# Performance of polyvinylidene fluoride (PVDF) and epoxy for binders of palm kernel shell waste as electrode on sediment microbial fuel cells

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**Abstract.** The demand for renewable and environmentally friendly energy continues to rise as fossil fuel resources decline and organic waste from the palm oil industry increases. One promising solution is the application of Sediment Microbial Fuel Cells (SMFC) utilizing biomass such as Palm Kernel Shell (PKS), which are able to generate electricity while simultaneously reducing pollutant loads. The performance of SMFC is strongly influenced by the electrode and binder used, since these components determine electron transfer efficiency, stability, and microbial interaction. Among commonly used binders, Polyvinylidene Fluoride (PVDF) and Epoxy show different properties in conductivity and durability. This study compares their performance in PKS-SMFC systems in terms of power output, Loss on Ignition (LOI), and Chemical Oxygen Demand (COD) removal. The results indicate that Epoxy-based electrodes produced lower power density, while PVDF-based electrodes provided significantly higher electrical output, reflecting superior electron transfer capability. For organic matter reduction, Epoxy electrodes showed moderate effectiveness, whereas PVDF exhibited greater removal ability. COD removal performance, however, varied according to wastewater type: in overlay water, both binders were comparably effective, while in pore water, Epoxy showed more consistent pollutant removal compared to PVDF. These findings suggest that PVDF is more suitable for enhancing energy production and organic matter reduction, whereas Epoxy ensures stable COD removal under certain wastewater conditions. Therefore, the choice of binder should be tailored to system objectives, whether prioritizing maximum power generation or ensuring reliable pollutant removal.

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# 1 Introduction

The rapid growth of domestic, industrial, and commercial activities has increased the volume of waste, particularly liquid waste. Sanitation activities and water use at the household level contribute significantly to the generation of wastewater, which has the potential to reduce environmental quality if it is not properly treated [1]. Environmental pollution caused by untreated wastewater remains a critical global concern due to its detrimental effects on aquatic ecosystems and human health. Sediment Microbial Fuel Cell (SMFC) is a domestic wastewater treatment technology that is currently being developed not only to reduce pollutants but also to generate electrical energy as an added value [2]. SMFCs utilize sediment as a substrate where anaerobic microorganisms carry out the oxidation of organic and inorganic compounds, thereby generating electrical energy while simultaneously supporting the aquatic wastewater treatment process. Another advantage of the remediation process using SMFCs is that it can be monitored more easily because the parameters involved are measurable and controllable [3]. Despite its advantages such as low operational costs, minimal maintenance, and environmental compatibility the practical application of SMFCs is still limited by low electrical output and high internal resistance, largely influenced by electrode performance

The performance SMFCs is strongly influenced by various components, particularly the electrode materials and binders used in electrode fabrication. An ideal electrode should possess good electrical conductivity, biocompatibility, mechanical stability, and high surface area to support microbial attachment and electron transfer. Biochar-based electrodes derived from agricultural waste have gained attention due to their high porosity, availability, and sustainability [4]. Palm kernel shell (PKS) biochar, in particular, has been widely explored because it is an abundant biomass residue in tropical countries such as Indonesia. However, the electrical conductivity of pure biochar remains relatively low, thereby reducing its efficiency in facilitating electron transfer within SMFC systems. Therefore, modification of biochar electrodes is necessary to enhance their electrochemical performance. However, its application often requires the use of binder materials to shape and stabilize the electrodes.

Among commonly used binders, Polyvinylidene Fluoride (PVDF) and epoxy resin are frequently utilized due to their durability and adhesive properties. Polyvinylidene fluoride (PVDF) and epoxy resin serve as effective binders for palm kernel shell (PKS)-based electrodes in energy storage applications, such as supercapacitors, by enhancing mechanical integrity, electrical conductivity, and electrochemical performance. PVDF offers advantages like excellent adhesion, high flexibility, and resistance to electrolyte degradation, leading to improved cycling stability and capacitance retention [5]. Epoxy resin provides superior mechanical strength, toughness, and thermal stability, which help maintain electrode structure under mechanical stress and prevent delamination, thereby extending the lifespan of PKS electrodes in harsh environments. Nevertheless, these binders differ in their impact on electrode conductivity and microbial interaction, which can significantly affect SMFC performance in terms of electricity generation and pollutant removal.

