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研究課題名（和文）Engineered Biofilms for Bioenergy Generation and Wastewater Treatment in Microbial Fuel Cells (MFCs)

研究課題名（英文）Engineered Biofilms for Bioenergy Generation and Wastewater Treatment in Microbial Fuel Cells (MFCs)

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　800,000円

研究成果の概要（和文）：この画期的な研究は、導電性ポリマーを使って人工バイオフィルムを作ることを目的としており、反応性を高めるためにナノ粒子を組み込むことでさらに強化できる可能性がある。この研究は、綿密なエネルギー生産・消費分析など、さまざまな課題に立ち向かうものである。

研究成果の学術的意義や社会的意義
The specific objectives were implementing the iron nanoparticles technology in the anode chamber as it represents the powerhouse of MFCs, and improving the iron performance and factors that affect the MFC response.

研究成果の概要（英文）：Microbial fuel cell (MFC) technology has emerged as a promising solution in addressing these global challenges. MFCs, a technology with promising applications in power generation and wastewater treatment, still face challenges that limit their practical use. The issues of high internal resistivity and low power generation are key concerns for researchers. In this study, we evaluated the impact of Fe0 nanoparticles on MFC performance, specifically in power generation and organic matter degradation. We used two different samples of sludge and found that the maximum daily voltage in the control MFC filled with S2 (COD= 37802 mg/L) increased by 182 % compared to the MFC filled with S1 (COD= 5561 mg/L). However, the addition of Fe nanoparticles led to a reduction in the daily voltage by 31 % and 9 % for the MFCs filled with S1 and S2, respectively. These findings have significant implications, highlighting the importance of considering organic matter content in optimizing MFC response.

研究分野：Environmental Engineering

キーワード：Microbial fuel cell　Biofilm　anaerobic digestion　biocatalysis　wastewater

１．研究開始当初の背景

Microbial fuel cell (MFC) technology has emerged as a promising solution in addressing these global challenges. Unlike conventional fuel cells that use expensive fuel and catalysts, MFCs use living bacteria to break down waste and generate electricity. This process can help reduce waste treatment costs. However, there are challenges with MFC technology, such as the need for higher power densities and a better understanding of microbiology, which require further research. MFCs have the advantage of running off widely available energy sources, but there's still work to be done before they can be widely used. Their potential applications include converting organic waste and biomass to electricity and powering vehicles, electronic devices, or households. However, technical developments are necessary for practical use, such as increasing power densities and better understanding of microbiology.

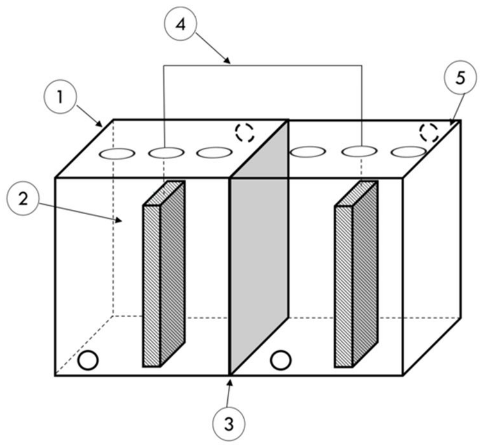
２．研究の目的

This research's overall objective was to study the effects of iron-based nanoparticles on the performance of a lab-scale microbial fuel cell (MFC). The specific objectives were improving the bacterial growth owing to the critical role in microbial fuel cell technology, implementing the iron nanoparticles technology in the anode chamber as it represents the powerhouse of MFCs, and improving the iron performance and factors that affect the MFC response.

