable. These results demonstrate

Table 2
Three parameters of MFC1 and MFC2.

Item	Operation time	MFC1	MFC2
Open circuit voltages (V)	Day 5	0.729 ± 0.012	0.698 ± 0.009
	Day 15	0.815 ± 0.008	0.716 ± 0.010
	Day 19	0.858 ± 0.009	0.718 ± 0.011
	Day 26	0.843 ± 0.008	0.812 ± 0.008
Internal resistances (Ω)	Day 5	1377.7 ± 12.5	1700.6 ± 10.2
	Day 15	975.1 ± 9.8	1419.4 ± 11.3
	Day 19	947.4 ± 10.5	1277.6 ± 12.1
	Day 26	763.3 ± 9.7	1126.5 ± 9.6
Maximum power densities (mW/m^2)	Day 5	18.86 ± 0.08	13.83 ± 0.06
	Day 15	38.34 ± 0.06	16.50 ± 0.07
	Day 19	45.05 ± 0.06	19.57 ± 0.08
	Day 26	45.07 ± 0.05	27.96 ± 0.06

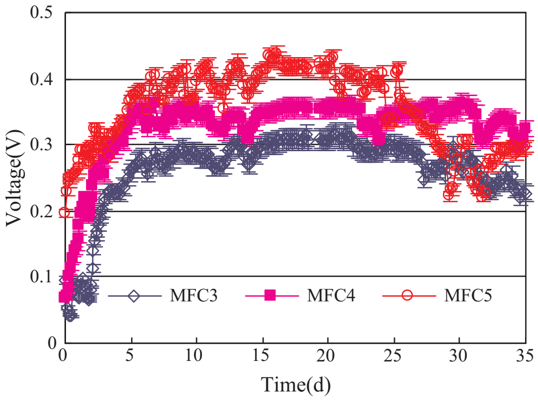

Fig. 3. Voltage outputs of MFC3–MFC5 during the test.

that the chosen pretreatments (sterilization and base pretreatment) could enhance the electricity production from sludge and the improvement in efficiency was greater in response to base pretreatment than sterilization. The enhancement may be due to the pretreatments releasing the cellular organic matter of sludge into water [15,16], thereby increasing the substrates of exoelectrogenic bacteria. Additionally, base pretreatment could increase ionic strength, which may also increase the electricity production [26].

When compared with other two-chamber MFC studies, the electricity production was similar. Using a two-chamber MFC, for example, Antonopoulou et al. [27] obtained 15.2 mW/m^2 from glucose and Liang et al. [28] produced 31 mW/m^2 from acetate. These results suggest that the two-chamber MFC characteristics employed in the present study were similar to those of previous studies. However, when compared with similar studies that employed sludge as the substrate, such as Liu et al. [14] who obtained 220.7 mW/m^2 using a single chamber floating-cathode MFC, electricity production in the present study was lower. These differences may relate to the type and structure of MFC employed. Additionally, the voltage outputs and power densities of MFC1 were higher than those of MFC3 although both MFCs add the raw sludge in the two chambers, which may be due to the sludge concentration in the MFC1 was higher than that in the MFC3 (Tables 3 and 4).

The three MFC parameters (open circuit voltage, internal resistance and maximum power density) for the three MFCs were also analyzed based on their polarization curves (data not shown) and the results are summarized in Table 5. The open circuit voltages of MFC3 (with raw sludge) were the highest, followed by those of MFC5 (with base pretreated sludge). The internal resistances of MFC5 (with base pretreated sludge) were the lowest, while those of MFC4 (with sterilized sludge) were the next lowest. The maximum power densities of MFC5 (with base pretreated sludge) were the highest and those of MFC3 (with raw sludge) were the lowest. The results show that the chosen pretreatments could decrease the internal resistance of MFC and increase the maximum power density of MFC. Additionally, the decrease in MFC internal resistance was a likely cause of the pretreatments' enhancement of electricity production from sludge. Moreover, the open circuit voltages and internal resistances of the three MFCs decreased during operation, while the maximum power densities of the three MFCs increased.

3.3. *Effect of two processes on sludge reduction*

Sludge was reduced during electricity production of the five MFCs and the results are summarized in Tables 3 and 4.

In the anode chambers of MFC1 and MFC2, the TSS and VSS of the sludge decreased and their reductions increased with the operation of MFCs, with those in MFC1 slightly higher than those in MFC2 (Table 3). At the end of the test, the reductions of sludge (TSS and VSS) in the anode chambers of two MFC reached 34.5% and 38.7% (MFC1) and 33.9% and 36.8% (MFC2), respectively. The higher sludge reductions (TSS and VSS) in the anode chamber of MFC1 were consistent with its higher electricity production. The results suggest that aerobic sludge digestion in the cathode chamber of MFC could enhance the sludge reductions during electricity production from sludge. The sludge reductions observed in the present study were higher than that observed by Jia et al. [13], who reported reductions of 27.3% (TSS) and 28.7% (VSS). This discrepancy may be due to the differences existed in the reaction process, the construct of MFC and the anaerobic time. Because sludge in the cathode chamber of MFC1 was subjected to aerobic digestion, its concentration also decreased during the test. As shown in Table 3, sludge reduction (TSS and VSS) reached 36.4% and 37.8%, respectively, by the end of the test. Additionally, the reduction of VSS in the test was slightly higher than that of TSS because most organic matter in the sludge was mineralized during the process.

