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Enhancing Microbial Fuel Cell Performance by Optimizing Banana Peel Slurry Concentration for Sustainable Energy Production

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Keywords：Microbial fuel cells (MFCs), Banana peel slurry, *E. coli*, Power, Bioenergy, Sustainable waste management.

ABSTRACT

This study explores using banana peel slurry as a substrate in microbial fuel cells (MFCs) to enhance bioelectricity generation and sustainable waste management. Banana peels, a widely available agricultural byproduct, are rich in organic matter, making them an attractive source for bioenergy production. In this research, banana peel extract was utilized as the sole fuel source for MFCs, with *E. coli* acting as biocatalysts for electron transfer. The substrate concentrations tested were 25 g/L and 50 g/L. The performance of the MFCs was evaluated in terms of power output and COD removal efficiency. The 50 g/L concentration outperformed the 25 g/L concentration, achieving an open circuit voltage (OCV) of 0.82 V compared to 0.68 V. It also recorded a higher maximum power density (0.09 W/m² vs. 0.019 W/m²) and maximum limited current density (0.3 A/m² vs. 0.07 A/m²). Both concentrations showed high COD removal efficiencies, with 91% for 50 g/L and 89% for 25 g/L. These results indicate that higher substrate concentration enhances microbial growth and electron flow, improving overall MFC performance. In conclusion, this study demonstrates that optimizing substrate concentration, mainly using banana peel waste with high reducing sugar content, can significantly enhance the performance of MFCs. These findings highlight the potential of banana peels as a viable and sustainable substrate for bioelectricity generation, contributing to effective waste management and bioenergy.

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INTRODUCTION

The increasing global demand for food, natural resources, and electricity, driven by population growth and industrial expansion, has led to a heavy reliance on fossil fuels for power generation (Verma & Mishra, 2023). Consequently, this dependency poses significant challenges to sustainable development, necessitating the search for efficient, renewable energy sources. Alarmingly, around 33% of the food produced globally is wasted (Mandal et al., 2024), contributing to significant economic and environmental issues. Therefore, this presents an opportunity to recycle or repurpose this waste as an industrial feedstock for high-value bioproducts, addressing pollution and climate change. Microbial Fuel Cells (MFCs) offer a promising alternative by converting organic waste into electricity, thus providing a sustainable solution to these pressing issues (Bazina et al., 2023).

Moreover, the performance of MFCs is closely tied to the type and characteristics of the substrate used. Substrates, including glucose, lactate, acetate, sucrose, and wastewater, have produced bioelectricity (Makhtar & Tajarudin, 2020). Easily degradable substrates support better microbial growth, leading to higher voltage outputs (Logroño et al., 2015; Khan and Obaid, 2015; Zhang et al., 2011; Zhuang et al., 2012). For instance, food waste, 30-40% of municipal solid waste, is rich in carbohydrates and lipids (Zhao & Li, 2023). For example, avocado waste achieved a voltage of 0.74 V, a power density of 566 mW/cm², and a current density of 5.165 A/cm² (Rojas-Flores et al., 2022). Similarly, tangerine peel outperformed other substrates with a current density of 72 mW/cm² and a peak voltage of 1.06 V (Flores et al., 2020). This high power density was attributed to the substantial glucose content in the substrate, achieving 0.20 W/m² at a current density of 0.27 A/cm² and a peak voltage of 0.58 V (Xin et al., 2018). Additionally, mango debris resulted in a power density of 0.30 mW/cm² and a current density of approximately 28 mA/cm² (Yaqoob et al., 2022). Building on existing research, wet crushed onions demonstrated the highest performance among tested substrates with a peak voltage of 1.01 V, a power density of 541 μW/cm², and a current density of 536 μA/cm², while tomatoes and potatoes showed comparatively lower outputs (Rojas-Flores et al., 2020).

