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LONG-TERM PLANT MICROBIAL FUEL CELL USING ELEOCHARIS PALUSTRIS

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ABSTRACT

Plant microbial fuel cells (PMFCs) have attracted increasing interest as alternative bio electrochemical systems due to their sustainability and environmental compatibility. This technology is based on the symbiosis between living plants and soil microorganisms. The rhizosphere-associated microbial community catalyses the degradation of plant root exudates, resulting in sustainable bioelectricity generation. The system performance is strongly influenced by several factors, including the plant species used and the sediment characteristics. Although many plant species have been tested in PMFCs, Eleocharis palustris has rarely been investigated for this application. This study evaluates the long-term performance of a PMFC utilizing Eleocharis palustris as a primary macrophyte, with sediment collected from Lake Mandrensko (Burgas, Bulgaria) serving as a microbial and electrochemical substrate. Sediment analysis showed elevated levels of organic matter and nutrients (COD - 3.6 g kg^{-1}, phosphate - 2.8 g kg^{-1}, and manganese - 1.3 g kg^{-1}), supporting the metabolic activity of electrogenic bacteria and indicating the suitability of the sediment as a substrate for sustainable PMFC operation. The system was configured as a single-chamber bio-electrochemical reactor, featuring an anode embedded in the sediment and a cathode exposed to atmospheric oxygen. During the 80-day operational period, the system exhibited three distinct voltage phases: an initial adaptation phase (60 - 80 mV), a fluctuation phase (150 - 230 mV), and a final phase characterized by declining voltage and substrate depletion. A clear correlation between COD concentration and voltage output was observed, with the highest substrate level of 10.53 g COD dm^{-3} corresponding to a power density peak of 2339.34 mW m^{-3}.

Keywords: microbial fuel cell, plants, sediment, organic degradation, electricity.

INTRODUCTION

The continuously increasing global energy demand, together with the non-renewable nature of conventional energy sources such as fossil fuels and coal, has intensified the search for sustainable, environmentally friendly and cost-effective energy technologies. Although renewable and green energy sources have been a major focus at the global level, meeting future energy needs through clean technologies remains a significant challenge, particularly in the context of rising greenhouse gas (GHG) emissions, ongoing socio-economic changes and existing environmental damage [1, 2]. Moreover, the development and large-scale implementation of innovative technologies for sustainable bioenergy production continue to face substantial obstacles [3, 4].

Different types of microbial fuel cells (MFCs) are often considered promising alternatives due to their dual capability for wastewater treatment and electricity generation [5, 6]. They can generate electricity through the metabolic activity of electrochemically active microorganisms that oxidize organic substrates present in waste streams [7]. However, like other technologies, MFCs also face several limitations that hinder their scalability and long-term applicability in real energy systems [5, 8, 9].

The Plant Microbial Fuel Cell (PMFC) represents an advanced version of the MFC by incorporating living plants as a continuous and renewable source of organic substrates. PMFCs utilize organic compounds secreted by plant roots, such as exudates and rhizodeposits as electron donors for microbial metabolism [10]. These photosynthetic byproducts are decomposed by rhizospheric microbial communities, which transfer electrons to an anode embedded within the substrate. The electrons are then transferred through an external circuit to a cathode, where they react with protons and oxygen to form water, generating a continuous electric current [11]. A schematic diagram of this process is shown in Fig. 1, illustrating the interplay between plant roots, microbial communities, and the electrochemical components of the PMFC.

The sustainability of electricity generation in PMFCs depends on plant-mediated processes, particularly the continuous release of root exudates. Several environmental and biological factors affect PMFC performance, including plant species selection, photosynthetic efficiency, light availability, microbial community composition, and reactor design [12, 13].

In recent years, various PMFC configurations have been investigated, such as single-chamber sediment MFCs, wetland-based systems, and direct photosynthetic MFCs, employing diverse microbial species, substrates, and macrophytes [14, 15]. Although numerous plant species have been tested for PMFC applications, those with high biomass productivity and strong photosynthetic capacity are generally favoured. Marsh vegetation, particularly grasses, has shown considerable promise due to its adaptability and beneficial rhizosphere characteristics [14]. Several plant species, including *Vigna radiata*, *Sporobolus arabicus*, *Canna stuttgart* and *Wachendorfia thyrsiflora*, have been investigated in PMFC and CW-MFC systems, demonstrating that plant selection strongly affects bioelectricity generation [15 - 18].

