ELECTROCHEMICAL EVALUATION OF THE *Stenocarpus sinuatus* PLANT FOR BIOENERGY RECOVERY USING PLANT MICROBIAL FUEL CELLS IN THE COASTAL ENVIRONMENT OF THE ATACAMA DESERT

EVALUACIÓN ELECTROQUÍMICA DE LA PLANTA *Stenocarpus sinuatus* PARA LA RECUPERACIÓN DE BIOENERGÍA MEDIANTE CELDAS DE COMBUSTIBLE MICROBIANAS DE PLANTAS EN AMBIENTE COSTERO DEL DESIERTO DE ATACAMA

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ABSTRACT

The potential of Plant Microbial Fuel Cells (PMFCs) for renewable energy generation using *Stenocarpus sinuatus* plants in the coastal environment of the Atacama Desert is evaluated. The electrochemical performance of PMFCs using different electrode materials (copper and AISI 316L) and configurations (series and parallel), as well as the effect of electrode size and spacing are analyzed. Maximum voltages of 0.318 V and 0.407 V were obtained using Cu/SS316L electrode pairs connected in series in three reactors. The smaller electrodes (5 × 0.5 cm²) showed better performance, attributed to lower internal resistance and higher electron transfer efficiency. The integration of PMFCs with locally adapted plants and suitable materials represents a viable strategy for decentralized clean energy generation in arid coastal regions, highlighting the need for corrosion-conscious design and appropriate maintenance strategies.

RESUMEN

Se evalúa el potencial de las Celdas de Combustible Microbianas de Plantas (PMFCs) para la generación de energía renovable utilizando plantas *Stenocarpus sinuatus* en el entorno costero del Desierto de Atacama. Se analiza el desempeño electroquímico de las PMFCs utilizando diferentes materiales de electrodos (cobre y AISI 316L) y configuraciones (en serie y en paralelo), así como el efecto del tamaño y espaciamiento de los electrodos. Se obtuvieron voltajes máximos de 0,318 V y 0,407 V utilizando pares de electrodos Cu/SS316L conectados en serie en tres reactores. Los electrodos más pequeños (5 × 0,5 cm²) mostraron un mejor rendimiento, atribuido a una menor resistencia interna y una mayor eficiencia en la transferencia de electrones. La integración de PMFCs con plantas localmente adaptadas y materiales adecuados representa una estrategia viable para la generación descentralizada de energía limpia en regiones áridas costeras, destacando la necesidad de un diseño consciente de la corrosión y estrategias de mantenimiento adecuadas.

Keywords: Plant Microbial Fuel Cells (PMFCs), renewable energy, *Stenocarpus sinuatus*, Atacama Desert
Palabras clave: Celdas de combustible microbianas (PMFC), energía renovable, *Stenocarpo sinuatus*, Desierto de Atacama

INTRODUCCIÓN

Over the past decade, Chile has experienced high and increasing electricity costs, largely driven by fluctuations in global coal and diesel prices. As a result, exploring new energy alternatives has become essential to address the country's growing energy demand. One promising approach is the adoption of systems based on non-conventional renewable energies (NCRE), capitalising on significant investment from both the public and private sectors in these areas of research (Mejía-Montero, 2025). Chile is actively contributing to the global fight against climate change by seeking to diversify its energy matrix and reduce its reliance on fossil fuels for national development. Currently, the net installed capacity of NCRE amounts to 47.4% (16,464 MW) of the country's total installed capacity, with approximately 99.7% of this connected to the national electric system. In November 2024, NCRE plants contributed 2,960 GWh to the national energy mix, representing 43.5% of total electricity generation in Chile (Amigo *et al*., 2021; Baran *et al*., 2025). With respect to compliance with the NCRE law, in October 2024, energy withdrawals required under the regulation totalled 1,037 GWh, while recognised renewable generation reached 2,947 GWh. A breakdown by technology shows contributions of 1,683 GWh from solar power, 843 GWh from wind energy, 273 GWh from mini-hydroelectric plants, 135 GWh from biomass, and 14 GWh from geothermal energy. Among the diverse array of renewable energy technologies currently being utilised, one of the least explored in Chile is the plant microbial fuel cell (PMFC) (Madrid *et al*., 2023; Chong *et al*., 2025). These electrochemical devices are capable of directly converting the biochemical energy produced by bacterial colonies (Barea *et al*., 2005; Arends, 2014) inhabiting the roots of the *Stenocarpus sinuatus* plant (Pillon *et al*., 2024) into electrical energy. PMFCs are an emerging and innovative technology with the potential to address both the national energy crisis and challenges related to clean water access (Ballestas *et al*., 2024; Chong *et al*., 2025). A microbial fuel cell (MFC) (Hernández-Fernández *et al*., 2015; Oon *et al*., 2015) is an electrochemical system that exploits the metabolic activity of microorganisms to convert the chemical energy contained in organic substrates into electricity (Moqsud *et al*., 2015). Under specific conditions, certain microorganisms release electrons as a byproduct of their metabolism. These electrons are transferred from the anode to the cathode through an external circuit, thereby generating electrical power (Roy *et al*., 2023).