However, some organic residues may resist degradation, affecting microbial growth and MFC efficiency (Pant et al., 2012), but they still hold promise as anode substrates for sustainable power generation (Schröder, 2007). These microenvironments influence the efficiency of extracellular electron transfer in MFCs. Acidophilic conditions facilitate faster oxidation and shorter electricity generation cycles (Raghavulu et al., 2009). Additionally, conductivity variations attributed to dissolved ions contribute to electron flow and reduce substrate resistance (Karthikeyan et al., 2016). However, increased conductivity did not always correspond to higher current values, suggesting that reduced mass transfer and slow proton flow rates may limit electricity generation (Malvankar et al., 2012). In short, the choice of substrate plays a critical role in the performance of microbial fuel cells. By leveraging substrates rich in easily degradable organic matter, it is possible to enhance microbial activity and power output.

Banana peels, rich in carbohydrates, proteins, and fibers, have significant potential in biotechnological applications. Approximately 60% of banana biomass is discarded post-harvest, providing a substantial resource for ethanol fermentation, biogas production, citric acid synthesis, and extraction of high-antioxidant compounds (Alzate Acevedo et al., 2021; Emaga et al., 2008; Hammond et al., 1996; Gebregergs et al., 2016; Serna-Jiménez et al., 2021; Karthikeyan and Sivakumar, 2010; González-Montelongo et al., 2010). Additionally, banana peels have been used as bio-adsorbents, in activated carbon production, and as electrode materials (Izhar et al., 2022; Tripathy et al., 2021). Despite their potential, large-scale utilization of banana peels faces technical and economic challenges. However, their high carbohydrate content supports robust microbial growth, making them excellent electron donors (Essien et al., 2005). Furthermore, lower lignin content facilitates easier degradation, enhancing their suitability as substrates (Brebu & Vasile, 2010). Mechanical treatments like crushing and natural processes such as ethylene-induced breakdown further improve their biodegradability (Gregoire & Becker, 2012; Sun and Cheng, 2002). Hence, banana peels are ideal for Microbial Fuel Cells due to their properties and abundance, making them a cost-effective and sustainable option for converting organic waste into electricity.

In Microbial Fuel Cells (MFCs), substrates' organic content and moisture levels are crucial for electricity generation. For instance, Wang et al. (2014) found that a moisture content above 80% is optimal for composting MFCs. Additionally, studies show that banana peel waste (BPW) can generate higher currents than orange peel waste (OPW), likely due to the higher cellulose fiber content in OPW hindering microbial degradation (Miran et al., 2016). Furthermore, Kalagbor et al. (2020) observed that banana slurry trends towards a neutral pH over time, with small organic acids as primary oxidation products (Liu et al., 2018). During ripening, ethylene increases inverted sugar content, enhancing electron flow and power output (Orwig, 2015). However, comparative studies show mixed results: damaged banana peels lead to declining voltage (Kalagbor et al., 2020), while untreated peels in single-chamber MFCs generate higher voltages and currents (Toding et al., 2018). Moreover, banana peels contain 0.1% to 0.5% reducing sugars (William et al., 2019). Components such as sucrose, amino acids, and ascorbic acid act as biocatalysts and electron donors in anodic reactions, while minerals serve as catalysts in essential metabolic processes (Amiard et al., 2004; Fukumorita & Chino, 1982; Girousse et al., 1991; Hughes & Poole, 1991; Goud et al., 2011). Additionally, variations in conductivity and biochemical oxygen demand (BOD) reflect changes in substrate properties affecting electrical output (Karthikeyan et al., 2016; Malvankar et al., 2012). Enhancing microbial concentration and electrode surface area can significantly boost current production, highlighting the multifaceted approach needed to optimize MFC systems using banana peels as substrates (Kim et al., 2002). Both dried and wet banana peels have been used in MFCs, with performance varying based on conditions (Table 1). Researchers have experimented with different concentrations and conditions, resulting in highly variable MFC performance. However, it remains unclear from existing data whether dried or wet biomass yields better results. Given that MFCs require adequate moisture content, this study focuses on using wet banana peels. Notably, no prior research has exclusively optimized the concentration of banana peel slurry for MFCs. Therefore, this study aims to fill that gap, providing novel insights into optimizing banana peel slurry for enhanced MFC performance.