Eleocharis palustris, also known as common spike rush, is a herbaceous plant with creeping underground rhizomes that inhabits wetlands, swamps, damp grasslands and marshes. These ecological characteristics make it a suitable candidate for application in PMFC systems. Since its electrochemical performance in PMFCs has not been widely reported, the objective of this study was to evaluate the long-term performance of a PMFC system utilizing *Eleocharis palustris*.

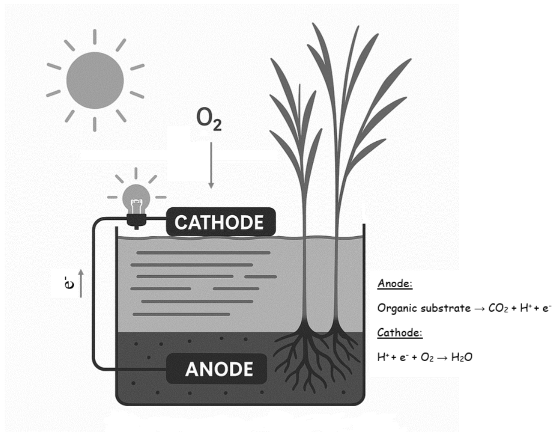

Fig. 1. Schematic representation of the anodic and cathodic processes in a Plant Microbial Fuel Cell (PMFC).

EXPERIMENTAL

Design and assembly of the plant microbial fuel cell

The experimental system consists of a cylindrical, transparent, open-top glass reactor with a working volume of 1.021 dm^3. A layer of lake sediment (0.3 dm^3) was placed at the bottom of the reactor. It was collected from Lake Mandrensko, near to Burgas, Bulgaria, which is classified as a lagoon-type water body. A liquid phase containing suspended sediment particles was then added above the sediment layer. Plants of the species *Eleocharis palustris* (L.) were planted within the sediment layer to simulate a natural rhizosphere environment.

The electrochemical system is equipped with carbon cloth plate electrodes with an active surface area of 126.8 cm^2 each. The anode was embedded within the sediment to ensure anaerobic conditions, facilitating microbial electron transfer. Protons and electrons were released as metabolic by-products by the sediment microorganisms through organic matter degradation. The cathode was placed in the overlying liquid phase, with its upper surface exposed to atmospheric oxygen, enabling aerobic reduction reactions.

The anode and cathode were connected via an external electrical circuit - a fixed resistor of 1000 Ω, allowing controlled current flow and voltage measurements. The electrons were transferred from the anode to the cathode through the external circuit, generating an electric current. The protons diffused through the liquid phase toward the cathode where oxygen from the air is reduced, resulting in the formation of water. The lab-scale PMFC is presented in Fig. 2.

Fig. 2. Lab-scale PMFC using Eleocharis palustris.

Chemical analysis

Liquid-phase samples were periodically collected from the overlying water of the PMFC reactor. Prior to analysis, the samples were allowed to settle and, when necessary, were diluted with distilled water to fit the measuring range of the respective cuvette tests. Chemical oxygen demand (COD) was determined using Hach Lange LCK 514 cuvette tests (100 - 2000 mg dm^{-3}) and a Hach Lange DR3900 spectrophotometer. Phosphate, ammonium, iron and manganese concentrations were measured using LCK 348, LCK 303, LCK 320 and LCW032 reagent sets, respectively, according to the manufacturer's instructions.

For sediment characterization, representative sediment samples were dried to constant mass, homogenized and finely ground. For the estimation of sediment organic load, a known mass of dried and homogenized sediment was acidified, and COD was determined in the obtained extract using the Hach Lange LCK 514 cuvette test. The result was recalculated and expressed as g COD kg^{-1} dry sediment. For the determination of inorganic components, acid digestion with concentrated H_2SO_4 and H_2O_2 was applied as a sediment pretreatment step, following the general principles of EPA Method 3050B [19]. The obtained concentrations were recalculated and expressed per kilogram of dry sediment.

Power density analysis

Voltage was measured daily using a digital multimeter (MASTECH MY-66) across an external resistance of 1000 Ω. Voltage values measured in mV were converted to V before power calculations. The generated power was calculated according to Eq. (1), while surface and volumetric power densities were calculated according to Eq. (2) and Eq. (3):

$$P = U^2/R \tag{1}$$

$$Ps = P/S_A \tag{2}$$

$$Pv = P/V_A \tag{3}$$

where P is the generated power, U is the measured voltage, R is the external resistance, P_S is the surface power density, P_V is the volumetric power density, S_A is the anode surface area, and V_A is the anode volume.