Therefore, this study examines the effect of PVDF and epoxy binders on performance of PKS biochar-based electrodes in SMFC systems, focusing on electricity generation, organic matter reduction, and overall pollutant removal efficiency. The findings are expected to provide deeper insight into electrode fabrication for bioenergy applications and contribute to the development of cost-effective and sustainable SMFC systems for environmental remediation.

# 2 Materials and Methods

## 2.1 Material

The main material used in this study was biochar derived from palm kernel shell (PKS), which served as the base material for electrode fabrication. Polyvinylidene fluoride (PVDF) and epoxy resin were used as binders for electrode preparation. N,N-Dimethylacetamide (DMAc) was used as a solvent for PVDF, while potassium hydroxide (KOH) was utilized for chemical activation of the biochar. Copper wire (Ø 1 mm) was used as the current collector. Distilled water was used in all preparation and rinsing processes. The SMFC reactors were constructed using 5-liter plastic buckets, and multimeter cables for connection to the measurement system.

## 2.2 Preparation of PKS-Biochar

Raw palm kernel shells were washed thoroughly to remove attached impurities and dried under sunlight for 24 hours. The dried shells were then pyrolyzed using a muffle furnace at a temperature of 900°C under limited oxygen supply [6]. The obtained charcoal was ground using a mechanical grinder and sieved to pass through a 100-mesh screen to obtain fine biochar powder. The sieved biochar was stored in sealed plastic containers to prevent moisture absorption.

## 2.3 Chemical Activation of Biochar

Chemical activation was performed to enhance pore development and increase the electroactive surface area of biochar. Biochar activation followed a weight ratio of carbon:KOH:distilled water = 1:4:1, consisting of 20 g of biochar, 6.667 g of KOH 0.01M, and 47 mL of distilled water. The mixture was stirred and allowed to soak for 4 hours to ensure complete impregnation. The activated biochar was filtered and washed repeatedly using distilled water until the rinsing water reached a neutral pH (pH ± 7). The resulting biochar was oven-dried at 105 °C for 60 minutes and cooled to room temperature in a desiccator.

## 2.4 Electrode Fabrication

### *2.4.1 PVDF-Bonded Electrodes*

PVDF-based electrodes were fabricated by mixing 5 g of PKS biochar with 3 g of PVDF binder. The binder was dissolved in 12 mL DMAc solvent while continuously heated at 60 °C and stirred until a homogeneous gel-like slurry formed. A copper wire (5 cm length) was positioned at the center of a square mold (8.5 cm x 8.5 cm) as a current collector before pouring the electrode mixture. The slurry was allowed to solidify at room temperature for 24 hours.

### *2.4.2 PVDF-Bonded Electrodes*

For epoxy-based electrodes, epoxy resin and hardener were mixed in a 2:1 volume ratio (7 mL epoxy resin: 3 mL hardener). The binder mixture was added to 5 g of PKS biochar and mixed thoroughly until a uniform composite paste was formed. A copper wire was embedded in the electrode mold similar to the PVDF process, and the paste was molded and cured at room temperature for 24 hours until the electrode hardened.

## 2.5 SMFC Reactor Setup

The Sediment Microbial Fuel Cell (SMFC) reactor used in this study was constructed from a 5 L plastic container. A mixture of river sediment and overlying water was added into the reactor at a volumetric ratio of 1:1, consisting of 2 L of sediment placed at the bottom and 2 L of water as the supernatant layer [7]. The anode electrode was embedded centrally within the sediment layer, while the cathode was positioned near the surface of the overlying water to allow direct contact with dissolved oxygen as the terminal electron acceptor. Both electrodes were connected to external circuitry using titanium wire, which was extended out of the reactor and linked to a mini breadboard. The electrical output of the SMFC system was measured using a digital multimeter (HIOKI LR8431-20) connected in parallel to a 1000 Ω external resistor installed on the breadboard. The reactor was operated under batch conditions at room temperature (See **Fig. 1**).

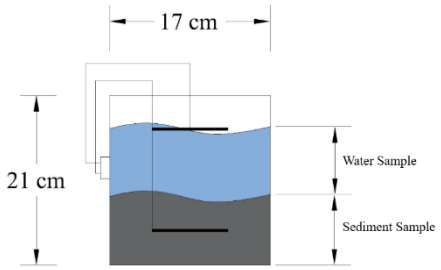


**Fig. 1.** Reactor Design of SMFC

## 2.6 Electrochemical Assessment

The electrochemical performance of SMFC system was evaluated through continuous monitoring of voltage and current generation as well as electrochemical characterization. The output voltage (V) was recorded daily using a digital multimeter connected in parallel to the circuit. Current (I) was calculated based on Ohm's law:

$$I\,(\text{mA}) = \frac{V}{R} \tag{1}$$

where $R$ represents the external resistance (1000 Ω) and $V$ represents the produced voltage (V).