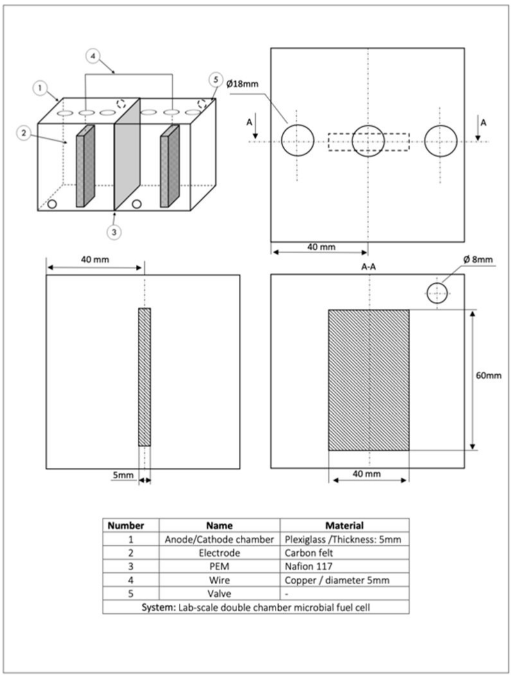
As per the literature, MFCs stand out for their high reliability in both wastewater treatment and energy generation. This is primarily attributed to the rich organic matter content in waste sludge. Moreover, when we consider the costs associated with wastewater treatment, MFCs demonstrate clear cost advantages over other techniques. Currently, numerous research projects are dedicated to developing cost-effective methods to meet the required performance standards. This pursuit involves a comprehensive investigation of microbial fuel cells, a technology that is distinguished by its unique features such as power density output, the total volatile solids analysis, and the coulombic efficiency (CE). The investigation focused on the anode chamber’s performance as it is a critical factor in determining power generation in MFCs. The experimental studies were carried out in lab-scale microbial fuel cells. A series of strategies were executed to improve overall system performance.

３．研究の方法

The experimental procedure went through construction of lab-scale MFCs, collection and characterization of waste sludge, synthesis and preparation of iron-based nanoparticles, and estimating bacterial growth improvement.



3.a MFC construction: In our study, two configurations of double-chamber MFCs were used. The first configuration consisted of a rectangular double-chamber MFC designed and constructed in our laboratory. The MFC consisted of two plexiglass chambers with a thickness of 5 mm. Each chamber had a volume of 640 cm^3. The two chambers were separated by a cation exchange membrane CEM (Nafion 117, thickness 0.007 in.), having a surface area of 168 cm^2. Carbon fiber tissue was used as the electrode material for both anode and cathode, with a surface are equal to 24 cm2. The two chambers were connected through an external circuit with a resistance value equal to 200 Ohm (Ω). Before the construction, we developed a mechanical drawing for the MFC unit, as shown in these figures. All MFCs were operated in a batch mode and meticulously incubated at a constant temperature (40 ºC) for almost 90 days of operation. Cathode chambers were filled with water.



MFC conception and construction in the Laboratory

All iron-based nanoparticles were introduced to the anode solution with a concentration of 10 mg/L to evaluate their effect on MFC's performances. The temperature value was selected based on the system conditions' significant impact on the initial bio-film formation process. Biofilms grown at higher temperatures (5 to 45 ºC) tend to be more electrochemically active than those at lower temperatures. A magnetic stirring was utilized to ensure a continuous mixing of the solution (500 rpm), which leads to a homogeneous medium and mass transfer resistance reduction. At the start of experiments, nitrogen gas N2 was meticulously bubbled into the anodic chamber for 10 min to ensure anaerobic conditions. The anode chambers were fed with waste sludge from the Mikasagawa domestic wastewater purification center in Fukuoka, Japan.

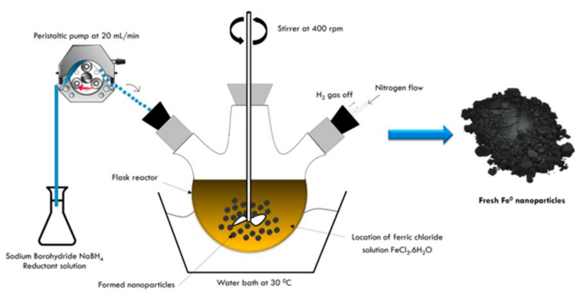
3.c Measurements: The conductivity in anode solution is a measure of the ability of anolyte to electric current. The more ions in the solution, the higher the anolyte's conductivity is. However, conductivity can be easily affected by the ion's concentrations and the substrate's type and dissolved solids used as a fuel in the anode chamber. Oxidative Reductive Potential (ORP) measurements can also indicate the degree to which a substance can oxidize or reduce another sense. ORP values can be: (i) positive when the essence is an oxidizing agent, or (ii) negative when the substance is a reducing agent. Our study aims to develop a strong anolyte that will be a good conductor of electricity, consequently, improve the MFC's response.