RESULTS AND DISCUSSION

Selection of plant species and sediment type

The plant species applied in the system was *Eleocharis palustris*, a perennial, rhizomatous graminoid. *E. palustris* is adapted to a wide range of soil types from sandy to clayey substrates and can tolerate both freshwater and brackish conditions. It plays a vital role in wetland ecosystems by stabilizing soil and sediment through its extensive rhizome network, thereby reducing erosion [20].

Despite its ecological relevance, *E. palustris* has not been systematically studied or widely applied in PMFCs, particularly in configurations reporting quantitative electrochemical metrics such as voltage, current density, or power output. A down-flow constructed wetland microbial fuel cell (CW-MFC) incorporating *E. palustris* as the dominant macrophyte was described in a doctoral thesis at Ohio State University. The system employed graphite sheet electrodes and semi-air cathodes. Although initial operation demonstrated promising voltage generation, performance declined after approximately two weeks, and voltage output became unstable over time [21].

In addition to plant selection, sediment quality also plays a crucial role in PMFC performance. Nutrient-rich sediment is essential for sustaining electrochemical processes. Organic matter is decomposed by resident microorganisms, which transfer electrons to the anode surface. The sediment used in this study was analysed for chemical oxygen demand (COD), phosphate, and ammonium ions, with the following concentrations: COD - 3.6 g kg^{-1}; phosphate - 2.8 g kg^{-1}; ammonia - 0.260 g kg^{-1}; total iron (Fe) - 0.1 g kg^{-1}; and manganese - 1.3 g kg^{-1} (Table 1).

This sediment composition is characterized by high levels of organic matter, phosphorus, and nitrogen, moderate manganese, and low iron concentrations. The abundant organic content provides a rich source of electron donors for electrogenic bacteria such as *Geobacter* and *Shewanella*, which is a key prerequisite for maintaining active microbial electron transfer. Phosphorus is critical for microbial growth, as it is a structural component of ATP, DNA, and phospholipids. The elevated phosphate concentration (2.8 g kg^{-1}) supports the development of diverse microbial communities. The manganese concentration (1.3 g kg^{-1}) falls within the typical range for riverine and lacustrine sediments and suggests the presence of Mn (IV) oxides, which can act as external electron acceptors for electrogenic microorganisms.

Voltage and organic content

The system operated for 80 days, during which voltage was measured daily, while chemical oxygen demand (COD) was monitored at regular multi-day intervals. Fig. 3 presents daily voltage measurements (in mV) alongside corresponding COD concentrations (in g O_2 dm^{-3}) over the 80-day operational period of the laboratory-scale PMFC. COD removal exhibited a trend comparable to voltage generation, suggesting a strong relationship between organic matter degradation and electrochemical activity. Statistical analysis confirmed a strong positive correlation between COD removal and voltage output (Pearson $r = 0.84$, $p < 0.01$; Spearman $\rho = 0.81$), indicating that increased microbial metabolism directly supported enhanced electron flow to the anode.

Three distinct performance phases can be identified: an initial adaptation phase, a subsequent fluctuation phase, and a final phase. During the initial phase (approximately days 1 - 20), the system exhibited relatively low voltage outputs ranging from 60 to 150 mV. This period corresponds to the establishment and adaptation of both plant roots and electroactive microbial communities within the reactor environment. The steady increase in voltage during this stage indicates successful rhizosphere colonization and the initiation of bio electrochemical activity.

The fluctuation phase (after day 20) was characterized by variable voltage outputs oscillating between 150 and 230 mV. This behaviour reflects dynamic interactions among microbial metabolism, root exudation rates, and environmental conditions. Notably, a rise in ambient temperature from 20 - 25°C to 25 - 30°C after day 41 coincided with more stable and elevated voltage output, suggesting enhanced microbial activity and increased root exudate production under higher temperatures.

Table 1. Lake sediment analysis.

Parameter	COD	Phosphate	Ammonia	Total iron	Manganese
Measurement unit, g kg^{-1}	3.6	2.8	0.260	0.1	1.3