Building on the findings of Herrero Hernandez et al. (2019), who demonstrated that a mediator-less MFC using *Escherichia coli (E. coli)* and platinized titanium mesh electrodes achieved a maximum power density of 627 mW/m², this study leverages the effectiveness of E. coli in facilitating electron transfer and generating electricity. Given the substantial amount of banana waste generated, there is a pressing need to eradicate this waste effectively. Therefore, *E. coli* was selected to evaluate the performance of MFCs using banana peel slurry as the substrate, with concentrations of 25 g/L and 50 g/L. The higher concentrations were chosen to ensure sufficient substrate availability for microbial activity, which is expected to enhance electron transfer and power generation. Additionally, substrate concentration must be carefully selected to ensure it is conducive to MFC performance, potentially resulting in enhanced power output and improved efficiency. Therefore, these concentration ranges were chosen to optimize the performance metrics such as Open Circuit Voltage (OCV), power density, current density, and COD removal efficiency, ultimately providing novel insights into the impact of substrate concentration on MFC efficiency. Ultimately, this study aims to provide novel insights into the effects of substrate concentration on MFC efficiency and explore innovative ways to enhance power generation using banana peel slurry with E. coli.

MATERIALS AND METHODS

Banana peel slurry substrate preparation

Fresh waste banana peels (Musa paradisiaca) were gathered from a fruit juice store and used as substrate in the current study. The fresh banana peel was washed in running tap water and thrice with DI water to remove the dirt and insects present in the waste. The samples were ground to a paste by adding water to a mixer grinder. The grained slurry was used as substrate in the microbial fuel cells (MFCs).

Inoculum preparation

Escherichia coli (*E. coli*), available in the TFBE lab, NIU, was used in this study. Luria-Bertani broth (LB broth) was used to culture *E. coli*; 25 g was dissolved in 1 liter of DI water. The media is then sterilized in the autoclave for 15 minutes at 121°C. First generation culture was prepared with 1 ml of glycerol stock of *E. coli* in 19 ml of LB broth. The second generation was prepared by using first-generation culture, and so on. The third-generation culture was used in the MFCs. The optical density (OD) values at 600 nm were used to determine the growth of the bacteria.

Electrode and membrane pre-treatment

Graphite felt was used as an electrode in both chambers. A uniform-sized electrode (dimensions of length: 8 cm, width: 3 cm, and thickness: 0.65 cm) was taken and incubated in 10% H_2O_2 at 90˚ C for 3 hr. Then, the electrodes were thoroughly washed with DI water. The electrodes were vacuum-dried in an oven at 50 °C until further use.

The Nafion 117 proton exchange membrane was used in this study. The suitable-sized membrane was pretreated with 5% H_2O_2 at 90˚ C for 1 hour. The membrane was washed thoroughly in DI water and incubated in 0.1M H_2SO_4 for 1 hour. After incubation, the membranes are washed thoroughly and soaked in distilled water until further used.

Setup of Microbial Fuel Cells

This study employed two standard 250-ml dual-chamber H-type microbial fuel cells (MFCs) as the setup **(**Fig.1). In the anodic chamber, 100 ml of *E. coli* culture was used as inoculum for the MFCs. Suitable grams of the banana peel slurry were used. Setup 1 contains 25 g of banana peel slurry, and Setup 2 includes 50 g. Potassium ferricyanide was used as catholytes in MFCs. The pretreated graphite-felt electrodes were used as anodes and cathodes. The electrodes were fixed with titanium wires to the external circuit of the 1kΩ resistor. The MFC experiment was conducted at 37°C in an incubator. The anolyte and catholyte were changed once when the potential dropped continuously or changed color due to ferricyanide ions. The experiments were conducted continuously for 35 days. The data acquisition system was used to record the voltage. A digital multimeter also ensures data acquisition once a day. The current density of the MFC was estimated by dividing the projected area of the anode with current values recorded in a multimeter, and the power density of the MFCs was determined by the following equation (1).

$$P= (V^* I)/A \tag{1}$$

where P is power density (W/m^2), V is the voltage (V), I is the current generated (A, ampere), and 'A' is the projected area of an anode (m^2).

