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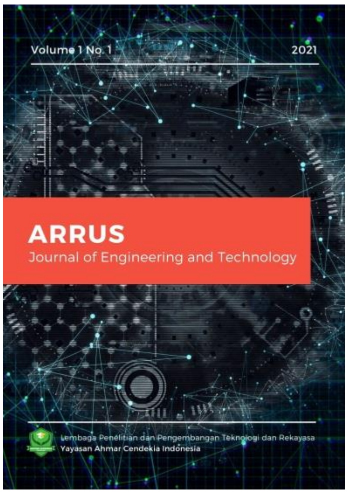

RESEARCH

Utilizing Sediment Microbial Fuel Cells (SMFCs) for Bioremediation in Coral Transplantation at Samalona Island

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Abstract: This study explores the potential of Sediment Microbial Fuel Cells (SMFCs) in the bioremediation of coral transplantation environments at Coral Garden Samalona, Samalona Island, Makassar. An experimental approach using marine aquariums was employed to assess the effects of SMFCs on the coral environment. Physicochemical parameters such as temperature, pH, salinity, and total dissolved solids (TDS) were monitored in real time using IoT technology. Statistical analysis using the Mann-Whitney test revealed significant effects of SMFCs on these parameters, with Asymp. Sig (2-tailed) < 0.05, revealing positive changes. The pH remained stable in an alkaline range (8.16-8.36), while TDS and salinity decreased by 3.19% and 15%, respectively. However, challenges related to temperature fluctuations in the SMFC group, likely due to microbial activity, were noted, as evidenced by peak voltage outputs ranging from 84.3 to 96.6 mV. Although this voltage remains low for broader applications, further research is needed to address temperature fluctuations, increase voltage output, and optimize SMFC design for real-world implementation.

Keywords: Electrochemical System, Environmental Monitoring, Physicochemical Parameters, Conservation

1. INTRODUCTION

Coral reefs, recognized as one of the ecosystems with the highest biodiversity and productivity, house 25% of the total marine biodiversity despite covering only 0.2% of the ocean floor (Shaver & Silliman, 2017; Silveira et al., 2017). This ecosystem functions as the ocean's rainforest, providing a range of ecosystem services, including nursery areas and habitats for marine life, coastal protection, support for sustainable fisheries, and serving as major attractions in the tourism industry (Cinner, 2014; Heery et al., 2018; Heron et al., 2017; Olguín-López et al., 2017; Reguero et al., 2018; Westoby & McNamara, 2019). However, coral reefs are experiencing a significant decline due to anthropogenic pressures such as pollution, overfishing, and climate change. These pressures erode the resilience of coral reefs and slow their natural recovery processes.

To address this decline, the United Nations launched the UN Decade on Ecosystem Restoration, aimed at restoring degraded ecosystems and supporting the achievement of Sustainable Development Goals (UNEP & FAO, 2020). Various coral restoration strategies have been implemented, including transplantation using coral fragments (Young et al., 2012). A two-stage approach, where coral fragments are cultivated in nursery facilities before being relocated to reefs, has proven more successful (Rinkevich, 2014). However, the issue of sediments containing hazardous pollutants remains a major challenge in coral transplantation (Erftemeijer et al., 2012; Fabricius, 2005; Jones et al., 2016; Mulligan et al., 2009; C. Rogers, 1990).

Sediment Microbial Fuel Cells (SMFCs) technology offers an innovative solution for sediment bioremediation and the surrounding aquatic environment at transplantation sites. SMFCs utilize anodes embedded in marine sediments and cathodes in seawater and can function as biosensors to measure various environmental parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and microbial activity (Cui et al., 2019; HS et al., 2020; Reimers et al., 2001). This technology has advantages such as low cost, rapid response time, and the ability for continuous monitoring in remote locations (Thobor et al., 2023). Previous studies have shown that SMFCs have not yet been specifically applied to coral transplantation, although they have demonstrated potential in bioremediation and biosensing (Abbas et al., 2019; Bose et al., 2021; Cui et al., 2019; Ferse et al., 2021; HS et al., 2020; Kabutey et al., 2019).

