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Research Paper

Evaluation of Stainless-Steel Mesh 304 Cathode Performance in a Microbial Fuel Cell for Tofu Wastewater Treatment

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Abstract
Currently, tofustewater (TWW) is one of the major environmental issues that must be addressed. When discharged untreated TWW into natural water bodies or soil, it poses a serious threat to the environment. Therefore, effective treatment of TWW is crucial before to disposal. As an advanced bio-electrochemical technology, the microbial fuel cell (MFC) offers a promising approach to reduce pollutants while simultaneously generating electricity. However, the choice of cathode material is crucial for enhancing MFC performance. This study aims to evaluate the performance of an MFC using an SSM-304 cathode with TWW as the target substrate. Several characteristics of TWW including pH, chemical oxygen demand (COD), biological oxygen demand (BOD), total solids (TS), total dissolved solids (TDS), and total suspended solids (TSS), were analyzed before and after MFC treatment. Additionally, the performance of the MFC system was further evaluated based on voltage output (V), current density (J), coulombic efficiency (CE), and MFC efficiency (ηMFC). The results show that COD and BOD were reduced by 69.56% and 64.00%, while TS, TDS, and TSS increased by 48.79%, 32.24%, and 45.15%, respectively. The MFC system with SSM-304 produced a voltage of 167 mV, a current density of 267.2 mA/m^2, a coulombic efficiency of 3.35%, power density of 27.89 mW, and MFC efficiency of 10.43%. Overall, this study demonstrated the potential of MFCs for simultaneous wastewater treatment and energy recovery.

Keywords
Tofu Wastewater (TWW), MFC, SSM – 304, Current Density, Coulombic Efficiency

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1. INTRODUCTION

Tofu is a protein-rich soft food made from curdled soy milk through coagulation and pressing processes (Ali et al., 2021; Guan et al., 2021). The widespread popularity of tofu has led to the expansion of the tofu industry across various regions in Indonesia. However, the industry remains largely dominated by home-based businesses that rely on traditional processing methods (Rozaki, 2021). Tofu consumption in Indonesia is projected to rise from 7.86 kg per capita in 2021 to 7.95 kg per capita in 2020 (Kariyasa, 2021). This fact is supported by the continuous increase in tofu production each year, highlighting the high level of tofu consumption among the Indonesian population.

In addition to solid waste in the form of tofu dregs, the tofu production proces also generates liquid waste, commonly known as tofu wastewater (TWW) (Shen et al., 2023). The TWW contains organic materials including 0.1% carbohydrates, 0.42% protein, 0.13% fat, 4.55% iron (Fe), 1.74% phosphorus, and 98.8% water (Wagiman et al., 2020). Unmanaged liquid waste discharged directly into rivers or other water bodies can alter the water's physical, chemical, and biological properties, impacting the aquatic ecosystem and its biota. Increased tofu production leads to higher pollution levels (Singh et al., 2023). According to the Indonesian Ministry of Environment Regulation No. 5 of 2014, TWW must meet the following standards: a maximum of 150 mg/L for BOD, 300 mg/L for COD, 200 mg/L for TSS, and a pH range of 6–9 (Hajar et al., 2021). Proper wastewater treatment can effectively reduce pollutant levels, ensuring compliance with industrial wastewater quality standards. Therefore, implementing environmentally friendly tofu wastewater management is crucial. Some effective treatment methods include activated carbon filtration, phytoremediation, coagulation, and flocculation (Kato and Kansha, 2024). However, these treatment methods still have limitations, such as long processing times and low efficiency in removing COD and BOD.

The microbial fuel cell (MFC) is an eco-friendly electrical device that is rapidly evolving into a sustainable system due to its dual capability of treating wastewater while simultaneously generating energy (Nawaz et al., 2022). The operating principle of the MFC system is based on bacteria generating electrons, which are then transferred from the anode to the cathode through a conductive device (Misto et al., 2024). MFC offers several advantages, including high efficiency, no need for external power input, and suitability for areas with limited electrical infrastructure (Obileke et al., 2021). MFCs can treat various types of wastewater, including industrial and agricultural wastewater, municipal wastewater, paper recycling wastewater, and landfill leachate (Ishaq et al., 2024).