## 2.7 Organic Matter Removal Efficiency (COD and LoI)

The treatment performance of SMFC system was evaluated based on removal efficiency of organic matter in both the aqueous and sediment phases. Chemical Oxygen Demand (COD) was analyzed to determine the concentration of biodegradable organic compounds in the overlying water, while Loss on Ignition (LoI) was used to quantify the organic matter content in the sediment. Overlying water samples were collected from the reactor supernatant before and after SMFC treatment using sterile syringes, then immediately filtered through Whatman filter paper to remove suspended solids. Sediment pore water was obtained by centrifugation to separate solids from liquid. COD was determined using the closed reflux colorimetric method according to Standard Methods [8]. A spectrophotometer was used to measure absorbance at 600 nm after digestion at 150 °C for 2 hours. COD removal efficiency was calculated using the equation:

$$\% \text{ COD Removal} = \frac{COD_{initial} - COD_{final}}{COD_{initial}} \times 100\% \quad (2)$$

Sediment samples were taken from the anode chamber at the beginning and end of the experimental period to determine LoI. Approximately 5 g of wet sediment was dried in an oven at 105 °C for 6 hours to constant weight and subsequently combusted in a muffle furnace at 600 °C for 4 hours. LoI was calculated as the percentage of mass loss due to organic matter volatilization using :

$$\% \text{ LoI} = \frac{W_{105\,°C} - W_{6000\,°C}}{W_{105\,°C}} \times 100\% \quad (3)$$

All measurements were performed in triplicate, and results were reported as mean values with standard deviations to ensure data accuracy.

## 3 Result and Discussion

### 3.1 Current Generation Performance

The **Fig. 2** revealed that the SMFC configured with the PVDF-binder electrode consistently achieved higher current output (peak ~0.34 mA) compared with the epoxy-binder variant (peak ~0.30 mA). The superior performance of the PVDF-bound electrode likely arises from its favourable combination of electrochemical and interfacial properties. PVDF-based electrodes have shown high current density in continuous operation with external loads, which is crucial for sustained electricity generation in bioelectrochemical systems [9]. This enhancement in current production corresponds to favorable condition that promote the metabolic rate of electroactive bacteria and improve the rate of electron release during substrate oxidation [10].

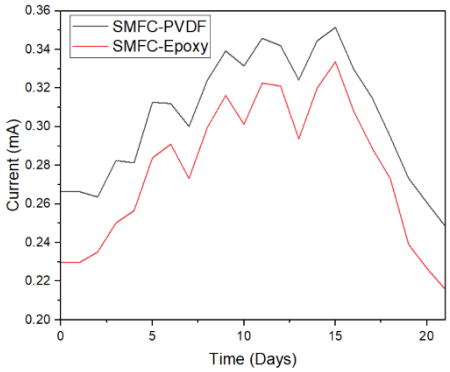


**Fig. 2.** Current production of SMFC with electrode binders variation

Additionally, the current profiles exhibited a rising phase (day 0-5) attributed to biofilm establishment, a peak (day ~10-15) linked with maximum electrogenic activity, and a subsequent decline (after day ~15) likely due to substrate depletion or biofilm ageing. The steeper decline observed in the epoxy-based system further suggests that the binder matrix may have restricted long-term stability of EET pathways or promoted detachment of the active microbial layer. Simeon et al [9]also mention that epoxy as electrode binders was not favorable for long-term operation. The steady performance of the PVDF based SMFC suggests enhanced microbial-electrode interaction and stable biofilm formation, which play critical roles in maintaining current density over time [11]

PVDF possesses high hydrophobicity, chemical resistance, and dielectric stability, which facilitate uniform microbial adhesion and improve ionic conduction within the electrode matrix [12]. These properties enable efficient electron transfer across the bioanode surface and enhance the overall catalytic activity of electroactive microorganisms. In contrast, epoxy-based electrodes may exhibit limited porosity and ion diffusion, leading to increased internal resistance and reduced current generation over time. Previous studies have similarly reported that polymeric binders with high ionic mobility and biocompatibility, such as PVDF or Nafion, significantly enhance the power density and long-term operational stability of microbial fuel cells [13]. Thus, the findings in this study further confirm that selecting an appropriate binder material is crucial for optimizing SMFC performance, particularly in natural sediment environments where conductivity and microbial activity fluctuate.

