

The MudBottle project

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Highlights

- MudBottle demonstrated the feasibility of harvesting electrical energy from a microbial fuel cell array for subsequent electrochlorination.
- MFC voltage increased substantially during optimisation, with the mean voltage increasing from 0.149 V to 0.432 V.
- MFCs operated with a cap showed a higher mean voltage than uncapped MFCs, although the difference was not statistically significant.
- Chitosan-coated cathodes produced measurable electrical output, with the 0.05 g/g chitosan coating showing the highest mean voltage among the tested cathode conditions.
- Increasing the chitosan coating from 0.05 to 0.1 g/g did not improve voltage output, indicating that coating composition and thickness require further optimization.

Abstract

The MudBottle project investigated whether energy generated by microbial fuel cells (MFCs) could be harvested and stored for subsequent electrochlorination of water. The concept combines a 27-cell MFC array with an e-peas AEM00940 energy-harvesting board and two 25 F, 2.7 V supercapacitors, allowing the low and continuous electrical output of the MFCs to be accumulated before use. Individual MFCs were characterised and optimised by investigating chitosan coating concentration and coating thickness. The mean MFC voltage increased from 0.149 V to 0.432 V during the optimisation period. Chitosan-coated cathodes produced measurable electrical output, with the 0.05 g/g chitosan coating showing the highest mean voltage among the tested cathode conditions. Increasing the chitosan coating to 0.1 g/g did not improve voltage output. Overall, the results demonstrate the potential of combining microbial energy generation, energy harvesting, energy storage and electrochlorination in a compact water-treatment prototype. Further optimisation of the MFC array, chitosan coating, energy storage and electrochlorination process is required to improve the performance and scalability of the MudBottle system.

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1. Introduction

Access to safe drinking water is fundamental to human health and sustainable development. Despite global improvements in water infrastructure, 2.1 billion people still lacked safely managed drinking-water services in 2024, including 106 million people relying directly on surface water sources (WHO, 2026a). Contaminated water can transmit diseases such as diarrhoea, cholera, dysentery and typhoid, making water quality an important global health challenge (WHO, 2023).

Improving access to safe drinking water is addressed directly by United Nations Sustainable Development Goal 6 (SDG 6): Clean Water and Sanitation. Target 6.1 aims to achieve universal and equitable access to safe and affordable drinking water, while Target 6.3 focuses on improving water quality and reducing pollution (United Nations, 2026a). Decentralised water-treatment technologies that require limited infrastructure and external resources may therefore contribute to this objective. However, water treatment often requires an energy input, which can become a limitation in areas with unreliable or limited access to electricity.

Chlorination is one of the most widely used methods for drinking-water disinfection. Chlorine-based disinfectants can effectively inactivate a broad range of pathogenic microorganisms when an appropriate disinfectant concentration and contact time are maintained (WHO, 2017). Electrochlorination offers a way of generating disinfecting chlorine species directly from chloride-containing water using electricity. This can reduce the need for storage and transportation of chlorine-containing chemicals, but the process still requires an electrical energy source.

One potential low-power energy source is a microbial fuel cell (MFC). MFCs are bioelectrochemical systems in which microorganisms oxidise organic matter and transfer electrons to an electrode, generating electrical energy (Santoro et al., 2017). Their power output is generally low, particularly for small-scale systems, which limits their use for applications requiring continuous or high instantaneous power. However, the continuous nature of MFC electricity generation creates an opportunity to accumulate energy over time and use it for short-duration processes.

The MudBottle project investigates this concept by combining a mud-based MFC system with an electrochlorination unit integrated into a 0.1 L bottle cap. Rather than using the MFC output directly, the electricity generated by the MFC array is first processed by an AEM00940 energy-harvesting board from e-peas. The harvested energy is stored in two 25 F supercapacitors until sufficient energy has accumulated to perform an electrochlorination cycle. This separates the slow, low-power energy generation of the MFCs from the short-duration power demand of electrochlorination. The stored electrical energy is subsequently supplied to the electrochemical cell, where chloride ions can be converted into chlorine species. In water, these form hypochlorous acid (HOCl) and hypochlorite (OCl⁻), which together contribute to free chlorine and provide the basis for chlorine-based disinfection (WHO, 2017).