There are several variants of MFCs (Takanezawa *et al*., 2010), including those that utilise marine or river sediments (Sudirjo *et al*., 2019) and operate with microorganisms such as Geobacter (Zhou *et al*., 2022; Guadarrama-Pérez *et al*., 2023). These anaerobic bacteria are capable of transferring electrons derived from catabolism to metal ions via the electron transfer (Zhou *et al*., 2022). Plant microbial fuel cells (PMFCs) focus on harnessing the activity of microorganisms that reside in the plant root zone (rhizosphere) (Chanway, 1997; Bonfante & Anca, 2009). This technology functions as an in-situ bioenergy source, where plants and soil bacteria (Kacmaz & Eczacioglu, 2024) work symbiotically to convert solar energy into electrical energy. Plants exude organic compounds (Schamphelaire *et al*., 2008), mainly carbohydrates through their roots, which are then metabolised by bacteria to release electrons (Bonfante & Anca, 2009). These electrons are captured by electrodes embedded within the fuel cell (Zhou *et al*., 2022; Chong *et al*., 2025). This study presents an opportunity to advance current knowledge on diversifying energy sources using microbial fuel cells applied to plant species native to northern Chile, as a means of bioenergy recovery (Garbini *et al*., 2023). The approach focuses on optimising the electrochemical system by refining the hydrodynamic design, selecting suitable electrode materials, and evaluating cell connection configurations (series and parallel). Accordingly, the study will assess the feasibility of employing such systems as a renewable energy source for a range of low-power applications (Kaku *et al*., 2008; Greenman *et al*., 2024)

MATERIALS AND METHODS

In this study, two independent variables were considered, each at two levels: electrode size (5 × 1 cm and 5 × 0.5 cm) and electrode spacing (1 cm and 5 cm). To carry out the experiments, three PMFC units were constructed using the following materials: (i) three acrylic tubes (20 cm in diameter and 34 cm in height), (ii) acrylic sheets, (iii) substrate consisting of 6 litres of Anasac commercial potting soil, and (iv) three *Stenocarpus sinuatus* plants (see Figure 1) (Timmers *et al*., 2013; Kuleshova *et al*., 2022).

Fig. 1: Use of *Stenocarpus sinuatus* -based reactors in Plant Microbial Fuel Cells.

Before starting the experiments, the initial dimensions of the *Stenocarpus sinuatus* plant were determined, as shown in Figure 2. The sample has a stem length of 63 cm and a root volume of approximately 0.005026 m^3.

Fig. 2: *Stenocarpus sinuatus* plant.

No analysis was performed on the substrate; therefore, reference values were based on the commercial soil used, which included: organic matter >20%, moisture content 30–45%, C/N ratio <50, and electrical conductivity ≤ 3 dS/m. For electricity recovery, the use of electrodes (anode and cathode) was essential. One of the initial steps therefore involved selecting materials with suitable properties for electrode application, considering factors such as electrical conductivity, standard electrode potential, and material availability. The materials used in this study were: (i) copper sheet as cathode, and (ii) AISI 316L sheet as anode. Electrodes of varying dimensions were tested, as shown in Table 1 (Ueoka *et al*., 2016; Azri *et al*., 2023).