MFC technology operates based on electrochemical principles, requiring electrode materials in both the anode and cathode chambers. Carbon-based materials are commonly used as anodes in MFC systems. Meanwhile, the cathode material can be made from various materials, including carbon foam enriched with a platinum catalyst (Pt/C), graphite felt - nikel (GF-Ni) (Satar et al., 2018), nickel-titanium (Ti/Ni) (Mahmoodzadeh et al., 2023), stainless steel (SS), and others. Among these materials, stainless steel (SS) is more attractive due to its heat resistance, availability, affordability, and corrosion resistance (Mecheri et al., 2018). Additionally, stainless steel (SS) materials have not been previously utilized as cathodes in microbial fuel cells (MFCs) for treating tofu wastewater. Mecheri et al. (2018) reported that stainless steel mesh exhibits high catalytic activity, facilitating the reduction reaction at the cathode of a (MFC). Therefore, this research tries to evaluate the effectiveness of stainless steel mesh type 304 (SSM-304) in treating tofu wastewater. The porous structure of SSM-304 enhances its catalytic performance compared to stainless steel plates. So far, no research has explored the use of an MFC system with an SSM-304 cathode for treating TWW. Thus, this study serves as a valuable reference, contributing to the advancement of knowledge and technology in wastewater treatment.

Previous research found that the efficiency of COD reduction in TWW treated with an MFC using stainless steel wire electrodes was around 30-60% (Rinaldi et al., 2018). This result is significantly lower compared to the findings of Satar et al. (2021) where an MFC with graphite foam (GF) electrodes achieved a COD reduction of 71.4%. In addition to using SS-304 as the cathode material, this study also utilized carbon foam as the anode, resulting in a significantly improved reduction of organic pollutant levels.

2. EXPERIMENTAL SECTION

2.1 Materials

All materials, including (D+) glucose monohydrate (99%, Merck), graphite foam (100%, Sigma Aldrich Malaysia Bhd), stainless steel mesh type 304 (SSM-304), HCl (0.1 N), NaOH (0.1 N), NH_4Cl (99.5%, Sigma Aldrich), KCl (99.9%, Merck), trace elements (Merck), KH_2PO_4 (99%, Merck), K_2HPO_4 (99.9%, Merck), NaCl (99.9%, Merck), cation exchange membrane (CMI 7000s), H_2SO_4 (98%, Merck), $K_2Cr_2O_7$, (99.9%, Merck), ferrous ammonium sulfate (FAS) (98%, Sigma Aldrich), acid reagent sulfate-silver sulfate (98%, Sigma Aldrich), ferroin indicator (98.5%, Merck), $MnSO_4$ (99%, Merck), alkali iodide azide (Merck), $Na_2S_2O_3$ (90%, Merck), starch indicator, $KH(IO_3)_2$ (99%, Merck), and Whatman 934 AH filter paper, were purchased from an online shopping platform.

2.2 Enrichment Process of Mixed Electroactive Bac teria (EAB) Culture

The TWW sludge was used as a source of anaerobic mixed culture. Enrichment process of anaerobic mixed-culture was conducted under anaerobic conditions in a 1-liter Duran bottle at room temperature as described by Kyriazis et al. (2025). The TWW sludge and glucose solution were mixed in a 1:1 ratio. Glucose served as the carbon source for microbial growth (Chen et al., 2023; Sun et al., 2020). This is supported by research from Quijano et al. (2024) which found that glucose is a more effective substrate for bacteria compared to sucrose and starch. The growth of the mixed culture in the bottle is indicated by the gas production. Then, anaerobic mixed-culture was applied in further experiment. In addition to gas production, parameters such as pH, COD, BOD, TS, TSS, and TDS of the substrate mixture (TWW:glucose) were evaluated during the enrichment stage.