During the experiment, MFCs output voltage (V) was recorded in regular intervals using a multimeter. Following ohm's law, the current (I= V/R) and power (P= V × I) were calculated based on the external resistance and voltage values. The power density was normalized to technical characteristics to compare the power output with other microbial fuel cell systems. Thus, to compare the system related to the MFC fuel like organic matter content in the anode chamber, the power output was normalized to the initial TVS value of the waste sludge.

3.d Nanoparticles synthesis:

Fe0 nanoparticles were prepared by the chemical reduction of 0.093 M FeCl3.6H2O by 0.58 M NaBH4 according to the equation below:

$$4Fe^{3+} + 3BH_4^- + 9H_2O \rightarrow 4Fe^0 \downarrow + 3H_2BO_4^- + 12H^+ + 6H^2 \uparrow$$



3.e Wastewater Characterization:

The concentration of Fe2+, the total dissolved Fe0 were measured using a UV spectropho- tometer (Hach DR 3900, USA). pH and ORP were controlled using a pH meter. Conductivity, resistivity, salinity, and total dissolved solids (TDS) were monitored us- ing a conductivity meter. (Chemical Oxygen Demand) COD values were controlled using the chemical acids that oxidize organic and inorganic substances in the waste sludge sample. 2 mL of the tested waste sludge sample is injected in the vial then heated at 150 oC for 2 hours using a UV spectrophotometer (Hach DR 3900, USA). TS and TVS were determined following the traditional method.

Sample name	Units	Sludge (S1)	Sludge (S2)
TS	g/L	4.785	34.46
TVS	g/L	3.82	27.68
TVS/TS	-	0.80	0.80
COD	mg/L	5561	37802
TDS	mg/L	358	0.04
pH	-	6.77	5.94
ORP	mV	-14	32
Conductivity	µS/cm	716	0.73
Resistivity	Ω.cm	1000	2000
Salinity	ppt	0.3	0

４．研究成果

Figure: Synthesis system for iron nanoparticles

The designed 4 MFCs were selected to examine their working using two different sludges (S1) and (S2). The anaerobic sludges (S1) and (S2) were different regarding organic matter content. Their COD values are 5561 mg/L and 37802 mg/L, respectively. Fe0 nanoparticles were added by 50 mg/L, and the MFCs were operated for 80 days. The extended operation time was due to the nature of the anaerobic reduction process, which always proceeds at a low rate.

This figure shows the daily voltage variation throughout the operation period. The maximum recorded daily voltage values were 60.20 mV and 41.30 mV for control S1 and Fe-supplemented S1 MFC.