The initial and final COD were analyzed on the initial (1st day) and final (40th day) according to APHA, 2005 Standard Methods. The percentage removal of the organic content was calculated using the following COD removal efficiency shown in equation (2**)**.

$$\text{COD Removal Efficiency (\%)} = 〔(\text{Initial COD}-\text{Final COD})/ \text{Initial COD}〕\times 100\% \tag{2}$$

RESULT AND DISCUSSION

Polarization curve and maximum power density

This study used *Escherichia coli* (*E. coli*) to evaluate microbial fuel cells (MFCs) with banana peel slurry as the substrate at 25 g/L and 50 g/L concentrations. A dual-chambered MFC setup with a 250-ml capacity was used (Fig. 1). The goal was to compare open circuit voltage (OCV), power density, current density, and COD removal efficiency between these concentrations. The findings suggest that using a 50 g/L concentration of banana peel slurry in microbial fuel cells (MFCs) provides better overall performance. This concentration offers a higher initial open circuit voltage (OCV), ensuring more stable current density and superior chemical oxygen demand (COD) removal efficiency. Therefore, these advantages make the 50 g/L concentration more suitable for practical, sustainable energy production and wastewater treatment applications.

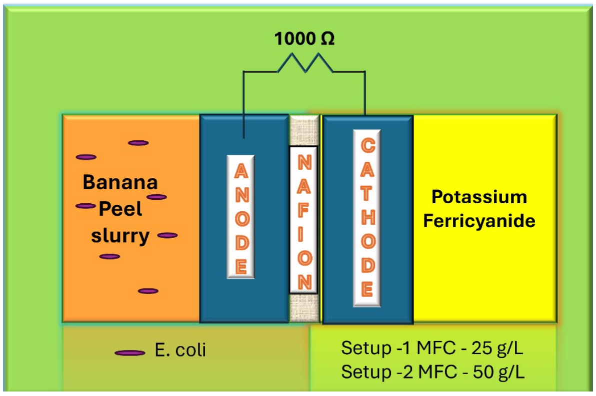

Fig. 1 MFC setup used in this study

Initially, the voltage in the MFC chambers was approximately 0.2 V. Over the following days, the voltage gradually increased. However, after seven days, a voltage drop was observed, prompting the replacement of the medium in the chambers, which led to a subsequent voltage increase. By the 29th day, the voltage stabilized around 0.79 V for the 50 g/L concentration and 0.65 V for the 25 g/L concentration. After replenishing the medium, the increase in voltage was minimal. On the 34th day, the voltage reached 0.82 V for the 50 g/L setup and 0.68 V for the 25 g/L setup, after which it remained stable.

Similar findings were reported by Rojas Flores et al. (2020), who observed an increase in voltage from 0.778 V to a peak of 1.01 V on the 21st day for onion substrates. For potato substrates, the voltage initially decreased from 0.900 V to 0.810 V, then slightly increased to 0.83 V. For tomato substrates, the voltage was 0.974 V on the sixth day and decreased to 0.757 V by the 21st day.

The observed increase in voltage indicates that the medium concentration is favorable for microbial activity and their electrogenic processes at both concentrations. The microbes effectively utilized the substrate, oxidizing it and generating electrons, contributing to the observed voltage increases. Furthermore, these variations in voltage trends across different substrates are attributed to the byproducts produced during the oxidation process. This study shows that the byproducts created during oxidation did not negatively impact the microorganisms' ability to generate electrons.

While the potential difference is gradually increasing, it is essential to assess power generation through a polarization graph to infer the internal resistances developed by the system. To investigate further, open circuit voltage (OCV) measurements were conducted for both concentrations of banana peel slurry to determine the maximum voltages achievable. Following this, a potentiodynamic study was carried out, starting with the initial OCV values and reducing the voltage to zero at a scan rate of 0.01 V/s. The resulting current and power density were calculated based on the recorded current and voltage values using a surface area of 0.024 m². Fig. 2 illustrates the voltage, power density, and current density for the different concentrations of banana peel slurry. The exploration of this graph leads to a better understanding of the internal resistances developed in the MFC.