2.3 Anode and Cathode Preparations

Anode and cathode was prepared based on the method as described by (Yaqoob et al., 2021). Graphite foam (GF) was used as the anode, while SSM 304 served as the cathode in this study. Both GF and SSM 304 were cut into 2.5 × 2.5 cm pieces, immersed in 0.1 N HCl for 1 hour, and then rinsed three times with distilled water. The SSM-304 was then soaked in a 0.1 N NaOH solution for 1 hour to remove inorganic substances. Afterward, it was rinsed three times with distilled water and dried in an oven at 80°C for 24 hours. Afterward, the electrode surface was analysed using SEM-EDS to examine its morphological structure and elemental composition before and after being used in the MFC system. The anode and cathode were integrated into the MFC system for further experiment.

2.4 Cation Exchange Membrane (CEM) Preparation

CEM was prepared based on the method as described by Yoon et al. (2019). CEM was cut in size of 10.0 × 10.0

cm and immersed in a 5% NaCl overnight. This process is carried out to enhance the permeability of the active membrane separator before its application in wastewater treatment. Then, CEM was rinsed three times using deionized. The morphology of CEM surfaces before and after use in the MFC was analyzed using SEM-EDS. Then, CEM was applied into the MFC system for further experiment.

2.5 MFC Construction and Operation

The MFC system was constructed using acrylic blocks measuring 5 × 10 × 10 cm as described by (Obileke et al., 2021). Each anode and cathode chamber had an active volume of 50 mL. The anode material was made of GF, while the cathode material was composed of SSM 304. A titanium sheet was used as the current collector, connecting both the anode and cathode. A 1000-ohm resistor was applied between the current collectors to facilitate the flow of electrons from the anode to the cathode. In addition, the anode and cathode compartments were separated by a cation exchange membrane (CEM, CMI 7000s) to prevent the mixing of anolyte and catholyte. The anolyte and catholyte were prepared using 1.0 g of glucose and a phosphate buffer solution (pH 7.0), respectively. The schematic of the MFC construction is presented in Figure 1.

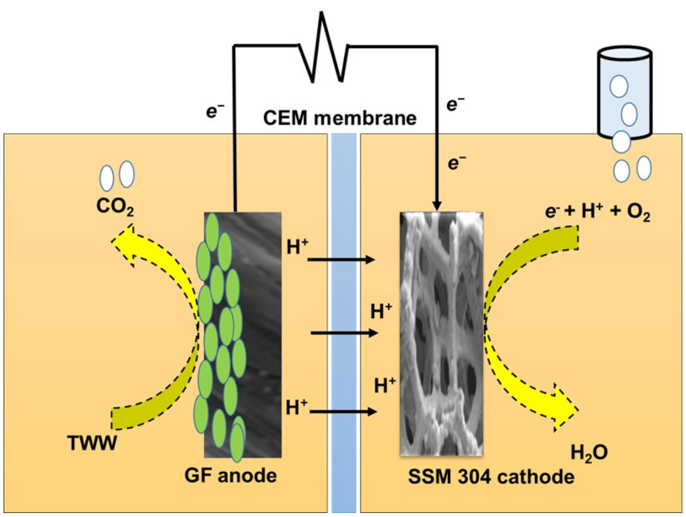

Figure 1. The Schematic of the MFC System

2.6 Characterization of TWW

According to (Satar et al., 2023), the quality of TWW can be assessed by comparing parameters such as pH, COD, BOD, TSS, TDS, and TS before and after MFC treatment. The pH value was measured using a pH meter, while COD and BOD values were analyzed using the reflux and iodometric titration methods, respectively. TS, TDS, and TSS values were evaluated using the gravimetric method. The overall characterization of TWW is presented in Table 1.