The integration of SMFC technology in coral transplantation environments is expected to address the pollutant impacts from sediments and provide effective long-term monitoring solutions in coral restoration projects. This approach responds to previous research findings indicating the significant negative impact of sediments on coral transplantation, such as low transplantation success rates and coral mortality due to sedimentation (Pelasula et al., 2022; Polapa, 2023).

Given the challenges faced in coral reef ecosystem restoration efforts, this study aims to explore the potential and challenges posed by Sediment Microbial Fuel Cells (SMFCs) technology in supporting the success of coral transplantation, with a specific focus on the context of sediment bioremediation and coral transplantation environments. It is hoped that this research will significantly contribute to the development of SMFC-based bioremediation technology and its applications in coral restoration projects, particularly in the waters around Samalona Island, Makassar. The findings from this study are expected to provide valuable insights for sustainable ecosystem management and support future coral reef conservation efforts.

2. Literature Review

Sediments are crucial components of marine ecosystems and serve as vital habitats for microorganisms that degrade organic matter and hazardous substances. However, sediments often become obstacles to the sustainability of coral transplantation. This study employs the technology of Sediment Microbial Fuel Cells (SMFCs) as a solution for sediment bioremediation and the surrounding aquatic environment at transplantation sites. SMFCs utilize fuel cells with anodes embedded in marine sediments, connected to cathodes in seawater through an external load (HS et al., 2020).

This technology excels because it utilizes natural fuels and oxidants from the marine environment and can be sustainably renewed (Reimers et al., 2001).Several studies have developed SMFCs as biosensors to measure environmental parameters such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Volatile Fatty Acids (VFA), Dissolved Oxygen (DO), toxicity, and microbial activity (Cui et al., 2019). SMFCs have rapid response times, do not require laboratory facilities, and can be automated for continuous monitoring, making them suitable for use in remote locations such as underwater. This technology is considered low-cost and can serve as an effective primary indicator in coral transplantation environments (Thobor et al., 2023).

Sediment microbial fuel cells (SMFCs) offer several advantages over conventional microbial fuel cells, particularly due to their ability to operate under fully anoxic conditions without requiring a separating membrane. This technology has significant potential for renewable energy production and heavy metal bioremediation, with the ability to utilize various biodegradable substrates, including glucose, glutamic acid, and acetate. One ideal inoculum

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for SMFCs is marine sediment, which is rich in microorganisms that have a high capacity for adapting to extreme environmental conditions and pollution (Abbas et al., 2017).

Microorganisms in marine sediments, including various types of bacteria and archaea, demonstrate a high capacity for breaking down pollutants and carrying out essential metabolic processes, including the degradation of organic matter and detoxification of heavy metals. These properties make marine sediments a highly effective source of inoculum applied in SMFC systems, which can not only generate electrical energy but also serve as real-time indicators of pollution levels and ecosystem changes in marine environments (Chen et al., 2019).

The utilization of marine sediments as SMFCs in coral transplantation areas has the potential to provide dual benefits, namely in bioremediation and renewable energy production. Marine sediments often pose challenges in coral transplantation efforts, as they can lead to clogging, abrasion, shading, and hinder coral recruitment. High sediment deposition rates contribute to the decline in water quality and can potentially cause widespread damage to coral reef ecosystems (C. S. Rogers & Ramos-Scharrón, 2022). Therefore, the integration of SMFC technology in coral transplantation areas is expected to mitigate the negative impacts of sediments while supporting the sustainability of coral reef ecosystems.