The first objective of the project was therefore to investigate how energy produced by MFCs could be used to support water disinfection. The system is designed around energy accumulation rather than

instantaneous power generation, allowing the MFCs to generate electricity gradually while the energy-harvesting circuit and supercapacitors accumulate the energy required for electrochlorination. The initial design was based on an estimated individual MFC output of approximately 50 μW after biological start-up, corresponding to approximately 4.3 J per day (MudBottle, 2026).

During development of the MFC system, a second objective emerged concerning the materials used in the electrodes. PTFE (polytetrafluoroethylene) is commonly used in MFC cathodes, but its high persistence raises environmental concerns regarding its use in a technology intended to provide a more environmentally considerate approach to energy generation and water treatment. This led to a second research question: Can PTFE be replaced by chitosan while maintaining suitable cathode performance? Chitosan was therefore investigated as an alternative material for the cathode, with the aim of reducing reliance on highly persistent fluorinated polymers.

The two objectives represent complementary aspects of the MudBottle project. The first focuses on whether biological electricity can ultimately be converted into a useful water-treatment process, while the second investigates whether the materials used in the MFC can be made more environmentally considerate. Together, they connect microbial energy generation, energy storage, electrochemistry, water treatment and materials development within a single prototype.

The project is intended as an experimental prototype rather than a certified drinking-water treatment device. Producing measurable free chlorine does not by itself guarantee microbiological safety, and appropriate microbial reduction testing would be required before claims of potable water production could be made (WHO, 2026b). The overall aim of this project is therefore to investigate whether microbial fuel cells can provide sufficient electrical energy for small-scale electrochlorination when combined with an energy-harvesting and storage system, and whether chitosan can serve as an alternative to PTFE in the MFC cathode.

2. Methods & Materials

The MFCs were constructed using carbon veil, activated carbon, PTFE, ceramic membranes, nickel-chromium wire and plastic casings. Wet mud, distilled water, sodium acetate, yeast extract and L-tryptophan were used for the microbial substrate. Chitosan was used as an alternative cathode coating to PTFE. The MFCs had a reactor volume of approximately 100 mL and an anode surface area of approximately 300 cm^2 .

The electrical system consisted of an AEM00940 energy-harvesting board from e-peas and two 25 F supercapacitors. A multimeter was used for electrical measurements. Sodium chloride and chlorine test strips were used for the electrochlorination experiments. The MudBottle prototype was designed for 0.1 L of water.

2.2 Preparation and assembly of the MFCs

Wet mud was collected approximately 15–20 cm below the surface and combined with a nutrient solution containing 10.0 g L⁻¹ L-tryptophan, 5.0 g L⁻¹ yeast extract and 2.0 g L⁻¹ sodium acetate. The mixture was prepared at a 1:10 mud-to-solution ratio and incubated at room temperature for approximately 12 h.

The anode consisted of carbon veil with an approximate surface area of 300 cm² and was wrapped around the ceramic membrane and secured with nickel-chromium wire. The cathode consisted of carbon veil coated with activated carbon and either PTFE or chitosan. For the PTFE reference, a 60% PTFE dispersion was used and the coating was fixed at approximately 150–200 °C. The assembled MFCs were filled with approximately 100 mL of microbial substrate and initially operated through a 64 Ω resistor.

2.3 Electrical characterisation

Open-circuit voltage was measured using a multimeter. Twenty-six MFCs were individually measured on 10 August 2026 and twice on 11 August 2026. MFC condition, including flooding, membrane damage and electrode contact, was recorded during measurements. An additional MFC designated “Original” was used as a reference.

2.4 MFC optimisation

2.4.1 Bottle-cap configuration

The effect of the bottle-cap configuration was investigated by comparing six MFCs operated with a lid and six operated without a lid. Open-circuit voltage and physical condition were recorded for each MFC.

2.4.2 Chitosan cathode coating

Chitosan was investigated as an alternative to PTFE. Two chitosan-to-activated-carbon ratios were tested: 0.05 g/g and 0.10 g/g. The resulting coatings were applied to carbon-veil cathodes and tested in MFCs. PTFE-coated cathodes were used as a reference for comparison.

2.4.3 Chitosan coating thickness

Thin and thick chitosan coatings were compared to investigate the effect of coating thickness on MFC voltage. Open-circuit voltage was measured at several time points during the experiment.

2.5 MFC array and energy harvesting

Twenty-seven MFCs were connected in a 3S9P configuration, consisting of three series-connected groups of nine parallel MFCs. The array was connected to an AEM00940 energy-harvesting board from e-peas, which transferred the generated energy to two 25 F supercapacitors.

