electrochem

MDPI

Article

Enhanced Performance of a Microbial Fuel Cell Using Double Oxidant-Treated Carbon Felts

Bhavi Pandya [1,2], Latesh Chaudhari [3,*] and Naresh R. Vaghela [2]

[1] Research Scholar, Gujarat Technological University, Chandkheda, Ahmedabad 382424, India; bmpandya@gecv.ac.in
[2] Chemical Engineering Department, Government Engineering College, Valsad 396001, India; nrvaghela@gecv.ac.in
[3] Chemical Engineering Department, R.N.G. Patel Institute of Technology, Bardoli 394620, India
* Correspondence: lbchaudhari@rngpit.ac.in

Abstract: The aim of this study was to enhance and maintain bioelectricity generation from distillery spent wash using a microbial fuel cell (MFC). Electrode materials play a critical role in the generation of bioelectricity in MFCs. Utilizing double oxidant-treated carbon felts in MFC applications increased current density to 749.56 mA/m^2 and increased peak power density to 125.23 mW/m^2. Electrochemical impedance spectroscopy (EIS) analysis further verified the improved electrocatalytic activity observed in the oxidized carbon felt, consistent with the findings from cyclic voltammetry (CV) and polarization curves, thereby confirming the enhanced performance of the oxidized carbon felt electrode. Overall, the study highlights the significance of electrode morphology and surface modifications in influencing microbial adhesion, electron transport, and the overall efficiency of fuel cells using distillery spent wash as a substrate.

Keywords: carbon felt; oxidized carbon felt; microbial fuel cell; spentwash; power density; current density

check for updates

Academic Editor: Michael Lyons

Received: 31 December 2024
Revised: 14 March 2025
Accepted: 24 March 2025
Published: 30 March 2025

Citation: Pandya, B.; Chaudhari, L.; Vaghela, N.R. Enhanced Performance of a Microbial Fuel Cell Using Double Oxidant-Treated Carbon Felts. *Electrochem* **2025**, *6*, 12. https://doi.org/10.3390/electrochem6020012

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Sugar cane molasses is the most crucial raw material in the alcohol industry. After using raw materials, the process releases a significant amount of effluent, ranging from 8 to 15 L for every liter of alcohol produced, which poses a substantial threat to the environment [1,2]. Distilleries using molasses produce an effluent with high organic matter (COD: 65,000–130,000 mg/L), high mineral concentration, dark brown color, and odor similar to burnt sugar. Various techniques, including evaporation, electrolysis, and fermentation (aerobic and anaerobic), have been used to treat and dispose of distillery spent wash. Bioelectricity production via microbial fuel cells (MFCs) is becoming increasingly important within the research community [3]. An MFC, a hybrid bioelectrochemical reactor, creates electrical energy by oxidizing organic substances with the aid of bacteria. The MFC is designed to recover energy from wastewater and comprises two chambers: an anode and a cathode. In the anode chamber, microbial biomass oxidizes the organic matter in wastewater, and in the cathode chamber, atmospheric oxygen is reduced [4,5].

In the last few years, MFCs have emerged as a relatively new option, serving the purpose of biological treatment and power generation. Although MFCs offer great promise for various applications, they still encounter specific bottlenecks that underscore the urgent need to enhance their performance. It is essential to enhance electricity generation in MFCs for practical applications, and various factors influence this process, such as anode

and cathode materials, wastewater characteristics, and the overall design of MFCs [6]. The performance of fuel cells relies heavily on the material used for anode and cathode electrodes, particularly the anode material, and plays a pivotal role in the power generation of microbial fuel cells (MFCs). It provides a surface for bacterial adhesion and facilitates the transfer of electrons generated during redox reactions [7]. The crucial prerequisites for potential anodes include enhanced power generation, electrocatalytic activity, surface suitability for bacterial adhesion, and biological affinity. Therefore, modifying anode materials is promising for mitigating potential losses. Owing to the modification of anode materials, both the physical and chemical properties of anodes change, leading to a better surface area for bacterial adhesion, thereby increasing the microbial adhesion, electron transport, and overall efficiency of microbial fuel cells [8,9].

Researchers have initiated efforts to introduce impactful modifications in anode materials. Carbon materials used as electrodes possess certain inherent drawbacks, including a limited presence of oxygen-containing functional groups on their surfaces and insufficient accessible surface area. These factors lead to the electrodes having less than optimal physical and electrochemical properties [10]. In one investigation, the effectiveness of various oxidative surface treatments—namely acid, electrochemical, and thermal—was examined for their role in activating carbon surfaces. The study authors concluded that carbon fibers treated with acid oxidation exhibited superior performance, primarily due to their enhanced interfacial adhesion properties [11]. One study examined the performance of dual-chamber microbial fuel cells utilizing carbon fiber (CF) anode surfaces treated with nitric acid (CF-HNO_3) for the inclusion of oxidative functional groups. The modified anodes demonstrated superior performance compared to bare electrodes. Specifically, CF-HNO_3 modification resulted in a 2.88-fold increase in maximum power density, achieving 193 mW/m^2, in contrast with the bare electrode anode, which exhibited a power density of 67 mW/m^2 [12]. A study examining the process of the electrochemical activation of commercial carbon cloth was performed using various acidic solutions, specifically 0.1 M H_2SO_4, 0.1 M HCl, and 0.1 M HNO_3. Results from electrochemical experiments indicated that the carbon cloth treated with these acids achieved a notably higher peak current than the untreated carbon cloth [13]. In a recent investigation, a novel high-performance anode was synthesized, comprising tricobalt tetraoxide (Co_3O_4) combined with a Y molecular sieve (Co_3O_4/Y). The study examined the influence of the Co_3O_4 ratio and the effects of hydrofluoric acid (HF) modification on the performance of the Co_3O_4/Y composite. Remarkably, the H-Co_3O_4/Y-CC variant demonstrated superior power generation performance, achieving a maximum stabilized output voltage of 448 mV, a peak power density of 1179 mW/m^2, and the lowest apparent internal resistance recorded at 466 Ω [14]. In addition, the inclusion of an ammonium group on the anode significantly enhances the power density and current density of the microbial fuel [15]. Modifying the anode electrode surface with acid, which is based on soil, coal, and other sediments (humic acid), and electrically depositing riboflavin, the microbial fuel cell (MFC) demonstrated outstanding electrocatalytic activity and reduced internal resistance [16]. An investigation was conducted to explore the impact of chitosan substrate and its nanometric form on the green energy yield of sediment microbial fuel cells (SMFCs). The researchers transformed chitosan microstructures into nanostructures and incorporated them as substrates in SMFCs. The findings demonstrated that SMFCs enhanced with nanochitosan achieved maximum power and current densities of 59.48 mW/m^2 and 290.45 mA/m^2, respectively [17]. Also, many researchers have aimed to enhance power generation from microbial fuel cells (MFCs) by incorporating conductive materials into the anode, such as nanomaterials [18–21]. While substantial advancements in MFC performance have been documented, the associated modification techniques require either sophisticated equipment or multi-step processes,