3. Research Method and Materials

3.1. Time and Place

This research was conducted at two main locations: the Coral Garden Spot in Samalona, Samalona Island, Makassar, and the Global Geoscience Indonesia Scuba (GGI Scuba) laboratory in Makassar. The Coral Garden Spot in Samalona is located approximately 436.34 meters from the shoreline of Samalona Island (Figure 1). The study was carried out from July to September 2024, encompassing field observations at the coral transplantation site and laboratory experiments for testing Sediment Microbial Fuel Cells (SMFCs).

Figure 1. Coral Transplantation Location at the Coral Garden Samalona, Samalona Island, Makassar

3.2. Equipment and Materials

The research equipment used included buckets, jerry cans, an oxygen pump (YES-100A 1500mAh), an aquarium, UV lamp (AUV-08A), aquarium box filter, and graphite electrodes with a surface area of 15.5744 cm^2. The data acquisition system utilized a pH meter (W3988) that includes sensors for physicochemical parameters, namely pH, Total Dissolved Solids (TDS), temperature, and salinity, along with a data logger. For electrical measurements, a HoldPeak 570T-APP multimeter and a data logger were employed. The

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materials used in the research included liquid calibration solutions (for pH, TDS, and salinity), 1 M HCl, and distilled water.

3.3 Study Overview

This study was divided into three main stages:

1. Field Observation

This stage assessed the physical environmental conditions at the Coral Garden Spot, Samalona, focusing on the physicochemical parameters of the coral transplantation site. Sediment and seawater samples were collected for subsequent laboratory experiments, forming the basis for further analysis.

2. SMFC Design

Two marine aquariums were constructed to simulate coral transplantation conditions—one as a control and the other integrated with a Sediment Microbial Fuel Cell (SMFC). In the SMFC aquarium, the anode was embedded 5 cm into the sediment, while the cathode was 7 cm above the sediment surface. An IoT-based data acquisition system was installed to monitor physicochemical parameters in real-time. The aquarium dimensions were 60 cm x 50 cm with a water depth of approximately 40 cm, equipped with a circulation and aeration system, an optimal filtration system, and UV lamp lighting.

3. SMFC Testing

The SMFC was tested over a 7-day period (168 hours) to evaluate its effectiveness in influencing the physicochemical parameters of the aquarium environment and to measure the generated open-circuit voltage (VOC). Collected data were analyzed statistically using IBM SPSS Statistics version 29. The Mann-Whitney test, a non-parametric method, was employed to compare differences between the control and SMFC treatment groups, allowing for insights into the significant effects of SMFC on the aquarium's physicochemical parameters and supporting conclusions regarding its effectiveness in maintaining environmental quality.

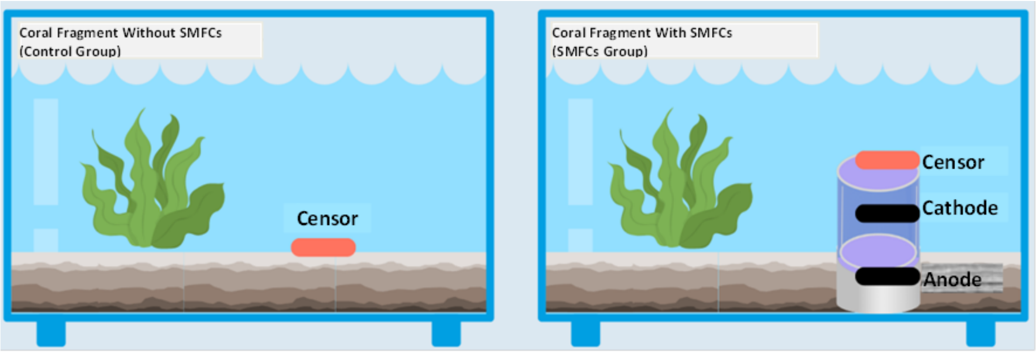

Figure 2. Design of the Marine Aquarium

4. Results and Discussion

4.1. Observation Of Coral Transplantation

The aim of this study's environmental monitoring is to identify the growth rates and survival of corals transplanted since 2021 **(Figure 3).** Various physicochemical parameters, such as temperature, pH, salinity, and total dissolved solids (TDS), were measured around coral fragments, specifically *Acropora sp.*, which is highly sensitive to environmental changes. The results of the environmental observations are presented in **Table 1.**