During energy-harvesting tests, input voltage and current and supercapacitor voltage were measured. Electrical power was calculated as:

$$P = VI$$

and stored energy as:

$$E = \frac{1}{2}CV^2$$

where P is power (W), V is voltage (V), I is current (A), E is energy (J) and C is capacitance (F).

2.6 Electrochlorination

The stored energy was intended to power an electrochlorination unit integrated into the MudBottle cap. Sodium chloride was used as the chloride source, and free chlorine was measured using chlorine test strips. The prototype was designed for treatment of 0.1 L of water.

3. Results

3.1 MFC voltage development

The electrical performance of the 26 MFCs was measured on 10 August and again on 11 August 2026. On 10 August, the mean open-circuit voltage across the 26 MFCs was 0.149 ± 0.075 V, with individual values ranging from 0.003 to 0.242 V. On 11 August, the first measurement gave a mean voltage of 0.312 ± 0.119 V, while the second measurement gave a mean voltage of 0.432 ± 0.095 V. Thus, the mean voltage increased by approximately 109% from the first measurement on 10 August to the first measurement on 11 August, and by approximately 190% from the first measurement on 10 August to the second measurement on 11 August.

The increase was observed across most of the individual MFCs. For example, MFC 1 increased from 0.003 V on 10 August to 0.160 V and subsequently 0.560 V on 11 August. Similarly, MFC 18 increased from 0.010 V to 0.520 V and 0.512 V, respectively. However, the magnitude of the increase varied considerably between individual cells. Some MFCs continued to show relatively low voltages, such as MFC 3, which measured 0.165 V and 0.105 V in the two measurements on 11 August.

A paired comparison of the 26 MFCs showed that both measurements on 11 August were significantly higher than the measurements from 10 August ($p < 0.001$). The second measurement on 11 August was also significantly higher than the first measurement on the same day ($p < 0.001$). These results indicate a substantial improvement in the electrical output of the MFC system during the optimisation period.

Several MFCs were noted as flooded or damaged during the measurements. MFC 3 was recorded as flooded and having a cracked component, while other cells were also affected by flooding. These observations indicate that the physical condition of individual MFCs contributed to the variation observed between cells.

3.2 Effect of bottle-cap configuration

The influence of the bottle-cap configuration was investigated by comparing six MFCs measured with a cap and six MFCs measured without a cap. The MFCs tested with a cap had a mean voltage of 0.135 ± 0.124 V, whereas the MFCs tested without a cap had a mean voltage of 0.104 ± 0.079 V.

Although the mean voltage was approximately 30% higher with the cap, the difference was not statistically significant ($p = 0.62$). Considerable variation was observed between individual MFCs, and several cells were affected by direct contact between the anode and cathode.

The results therefore indicate a tendency towards higher voltage in the capped configuration, but the present dataset does not provide sufficient evidence to conclude that the presence of the cap itself caused the difference.

3.3 Cathode performance: chitosan vs. PTFE

The performance of chitosan-coated cathodes was compared with that of PTFE-based cathodes. Both cathode materials produced measurable electrical output throughout the experiment. As shown in Figure 1, the voltage output increased for both cathode types during the measurement period, with the chitosan-coated cathodes showing higher voltage at the later measurement points.

The individual measurements also showed considerable variation between MFCs (Figure 2). Overall, the chitosan-coated cathodes showed promising electrical performance compared with the PTFE reference under the tested conditions. However, the variation between individual MFCs and the limited number of measurements make it difficult to determine whether the observed difference is caused by the cathode material alone.