coupled with prolonged treatment durations. These factors would inevitably escalate MFC production costs and hinder their widespread implementation [22]. Also, microbial fuel cell (MFC) performance is largely influenced by the substrate, which is vital for the metabolic functions of the microbes within the system. The majority of existing research has focused on the application of oxidative surface treatments using synthetic wastewater as the substrate, which is known to enhance microbial activity. Nonetheless, the exploration of oxidative surface treatment in combination with industrial wastewater remains insufficiently addressed in the literature.

Taking these factors into consideration, this study aimed to enhance bioelectricity production from distillery wastewater, called spentwash, as a substrate in microbial fuel cells (MFCs) by oxidizing carbon felt using a combination of double oxidants, namely HNO_3 and H_2O_2. The performance of oxidized carbon felt (CF) was compared with a similar MFC setup using bare CF as the anode electrode. The focus was on assessing the efficiency of the MFC in terms of circuit voltage without an external load and enhancing power generation. Additionally, the morphology of the electrodes and the membrane before and after operation were examined using scanning electron microscopy, impedance spectroscopy, and cyclic voltammetry to assess MFC performance.

2. Materials and Methods

2.1. Chemicals and Materials

The synthetic wastewater used for MFC inoculation was produced as follows (per L of DI water): 1000 ± 10 mg glucose, 85 ± 5 mg protein, 25 ± 5 mg $NaHCO_3$, 14 ± 5 mg KH_2PO_4, 60 ± 5 mg NH_4Cl, 20 ± 3 mg $CaCl_2$, and 25 ± 3 mg $MgSO_4$. The synthetic wastewater had a pH of 7.24, and a 0.1 M potassium phosphate buffer solution was used to reduce the pH. All chemicals (AR grade) used to prepare the synthetic wastewater were procured from Finar Chemicals, Ahmedabad, India. Synthetic wastewater was prepared using demineralized water. The distillery spent wash used in the present study was procured from the local sugar industry in Chalthan, Surat, India.

2.2. Preparation of Electrodes

A mixed solution comprising HNO_3 and H_2O_2 was initially prepared. The concentration of HNO_3 and H_2O_2 was 15 mol L^{-1} and 7.5 mol L^{-1}. Prior to modification, the carbon felt electrode surfaces underwent a pretreatment process. This procedure entailed immersion in a dilute HCl solution for 2 h, followed by 2 h of acetone sonication. The pretreated carbon felt were subsequently rinsed with deionized water and subjected to drying at 60 °C for 24 h. Following pretreatment, the carbon felts were immersed in the HNO_3 and H_2O_2 mixture and ultrasonically dispersed at ambient temperature for 0.5 h. The carbon felt was then heated in air at 450 °C for an additional 0.5 h. To obtain the desired carbon felt, the treated material was allowed to dry overnight at 60 °C (Figure 1).

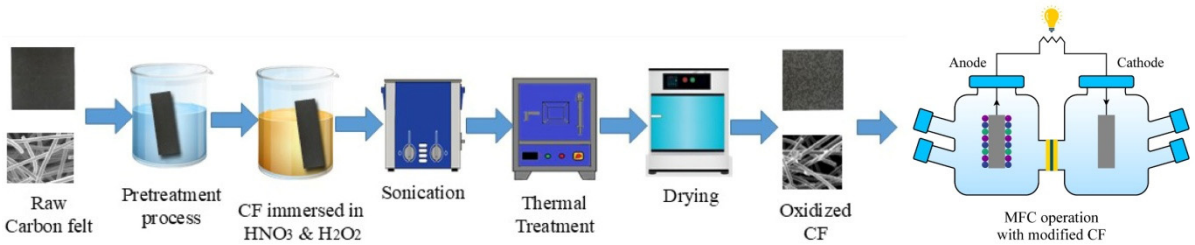


Figure 1. Schematic of the preparation of electrodes.

2.3. Microbial Fuel Cell Setup

The study used a 100 mL MFC setup. The double-chambered MFC was made of borosilicate glass. The volume of both the anode and cathode chambers was 100 mL, with a working volume of 80 mL. Carbon felt with a geometric area of 2 × 5 cm^2 was used as an electrode in both chambers. The anode and cathode chambers were connected externally using copper wire. A proton exchange membrane (Nafion 117; Vinpro Technologies, Hyderabad, India) was used to separate the anode and cathode chambers. The anode substrate was distillery spent wash, and the cathode solution was analytical-grade potassium ferricyanide 0.2 g/L. Wetland sediment was used to inoculate the anode chamber, and the setup used in this study is shown in Figure 2.