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Table 1. The Fresh TWW Characterisations

Parameters	Units	This Study*	Quality Standards**
pH	–	6.99 ± 0.17	6–9
COD	mg/L	21908.27 ± 4365.06	250
BOD	mg/L	55.56 ± 10.18	100
TS	mg/L	17626.67 ± 127.02	–
TDS	mg/L	14393.33 ± 141.89	1500
TSS	mg/L	2820.00 ± 111.35	100

Note: * = TWW Characterizations Zefore Being Treated with MFC System; ** = All Data Were Collected from the References of (Setianingsih et al., 2015)

2.7 haracterization of Electrodes and Cation Exchange Membrane

The morphology of the electrodes and the CEM membrane was analyzed using scanning electron microscopy-energy dispersion X-ray (SEM-EDX, Hitachi type MC1000), following the method described by (Barthelay et al., 2025). The graphite foam (GF) anode was coated with gold (Au) to protect the microbes damage on the GF surface. Meanwhile, the SSM-304 cathode and CEM membrane were not coated with gold (Au) since there were no microbes to protect. Surface images were captured at resolutions of 500×, 1000×, 5000×, and 20,000×. In addition to surface morphology, the elemental composition of the material surface was analyzed in detail.

2.8 Analytical Measurement and Calculations

The analytical procedures and performance calculations for the MFC were carried out following the method outlined by Karamzadeh et al. (2023). Performance of MFC system were evaluated based on the coulombic efficiency (CE), power (P), current (I), and energy efficiency (ηMFC). The CE, P, I, and ηMFC were calculated using Equations 1-4, respectively as follow;

$$CE = \left(\frac{8 \times \int I \, dt}{V_{\text{an}} \times \Delta COD \times F} \right) \times 100\% \tag{1}$$

$$P = I \times V \tag{2}$$

$$I = \frac{V}{R} \tag{3}$$

$$\eta_{\text{MFC}} = \frac{\int_0^{t^c} P \, dt}{n \times \Delta H} \times 100\% \tag{4}$$

Where V_{an} is the active volume of the anode (mL), t represents the operation time (seconds) of the MFC system,

Figure 2. The Enrichment Process of the Mixed EAB Culture Lasted for 20 Days; (a) Schematic and (b) Photograph of the Enrichment System

ΔCOD or $COD_{removal}$ denotes the chemical oxygen demand removal ($COD_{in} - COD_{out}$), F is the Faraday constant (96,485 C/mol), V represents the voltage (V) generated by the MFC, R is the external resistor used (Ω), n denotes the moles of organic substrate based on $COD_{removal}$, and ΔH is the combustion heat of the organic substrate ($\Delta H =$ 506.445 kJ/mol).

3. RESULTS AND DISCUSSION

3.1 Enriching Electroactive Bacteria (EAB)

Anaerobic sludge from TWW was used as a source of mixed electroactive bacteria (EAB) culture (An et al., 2023). The enrichment process was conducted in a 1 L Duran bottle for 20 days (Figure 2). A total of 48 mL of biogas was produced during this period. Biogas production indicates EAB activity in consuming and converting the organic substrate (Almomani and Bhosale, 2020). Biogas is primarily produced by EAB through the decomposition of organic substrates. in general, biogas consist of methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), hydrogen (H_2), and ammonia (NH_3) (Calbry-Muzyka et al., 2022). In addition to biogas, chemicals and organic acids (e.g., acetic acid) were also produced at this stage. The presence of organic acids was indicated by a low pH value (pH <7.0). In this study, the substrate pH decreased from 7.22 to 6.07 (see Table 2). Organic substrates (e.g., glucose) were converted by EAB to produce biogas, water (H_2O), and organic acids (Ncube et al., 2021).

As shown in Table 2, the organic pollutants in the substrate were reduced by approximately 11,430.37 mg/L, corresponding to a 47.99% COD removal, while the BOD was reduced by around 15.55 mg/mL. These conditions also indicate the presence and activity of EAB in the bottle, contributing to the reduction of organic pollutants. Meanwhile, the increase in TS, TSS, and TDS indicates the presence of biomass resulting from EAB activity. Thus, the accumulation of biomass contributes to higher solid and suspended material levels in the system (Gheibi et al., 2023).