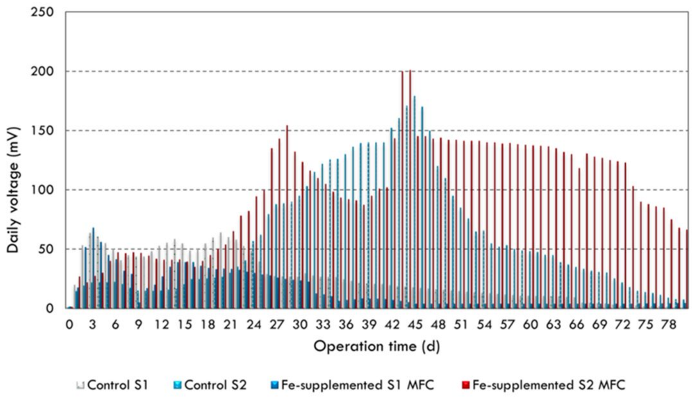


Figure: Daily voltage variations in MFCs

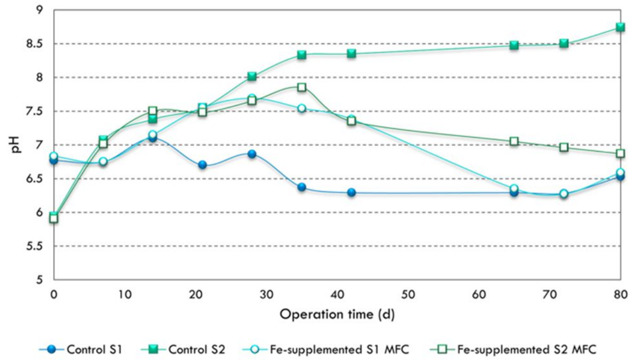
The following table summarizes the four MFC characteristics after 80 days of operation. The maximum daily voltage obtained in the control MFC filled with S2 increased by 182 % compared to the MFC filled with S1. The addition of Fe nanoparticles reduced the daily voltage by 31 % and 9 % for the MFCs filled with S1 and S2, respectively. We executed COD measurements for the first 12 days of operation.

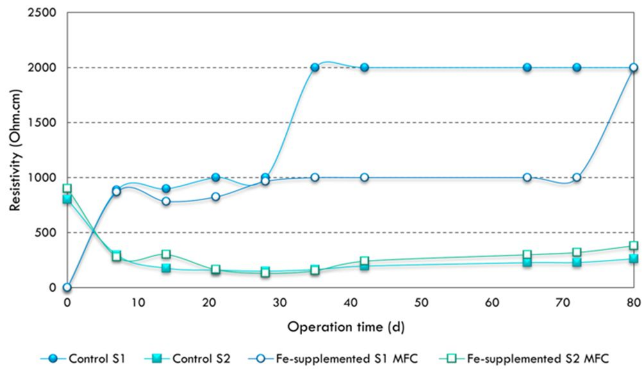
parameter	Description	Control S1	Control S2	Fe-S1	Fe-S2
$V_{max,cell}$	Maximum daily voltage measured (mV)	60.20	170.00	41.30	154.40
P_{max}	Maximal daily power output (µW)	18.12	144.5	8.52	119.19
I_{max}	Maximal daily current (mA)	0.30	0.85	0.20	0.77
Δ COD	Reduction of COD concentration (mg/L)	4132	3861	47371	N
P_{An}	Maximum daily power output density (mW/m^2)	7550	60208	3550	49662
$P_{g.VS}$	Maximum daily power output density (µW/g.vs)	9.48	75.65	4.46	62.40

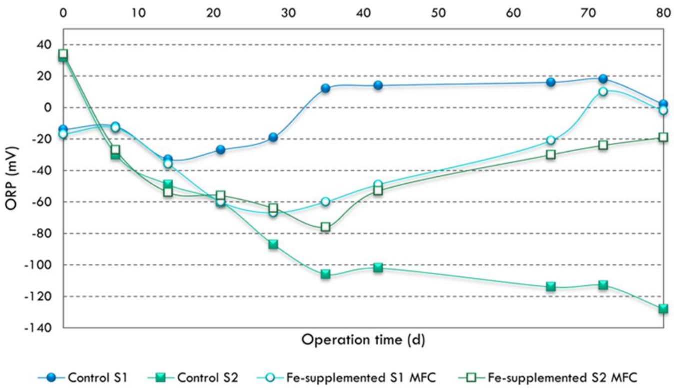
Measurement values recorded and calculated from the experiments

The addition of iron could reduce the COD to 1429 and 824 mg/L for control S1 and Fe-supplemented S1 MFC, which proved the acceleration of the organic matter digestion in the anolyte compared to the other MFCs. Therefore, it is necessary to find a solution to increase the fraction of organic matter converted into electricity.