Table 1: Dimensions of the electrodes

ELECTRODE DIMENSIONS (cm)		
Material	**Long**	**Broad**
Copper	15	5
Copper	10	5
Copper	5	1
Copper	5	0,5
SS316L	15	5
SS316L	10	5
SS316L	5	1
SS316L	5	0,5

To record data and characterise the performance of the PMFC, two monitoring devices were employed. A Data Logger L452 was used to continuously capture voltage fluctuations over time, while a Fluke 772 meter was utilised to measure current at specific intervals (Deng *et al*., 2012).

RESULTS AND DISCUSION

Effect of Electrode Size on Output Potential

The relationship between electrode dimensions and performance was evaluated, maintaining an anode-to-cathode distance of 5 cm. The aim was to determine whether electrode size significantly affects energy recovery capacity. This is illustrated in Figure 3, which presents the corresponding cell potential versus time curves.

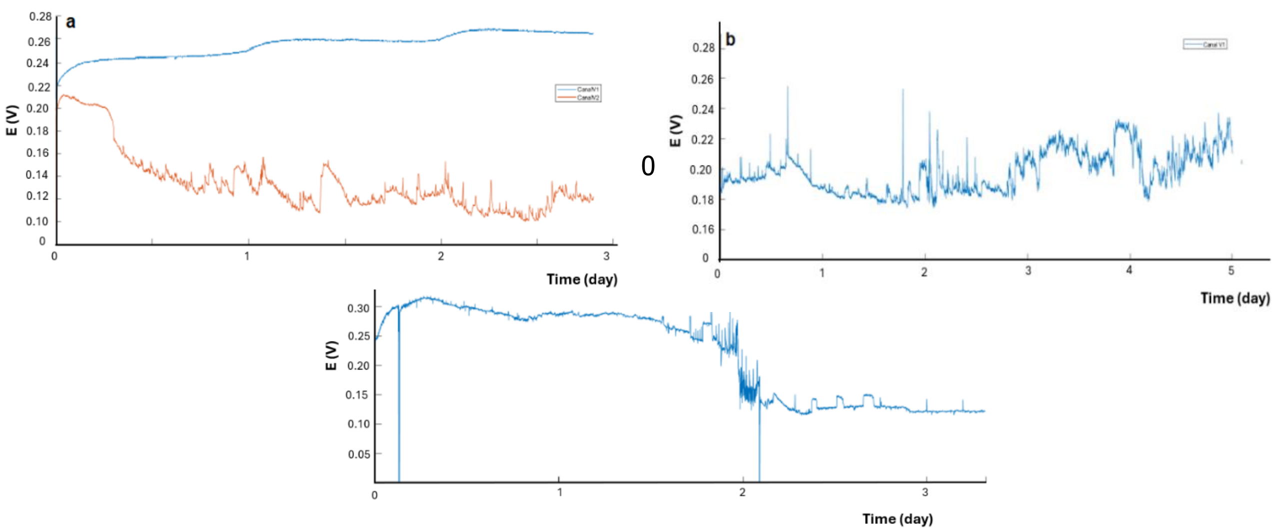

Fig. 3: Potential Measurement (V) versus Time (dias). (a) Electrodes 15 × 5 cm² (blue line) and 10 × 5 cm² (orange line), (b) Electrodes 5 × 1 cm². (c) Electrodes 5 × 0.5 cm².

