Journal of Energy and Safety Technology

JEST

RESEARCH ARTICLE Open Access

COMBINED EFFECTS OF WATER DEPTH, ELECTRODE SPACING, AND ADDITIONAL SUBSTRATE IN A SOIL MICROBIAL FUEL CELL FOR SUSTAINABLE BIOELECTRIC

E Chau Yong*, Umi Aisah Asli
School of Chemical & Energy Engineering, Faculty of Engineering,
Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

**Corresponding author: eyong@graduate.utm.my*

Article History

Received:	Received in revised form:	Accepted:	Published:
May 6, 2025	June 30, 2025	July 4, 2025	December 12, 2025

Abstract

The Soil Microbial Fuel Cell (SMFC) is a technology that utilizes the metabolic activity of soil microorganisms to produce bioelectricity. SMFC provides a sustainable and environmentally friendly energy solution that has the capacity to alleviate the negative consequences of fossil fuel consumption. Unfortunately, there are many factors such as water depth, electrode spacing and types of additional substrate used will affect the performance of a soil microbial fuel cell (SMFC). Therefore, in order to improve and enhance the efficiency of SMFC, factors that contribute to low bioelectricity production need to be studied. In this study, there were 3 different parameters that were investigated for their effect towards the performance of soil microbial fuel cell (SMFC), which were the water depth, electrode spacing and extra substrate types added. SMFC's configuration in this study was built in a 10cm x 10 cm x 12cm PVC box, with attached stainless steel's activated carbon felt as electrodes and rice washing water (RWW) as control substrate and with high clay content soil in fixed 10 cm soil level. The experiment was conducted for 3 months duration and multimeter was used to record the voltage output of SMFC. Total Bacteria Count (TBC) analysis was also conducted to study the relationship between number of microorganisms and voltage generation (mV). Combined effects of SMFC were observed at the end of the experiment. Throughout the study, it was found that the SMFC with 10 cm water depth, 5 cm electrode spacing and using only rice washing water (RWW) as substrate without any addition of other substrate was the best condition with the maximum voltage output of 711 mV. Moreover, with TBC analysis, this setup has proven that the more the number of microorganisms in the fuel cell, the higher the voltage output (mV) as it has the highest amount of microorganisms up to 141×10^6 of microorganisms at its highest voltage output's peak.

Keywords: fossil fuel consumption; Soil Microbial Fuel Cell; bioelectricity; microorganism; voltage output.

INTRODUCTION

Oil and coal are used to generate electricity worldwide due to rising energy demand. Despite growing awareness of these fuels' environmental impact and limited availability, many communities still rely on them for energy. This dependence is caused by infrastructure constraints, economic factors, and energy source perceived ease of use [1]. Due to the slow and inefficient shift to renewable energy, roughly half of the world's population still receives electricity from non-renewable sources. According to Smil (2014), globally converting to renewable energy will take decades. Due to renewable energy's limits, fossil fuel contribution to global energy only fell from 88 to 87 percent between 1990 and 2012 [2]. This situation hinders sustainable growth since fossil fuel extraction, refinement, and burning cause environmental damage, air pollution, and greenhouse gas production [3]. Soil Microbial Fuel Cells (SMFCs) are a promising renewable energy source [4], especially in areas where chemical batteries and solar panels are limited. In damp, overgrown areas, dirt or vegetation can obstruct solar panels at night. Unattended batteries can pollute the environment [5]. Tin and cobalt, used to make solar panels, have serious environmental implications. Instead, SMFCs create energy from environmental microorganisms. Many local biomass-derived components make up SMFCs [6]. As a result, SMFCs have smaller, and sometimes negative in terms of carbon footprints. Their deployment is flexible since they can be planted in practically any soil and scaled up or down to meet changing energy needs without the hassle of finding or processing uncommon ingredients. Soil Microbial Fuel Cells (SMFCs) generate electricity from soil microbial metabolism. Numerous fungi and bacteria in the soil break down organic matter as part of their life cycle [7]. During this process, microorganisms colonise the organic substrate-immersed anode [8]. Bacteria send metabolic byproduct electrons from organic material to the anode for oxidation. Soil Microbial Fuel Cells (SMFCs) use an anode to capture released electrons and a cathode to accept electrons from an external circuit. Electrons moving from the anode to the cathode form an electric current that can power electronics or be stored [7]. Research on soil microbial fuel cells (SMFCs) has yielded mixed results. After a 60-80-day experiment, Gagliardi (2024) discovered that soil microbial fuel cells with low Polychlorinated biphenlys (PCB) contamination produced more electricity, with 207 ± 80 mW/m^2 compared to 1.5 ± 0.2 mW/m^2 [9]. In another study, Mashkour (2021) examined a cellulose-based membrane electrode to generate more electricity [10]. In another study, Maan (2024) found that biochar-based anodes made from peanut nutshells outperformed activated carbon and graphite electrodes [11]. Zafar (2024) achieved 43.11 mA of maximum current with 6.65 Ω solution resistance using diesel contaminated soil as electrolyte in a series circuit air-cathode MFC [12]. Nandy (2023) found that carbon-based cathodes affected biofilm composition and electrochemical performance [13]. From recent study by Nguyen (2022), utilized muddy soil from rice paddy as the living medium and rice washing wastewater (RWW) as organic sources. They investigated the effect of soil types and types of substrate and successfully produced bioelectricity approximately of 800 mV [14]. This study offers a novel combination of high clay content soil, rice washing wastewater, and structural configurations to enhance bioelectricity generation in SMFCs. Therefore, in order to further investigate the other factors that affecting to enhance the performance of SMFC. In this study, high clay content soil were used as the living medium for the microorganism. Activated-carbon felts electrodes were used in a single chamber configuration and rice washing wastewater (RWW) as the control substrate. The effect of different water depth, different electrode spacing and different addition of substrate were studied and discussed. Electrochemical tests were performed over extended periods of operation to measure the output voltage and record the data.