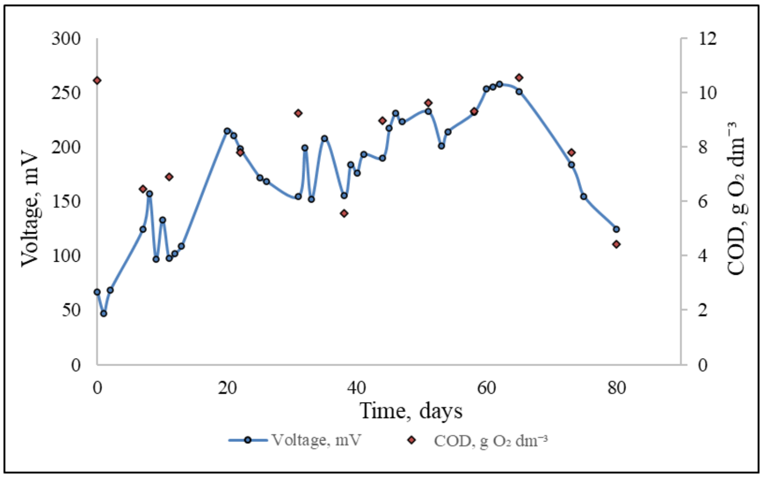

Fig. 3. Voltage output and COD concentration during PMFC operation. COD values are shown as measured sampling points.

Throughout this phase, COD levels remained relatively stable (about 9 g dm^{-3}), providing a sustained supply of electron donors. Temporary drops in COD concentration, such as the decrease to 5.54 g dm^{-3} on day 38, were accompanied by corresponding voltage declines (e.g., 155 mV), indicating a direct correlation between substrate availability and bioelectricity generation.

The third phase was observed after day 65, with voltage output steadily declining to 124.5 mV by day 80. This decrease strongly correlates with a reduction in COD concentration to 4.43 g dm^{-3}, indicating substrate depletion and reduced microbial activity.

Power density analysis

The power density (PD) analysis was conducted during the 80-day operation of the PMFC system. The surface power density (P_S) ranged from 0.176 mW m^{-2} to 5.22 mW m^{-2}, while the volumetric power density (P_V) varied between 79.06 mW m^{-3} and 2339.34 mW m^{-3}. In the initial stage (days 0-20), both P_S and P_V were relatively low and fluctuating, with P_S values below 1 mW m^{-2} and P_V not exceeding 420 mW m^{-3}. This behaviour is indicative of the system start-up phase, during which microbial community establishment and biofilm formation on the electrodes were still in progress.

A gradual increase in power output was observed after day 20, marking the transition toward a more stable and active electrochemical state. Between days 20 and 35, P_S increased from 3.65 mW m^{-2} to approximately 3.41 mW m^{-2}, while P_V ranged between 1395 and 1633 mW m^{-3}, suggesting improved electron transfer efficiency and enhanced microbial activity.

The most notable performance was recorded during the period from day 45 to day 65, which represents the peak operational phase of the PMFC system. During this interval, surface power density consistently remained above 3.5 mW m^{-2}, while volumetric power density exceeded 1600 mW m^{-3}. The maximum values were achieved on day 62, with a P_S of 5.22 mW m^{-2} and a P_V of 2339.34 mW m^{-3}, reflecting optimal system conditions, mature biofilm development, and stable electrochemical interactions.

When compared to existing studies in the literature, the system demonstrates competitive performance. Previously published results investigated catalyst-assisted microbial fuel cells, reporting a maximum surface power density of approximately 0.36 mW m^{-2}, achieved using MnO_2-based catalysts on the cathode to enhance oxygen reduction reactions [22]. A surface power density of 0.35 mW m^{-2} was reported for a 30-day PMFC system using *Vigna radiata* [15]. A volumetric power density of 1036 ± 59 mW m^{-3} was achieved using *Wachendorfia thyrsiflora* over a 54-day period [18]. The volumetric power densities reported in our study exceed these previously published values.

In addition, the system employed *Eleocharis palustris*, a plant species that has not been widely explored in Plant-MFC research. Its rhizosphere appears to support electrogenic microbial communities effectively, contributing to stable and relatively high-power outputs, particularly in volumetric terms. These findings suggest that *E. palustris* may represent a promising candidate for future PMFC optimization efforts.

CONCLUSIONS

The long-term performance of a plant microbial fuel cell utilizing *Eleocharis palustris* demonstrated stable voltage generation and sustained power output over an 80-day period. The system achieved a maximum volumetric power density of 2339.34 mW m^{-3}, exceeding values reported in comparable studies. Sediment enriched with organic matter, phosphates, and manganese supported the metabolic activity of electrogenic bacteria, contributing to enhanced bioelectricity production. A strong correlation between COD concentration and voltage output confirmed the critical role of substrate availability. These findings underscore the potential of *E. palustris-based* PMFCs for sustainable energy generation and wastewater treatment applications.

Authors' contributions

G.P.: Conceptualization, Methodology, Writing - Original Draft preparation; R.K.: Visualization, Writing - Original Draft Preparation, Editing of the manuscript.

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