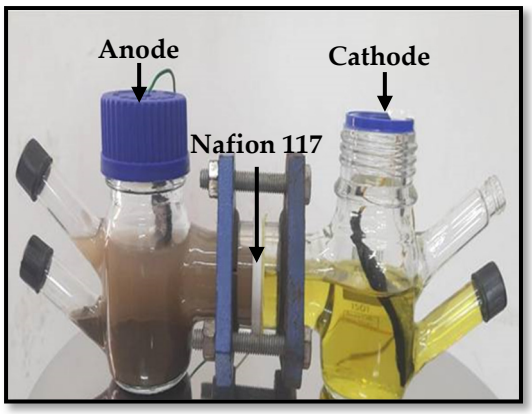


Figure 2. Microbial fuel cell setup.

The membrane was coupled with both chambers using a nozzle gasket arrangement with a screw fitting. Both chambers were equipped with two sampling ports. The cathode chamber was left open to maintain an aerobic environment and the anode chamber was sealed to maintain an anaerobic anode environment. Two sets of MFCs were prepared, one with a bare carbon felt electrode, designated MFC-1, and the other with an oxidized carbon felt electrode, designated MFC-2.

2.4. Calculation and Analysis

The voltage between the two chambers was recorded daily. A digital multimeter (Rish Multi 12S, Rishabh Instruments, Nashik, India) was used to record the voltage. The current density was determined using V/RA (where A = anode surface area, V = voltage, and R = resistance). $P_d = V^2/RA$ was used to calculate the power density. The characterization of the current as a function of the cell voltage was performed by utilizing a polarization curve. To achieve maximum power output, it is crucial to minimize voltage reduction as the current increases. Consequently, the microbial fuel cell (MFC) underwent closed-circuit voltage testing across a range of external loads from 50 to 500 Ω. The redox activities of the anode and cathode chambers of the MFC were evaluated through cyclic voltammetry analysis (M204, Metrohm Autolab with 10A Booster, Herisau, Switzerland). Voltammetry was performed by applying a scan rate of 5 mV/s over a voltage range of −1 V to +1 V to the enriched carbon felt as the working electrode, and the reference electrode was Ag/AgCl. Electrochemical impedance spectroscopy (EIS) was employed to elucidate the ohmic resistance and charge-transfer impedance. This analytical method involves the implementation of an alternating current potential at a 0.05 V amplitude and a frequency spectrum spanning from 100,000 to 0.1 Hz. Experiments were carried out in an aqueous solution of 3 M KCl, employing each carbon cloth electrode under investigation as the working electrode, alongside an Ag/AgCl reference electrode with a potential of 0.197 V.

The morphologies of the prepared electrodes and membrane fouling were examined using SEM (JSM-6380LV, JEOL Ltd., Tokyo, Japan).

3. Results

3.1. Electrode Characterization

The morphological characteristics of the prepared electrodes were investigated using scanning electron microscopy at multiple magnification levels. It was observed that macro pores, cracks, collapsed filaments, or any other macroscopic surface impairment were absent, and large numbers of smooth and clean carbon fibers were observed on untreated carbon felts (Figure 3a). In addition, the SEM image of oxidized carbon felt resulted in a rough surface compared to the simple smooth surface of the untreated electrode. A clear, visible, scattered, and rough oxidized carbon surface enhances the overall surface area for microbial adhesion (Figure 3b).

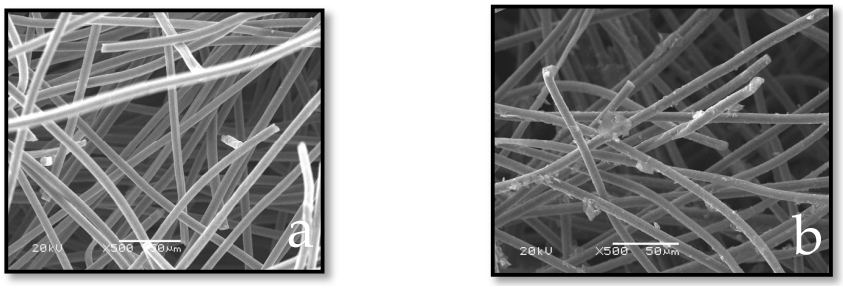


Figure 3. SEM images for (**a**) raw carbon felt and (**b**) oxidized carbon felt.

3.2. Voltage and Power Generation

The initial operation of the microbial fuel cell was conducted under open-circuit voltage conditions. This configuration represents the theoretical maximum voltage attainable by the system in ideal circumstances and remains unaffected by the flow of electric current through the circuit. There is no load connected to it, meaning there is infinite resistance. During the initial operational phase, synthetic wastewater was used as the anolyte medium for both MFC-1 and MFC-2. Initially, stable voltage was obtained in 7 days (0.620–0.650 V) of retention time, meaning that the carbon felt in both MFCs became thoroughly infused with bacterial culture. After this, the synthetic wastewater was replaced with 5000 mg/L of COD strength spentwash [23]. The experimental results revealed that the maximum open-circuit voltage (OCV) attained by the two microbial fuel cell systems differed significantly. MFC-1 reached its peak OCV of 0.454 V on day 5, while MFC-2 demonstrated superior performance with a maximum OCV of 0.702 V during the same period (Figure 4).