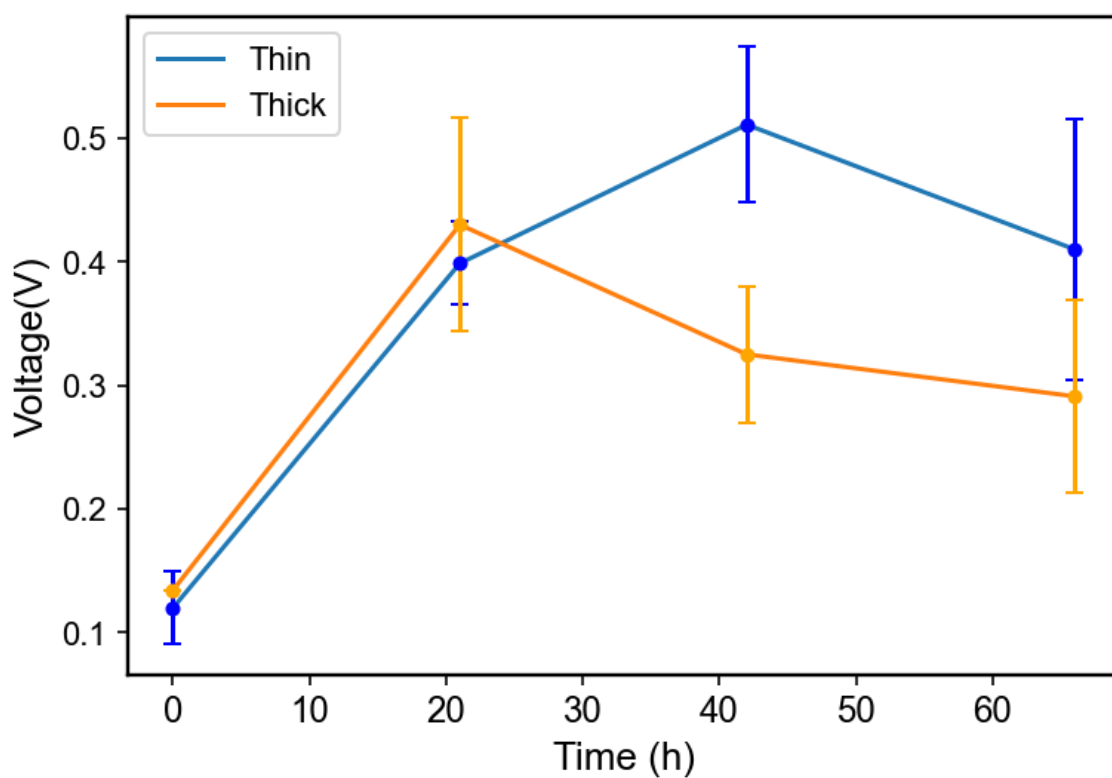


Figure 1: Mean voltage output of MFCs equipped with chitosan- and PTFE-coated cathodes measured over time. Error bars represent standard deviation.