When comparing the curves in Figure 3(a), the 15 × 5 cm² electrodes exhibit stable behaviour, with cell potential values ranging between a maximum of 0.269 V and a minimum of 0.208 V. In contrast, the 10 × 5 cm² electrodes start at a maximum potential of 0.212 V, but this gradually declines over time, reaching a minimum of 0.095 V, indicating lower energy recovery. The best performance in this case was achieved with the 15 × 5 cm² electrode pair. Comparing the results from Experiment 1 (Figure 3a) with those from Experiment 2 (Figure 3b), it is evident that the 5 × 1 cm² electrodes exhibit a similar behaviour to that observed with larger electrodes (Kuleshova *et al*., 2022). The impact of using significantly smaller electrodes is further examined in Figure 3c, where the 5 × 0.5 cm² electrodes show improved performance compared to both the 15 × 5 cm² and 10 × 5 cm² configurations. Taken together, the results from Experiments 1, 2, and 3 suggest that electrode size has a marked effect on the magnitude of recovered potential. Specifically, reducing the electrode size appears to enhance energy recovery performance. This improvement can be attributed to the increased stability of microbial anodization at smaller surface areas, which facilitates more efficient electron transfer to the cathode with reduced resistance. Additionally, energy losses are minimised, as fewer electrons are diverted to secondary reactions such as nitrogen and sulphur reduction. The ORR converts dissolved oxygen in water into reduced species such as H_2O or H_2O_2, depending on the pathway (four- or two-electron transfer). This reaction not only enables the completion of the electrochemical cycle, but also directly affects the energy efficiency of the system: an efficient ORR reduces cathodic overpotential losses and improves cell voltage. Conversely, slow kinetics or poor cathode design can lead to electron accumulation, voltage drop, and ultimately an inefficient bioenergy system (Wetser, 2015).

Effect of spacing between electrodes on output potential

The effect of electrode spacing on the output potential was evaluated. The tested distances were 5 cm and 2 cm, respectively (see figure 4).

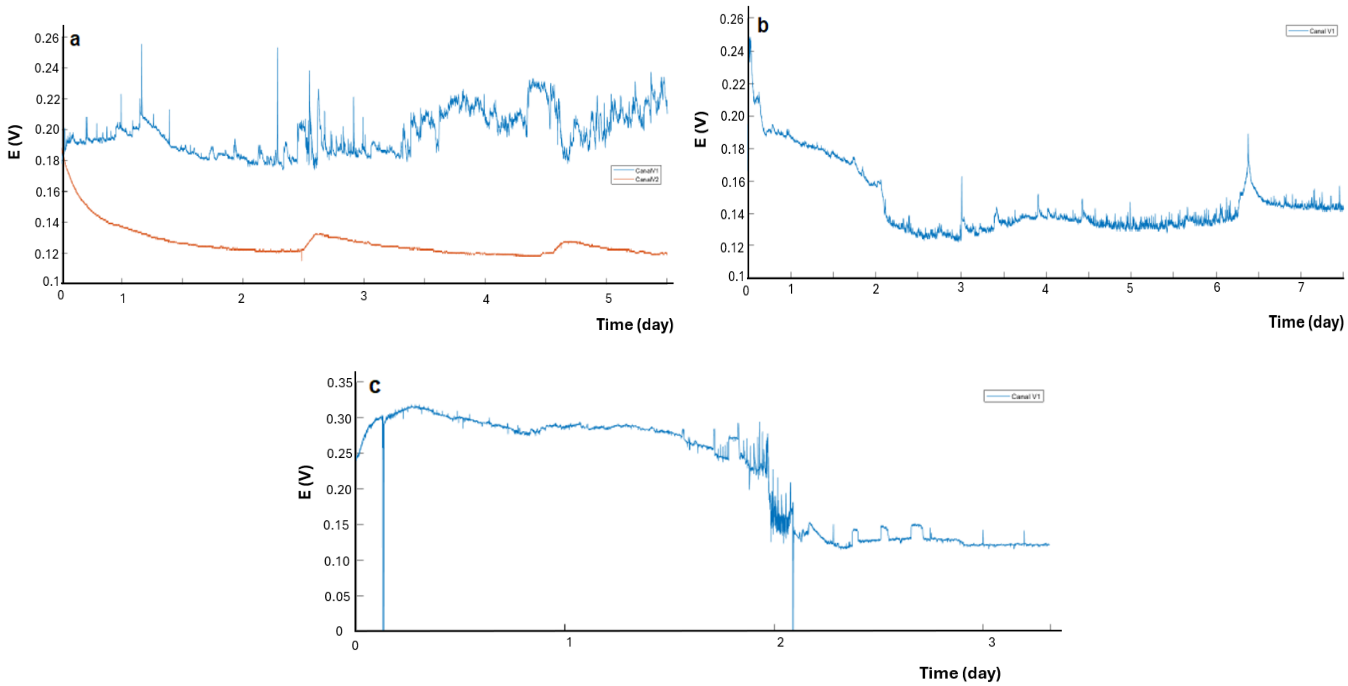

Fig. 4: Voltage (V) versus Time (dias) Measurement. (a) Electrodes 5 × 1 cm², spaced 5 cm (blue) and 2 cm (red). (b) Electrodes 5 × 0.5 cm², spaced 2 cm. (c) Electrodes 5 × 0.5 cm², spaced 5 cm.