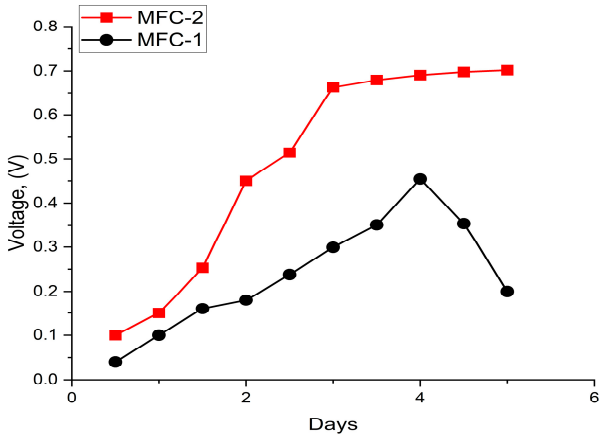
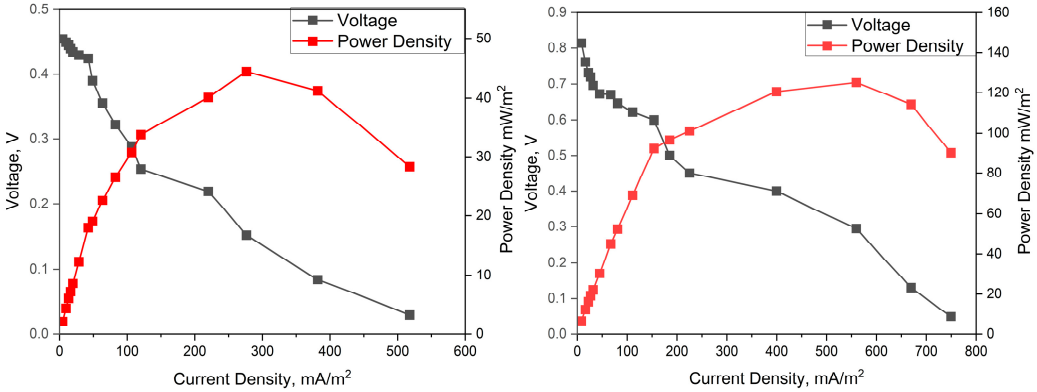


Figure 4. Open circuit voltage for MFC-1 and MFC-2.

Subsequently, a reduction in voltage was observed, indicating the necessity for introducing fresh inoculum to sustain metabolic functions [24]. The characterization of current as a function of cell voltage was accomplished through the utilization of a polarization curve. During close circuit conditions, the voltage remained relatively constant at 1.815 ± 0.035 V when the resistance was decreased from 500 Ω to 153 Ω. A sharp decline in voltage was observed upon further reduction in the external load from 153 to 50 Ω. This finding suggests that maintaining an external load of 153 Ω enables the generation of substantial current with minimal voltage drop. As a result, an external resistance of 153 Ω was selected for subsequent experimental investigations. The experimental results revealed peak current densities of 517.85 mA/m^2 and 749.56 mA/m^2 for MFC-1 and MFC-2, respectively (Figure 5a), with corresponding peak power densities of 44.42 mW/m^2 and 125.23 mW/m^2 (Figure 5b). Subsequently, both microbial fuel cells experienced a reduction in these parameters. This decrease may be attributed to membrane fouling, which potentially influences several factors, such as ion exchange capacity and proton transfer conductivity [25]. The elevated power density observed in MFC-2 may be attributed to enhanced microbial attachment, which facilitates improved electron transfer mechanisms and consequently diminishes the system's internal resistance [26,27].



(**a**) (**b**)

Figure 5. Polarization curve for (**a**) MFC-1 and (**b**) MFC-2.

3.3. Cyclic Voltammetry (CV)

At the conclusion of the experiments, the electrochemical characteristics of the microbial fuel cell (MFC) were assessed by utilizing cyclic voltammetry methodology. The redox activities of the anode and cathode chamber were evaluated through cyclic voltammetry analysis. Voltammetry was employed to examine the electrochemical characteristics of the system. This analytical technique involved the application of a potential sweep ranging from −1 V to +1 V at a rate of 5 mV/s. The experimental setup utilized enriched carbon felt as the working electrode and Ag/AgCl as the reference electrode. Cyclic voltammetry analysis yielded distinct redox peaks for both MFC-1 and MFC-2, with the latter exhibiting more pronounced electrochemical activity (Figure 6). The observed redox potentials and corresponding current intensities for MFC-1 were (0.68 V, 0.0082 A) and (−0.23 V, −0.036 A), while MFC-2 displayed redox characteristics at (0.77 V, 0.012 A) and (−0.23 V, −0.005 A). Higher redox peaks in MFC-2 are attributed to higher capacitive currents [28]. Also, shallow redox peaks were observed with MFC-1, indicating lower capacitive currents and less metabolic activity by microbes [29,30]. One way to describe the electrode's capacitance is by measuring the closed area of the CV curve [31]. The observed increase in anode capacity may be attributed to the charge storage capabilities of the bacterial cytoplasmic surface and the presence of redox enzymes within the cell membrane. The identified redox peak

exhibited consistency with previously reported values [32–34]. The observed outcome aligns with the enhanced cyclic voltammetry plot and polarization characteristics.

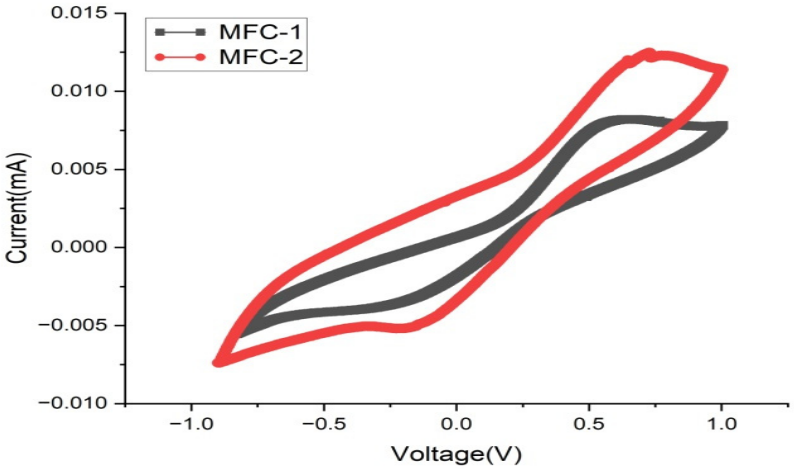


Figure 6. Cyclic voltammetry profile.