3.2 MFC Performance at the Enrichment Stage

The mixed EAB culture from the enrichment process was used as a biocatalyst in the GF anode of the MFC system, with 1.0 g/L of glucose as the sole substrate (anolyte). Pre-enriching the GF anode with EAB is essential to ensure optimal performance (Christgen et al., 2023). Furthermore, during the enrichment of the GF anode, the current must be monitored to confirm the completion of the enrichment process. As shown in Figure 3, the voltage production of the MFC was very low, measuring approximately 10.0 mV over 200 hours. This suggests that the enrichment process of EAB in the anode was not fully completed due to the low voltage generation. It is well known that a GF anode enriched with EAB can consume more substrate while simultaneously generating higher voltage. Also, the activity of the mixed EAB culture in the anode can be monitored through pH values. A neutral pH of the anolyte indicates that the mixed EAB culture has not yet converted the pollutants into organic acids. At this stage, the pH value was observed to range between 7.22 and 6.80.

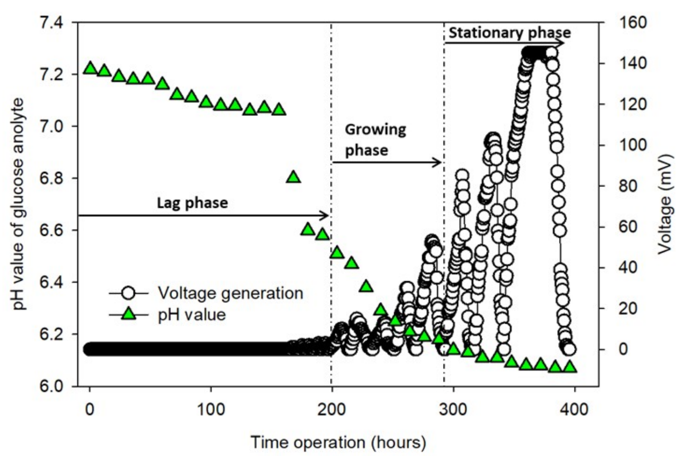

Figure 3. The Voltage Generation Trends During GF Anode Enrichment in the MFC System

Furthermore, the voltage increased from 13.0 mV to 145.0 mV after 200 hours of MFC operation and remained stable after 350 hours. Under stable voltage generation (referred to as the steady-state condition), the pH value was observed to be around 6.07, which was lower than that at 200 hours of MFC operation. This indicates that the GF anode surface was enriched with the mixed EAB culture. In addition to the decrease in anolyte pH, biogas (e.g., CO_2, CH_4) was also produced in the anode compartment. Based on the increase in voltage generation, the decrease in anolyte pH, and biogas production, it can be concluded that the GF anode was successfully enriched with the mixed EAB culture.

Table 2. Glucose Substrate Characteristics During the Enrichment Stage

Parameters	Glucose substrate condition			
	Influent	Effluent	Difference	Percentage of Effectiveness (%)
pH	7.22	6.07	1.15	15.92
COD (mg/L)	23813.30	12382.93	11430.37	47.99*
BOD (mg/L)	26.66	11.11	15.55	58.32*
TS (mg/L)	30306.67	50820.00	20513.33*	67.68**
TDS (mg/L)	23526.67	40206.67	16683.00*	70.91**
TSS (mg/L)	3933.33	7166.67	3233.34*	82.20**

Note: * = Similarly with the $COD_{Removal}$ and $BOD_{Removal}$; ** = The Values Tend to Increase due to the Presence of Biomass in the Substrate.

3.3 MFC Performance Using Glucose and TWW Substrates

Furthermore, the sole substrate of glucose was replaced with TWW to further evaluate the performance of the MFC with the SSM-304 cathode. Figure 4 shows the voltage generation trend when using TWW as the anolyte in the MFC system. Over three consecutive cycles, the highest voltage produced was approximately 168.0 mV, while the lowest anolyte pH was around 5.7. In general, EAB activity declines when the anolyte pH is low. In addition to the pH drop, both COD and BOD also drop along with the voltage generation. The COD and BOD removal rates were observed to be approximately 69.56% and 64.00%, respectively (see Table 3). In addition to voltage generation, these results indicate that the MFC with an SSM-304 cathode effectively reduced both COD and BOD levels. Although the performance of the MFC was relatively good, further experiments are needed to reduce the COD levels to meet the Regulation of the Minister of Environment and Forestry in Indonesia. On the other hand, TS, TDS, and TSS increased during long-term MFC operation. This phenomenon has been explained in the previous section. Actually, the levels of TS, TDS, and TSS in the effluent were significantly higher than those in the influent. These conditions can be addressed through physical treatment methods, such as filtration, before the effluent is discharged into the environment (Niju et al., 2025).