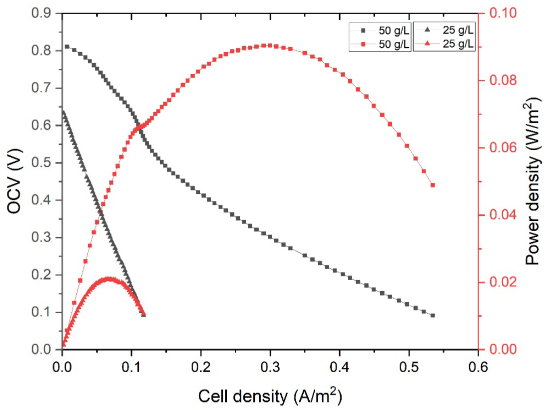

Fig. 2. Polarization curve derived from the current study using different concentrations of banana peel slurry as a substrate in MFC.

The internal resistance of microbial fuel cells (MFCs) can be inferred from the polarization graph by examining the slope of the voltage curve as current density increases. This resistance is influenced by factors such as the electrolyte, electrodes, and microbial activity. The polarization curve reveals three key regions: rapid voltage drops at low current densities due to overpotentials, a linear decrease at moderate densities, and a sharp decline at high densities (Goenka et al., 2018). Overpotentials dominate at low current densities, including activation losses, bacterial energy consumption, and mass transport losses. Ohmic losses, related to ion transport and electron flow, also significantly impact MFC performance. Internal resistance, including these losses, restricts current flow and reduces efficiency significantly above low current densities before maximum power production is reached.

When comparing the concentrations, the voltage curve for the 50 g/L concentration exhibits a gentler initial decline, indicating lower activation losses. It also flattens out more quickly, suggesting lower ohmic resistance than the 25 g/L concentration. This higher concentration likely provides a more consistent supply of nutrients, thereby reducing the impact of activation losses and enhancing the overall performance of the MFCs. This implies that the internal resistance is lower at moderate current densities, allowing for higher power densities. Conversely, the 25 g/L concentration shows a steeper initial decline, indicating higher activation losses, and does not flatten as much, suggesting higher ohmic resistance. Additionally, there are significant voltage losses due to bacterial metabolism and mass transfer losses, limiting the achievable maximum power density.

The results indicate that the maximum power density and current density for the 50 g/L concentration are approximately 0.09 W/m² and 0.3 A/m², respectively. In contrast, the 25 g/L concentration achieved a maximum power density of 0.019 W/m² and a current density of 0.07 A/m² (Table. 1). The extrapolated short circuit current, where the voltage drops to zero, is approximately 0.62 A/m² for the 50 g/L concentration and 0.13 A/m² for the 25 g/L concentration. These findings suggest that the 50 g/L concentration significantly outperforms the 25 g/L concentration in power and current density. The higher substrate concentration provides more nutrients for the microbes, enhancing their metabolic activity and electron production. This aligns with findings from other studies, such as William et al. (2019) and Toding et al. (2018), highlighting the importance of substrate concentration in microbial fuel cell performance.

Studies have shown that substrate concentration plays a crucial role in the performance of microbial fuel cells. According to William et al. (2019), 0.2 grams of dried banana peel powder produced a significantly higher voltage of 0.246 V compared to sugarcane, indicating banana peel as a more efficient substrate. On the other hand, Chibueze and Chima (2018) found that using 20 grams of dry banana peel powder with Pseudomonas aeruginosa resulted in a low power output of 1.434×10^{-4} W, which was less efficient compared to pineapple powder. Makhtar and Tajarudin (2020) reported that 20 grams of dry banana peel in a membrane-less MFC resulted in 271 mV and 0.152 mW with 49.1% COD removal efficiency.