Figure 4a presents the performance of 5 × 1 cm² electrodes spaced at 5 cm and 2 cm. The observed voltage differences can be attributed to resistive effects within the cell, arising from electron transport *(Chiranjeevi et al.*, 2012) and capture losses (Zhou *et al.*, 2022). The blue curve, representing electrodes spaced 5 cm, displays a higher cell potential but with greater variability in energy recovery. In contrast, the red curve, corresponding to a 2 cm spacing, shows lower output potentials and a steady decline over time, suggesting that reduced electrode separation increases resistive losses. Figure 4b illustrates the variation in cell potential over time. Notable peaks occur at similar times of day, likely reflecting the influence of solar radiation on cell performance. Consistent with earlier experiments, smaller electrode sizes tend to deliver better energy recovery. In Figure 4c, it is evident that energy recovery improves when using electrodes with a surface area of 5 cm². When evaluating whether changes in electrode spacing significantly affect performance, the results reveal a clear distinction between the 2 cm and 5 cm configurations. Electrodes spaced 2 cm show reduced performance and a decline the cell potential over time. This may be attributed to: (i) accelerated depletion of organic matter surrounding the electrodes, and (ii) increased resistive effects due to the reduced spacing (Ueoka *et al.*, 2016).

Electrode Arrangement into PMFC

To assess the impact of electrode configuration on system performance, an experimental setup was designed using two pairs of electrodes placed within the same reactor (Figure 5). As shown in Figure 5a, no interference was observed with this arrangement, and the average cell potential remained stable. The energy capture level was comparable, and the lower voltage observed in the red curve cannot be attributed to the presence of two electrode pairs within the same microbial fuel cell. However, in Figure 5b, some interference between electrodes within the same reactor is evident. This may be due to the arrangement of the anodes—when positioned too close together, they interfere with one another, leading to a reduction in the cell potential of one of the electrode pairs. In this instance, the blue curve displays a noticeable voltage drop. In both cases, the electrodes were arranged linearly with a 2 cm spacing, and all electrodes measured 5 × 1 cm². When comparing the performance of both configurations, the results were broadly similar in terms of maximum cell potential. The main difference lay in the time required for system stabilisation, as illustrated in Figure 6. In the configuration represented by the blue curve comprising one AISI 316L cathode and two copper anodes a longer adaptation period was observed. This resulted in lower energy recovery during the initial phase compared to the red configuration, which included two SS316L cathodes and a single copper anode. These findings suggest that proximity between anodes leads to mutual interference, reducing the energy recovery of one anode and diminishing overall performance. Conversely, when one anode is paired with two cathodes, the reduction of O_2 to H_2O is more efficient, enhancing the electrical output and thereby increasing the cell potential (Ueoka *et al*., 2016).