3.4. Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy (EIS) was performed to quantify impedance. This was accomplished by employing an alternating current potential with a 0.05 V amplitude across a frequency spectrum ranging from 100,000 to 0.1 Hz. The Nyquist plot in Figure 7 illustrates the relationship between the real and imaginary impedance values. The experimental spectra underwent fitting to an equivalent circuit model. Figure 8 illustrates the R_s (CPE(R_1W)) configuration employed for this purpose. This model comprises solution resistance (R_s), charge transfer resistance (R_1), Warburg diffusion resistance (w), and constant phase elements (CPE). CPE components were utilized instead of pure capacitors to account for the electrodes' porous nature and the system's distributed capacitive response. ZSimpWin 3.10 software (Echem, Ann Arbor, MI, USA) facilitated the fitting of experimental spectra to this equivalent circuit model. The charge transfer resistance (R_{ct}) of an electrodes serves as a key metric for assessing the activation energy required for redox reactions. A higher R_{ct} value corresponds to a greater activation barrier, while a lower value indicates a reduced barrier. In this investigation, the enhanced biofilm formation and electrochemical activity resulted in a lower R_{ct} value of 1034 Ω for MFC-2, compared to 1595 Ω for MFC-1. It is noteworthy that the R_{ct} value of MFC-1 was 54.25% greater than that of the modified anode MFC-2. Electrochemical impedance spectroscopy analysis revealed multiple arcs across various frequency ranges. The initial arc was observed at higher frequencies, spanning from 100 kHz to 630 kHz. In the case of MFC-2, a semicircular arc was detected at an intermediate frequency of 501 Hz. Furthermore, a low-frequency arc, oriented at an approximate angle of 45° on the complex plane, was identified. This latter arc is indicative of mass transport limitations and can be attributed to diffusional processes occurring within the system [35]. The area of the semicircle represents the impedance of the MFC [36]. The diameter of the semicircle, representing the electrode charge transfer resistance (R_{ct}), provided insights into the charge transport mechanisms and phenomena occurring at the electrode–electrolyte interface [37]. Modification of electrodes was induced by acids, heat, and advanced electrochemical oxidization oxides [38,39]. MFC-2 showed a considerably lower charge transfer resistance than bare MFC-1. The lower charge transfer resistance could be attributed to an increased number of carboxylic groups, which benefited from the formation of an intense biofilm. This observation aligns with the cyclic voltammetry and polarization curve data, further corroborating that oxidized carbon felt is

a superior choice for promoting anodic power generation, thus confirming the enhanced performance of MFC-2.

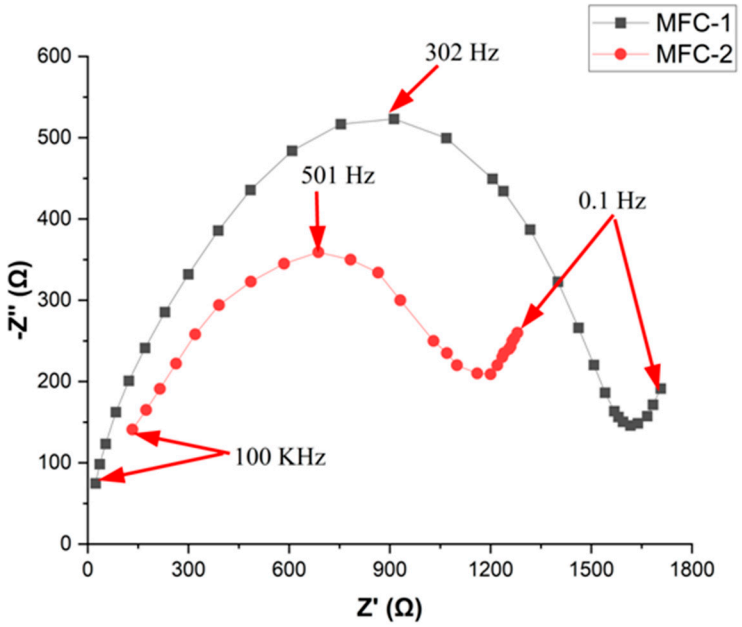


Figure 7. Nyquist plot.

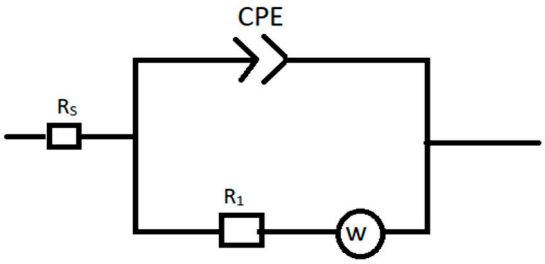


Figure 8. Equivalent circuit model.

3.5. Membrane Fouling

The results indicate that the membrane exhibited a mosaic-like structural configuration. During long-term MFC operation, the proton exchange membrane is easily contaminated by microbes, extracellular polymers, and inorganic salts, impairing MFC effectiveness [40]. Several studies have demonstrated that fouling can potentially modify the ion exchange capacity and permeability of membranes through physical obstruction [41]. Evidence suggests that the fouling process of the cation exchange membrane (CEM) is exacerbated by biopolymers derived from biocatalysts and cations present in the electrolyte solution. This enhancement in biofouling is believed to result from the formation of intermolecular bridges connecting organic foulants with cations, thereby intensifying the accumulation of undesirable substances on the CEM surface [42,43]. The experimental results revealed that MFC-1 and MFC-2 achieved maximum power densities of 44.42 mW/m^2 and 125.23 mW/m^2, respectively. Subsequently, both fuel cells experienced a decline in these values. Membrane fouling, which may lead to decreased efficiency, can be attributed to several factors. These include the encapsulation of bacterial cells within extracellular polymeric matrices, the accumulation of sludge components, and the formation of inorganic salt precipitates on the membrane surface. Scanning electron microscopy (SEM)analysis of the membrane was conducted before and after operation (Figure 9a–c), providing visual evidence of membrane fouling, which negatively influences the efficacy of (MFCs) efficacy. This observation is consistent with results obtained from other electrochemical techniques, including open-circuit

voltage (OCV) measurements, polarization curve analysis, cyclic voltammetry (CV), and electrochemical impedance spectroscopy (EIS).