Figure 3. Observation of Coral Transplantation

Table 1: Seawater Quality Parameters at the Coral Transplantation Site in Spot Coral Garden, Samalona Island

No.	Parameter	Value	Unit	Marine Water Quality Standard for Coral (PP No. 22 of 2021)
1.	Suhu	30,63	°C	28 – 30 °C
2.	pH	8,16	-	7 – 8,5
3.	Salinitas	4,42	%	3,3 – 3,4 %
4.	TDS (*total dissolved solids*)/ padatan terlarut total	35940*	mg/L	-

Based on observations, coral transplantation conducted since 2021 has shown promising development. Coral growth has begun to spread around the transplant framework, although coral coverage has not yet reached optimal density. The recovery and formation of a healthy coral reef ecosystem can take years until full coral coverage is achieved and a sustainable reef system develops.

The environmental conditions supporting the coral transplantation process can be evaluated through several parameters listed in Table 1. The pH value remains within the optimal range of marine water quality standards for coral environments. However, both temperature and salinity are recorded to be higher than the recommended limits, likely due to the effects of global warming. This phenomenon indicates the impact of climate change on the balance of the marine environment, which is crucial for the survival and growth of coral reefs. Nevertheless, it is important to note that other dissolved substances, such as minerals and organic pollutants, can also affect water quality and the health of coral reef ecosystems.

Therefore, continuous monitoring of these conditions is essential, as changes in dissolved substance concentrations can impact the balance of the coral ecosystem and slow coral growth. Proper environmental management is necessary to ensure that physicochemical parameters remain within limits that support the success of coral transplantation and the recovery of coral reefs.

4.2. vPotential of SMFCs at Coral Transplantation Locations

This research employs an experimental method by simulating the coral transplantation environment in a marine aquarium, as illustrated in **Figure 4**. All ecosystem components used in this aquarium, including seawater, substrate, and microorganisms, were directly sourced from the natural coral transplantation environment to ensure similarity to the original habitat. An evaluation of the impact of adding Sediment Microbial Fuel Cells (SMFCs) on physicochemical parameters such as pH, total dissolved solids (TDS), salinity, and temperature was conducted.

Figure 4. Marine Aquarium Experimental Setup

The graphs displayed in Figure 5 clearly show that the addition of SMFCs had a significant impact on the physicochemical parameters measured, compared to the control system. Overall, the system with SMFCs (indicated by the red line) displayed more dynamic changes compared to the control system (indicated by the blue line), highlighting the influence of this treatment in stabilizing water quality. For instance, the faster decrease in TDS in the SMFC system demonstrates the active role of microorganisms in the biological purification of water. Additionally, the higher temperature fluctuations in the SMFC system point to electrogenic microbial activity, which generates heat and affects the water temperature.

The experimental results indicate that the system equipped with SMFCs successfully maintained a stable pH range of 8.16 to 8.36 throughout the testing period. This pH range is ideal for supporting critical physiological processes in coral reef ecosystems, particularly calcification, which is the process of forming the calcium carbonate skeleton of corals that heavily relies on pH stability. This suggests that SMFCs are capable of creating a more stable microenvironment around the corals, thereby supporting optimal conditions for calcification and overall ecosystem health. In contrast, the control system without SMFCs experienced a significant pH decrease of 2.94% from the initial value, indicating increased acidity in the water. This pH reduction could disrupt essential calcification processes for coral skeletal formation, and sustained acidity could lead to the long-term degradation of coral reefs (Jones et al., 2016; Wijgerde et al., 2014).