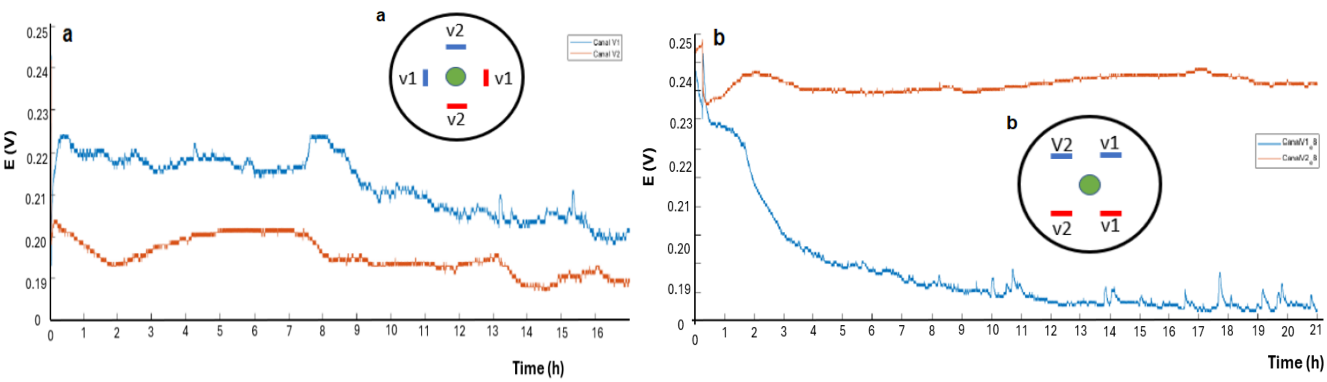

Fig. 5: Electrode arrangement, where the anode is shown in red and the cathode in blue. (a) Electrodes 10 × 5 cm², and (b) Electrodes 10 × 5 cm²

Series-Parallel Systems

Various electrode configurations were evaluated connected in series, in parallel, or using a combination of both either within the same reactor or in separate units. The aim was to assess the cell potential that could be harnessed and to analyse how the internal resistance of the medium is affected when multiple electrodes are installed in a single reactor (see Figure 6).

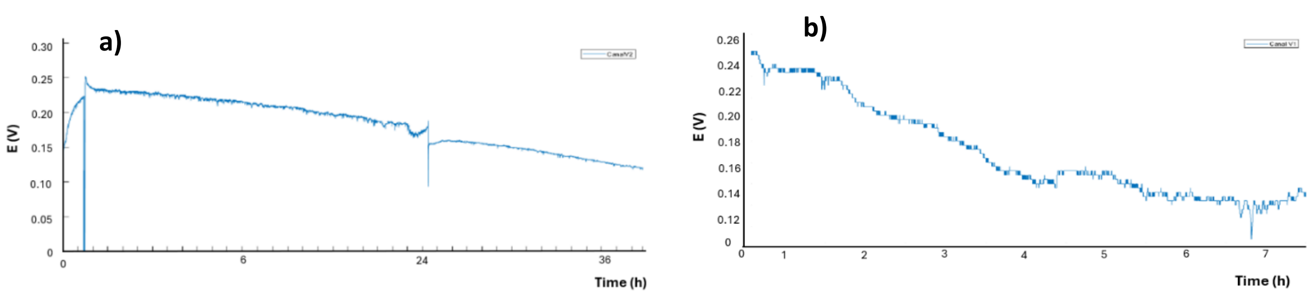

Fig. 6: (a) Series configuration, and (b) Parallel configuration for a single cell.

The results reveals that the cell potential is lower compared to tests using a single electrode of the same dimensions. This is because, as more electrodes are installed within the same microbial fuel cell, the internal resistance of the medium increases, thereby reducing the overall cell potential. However, despite the decrease in potential generation, configuring electrodes in series improves the stability of the recovered cell potential. This behaviour results in either a temporary polarity inversion or a sudden drop in potential, which can be attributed to the laminar flow of water within the reactor, because Kuleshova, T.E *et al*, indicate that increase of energy when is connected in series-parallel (Kuleshova *et al*., 2021). This effect reduces microbial activity in the vicinity of the anode, thereby lowering the electrode's energy capture efficiency. Following this, three anodes and three cathodes (each measuring 5 × 1 cm²) were installed and connected in parallel within the same reactor.

In the parallel configuration, the resulting cell potential exhibited behaviour like cases involving anode interference, with an accelerated decline in potential. These effects can be attributed to an increase in the internal resistance of the cell and the passivation surface due corrosion mechanism. When additional electrode pairs are connected in parallel, electron transport intensifies, which reduces the amount of electrical work performed and consequently lowers the cell potential. However, energy recovery from the areas surrounding the electrodes increases proportionally to the number of electrodes connected in series, up to the point of reaching the short-circuit current. Beyond this point, the cell potential drops to zero, leading to the rapid depletion of readily degradable organic matter, such as root exudates. During the experiment, the performance of three pairs of 5 × 1 cm² electrodes connected in series each placed in a separate microbial fuel cell was evaluated. The aim was to avoid the negative impact of increased internal resistance, which typically arises when multiple electrode pairs are housed within the same reactor. The results of this configuration are shown in Figure 6b. When the three reactors are connected in series (see figure 7), each with a pair of installed electrodes, the performance of the cells in series circuit configurations can be evaluated. Theoretically, the total potential should correspond to the sum of the cell potentials of each reactor.