Khan et al. (2021) found that Saccharomyces cerevisiae produced a lower current output of 0.97 mA with 26 grams of banana peel in 100 ml, likely due to the high substrate concentration. In contrast, Toding et al. (2018) found that wet banana peel waste generated 0.492 V and 0.101 mA, while wet orange peel waste produced 0.563 V and 0.017 mA. They suggested the lower voltage and current might be due to the low substrate concentration. Kalagbor et al. (2020) also observed that wet-ripened banana peels generated voltages ranging from 1.2 to 3.1 V for quantities between 5 kg and 20 kg. They used waste battery metals as electrodes, which may have contributed to the lower output. Furthermore, they noted that damaged bananas produced current, but a voltage drop occurred due to organic acids from ripened bananas, making them unsuitable for electricity production. Our findings support these positive results, confirming that banana peel of 50 g/L can be an effective substrate for microbial fuel cells. However, increasing the concentration of banana peel even further may reduce power output due to the presence of organic acids.

In conclusion, while dry and wet banana peels are potential substrates for microbial fuel cells, their efficiency varies significantly. Wet banana peels generally produce higher voltages and power outputs, but factors such as substrate concentration, type of microorganism, and electrode type can dramatically influence the results. Further optimization and standardization are necessary to maximize their potential for sustainable energy production.

Analysing the polarization curve reveals that the 50 g/L concentration has lower internal resistance, resulting in higher power and current densities. This makes using 50 g/L banana peel slurry in microbial fuel cells promising for sustainable energy and wastewater treatment, thanks to its higher power density and COD removal efficiency. However, challenges such as medium replacement, the impact of organic acids on power output, and scalability must be addressed.

In conclusion, the findings from this study demonstrate that the 50 g/L concentration of substrate significantly enhances MFC performance, surpassing the results of other studies in terms of power density, current density, and voltage. This highlights the potential of optimizing substrate concentration to improve MFC efficiency. Hence, carefully selecting and balancing substrates makes it possible to significantly improve the performance and sustainability of MFCs for practical applications.

COD removal efficiency

The COD removal efficiency of the MFCs was assessed by measuring the decrease in COD concentration in the anode chamber over time. MFCs utilizing banana peel slurry achieved an average COD removal efficiency of 91% and 89% for 25 g/L and 50 g/L compositions throughout the operation. Fig. 3 shows the initial and final COD concentrations observed in this study. These results indicate that banana peel extract is a sustainable MFC substrate with significant potential, demonstrating high power generation and COD removal efficiency.

The increased power production over time suggests biofilm maturity and microbial adaptability, which enhance electron transfer efficiency (Makhtar & Tajarudin, 2020). In other studies, COD removal rates have reached 70%-80% or above 80% (Verma & Mishra, 2023). The higher power output seen in MFCs with a 50 g/L banana peel extract concentration can be attributed to the greater availability of substrate, providing more organic matter for microbial metabolism. From the quoted references, *Pseudomonas aeruginosa* and

Table. 1 Different food/fruit waste used as substrate in MFC

Food waste	**Grams**	**Dried/wet**	**Voltage**	**Power density**	**Current density**	**COD removal efficiency**	**Reference**
Banana peel	0.2g	Dried	0.246 V	-	-	-	William et al 2019
Sugarcane outer layer			0.0126 V	-	-	-	
Sugarcane inner layer			0.0024 V	-	-	-	
Onions	120 ml	Wet crushed	1.01 V	541 µW/cm^2	536 µ A/cm^2	-	Rojas Flores et al. 2020
Tomato			0.974 V	509 µW/cm^2	520 µ A/cm^2	-	
Potato			0.900	420 µW/cm^2	472 µ A/cm^2	-	
Glucose (Commercial)	20 g	Dry	-	7.57×10^{-4} W	-	-	Chibueze, & Chima 2018
Banana	20 g		-	1.434×10^{-4} W	-	-	
Pineapple	20 g		-	2.402×10^{-4} W	-	-	
Dextrose	20 g in 100 ml	-	-	56.9 mA	-	-	Khan et al. 2021
Maltose		-	-	105.3 mA	-	-	
Sucrose		-	-	26.7 mA	-	-	
Potato peels	26 g / 100 ml	-	-	83.7 mA	-	-	
Banana peel		-	-	0.97 mA	-	-	
Banana peel waste	-	Wet	0.492 V	0.101 mA	-	-	Toding et al. 2018
Orange peel waste			0.563 V	0.017 mA	-	-	
Avocado waste	150 ml of extract	Dry	0.74 V	566 mW/cm^2	5.165 A/cm^2		Rojas-Flores et al. 2022
Rejected tomatoes	5 kg, 10 kg, 15 kg, 20 kg	Wet	1.6 V 2.6 V 3.7 V 4.2 V -	-	-	4.4-5.8 mg/L	Kalagbor et al. 2020
Damaged banana		Wet	1.2 V 1.5 V 2.5 V 3.1 V -	-	-	3.3-6.8 mg/L	
Unusable Pineapple fruit peels		Wet	0.8 V 1.6 V 2.6 V 3.0 V -	-	-	5.0-8. mg/L	
Corn barn	20 g	Dry	176 mV	0.081 mW	-	41.64%	Makhtar& Tajarudin 2020
Banana peel			271 mV	0.152 mW	-	49.1%	
Palm oil mill effluent		Wet	138 mV	0.141 mW	-	24.40%	
Pineapple waste	2 L	Dried and extracted juice	0.99 V	513 mW/m^2	6.123 A/m^2	-	Rojas-Flores et al. 2022
Banana peel slurry	25 g	Wet	0.68	0.019 W/m^2	0.007 A/m^2	89%	This study
	50 g		0.82	0.09 W/m^2	0.3 A/m^2	91%	