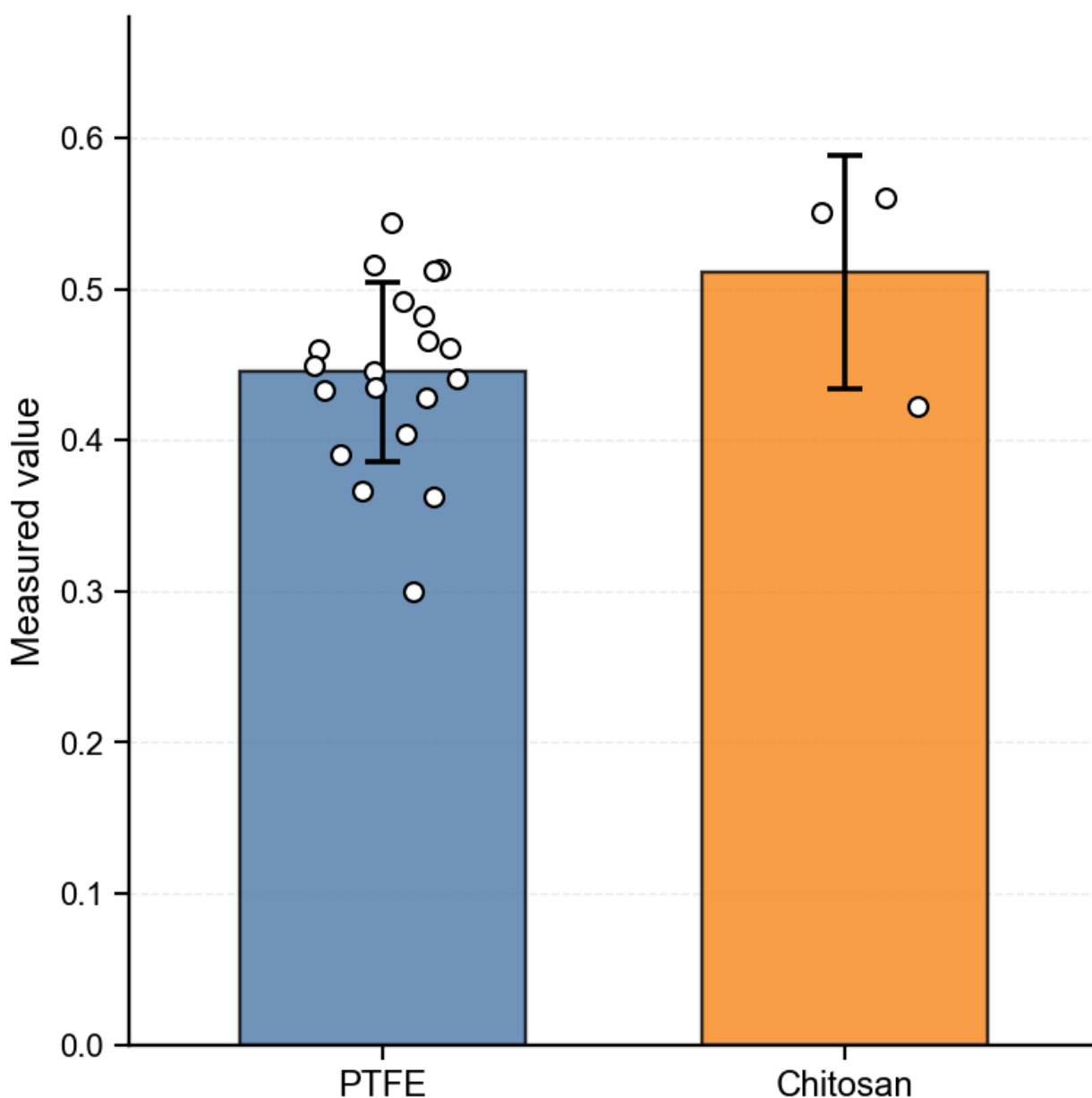


Figure 2: Individual voltage measurements of MFCs equipped with chitosan- and PTFE-coated cathodes.

3.4 Effect of chitosan coating concentration

The effect of chitosan coating concentration was investigated by comparing PTFE-coated cathodes with chitosan coatings containing 0.05 and 0.10 g chitosan per gram of activated carbon (Figure 3).

The mean voltage was approximately 0.32 V for the PTFE-coated cathodes, 0.41 V for the 0.05 g/g chitosan coating and 0.29 V for the 0.10 g/g chitosan coating. The 0.05 g/g chitosan coating therefore produced the highest mean voltage among the tested conditions, while the 0.10 g/g coating produced the lowest.

The results indicate that increasing the chitosan-to-activated-carbon ratio did not result in increased voltage output. Instead, the intermediate concentration tested showed the highest mean voltage. Considerable variation was observed between individual MFCs, and the number of measurements was limited.