In addition to pH stability, TDS analysis also yielded interesting results. Although there was a decrease in TDS in both systems, the system with SMFCs showed a more significant reduction, from 35,940 ppm to 34,793 ppm. This reduction is likely related to the role of microorganisms in SMFCs, which contribute to the breakdown of dissolved substances or the precipitation of particles in the water. This microbial activity may lower the concentration of excess dissolved compounds in the water, thereby helping to stabilize other physicochemical parameters. Conversely, the control system exhibited a less significant TDS reduction, indicating that SMFCs play a role in improving water quality through biological purification mechanisms. This is evident from the TDS data (Figure 5), where the SMFC system shows a steeper decline in TDS over time compared to the control, highlighting stronger biofiltration processes driven by SMFC.

Salinity also experienced a significant change in the SMFC-equipped system, decreasing by 3.19% from the initial value. This salinity reduction mechanism is suspected to be associated with the ability of microorganisms in SMFCs to neutralize salt ions. The salinity decrease observed in the SMFC system (Figure 5) is much more pronounced compared to the control system, which remained relatively stable. This phenomenon, although not yet fully understood, suggests that SMFCs have the potential to support seawater quality management in coral transplantation applications. Meanwhile, the control system showed stable salinity with no significant changes throughout the study period.

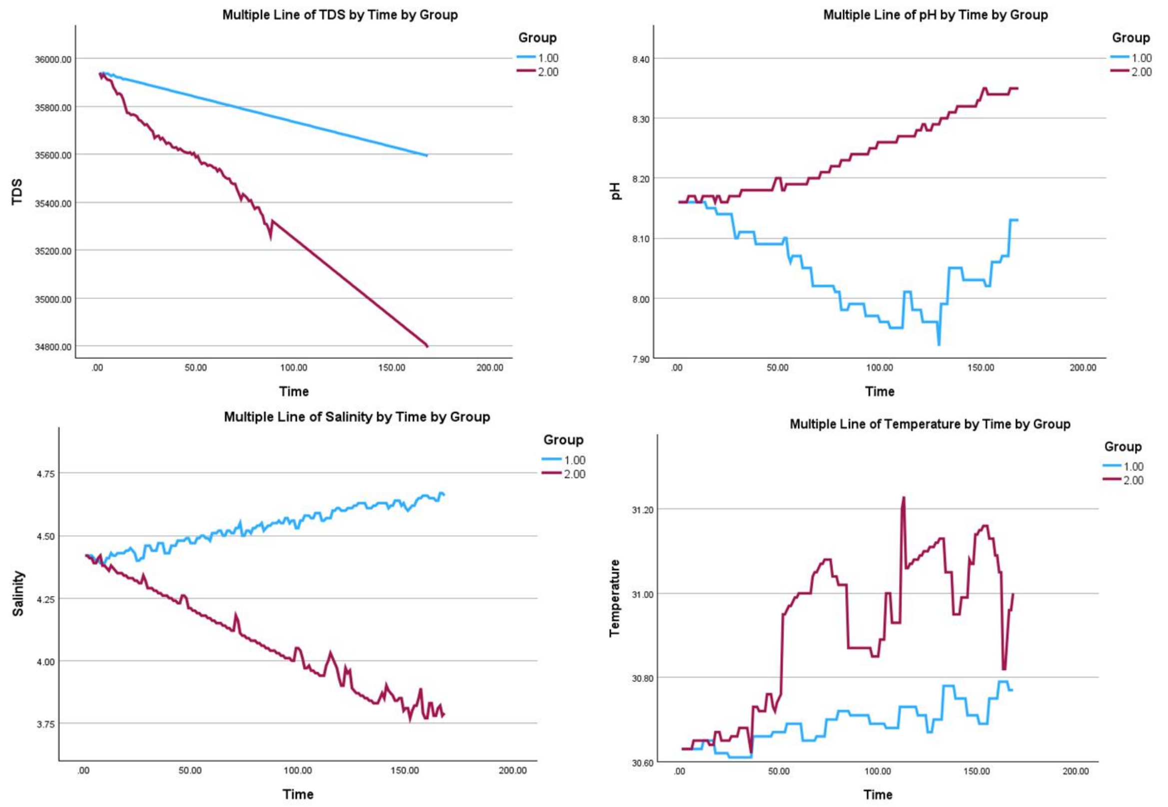

Figure 5. Graph comparing pH, TDS, salinity, and temperature values (Y-axis) over time (X-axis) between the addition of SMFC treatment (Red Line) and control (Blue Line).