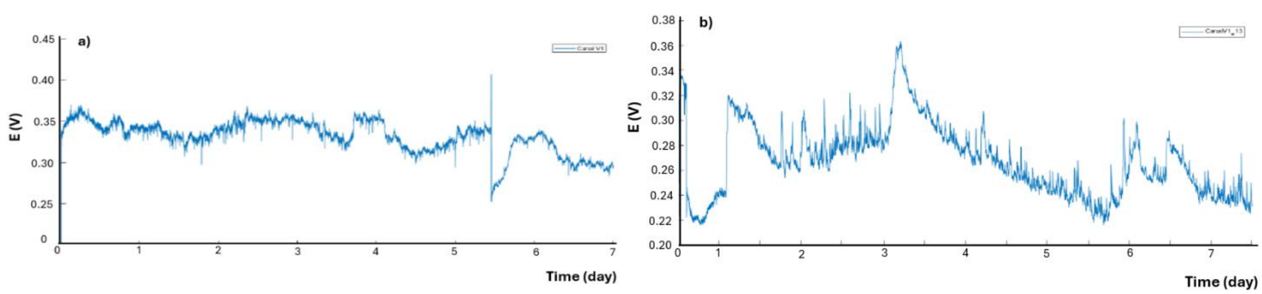

Fig. 7: (a) Series configuration, and (b) Parallel configuration

However, internal resistance effects in microbial fuel cells reduce the total cell potential, making it lower than the sum of the individual reactors. For the series connection of reactors, an increase in both stability and maximum/average power generation is observed compared to using a single pair of electrodes in a microbial fuel cell. The anomaly of cell potential polarity inversion observed during the measurement behaves similarly to what occurs when the reactor is watered. During this moment, polarity is reversed as water flows through the microbial fuel cell, affecting the electromigration of H^+ ions and root exudates (Guan *et al*., 2019; Lin *et al*., 2023). In the potential versus time curve, the generation peaks are clearly visible, occurring cyclically during periods of higher solar radiation. The measurements were taken in June, a time of the year when solar radiation is lower compared to the summer months, where higher cell potential peaks are expected. This indicates that once the plant is fully established in the reactor, energy generation is directly proportional to solar radiation. Additionally, when comparing the behaviour of a series-connected cell to a parallel-connected cell, the fluctuations are more pronounced in parallel-connected cells. This is because the current flow is higher in the parallel configuration, making these cells more susceptible to internal resistance effects (Rusyn *et al*., 2021).

Electrode Corrosion

Although the primary focus of this study was on evaluating energy recovery performance, it is important to consider the electrochemical stability and degradation of the electrode materials over time. In particular, the use of copper as a cathode in a humid, biologically active substrate raises concerns about corrosion. Copper is known to undergo pitting and localised corrosion in the presence of organic acids, ammonia, and sulphide ions, which can be generated by root exudates and microbial metabolism (Han *et al*., 2021). These processes may not only degrade the electrode but also leach Cu ions into the substrate, potentially affecting microbial communities and reducing long-term cell performance (Afonso *et al*., 2009). Similarly, AISI 316L (Balakrishnan *et al*., 2023), though corrosion-resistant, may suffer from crevice corrosion or passive film breakdown under low oxygen conditions and in the presence of chloride ions. Given the environmental conditions and the electrical gradients established within the PMFC, localised zones of differing pH and redox potential could accelerate these degradation mechanisms. Future work should include post-operational characterisation of electrode surfaces using techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), or Raman spectroscopy to evaluate oxide layer formation, surface roughening, and elemental leaching. Additionally, electrochemical impedance spectroscopy (EIS) and polarisation curve measurements could provide insights into the evolving corrosion resistance of the electrode materials during operation (Srivastava & Balasubramaniam, 2005; Kotni *et al*., 2024; Zhao *et al*., 2024).