As mentioned above, higher COD and BOD levels in the substrate are closely related to the performance of the MFC in generating voltage. Higher COD and BOD levels in the substrate can provide more feed sources for electroactive bacteria (EAB), leading to higher voltage, current and power generations (Sonawane et al., 2022). According to previous data, the COD level in the simple glucose substrate was lower than that in the TWW substrate; therefore, the voltage, current, and power generations were also lower. As presented in Table 4, the MFC using TWW as a substrate produced a voltage of 167.0 mV, a current of 0.167 mA, and a power output of 27.89 mW. In comparison, the system using glucose generated approximately 144.0 mV, 0.144 mA, and 20.74 mW, respectively. Although the MFC performance using TWW showed slightly higher voltage, current and power generations compared to glucose, the MFC with glucose demonstrated better performance in terms of coulombic efficiency (CE) and overall system efficiency (ηMFC). These facts indicate the simple substrates can be more easily and efficiently converted into energy (Ngabala and Emmanuel, 2024), whereas substrates with higher organic pollutant content tend to generate higher voltage, current, and power in the MFC system.

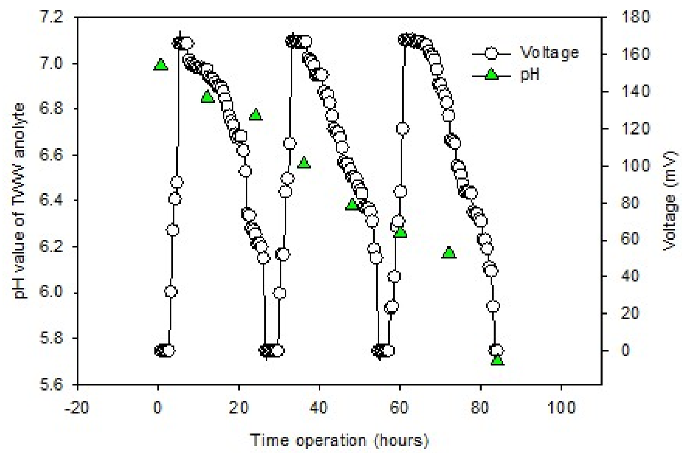

Figure 4. The Voltage Generation When Using TWW Substrate in MFC with SSM-304 Cathode

3.4 Surface Morphology of Anode, Cathode, and Cation Exchange Membrane

As presented in Table 5, the elemental compositions of the GF anode, SSM 304 cathode, and CEM membrane showed slight variations after MFC operation. Notably, the carbon content on the GF surface decreased from 100% to 78.8%. This decline may be due to the attachment and growth of electroactive bacteria (EAB), which likely formed a biofilm that partially covered the GF surface, reducing the detectable carbon content during elemental analysis (Garbini et al., 2023). Additionally, other elements appeared on the GF surface, possibly introduced by components of the anolyte or byproducts of microbial activity. In addition, the

Table 3. The Characteristic of TWW Before (Influent) and After Treating (Effluent) Using MFC with SSM-304 Cathode

Parameters	The Characteristics of TWW in MFC System			
	Influent	Effluent	Difference	Percentage of Effectiveness (%)
pH	6.99	5.70	1.29	18.45
COD (mg/L)	21908.27	6667.73	15240.54	69.56*
BOD (mg/L)	55.56	20.00	35.56	64.00*
TS (mg/L)	17626.67	26226.67	8600.00	48.79**
TDS (mg/L)	14393.33	19033.33	4640.00	32.24**
TSS (mg/L)	2820.00	4093.33	1273.33	45.15**

Note: * = similarly with the $COD_{removal}$ and $BOD_{removal}$; ** = The Percentage of Effectiveness Increases Due to the Presence of Biomass.