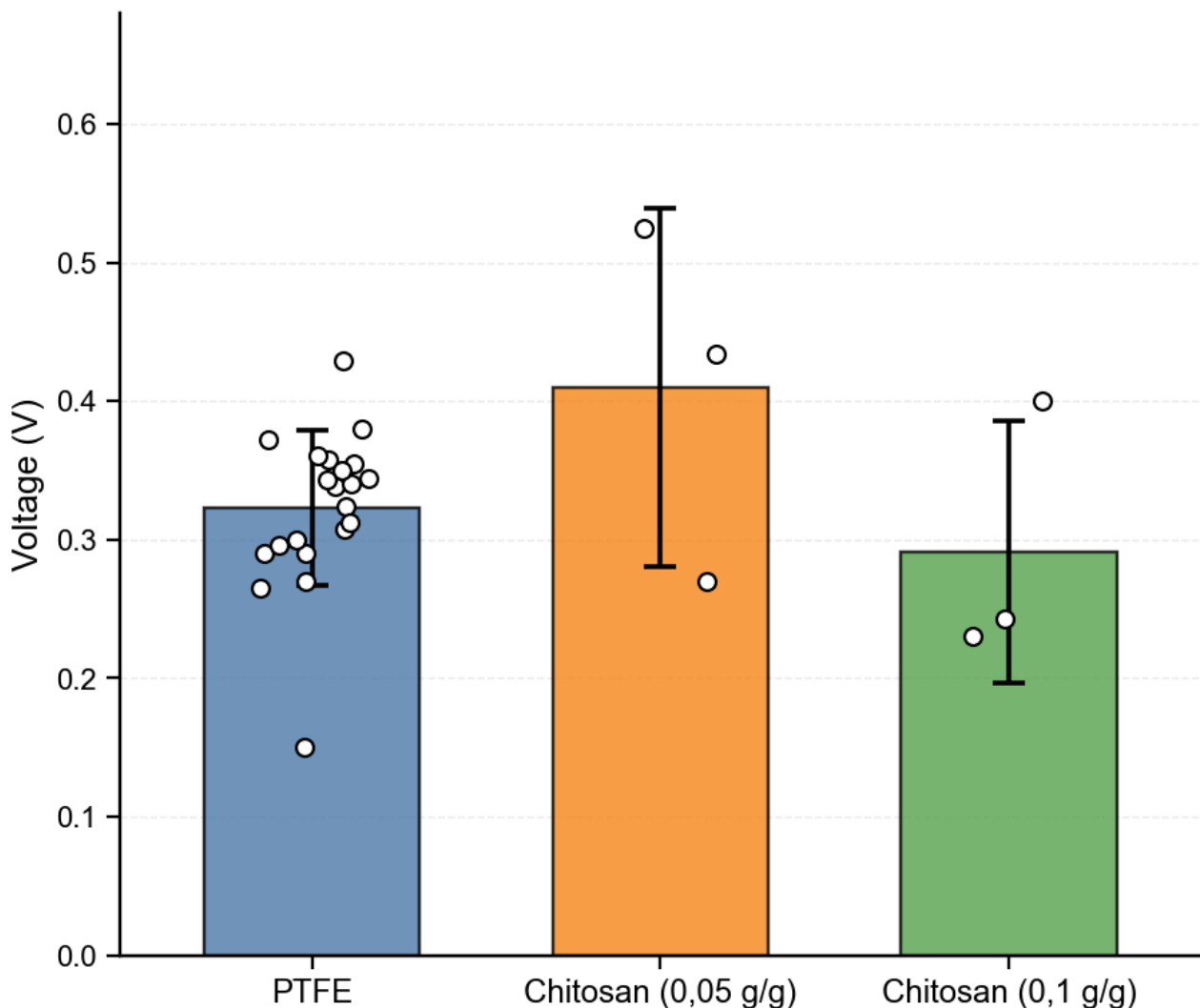


Figure 3: Individual voltage measurements and mean voltage of MFCs equipped with PTFE-, 0.05 g/g chitosan- and 0.10 g/g chitosan-coated cathodes. Error bars represent standard deviation

3.5 Effect of chitosan coating thickness

The effect of chitosan coating thickness was investigated by comparing thin and thick chitosan coatings over time (Figure 4).

Both coating configurations showed an increase in voltage during the first 21 h. The thin coating reached a mean voltage of approximately 0.40 V after 21 h and increased further to approximately 0.51 V after 42 h, before decreasing to approximately 0.41 V after 66 h. The thick coating reached

approximately 0.43 V after 21 h, followed by a decrease to approximately 0.32 V and 0.29 V after 42 and 66 h, respectively.

The thin coating therefore showed higher voltage output at the later measurement points, whereas the thick coating showed a slightly higher voltage at 21 h. The results indicate that coating thickness may influence cathode performance under the tested conditions.

Figure 4. Mean voltage output of MFCs equipped with thin and thick chitosan-coated cathodes measured over time. Error bars represent standard deviation.

3.6 Energy-harvesting system

The MFC array was subsequently connected to the energy-harvesting system. During one measurement, an input voltage of 770 mV and an input current of 12 mA were recorded. If these measurements represent the same operating point, the corresponding instantaneous electrical power can be calculated as:

$$P = V \times I$$

$$P = 0.770 \text{ V} \times 0.012 \text{ A} = 9.24 \text{ mW}$$

This measurement represents the electrical input to the energy-harvesting system under the recorded conditions. It should not be directly compared with the individual MFC open-circuit voltage measurements, as the input voltage and current were measured under different electrical conditions.

The energy-harvesting system was connected to two 25 F supercapacitors, allowing electrical energy generated by the MFC array to be accumulated before use in the electrochlorination process. Further measurements under a defined load are required to determine the actual power output and energy-harvesting efficiency of the complete MFC array.

3.7 Overall MFC performance

Overall, the electrical measurements demonstrated a substantial increase in MFC voltage during the optimisation period. The mean voltage across the 26 MFCs increased from 0.149 V on 10 August to 0.312 V and subsequently 0.432 V on 11 August. At the same time, substantial variation between individual MFCs remained, partly due to flooding, electrode contact and physical damage.