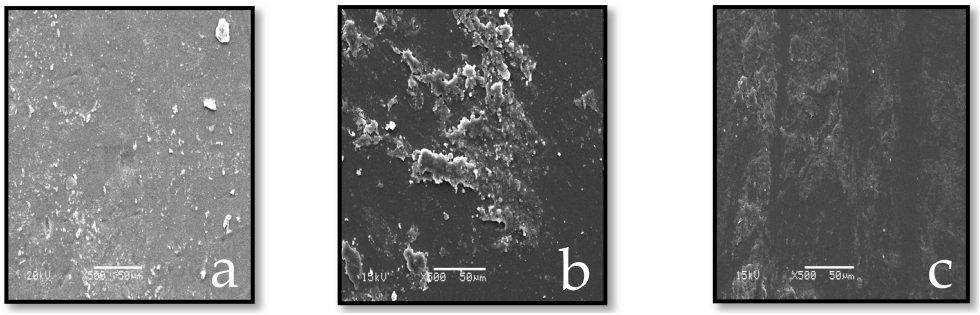


Figure 9. SEM images for (**a**) Raw Nafion 117; (**b**) MFC-1 Nafion 117 (after use); and (**c**) MFC-2 Nafion 117 (after use).

3.6. Limitations and Future Scope

Numerous design configurations exhibit significant limitations, including elevated internal resistance, suboptimal electrode spacing, and undesired anolyte–catholyte exchange across the proton exchange membrane (PEM) during scale-up and extended operation. Furthermore, the identification of economically viable electrode materials and PEM components (when applicable) for microbial fuel cells (MFCs) remains a substantial challenge. An additional hurdle involves the selection of appropriate electroactive microorganisms, as the interaction between microbial surface charges and electrode surface charges plays a crucial role in determining suitable materials for MFC systems. Consequently, extensive research efforts are required to address these obstacles and improve the overall efficacy of MFCs before their implementation at an industrial scale. To mitigate these challenges, several promising options for future research and development emerge. These include the creation of novel electrode materials exhibiting enhanced conductivity, the synergistic integration of MFCs with alternative renewable energy technologies such as solar and wind power to form hybrid systems, and the utilization of co-cultures or genetically engineered microorganisms to optimize overall system efficiency and performance.

4. Conclusions

The experimental findings reveal that the oxidation of carbon felts with HNO_3/H_2O_2 led to an elevated open-circuit voltage (OCV) in MFC-2 (0.702 V), likely attributable to augmented biofilm formation and enhanced electron transport mechanisms. Additionally, MFC-2 demonstrated a current density of 749.56 mA/m^2 and a power density of 125.23 mW/m^2. A reduction in charge transfer resistance (R_{ct}) to 1034 Ω was observed in MFC-2, compared to 1595 Ω in MFC-1, indicating superior metabolic activity and electron transfer. The redox potentials and corresponding current intensities were measured at (0.68 V, 0.0082 A) and (−0.23 V, −0.036 A) for MFC-1, while MFC-2 exhibited characteristics of (0.77 V, 0.012 A) and (−0.23 V, −0.005 A), suggesting more pronounced redox peaks in the latter. These results substantiate the enhanced efficiency and performance of oxidized carbon felts in MFC-2, emphasizing the importance of electrode morphology and surface modifications in promoting microbial adhesion, facilitating electron transport, and optimizing overall MFC performance.