Saccharomyces cerevisiae were unsuitable for using banana peels. The COD removal efficiency of the current study indicates that *E. coli* is effectively degrading the organic materials in the banana peel extract. However, changes in microbial population dynamics or substrate depletion may cause a gradual drop in removal efficiency.

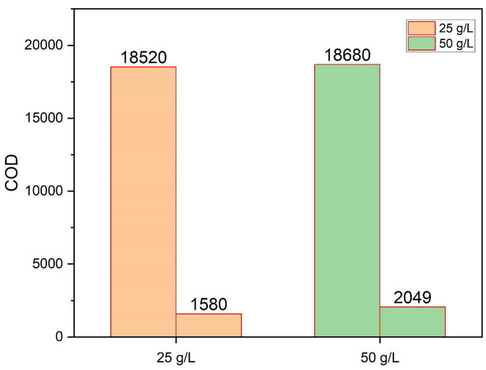

Fig. 3 Initial and final COD concentrations for banana peel slurry at 25 g/L and 50 g/L

Our study on MFCs using banana peel slurry as a substrate has shown that higher substrate concentrations lead to more efficient electron production, which is crucial for generating electricity. However, the lack of comprehensive pH data and byproduct analysis poses a limitation, as variations in these can affect microbial activity and system stability, leading to inconsistent results. Despite being midway through our research, we have significantly progressed in utilizing higher substrate concentrations effectively. The next critical step is to overcome the challenges of reducing internal resistance, which will enhance power performance and pave the way for real-time applications in waste-to-energy conversion. This research aligns with sustainable development goals, offering a promising renewable energy production and waste management solution.

CONCLUSIONS

In conclusion, this research demonstrates the significant potential of banana peel waste as a sustainable and cost-effective substrate for microbial fuel cells (MFCs). The performance of MFC was evaluated using two substrate concentrations: 50 g/L and 25 g/L. The 50 g/L concentration demonstrated superior performance with an Open Circuit Voltage (OCV) of 0.82 V, compared to 0.68 V for the 25 g/L concentration. It also achieved a higher maximum power density of 0.09 W/m² versus 0.019 W/m² and a greater maximum current density of 0.3 A/m² compared to 0.07 A/m². Additionally, the short circuit current was higher at 0.62 A/m² for the 50 g/L concentration than at 0.13 A/m² for the 25 g/L concentration. These results indicate that the higher substrate concentration enhances microbial growth and electron flow, leading to better overall performance in MFCs. The study also achieved high COD removal efficiencies of 91% for the 50 g/L concentration and 89% for the 25 g/L concentration, highlighting effective organic material degradation by *E. coli*. Optimizing substrate concentration, mainly using banana peel waste with high reducing sugar content, can significantly improve MFC performance, making it a viable option for waste management and bioenergy production.

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