The voltage increased to 1.96 V (control S1) and 1.25 V (Fe-supplemented S1 MFC) after 80 days of operation. It was clear that Fe0 nanoparticle treatment reduced the overall voltage generation. As shown in this figure, the current generation was decreased by 36.27 % for Fe-supplemented S1 MFC compared to control S1. In contrast, the effect of Fe0 nanoparticles addition could improve the current generation by 63.08 % using (S2). During 80 days of operation, the voltage increased to 4.91 V and 8.01 V for control S2 and Fe-supplemented S2 MFC, respectively. Adding 50 mg/L enhanced the reactor's properties (resistivity, ORP, pH). Data measurement reported that resistivity values decreased by 24.07 % and 15.13 % for Fe- supplemented MFCs by S1 and S2, respectively. The system could be maintained around neutral conditions using waste sludge S1; however, pH values increased to 8.74 for control S2, as shown in the figure above. Fe0 addition could lower the pH and maintain neutral conditions owing to its buffer capacity. ORP variations were recorded in Figure 4.5. Values could be reduced under Fe0 addition using S1.







However, values comparatively increased using S2. Fe0 and organic matter sedimentation aggregation can explain the voltage output reduction. For the MFC work, the performance is affected by the anode surface, meaning the bacteria should be attached to the anode surface to release and transfer electrons to the anode during the organic matter digestion. Fe0 did not improve the voltage using waste sludge S1 because the anolyte was not homogeneous, whereas S2 possessed a highly compact and dense sludge, and the anode surface was in contact with the sludge particles. Overall, control S2 generated a higher current than control S1. Fe-supplemented S1 MFC showed less resistance to Fe0 nanoparticles, unlike Fe-supplemented S2 MFC, where the impact of iron nanoparticles was positive. These results confirmed that the organic matter content affected the MFC response.

MFCs, a technology with promising applications in power generation and wastewater treatment, still face challenges that limit their practical use. The issues of high internal resistivity and low power generation are key concerns for researchers. In this study, we evaluated the impact of Fe0 nanoparticles on MFC performance, specifically in power generation and organic matter degradation. We used two different samples of sludge and found that the maximum daily voltage in the control MFC filled with S2 (COD= 37802 mg/L) increased by 182 % compared to the MFC filled with S1 (COD= 5561 mg/L). However, the addition of Fe nanoparticles led to a reduction in the daily voltage by 31 % and 9 % for the MFCs filled with S1 and S2, respectively. These findings have significant implications, highlighting the importance of considering organic matter content in optimizing MFC response.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　1件）

１．著者名 Khaoula Bensaida, Osama Eljamal	４．巻 10
２．論文標題 Investigations on the effect of iron-based nanocomposites on bioelectrochemical systems for wastewater treatment and nutrients recovery.	５．発行年 2024年
３．雑誌名 The 10th International Exchange and Innovation Conference on Engineering & Sciences (IEICES 2024)	６．最初と最後の頁 not yet
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計2件（うち招待講演　2件／うち国際学会　0件）

１．発表者名 Khaoula Bensaida
２．発表標題 Microbial Fuel Cell Technologies for Renewable Power and Biofuels Production from Biomass
３．学会等名 Sakura Science Program（招待講演）
４．発表年 2023年

１．発表者名 Khaoula Bensaida
２．発表標題 Hybrid Microbial Electrolysis Cell for Green Hydrogen Production (HYMEC)
３．学会等名 Invitation to a research institute（招待講演）
４．発表年 2023年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

MFCs, a technology with promising applications in power generation and wastewater treatment, still face challenges that limit their practical use. The issues of high internal resistivity and low power generation are key concerns for researchers. In this study, we evaluated the impact of Fe0 nanoparticles on MFC performance, specifically in power generation and organic matter degradation. We used two different samples of sludge and found that the maximum daily voltage in the control MFC filled with S2 (COD= 37802 mg/L) increased by 182 % compared to the MFC filled with S1 (COD= 5561 mg/L). However, the addition of Fe nanoparticles led to a reduction in the daily voltage by 31 % and 9 % for the MFCs filled with S1 and S2, respectively. These findings have significant implications, highlighting the importance of considering organic matter content in optimizing MFC response.

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関