### 3.2 COD Removal Efficiency

The chemical oxygen demand (COD) removal efficiency of SMFC–PVDF and SMFC–Epoxy was evaluated under two operational conditions: overlying water (OW) and pore water (PW). SMFC–PVDF exhibited high performance compared to SMFC–Epoxy in both cases, with COD removal efficiencies of 55% and 62% for OW and PW, respectively. In contrast, SMFC–Epoxy achieved 42.34% (OW) and 48.00% (PW) (**Fig. 3**). The higher COD removal observed in SMFC–PVDF suggests a more efficient degradation of organic pollutants and enhanced electron transfer activity within the bioanode region.

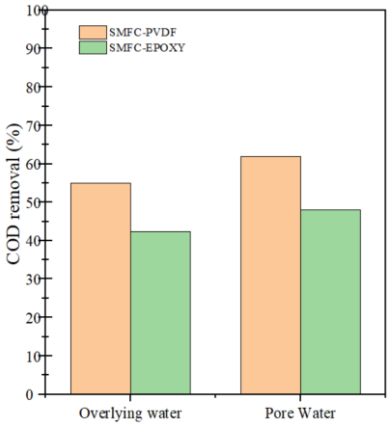


**Fig. 3.** COD Removal of SMFC with electrode binders variation

The improved performance of the PVDF-based system may be attributed to the favorable surface characteristics of PVDF, which support better microbial adhesion and biofilm development. Studies show that PVDF membranes exhibit high hydrophobicity and a surface structure conducive to microbial attachment and biofilm formation. The polymer's chemical resistance and surface charge also contribute to enhanced microbial interactions, promoting stable biofilms on the electrode surface. Compared to modified hydrophilic membranes, the original PVDF surface shows increased microbial adhesion due to its hydrophobic nature, which facilitates stronger interactions with microbial cells, aiding biofilm growth [14]. A stable and dense biofilm facilitates more effective oxidation of organic matter, thereby increasing COD removal and electron generation [10]. Furthermore, the higher COD removal in PW compared to OW for both systems indicates that microbial activity is more concentrated in the sediment water interface, where substrate availability and redox potential gradients are optimal for electrogenic bacteria.The lower removal efficiency observed in SMFC–Epoxy may result from its less porous and less hydrophilic nature, which limits microbial colonization and substrate diffusion within the electrode surface [13].

### 3.3 LOI Removal Efficiency

Loss on Ignition (LOI) represents the organic matter content in sediments and serves as an indicator of the extent of organic degradation achieved by microbial activity in sediment microbial fuel cells (SMFCs). SMFC–PVDF demonstrated higher LOI removal (52%) compared to SMFC–Epoxy (45%) (**Fig. 4**). This result indicates that the PVDF-based system achieved a greater degree of organic matter decomposition, which correlates with enhanced microbial oxidation processes and improved bioelectrocatalytic performance.

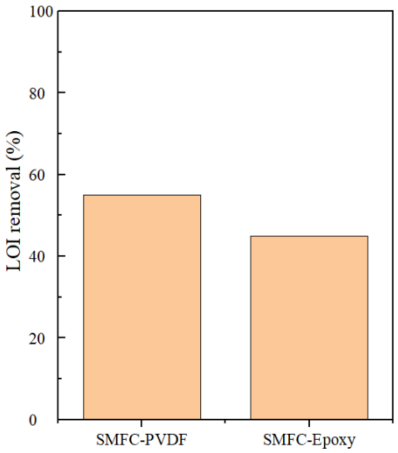


**Fig. 4.** LOI Removal of SMFC with electrode binders variation

The high LOI removal efficiency observed in SMFC–PVDF can be attributed to its favorable electrode–microbe interaction and better electron transfer characteristics. The PVDF binder facilitates stronger microbial adhesion and biofilm formation, creating a stable electroactive layer that enhances substrate utilization and accelerates organic matter degradation. In contrast, SMFC–Epoxy exhibited relatively lower performance due to its limited surface porosity and lower biocompatibility, which may hinder electron exchange and reduce microbial colonization on the electrode surface [13]. The correlation between high LOI removal and elevated current generation observed in SMFC–PVDF supports the role of electroactive biofilms in promoting both organic matter removal and electron flow [10].

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