Temperature is also a critical parameter for coral survival, and the experimental results indicate that temperature fluctuations were more pronounced in the SMFC system. At hour 112, the water temperature in the SMFC system significantly increased to 31.23°C, while the control system demonstrated more consistent temperature stability. This temperature increase is likely due to the electrogenic microbial activity within the SMFCs, which generates heat as part of the metabolic process. The recorded temperature range of 30°C to 45°C is known to support electrogenic microbial activity (Umar et al., 2021); however, uncontrolled temperature increases can elevate the risk of thermal stress on corals. The temperature data (Figure 5) shows that the control group maintained more consistent temperatures, whereas the SMFC group experienced several temperature spikes, highlighting challenges that need to be addressed to safely use SMFC technology in coral reef environments. An increase in temperature exceeding the coral's tolerance threshold can trigger coral bleaching and accelerate the degradation of coral reef ecosystems, as recorded in Bunaken National Park in 2017, where rising temperatures and salinity changes led to a drastic decline in coral conditions(Attamimi & Saraswati, 2019; Hs, 2024).

In summary, SMFCs have demonstrated effectiveness in stabilizing key environmental quality parameters—specifically pH, TDS, and salinity—crucial for coral transplantation. However, the influence of SMFCs on temperature requires further investigation to mitigate negative effects on corals from harmful fluctuations. Continued research is necessary to optimize SMFC technology for effective application in coral reef conservation.

Statistical analysis using the Mann-Whitney U test was performed to compare the physicochemical parameters between the SMFC treatment and control groups. The test results indicated significant differences in all measured parameters, with Asymp. Sig (2-tailed) < 0.05. This finding confirms that the inclusion of SMFCs significantly impacts water quality improvement and optimization of environmental conditions within the coral transplantation system. The Mann-Whitney test further supports the superiority of SMFC treatment in reducing harmful organic compounds and maintaining more stable environmental parameters compared to the control, which is essential for supporting coral health and growth.

4.3. Potential of SMFCs as Renewable Energy

Figure 6. shows the graph depicting fluctuations in open circuit voltage (VOC) during testing. In the initial phase, there was a significant increase in voltage, ranging from 1.4 to 30 mV, reflecting the early phase of microbial biofilm formation on the SMFC electrodes. During this period, microorganisms began to colonize the electrode surfaces and initiated the degradation of organic materials, resulting in electron generation and voltage increase. After reaching a peak voltage of 84.3–96.6 mV, there was a drastic drop in VOC values, likely due to various factors such as decreased microbial activity, metabolic fatigue, substrate depletion, or accumulation of by-products that inhibit the bioconversion process (Hs et al., 2024; Umar et al., 2021). After approximately 120 hours, voltage began to increase again, albeit not as rapidly as in the initial phase, indicating a recovery of microbial activity or adaptation to changing environmental conditions.

These results align with findings from Volchenko et al. (Volchenko et al., 2023), who also noted voltage fluctuation patterns in MFC systems. In their study, the initial voltage was also low, ranging from 5 to 40 mV, and gradually increased to 130–140 mV after several days, coinciding with the shift of microorganisms from aerobic respiration to anaerobic metabolism. After peaking at 200–250 mV, voltage fluctuations became evident, influenced by external factors such as physical damage to devices and interactions with benthic biota. Despite temperature decreases, electrogenic activity did not significantly decline, indicating microbial adaptability to environmental changes. These findings reinforce the current research results, where, following voltage decreases, microorganisms exhibited the ability to adapt and recover bioelectrogenesis activity, potentially leading to system stabilization and increased efficiency of the SMFCs.