Author Contributions: Conceptualization, L.C. and B.P.; methodology, L.C. and N.R.V.; validation, L.C. and N.R.V.; formal analysis, B.P.; investigation, B.P.; data curation, B.P.; writing—original draft preparation, B.P.; writing—review and editing, B.P. and L.C.; supervision, L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to sincerely thank the Electrical Research and Development Association (ERDA), Vadodara, Gujarat, India, for providing analytical facilities.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Asaithambi, P.; Yesuf, M.B.; Govindarajan, R.; Niju, S.; Periyasamy, S.; Rabba, Z.A.; Pandiyarajan, T.; Kadier, A.; Mani, D.; Alemayehu, E. Combined ozone, photo, and electrocoagulation technologies-An innovative technique for treatment of distillery industrial wastewater. *Environ. Eng. Res.* **2024**, *29*, 230042. [CrossRef]
2. Ratna, S.; Rastogi, S.; Kumar, R. Current trends for distillery wastewater management and its emerging applications for sustainable environment. *J. Environ. Manag.* **2021**, *290*, 112544. [CrossRef]
3. Selvamurugan, M.; Doraisamy, P.; Maheswari, M.; Valliappan, K. An integrated approach to achieve a circular bioeconomy in the treatment and disposal of distillery spentwash. *Biomass Convers. Biorefin.* **2024**. [CrossRef]
4. Jadhav, D.A.; Das, I.; Ghangrekar, M.M.; Pant, D. Moving towards practical applications of microbial fuel cells for sanitation and resource recovery. *J. Water Process Eng.* **2020**, *38*, 101566. [CrossRef]
5. Jadhav, D.A.; Carmona-Martínez, A.A.; Chendake, A.D.; Pandit, S.; Pant, D. Modeling and optimization strategies towards performance enhancement of microbial fuel cells. *Bioresour. Technol.* **2021**, *320*, 124256. [CrossRef]
6. Li, Y.; Liu, J.; Chen, X.; Yuan, X.; Li, N.; He, W.; Feng, Y. Enhanced electricity generation and extracellular electron transfer by polydopamine–reduced graphene oxide (PDA–rGO) modification for high-performance anode in microbial fuel cell. *Chem. Eng. J.* **2020**, *387*, 123408. [CrossRef]
7. Yaqoob, A.A.; Ibrahim, M.N.M.; Rodríguez-Couto, S. Development and modification of materials to build cost-effective anodes for microbial fuel cells (MFCs): An overview. *Biochem. Eng. J.* **2020**, *164*, 107779. [CrossRef]
8. Zhao, Y.; Ma, Y.; Li, T.; Dong, Z.; Wang, Y. Modification of carbon felt anodes using double-oxidant HNO_3/H_2O_2 for application in microbial fuel cells. *RSC Adv.* **2018**, *8*, 2059–2064. [CrossRef]
9. Yaqoob, A.A.; Mohamad Ibrahim, M.N.; Umar, K.; Bhawani, S.A.; Khan, A.; Asiri, A.M.; Khan, M.R.; Azam, M.; AlAmmari, A.M. Cellulose Derived Graphene/Polyaniline Nanocomposite Anode for Energy Generation and Bioremediation of Toxic Metals via Benthic Microbial Fuel Cells. *Polymers* **2021**, *13*, 135. [CrossRef]
10. Zhou, X.L.; Zeng, Y.K.; Zhu, X.B.; Wei, L.; Zhao, T.S. A high-performance dual-scale porous electrode for vanadium redox flow batteries. *J. Power Sources* **2016**, *325*, 329–336. [CrossRef]
11. Sutrisnoh, N.A.A.; Lim, G.J.H.; Chan, K.K.; Raju, K.; Teh, V.; Lim, J.J.N.; Fam, D.W.H.; Srinivasan, M. Toward High-Capacity Carbon Fiber Cathodes for Structural Batteries using Electrophoretic Deposition: Effects of Oxidative Surface Treatment on Carbon Fibers. *Adv. Eng. Mater.* **2023**, *25*, 2300694. [CrossRef]
12. Altın, N.; Uyar, B. Impact of anode surface modifications on microbial fuel cell performance and algal biomass production. *Environ. Technol.* **2024**, 1–12. [CrossRef]
13. Ozer, T. Electrochemical activation and characterization of carbon cloth. *Eur. Chem. Biotechnol. J.* **2025**, *3*, 11–20. [CrossRef]
14. Wang, Y.; Zhang, T.; Tan, W.; Ye, J.; Liu, C.; Feng, Q.; Xu, L. Effect of hydrofluoric acid-modified Co_3O_4/Y-type molecular sieves on MFC performance. *J. Water Process Eng.* **2024**, *59*, 104946. [CrossRef]
15. Mohamed, H.O.; Sayed, E.T.; Cho, H.; Park, M.; Obaid, M.; Kim, H.-Y.; Barakat, N.A.M. Effective strategies for anode surface modification for power harvesting and industrial wastewater treatment using microbial fuel cells. *J. Environ. Manag.* **2018**, *206*, 228–235. [CrossRef]
16. Huang, W.; Chen, J.; Hu, Y.; Chen, J.; Sun, J.; Zhang, L. Enhanced simultaneous decolorization of azo dye and electricity generation in microbial fuel cell (MFC) with redox mediator modified anode. *Int. J. Hydrogen Energy* **2017**, *42*, 2349–2359. [CrossRef]
17. Karthikeyan, C.; Sathishkumar, Y.; Lee, Y.S.; Kim, A.R.; Yoo, D.J.; Kumar, G.G. The Influence of Chitosan Substrate and Its Nanometric Form Toward the Green Power Generation in Sediment Microbial Fuel Cell. *J. Nanosci. Nanotechnol.* **2017**, *17*, 558–563. [CrossRef]
18. Qiang, Y.; Ouyang, D.; You, L.; Liu, D.; Zhao, X. Liquid flow fuel cell with an electrodeposition-modified nickel foam anode for efficient oxidation of 5-hydroxymethylfurfural to produce 2, 5-furandicarboxylic acid with co-generation of electricity. *Chem. Eng. J.* **2023**, *469*, 143832. [CrossRef]
19. Santos, J.S.; Tarek, M.; Sikora, M.S.; Praserthdam, S.; Praserthdam, P. Anodized TiO_2 nanotubes arrays as microbial fuel cell (MFC) electrodes for wastewater treatment: An overview. *J. Power Sources* **2023**, *564*, 232872. [CrossRef]