Table 4. The Performance of MFC-SSM 304 Using Glucose and TWW Substrate

Parameters	Glucose Substrate	TWW Substrate
V (mV)	144.0 ± 1.0	167.0 ± 1.0
I (mA)	0.144 ± 0.001	0.167 ± 0.001
P (mW)	20.74 ± 0.29	27.89 ± 0.33
J (mA/m^2)	230.4 ± 1.6	267.2 ± 1.6
CE (%)	8.62 ± 0.10	3.35 ± 0.03
η_{MFC} (%)	25.82 ± 0.01	10.43 ± 0.21

presence of oxygen (O) on the GF surface indicates oxidation of the surface, possibly due to the microbial activity producing oxygenated metabolites, Water oxidation and adsorption of hydroxyl or carboxyl groups, and/or Biofilm matrix components (e.g., extracellular polymeric substances) (Haque et al., 2021). The GF anode surface undergoes significant chemical and biological changes, confirming its active role in electron donation and microbial interaction. These modifications can impact conductivity, biofilm-electrode interaction, and long-term anode stability.

In contrast, the elemental composition of the SSM 304 cathode remained largely unchanged, likely due to their resistance to chemical and biological reactions during MFC operation. The primary elements of stainless steel remained consistent, indicating good resistance to corrosion and preservation of structural integrity. Slight decreases in Fe and Ni may suggest minimal oxidative leaching or elemental redistribution. Overall, the SSM 304 cathode demonstrated strong chemical stability, which is crucial for long-term operation. However, minor surface fouling and oxidative deposition could potentially impact oxygen reduction kinetics and, consequently, the overall efficiency of the MFC system over time (Chen et al., 2020).

Similarly, the CEM exhibited stable levels of carbon and fluorine, which are fundamental components of its perfluorinated polymer backbone (similar to Nafion-type membranes). This elemental stability suggests strong resistance to chemical degradation under MFC operating conditions, allowing the membrane to retain key properties such as ion selectivity and proton conductivity. However, visible surface damage observed via SEM may indicate mechanical stress. Combined with potential ion accumulation, this could gradually affect membrane performance during prolonged operation (Tauk et al., 2025).

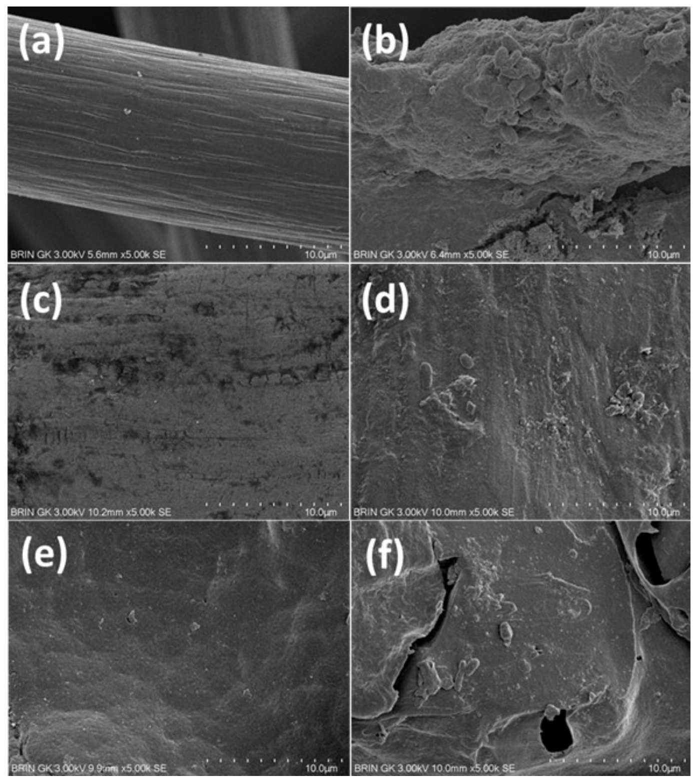

Figure 5. SEM Images of the Electrode and CEM Surfaces. (a) GF Anode Surface Before MFC Operation; (b) GF Anode Surface After MFC Operation; (c) SSM 304 Cathode Surface Before; (d) SSM 304 Cathode Surface After; (e) CEM Surface Before; and (f) CEM Surface After MFC Operation