From a researcher's perspective, the initiative to develop Plant Microbial Fuel Cells (PMFCs) using *Stenocarpus sinuatus* in the coastal environment of the Atacama Desert represents a remarkable advancement with direct and significant implications for the Chilean SME (Small and Medium-sized Enterprise) sector. This technology not only offers a renewable bioenergy source that harmonises with the natural environment but also opens doors to a more diversified and sustainable economy. SMEs can foresee opportunities in energy diversification, reducing their reliance on the centralised grid and fossil fuels—particularly valuable for operations in remote areas or those with specific energy needs. Beyond direct energy generation, new market niches emerge along the associated value chain: from the manufacture of specialised components (e.g., electrodes optimised for saline environments such as AISI 316L and solutions for copper corrosion) to the provision of engineering, installation, and maintenance services for these systems (De La Rosa *et al*., 2019; Doglioni *et al*., 2024). Moreover, integrating energy generation with revegetation adds further value, enabling SMEs to explore business models that combine bioenergy with ecological restoration or sustainable tourism.

CONCLUSIONS

For these emerging technologies, high efficiencies cannot yet be expected. However, this does not mean that research should be halted, as they represent a promising source of clean, sustainable, and environmentally friendly energy generation, being a type of solar-biological cell. The best performances were observed with the use of smaller electrodes, as demonstrated in experiment 3, with the most favourable results achieved using electrodes with an area of 0.00025 m^2 (electrodes of 5×0.5 cm^2). Additionally, it was confirmed that combining series-parallel systems for different connected reactors yields better results than using one, whether in series or parallel configuration. After analysing the results and making comparisons, it can be inferred that the most influential factor in energy recovery is the use of materials with a high standard potential. With better electrodes, recovery is greater, and the cell potential is closer to the open-circuit potential. Importantly, despite the promising energy outputs observed, future developments of PMFC technology must consider the electrochemical degradation of the electrodes in prolonged contact with biologically active substrates. Copper, widely used as a cathode in this study, is susceptible to corrosion processes accelerated by root exudates, microbial metabolites (e.g., organic acids, sulphides), and variable redox conditions in the rhizosphere, potentially leading to surface passivation or leaching of copper ions. Likewise, while AISI 316L exhibits good corrosion resistance, it can experience localised degradation in low-oxygen or chloride-rich environments, especially under galvanic conditions. These phenomena could compromise the long-term performance and stability of the electrodes. Therefore, future research should include post-operational characterisation and corrosion analysis of the electrodes, integrating techniques such as SEM, EIS, or XPS, to optimise material selection and ensure the durability of PMFC systems. Regarding the biology associated with PMFC, selecting the appropriate species is crucial, as climatic conditions significantly impact cell performance. Three highly significant factors were identified:

• Soil moisture, which plays a key role in physical effects such as the internal resistance of the cell, directly influencing the potential generation.
• Solar radiation, as peak generation was found to be directly related to hours of maximum solar exposure.
• The plant's photosynthetic pathway, which integrates the previous factors, as its photosynthetic mechanism determines adaptability to climatic effects, the amount of recoverable cell potential, and tolerance to moisture. C4-type plants were found to be the best adapted for use in northern Chile due to their high tolerance to solar radiation and ability to withstand varying moisture levels.

However, as a researcher, it is crucial to highlight that the large-scale viability and profitability of PMFCs for SMEs depend on overcoming inherent technical challenges. Electrode corrosion—particularly in chloride-rich environments with microbial activity—requires ongoing research into materials and protection strategies to ensure system stability and longevity. Variability in energy output, influenced by environmental factors such as soil moisture and solar radiation, will necessitate complementary energy storage solutions, potentially increasing initial costs. For SMEs to adopt this technology, access to specialised funding programmes and collaboration with research centres will be essential to transfer knowledge and optimise the technology. Ultimately, PMFCs represent a promising innovation pathway for Chilean SMEs, with the potential to transform waste and challenging ecosystems into sources of economic and sustainable development.

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