Sludge reductions in the anodes chamber also increased with the operation of MFCs, with those for sterilized sludge the highest, followed by those for base pretreated sludge (Table 4). At the end of the test (31th d), the sludge reductions (TSS and VSS) were, 32.8% and 34.6% (sterilized sludge), 25.5% and 26.7% (base pretreated sludge), and 25.1% and 22.8% (raw sludge), respectively. The results demonstrate that the chosen pretreatments could also enhance the sludge reductions during electricity production from sludge. The reason for the higher sludge reductions in the anode of MFC with sterilized sludge (MFC4) than that with base pretreated sludge (MFC5) was likely that matter dissolved under the basic pH conditions in the base pretreatment of sludge became insoluble when pH decreased during electricity production (from 7.5 to 5.6, detailed data not shown) [29]. Like the electricity production, the sludge reductions of the anode chamber of MFC1 were higher than those of MFC3, which may also be due to the difference of sludge concentration (Tables 3 and 4).

Table 3
Sludge concentrations and reductions in the MFC1 and MFC2.

	Item	MFC1		MFC2
		Anode chamber	Cathode chamber	Anode chamber
0 d	TSS (g/L)	24.2 ± 0.4	25.1 ± 0.3	24.2 ± 0.4
	VSS (g/L)	16.3 ± 0.3	16.1 ± 0.2	16.3 ± 0.3
Day 12	TSS reduction (%)	26.7 ± 0.2	21.8 ± 0.3	26.6 ± 0.3
	VSS reduction (%)	29.7 ± 0.2	20.1 ± 0.2	28.7 ± 0.2
Day 35	TSS reduction (%)	34.5 ± 0.4	36.4 ± 0.2	33.9 ± 0.3
	VSS reduction (%)	38.7 ± 0.3	37.8 ± 0.2	36.8 ± 0.2

Table 4
Sludge concentrations and reductions in the anodes of MFC3–MFC5.

	Item	MFC3	MFC4	MFC5
0 d	TSS (g/L)	10.5 ± 0.3	10.9 ± 0.1	14.2 ± 0.3
	VSS (g/L)	7.7 ± 0.2	8.1 ± 0.1	7.8 ± 0.2
Day 7	TSS reduction (%)	10.3 ± 0.4	16.3 ± 0.5	10.7 ± 0.3
	VSS reduction (%)	8.2 ± 0.3	16.1 ± 0.4	11.2 ± 0.2
Day 21	TSS reduction (%)	20.1 ± 0.3	28.9 ± 0.4	21.6 ± 0.3
	VSS reduction (%)	20.2 ± 0.2	32.2 ± 0.3	18.0 ± 0.2
Day 31	TSS reduction (%)	25.1 ± 0.4	32.8 ± 0.3	25.5 ± 0.2
	VSS reduction (%)	22.8 ± 0.3	34.6 ± 0.2	26.7 ± 0.2

Table 5
Three parameters of MFC3–MFC5.

Item	Operation time	MFC3	MFC4	MFC5
Open circuit voltages (V)	Day 7	0.807 ± 0.013	0.741 ± 0.011	0.768 ± 0.012
	Day 15	0.762 ± 0.011	0.732 ± 0.009	0.735 ± 0.010
	Day 21	0.725 ± 0.009	0.712 ± 0.012	0.717 ± 0.008
Internal resistances (Ω)	Day 7	1927.2 ± 9.8	1173.2 ± 11.5	1023.7 ± 10.6
	Day 15	1411.4 ± 12.4	1097.8 ± 9.5	700.4 ± 11.4
	Day 21	1207.7 ± 10.3	974.6 ± 10.7	614.9 ± 9.7
Maximum power densities (mW/m^2)	Day 7	17.29 ± 0.07	22.01 ± 0.06	30.08 ± 0.08
	Day 15	21.31 ± 0.05	24.80 ± 0.07	40.22 ± 0.05
	Day 21	23.86 ± 0.08	27.26 ± 0.04	45.34 ± 0.06

4. Conclusions

Both aerobic sludge digestion in the cathode chamber and the sludge pretreatments (sterilization and base pretreatment) prior to the addition of sludge into the anode chamber could enhance simultaneous electricity production and reduction of sewage sludge in two-chamber MFC.

The voltage outputs of MFC increased from 0.28–0.31 V to 0.41–0.43 V and the power densities increased from 17.3–21.2 mW/m^2 to 36.8–40.1 mW/m^2 with aerobic sludge digestion in the cathode chamber. Aerobic sludge digestion in the cathode chamber increased sludge reduction (TSS and VSS) in the anode chamber from 33.9% and 36.9% (without aerobic sludge digestion) to 34.5% and 38.7% (with aerobic sludge digestion). Additionally, the voltage outputs of MFC increased from 0.30–0.32 V (raw sludge) to 0.34–0.36 V (sterilized sludge) and 0.41–0.43 V (base pretreated sludge) and the power densities of MFC increased from 19.9–22.6 mW/m^2 (raw sludge) to 25.5–28.6 mW/m^2 (sterilized sludge) and 37.1–40.8 mW/m^2 (base pretreated sludge), respectively. The chosen pretreatments increased sludge reduction (TSS and VSS) from 25.1% and 22.8 to 32.8% and 34.6% (sterilization), 25.5% and 26.7% (base pretreatment), respectively. Additionally, both the aerobic sludge digestion and sludge pretreatment increased the maximum power densities of MFC and decreased its internal resistances.

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