The surface morphology of the anode, cathode, and CEM is visually presented in Figure 5. As shown in Figure 5(a), the GF anode surface appears smooth and uniform, indicat-

Table 5. The Elemental Composition of the Anode, Cathode, and Cation Exchange Membrane (CEM) Was Analyzed Before and After the Microbial Fuel Cell (MFC) Operation

Types of Elements	GF		SSM-304		CEM, CMI 70000s	
	Before	After	Before	After	Before	After
C	100	78.8	4.7	5.9	43.7	43.6
O	-	13.5	2.1	2.8	22.4	23.3
Fe	-	1.3	67.4	64.2	-	-
Si	-	0.2	0.5	0.4	0.5	0.6
Cu	-	1.9	-	0.7	-	-
K	-	1.9	-	0.2	-	-
Mn	-	-	1.6	1.6	-	-
Ni	-	-	7.8	7.1	-	-
F	-	-	-	-	28.7	29.7
Cr	-	-	15.6	15.7	-	-
Others	-	2.4	0.3	1.4	4.7	2.8

ing that it is clean and unmodified. The absence of deposits or cracks suggests that the surface has not yet undergone electrochemical reactions. Its fibrous structure is advantageous for providing a high surface area, which facilitates electron transfer during redox processes. In contrast, Figure 5(b) shows a roughened GF surface with visible deposits or corrosion by-products. This implies the accumulation of species from the electrolyte, such as metal ions or oxidized compounds. While increased surface roughness can enhance catalytic activity, it may also compromise conductivity or structural stability over time (Mahene et al., 2023). These changes reflect the GF anode's active involvement in redox reactions and possible fouling during MFC operation.

Figure 5(c) shows the SSM 304 cathode surface as relatively clean and untreated, indicating that no significant electrochemical reactions had occurred. The smooth and uniform appearance confirms its condition as a fresh electrode. In contrast, Figure 5(d) reveals a rougher and more irregular surface compared to (c), with noticeable morphological changes. These alterations suggest possible corrosion, the formation of oxide layers such as Cr_2O_3 or Fe_2O_3, or deposition resulting from electrochemical activity. Such surface modifications may affect the cathode's long-term durability and electrical conductivity (Feidenhans'l et al., 2024; Mahene et al., 2023). Figure 5(e) shows the CEM surface as smooth and flat, with only minor undulations, indicating that the membrane remained unreacted prior to MFC operation. This condition suggests good ion selectivity and minimal fouling, which are essential for efficient proton transport while preventing the crossover of reactive species. In contrast, Figure 5(f) reveals noticeable surface damage, including the presence of pores or cracks. These features suggest membrane degradation caused by operational stress, chemical attack, or ion accumulation during MFC operation. Such deterioration could compromise ion selectivity, potentially leading to efficiency losses or the leakage of undesirable ions (Tauk et al., 2025).

4. CONCLUSIONS

The stainless-steel mesh 304 (SSM-304) cathode demonstrated effective performance in a microbial fuel cell (MFC) by significantly reducing the organic load in tofu wastewater, achieving chemical oxygen demand (COD) and biological oxygen demand (BOD) removal efficiencies of 69.56% and 64.00%, respectively. Additionally, the SSM-304 cathode was capable of generating electricity, producing a voltage of 167.0 mV and a current density of 163.2 mA/m2Overall, the SSM-304 cathode exhibited strong performance in the MFC system by effectively reducing organic pollutants in tofu wastewater while simultaneously generating renewable energy.

5. ACKNOWLEDGEMENT

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