The bottle-cap experiment showed a tendency towards higher voltage with a cap, although the difference was not statistically significant. The cathode experiments demonstrated that chitosan-coated cathodes could operate without PTFE and showed promising electrical performance. Among the tested concentrations, the 0.05 g/g chitosan coating produced the highest mean voltage, while increasing the coating ratio to 0.10 g/g did not improve performance. The thin chitosan coating also showed higher voltage output at the later measurement points compared with the thick coating.

4. Discussion

The MFC optimisation experiments showed a clear increase in electrical output during the experimental period. The mean open-circuit voltage increased from 0.149 V on 10 August to 0.432 V in the second measurement on 11 August. This indicates that the MFCs became more electrically active during operation and optimisation. However, considerable variation remained between individual MFCs, partly due to flooding, damaged membranes and electrode contact. Such factors can negatively affect MFC performance, while electrode properties and electron-transfer processes are also important determinants of electrical output (Santoro et al., 2017; Rahimnejad et al., 2015).

The bottle-cap experiment showed a higher mean voltage for capped MFCs than for uncapped MFCs, but the difference was not statistically significant. The result therefore does not provide sufficient evidence that the cap itself improved electrical performance. Differences between individual MFCs and electrode contact may have contributed to the observed variation.

The second objective was to investigate whether PTFE could be replaced by chitosan in the cathode. Chitosan-coated cathodes produced measurable electrical output, demonstrating that chitosan can function as a PTFE-free cathode coating. The 0.05 g/g chitosan coating showed the highest mean voltage among the tested cathode conditions, while the 0.10 g/g coating showed lower output. This suggests that increasing the chitosan content does not necessarily improve cathode performance. Previous work has also demonstrated the potential of chitosan as a non-fluorinated binder in MFC cathodes (Ge et al., 2017).

The coating thickness experiment further indicated that cathode structure influences performance. The thin chitosan coating showed higher voltage at the later measurement points than the thick coating. Differences in coating thickness may affect electrode accessibility, coating distribution and mass transfer, all of which can influence cathode performance (Wei et al., 2011). However, the limited number of measurements means that these trends require further experimental validation.

The energy-harvesting system addresses the low power output that limits direct use of MFCs for higher-power applications (Logan et al., 2019). Connecting the MFC array to the AEM00940 energy-harvesting board and two 25 F supercapacitors allows energy to be accumulated over time before being used for electrochlorination. Increasing the number of MFCs and optimising their series/parallel configuration could further increase the available energy.

Overall, the results support the MudBottle concept and demonstrate that MFC-generated electricity can be combined with energy harvesting and storage. The experiments also show that chitosan is a promising PTFE-free cathode material, with coating concentration and thickness affecting performance. Further work should focus on improving MFC consistency, optimising the chitosan coating and increasing the amount of energy that can be generated and stored before electrochlorination.

5. Conclusion and further experiments

The MudBottle project demonstrated the potential of combining microbial fuel cells with energy harvesting and energy storage to power electrochlorination for small-scale water treatment. The mean MFC voltage increased from 0.149 V to 0.432 V during the optimisation period. The MFC array was successfully connected to an AEM00940 energy-harvesting board and two 25 F supercapacitors, allowing the low and continuous electrical output to be accumulated before use.

Chitosan was successfully used as a PTFE-free cathode coating. The 0.05 g/g chitosan coating showed the highest mean voltage among the tested cathode conditions, while increasing the concentration to 0.10 g/g did not improve performance. Coating thickness also influenced voltage output.

Overall, the results support the MudBottle concept while highlighting the need for further optimisation of MFC consistency, cathode performance, energy generation and storage.

Further experiments

Further work should focus on optimising the chitosan cathode by testing different concentrations, coating thicknesses and preparation conditions. Long-term measurements should also be performed to determine whether the observed performance is maintained. A chitosan-silicone coating could be investigated as a potential alternative for improving coating stability.

The MFC array could be further scaled and different series/parallel configurations, such as 5S6P, could be tested to optimise the voltage and current supplied to the energy-harvesting system. The two 150 F supercapacitors could also be evaluated to increase energy storage and enable treatment of larger water volumes.

The electrochlorination process should be optimised by investigating electrode design, NaCl concentration, treatment time and electrical input. Quantitative measurements of free chlorine would provide a more precise evaluation of the process.

Finally, the MudBottle cap could be redesigned to fit standard 0.5 L bottles and be easier to reproduce or manufacture in larger quantities.

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