20. Wu, J.; Liu, R.; Dong, P.; Li, N.; He, W.; Feng, Y.; Liu, J. Enhanced electricity generation and storage by nitrogen-doped hierarchically porous carbon modification of the capacitive bioanode in microbial fuel cells. *Sci. Total Environ.* **2023**, *858*, 159688. [CrossRef]
21. Zahran, M. Iron- and carbon-based nanocomposites as anode modifiers in microbial fuel cells for wastewater treatment and power generation applications. *J. Water Process Eng.* **2024**, *64*, 105679. [CrossRef]
22. Mahmoud, R.H.; Gomaa, O.M.; Hassan, R.Y.J.R.a. Bio-electrochemical frameworks governing microbial fuel cell performance: Technical bottlenecks and proposed solutions. *RCS Adv.* **2022**, *12*, 5749–5764.
23. Zhong, D.; Liu, Y.; Liao, X.; Zhong, N.; Xu, Y. Facile preparation of binder-free NiO/MnO_2-carbon felt anode to enhance electricity generation and dye wastewater degradation performances of microbial fuel cell. *Int. J. Hydrogen Energy* **2018**, *43*, 23014–23026. [CrossRef]
24. Najihah Mohamad Daud, N.; Nasir Mohamad Ibrahim, M.; Ali Yaqoob, A.; Suriaty Yaakop, A.; Hazwan Hussin, M.; Shen, C.Y.; AlObaid, A.A. Optimizing microbial fuel cells performance: An innovative approach integrating anode materials, dual-pollutant treatment, and long-term operation. *Fuel* **2024**, *364*, 131160. [CrossRef]
25. Tian, E.; Liu, Y.; Yin, F.; Lu, S.; Zheng, L.; Wang, X.; Wang, Z.; Liu, H. Facilitating proton transport by endowing forward osmosis membrane with proton conductive sites in osmotic microbial fuel cell. *Chem. Eng. J.* **2023**, *451*, 138767. [CrossRef]
26. Guo, W.; Chen, Y.; Wang, J.; Cui, L.; Yan, Y. Enhanced electroactive bacteria enrichment and facilitated extracellular electron transfer in microbial fuel cells via polydopamine coated graphene aerogel anode. *Bioelectrochemistry* **2024**, *160*, 108769. [CrossRef]
27. Cheng, X.; Liu, B.; Qiu, Y.; Liu, K.; Fang, Z.; Qi, J.; Ma, Z.; Sun, T.; Liu, S. Enhanced microorganism attachment and flavin excretion in microbial fuel cells via an N,S-codoped carbon microflower anode. *J. Colloid Interface Sci.* **2023**, *648*, 327–337. [CrossRef]
28. Yaqoob, A.A.; Ibrahim, M.N.M.; Yaakop, A.S.; Ahmad, A. Application of microbial fuel cells energized by oil palm trunk sap (OPTS) to remove the toxic metal from synthetic wastewater with generation of electricity. *Appl. Nanosci.* **2021**, *11*, 1949–1961. [CrossRef]
29. Arkatkar, A.; Mungray, A.K.; Sharma, P. Bioelectrochemical behaviour of a sequentially added biocatalytic coculture in a microbial fuel cell. *J. Basic Microbiol.* **2020**, *60*, 562–573. [CrossRef]
30. Dolatabadi, M.; Ahmadzadeh, S. A rapid and efficient removal approach for degradation of metformin in pharmaceutical wastewater using electro-Fenton process; optimization by response surface methodology. *Water Sci. Technol.* **2019**, *80*, 685–694. [CrossRef]
31. Jin, X.; Guo, F.; Liu, Z.; Liu, Y.; Liu, H. Enhancing the Electricity Generation and Nitrate Removal of Microbial Fuel Cells with a Novel Denitrifying Exoelectrogenic Strain EB-1. *Front. Microbiol.* **2018**, *9*, 2633. [CrossRef]
32. Yaqoob, A.A.; Al-Zaqri, N.; Alamzeb, M.; Hussain, F.; Oh, S.-E.; Umar, K. Bioenergy Generation and Phenol Degradation through Microbial Fuel Cells Energized by Domestic Organic Waste. *Molecules* **2023**, *28*, 4349. [CrossRef]
33. Tahir, K.; Miran, W.; Jang, J.; Maile, N.; Shahzad, A.; Moztahida, M.; Ghani, A.A.; Kim, B.; Lee, D.S. $MnCo_2O_4$ coated carbon felt anode for enhanced microbial fuel cell performance. *Chemosphere* **2021**, *265*, 129098. [CrossRef]
34. Ahmad, A.; Alshammari, M.B.; Ibrahim, M.N. Impact of Self-Fabricated Graphene–Metal Oxide Composite Anodes on Metal Degradation and Energy Generation via a Microbial Fuel Cell. *Processes* **2023**, *11*, 163. [CrossRef]
35. Paudel, D.R.; Kaphle, G.C.; Poudel, B.R.; Kc, M.; Singh, M.; Ojha, G.P. Enhanced Hydrogen Evolution Reaction of a Zn+2-Stabilized Tungstate Electrocatalyst. *Electrochem* **2025**, *6*, 3. [CrossRef]
36. Hu, M.; Li, X.; Xiong, J.; Zeng, L.; Huang, Y.; Wu, Y.; Cao, G.; Li, W. Nano-Fe_3C@PGC as a novel low-cost anode electrocatalyst for superior performance microbial fuel cells. *Biosens. Bioelectron.* **2019**, *142*, 111594. [CrossRef]
37. Yaqoob, A.A.; Ibrahim, M.N.M.; Yaakop, A.S.; Rafatullah, M. Utilization of biomass-derived electrodes: A journey toward the high performance of microbial fuel cells. *Appl. Water Sci.* **2022**, *12*, 99. [CrossRef]
38. Sonawane, A.V.; Rikame, S.; Sonawane, S.H.; Gaikwad, M.; Bhanvase, B.; Sonawane, S.S.; Mungray, A.K.; Gaikwad, R. A review of microbial fuel cell and its diversification in the development of green energy technology. *Chemosphere* **2024**, *350*, 141127. [CrossRef]
39. Bazina, N.; Ahmed, T.G.; Almdaaf, M.; Jibia, S.; Sarker, M. Power generation from wastewater using microbial fuel cells: A review. *J. Biotechnol.* **2023**, *374*, 17–30. [CrossRef]
40. Xu, J.; Sheng, G.-P.; Luo, H.-W.; Li, W.-W.; Wang, L.-F.; Yu, H.-Q. Fouling of proton exchange membrane (PEM) deteriorates the performance of microbial fuel cell. *Water Res.* **2012**, *46*, 1817–1824. [CrossRef]
41. Rikame, S.S.; Mungray, A.A.; Mungray, A.K. Electricity generation from acidogenic food waste leachate using dual chamber mediator less microbial fuel cell. *Int. Biodeterior. Biodegrad.* **2012**, *75*, 131–137. [CrossRef]
42. Li, Q.; Elimelech, M. Organic Fouling and Chemical Cleaning of Nanofiltration Membranes: Measurements and Mechanisms. *Environ. Sci. Technol.* **2004**, *38*, 4683–4693. [CrossRef] [PubMed]
43. Choi, M.-J.; Chae, K.-J.; Ajayi, F.F.; Kim, K.-Y.; Yu, H.-W.; Kim, C.-w.; Kim, I.S. Effects of biofouling on ion transport through cation exchange membranes and microbial fuel cell performance. *Bioresour. Technol.* **2011**, *102*, 298–303. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.