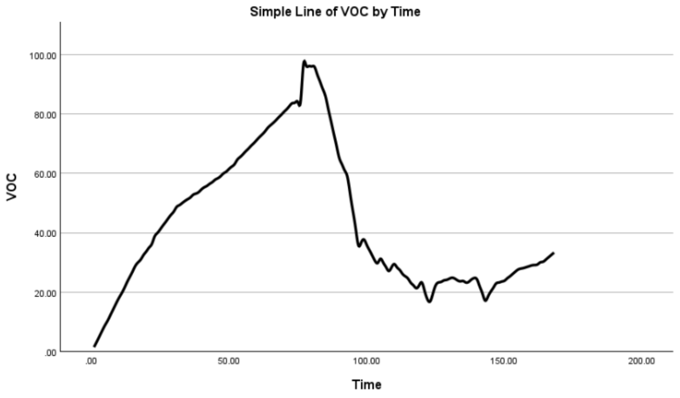

Figure 6. Graph of open circuit voltage (VOC) from SMFCs.

The low voltage values in this study can be attributed to fluctuations in the pH of the surrounding marine sediment, which affect microbial activity and electricity generation in sediment microbial fuel cells (SMFCs). External pH changes impact physiological processes in microbes, such as ion concentration, cytosolic pH, and electron transfer efficiency, influencing voltage production (Umar et al., 2021). The low voltage generated may be due to suboptimal pH conditions for electrogenic microorganisms, particularly in alkaline pH above 7 as observed in this study. Microbial activity is generally optimal at neutral to slightly alkaline pH, ranging from 6.3 to 7.8.

In the future, collaboration among scientists from various disciplines, including marine biology, microbiology, materials science, and electrical engineering, is essential for developing more effective solutions to optimize the performance of sediment microbial fuel cells (SMFCs). With this interdisciplinary approach, we can enhance not only the energy production from SMFCs but also the success of coral transplantation, which is a crucial step in conserving vulnerable coral reef ecosystems. Such efforts will not only support the recovery of coral reefs but also contribute to the overall sustainability of marine ecosystems.

5. Conclusion

This study demonstrates that the application of Sediment Microbial Fuel Cells (SMFCs) can create a more stable environment for coral transplantation. The data obtained indicate significant reductions in important physicochemical parameters: pH decreased from 8.36 to 8.16, total dissolved solids (TDS) dropped from 35,940 ppm to 34,793 ppm, and salinity declined by 3.19%. The maximum recorded temperature reached 31.23°C, with the highest measured open circuit voltage (VOC) at 96.6 mV. While SMFCs show the ability to improve environmental quality, the high temperature fluctuations must be closely monitored, as they may increase the risk of thermal stress on corals, potentially affecting their survival and growth.

To optimize the performance of SMFCs, interdisciplinary collaboration is essential, involving environmental scientists, marine biologists, microbiologists, as well as materials and electrical engineers. Such collaboration will support bioremediation efforts and enhance the efficiency of SMFC electricity production. The involvement of policymakers is crucial to support regulations for SMFC use, alongside the development of educational programs for local communities aimed at raising awareness about the importance of coral transplantation and marine ecosystem sustainability.

Further experimental research in natural environments is necessary, requiring careful and thorough preparation, to evaluate the effectiveness of SMFCs under real ecosystem conditions. This research will not only provide deeper insights into the interactions of SMFCs with natural environments but also pave the way for the development of sustainable technologies that can support coral reef conservation and the recovery of marine ecosystems in the future. Thus, cross-disciplinary collaboration and evidence-based approaches are vital to ensure the success of coral transplantation initiatives and the protection of marine biodiversity.

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