METHODOLOGY

Soil Sampling

High clay content soils used were sampled by the pond bank of Tasik Ilmu in Universiti Teknologi Malaysia, located in Skudai, Johor Bahru. The top part of the soil (5 cm to 25 cm) were collected. Soil samples were collected using sterile tools to prevent contamination, ensuring that the microbial communities within the soil are preserved in their natural state.

Material Preparation

Activated-carbon felt electrodes were utilized as both anode and cathode in the SMFC. The specified dimensions for each electrode are 8 cm x 8 cm x 1.5 cm. The electrodes were coated with a stainless steel mesh layer measuring 8 x 8 x 0.2 cm. Stainless steel mesh enhances the efficiency of electron transport to the cathode. The stainless steel meshes were obtained from local hardware or coating stores. Each electrode was coated and affixed with a stainless steel mesh on either side using epoxy 4-minute adhesive. This was followed by a drying procedure at room temperature of 30 °C for 15 minutes. Subsequently, locally sourced white grain rice was acquired from a nearby store to facilitate the preparation of rice washing wastewater. Rice washing wastewater (RWW) was created by washing and soaking 300 g of white rice grains in 500 mL of tap water for 2 minutes and utilized as the substrate of this study. GranuCult ® Nutrient agar mixed with C0014-187010 Bendosen agar powder for the preparation of Total Bacteria Count (TBC).

SMFC Configuration

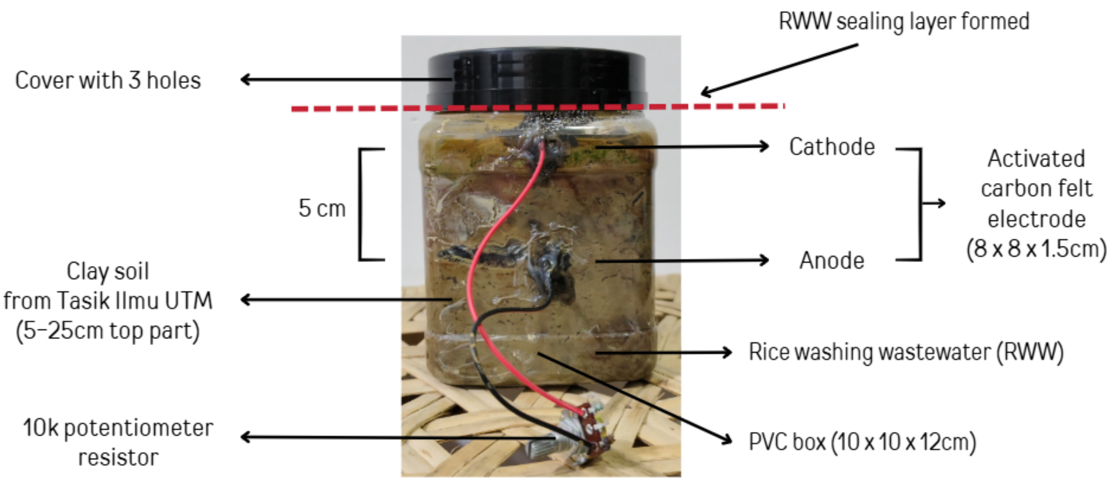

Figure 1. SMFC Schematic Diagram

The design of the SMFC reactor utilized in this study is illustrated in Figure 1. The SMFC comprised two activated-carbon felt electrodes, each measuring 8 x 8 x 1.5 cm. The anode and cathode were positioned with a 5 cm electrode spacing to facilitate the water level experiment. The chamber box used for the placement of the SMFC is constructed from PVC. The boxes measured 10 x 10 x 12 cm and contained a soil level of 10 cm each. The anode was buried in the soil, while the cathode was exposed to the air. The container boxes were modified with three holes to facilitate air flow within the microbial fuel cell. A 10k potentiometer resistor was utilized to complete the circuit for electron flow. Rice washing wastewater was utilized to create a water sealing layer on the soil surface.

RESULTS AND DISCUSSION

Water Depth

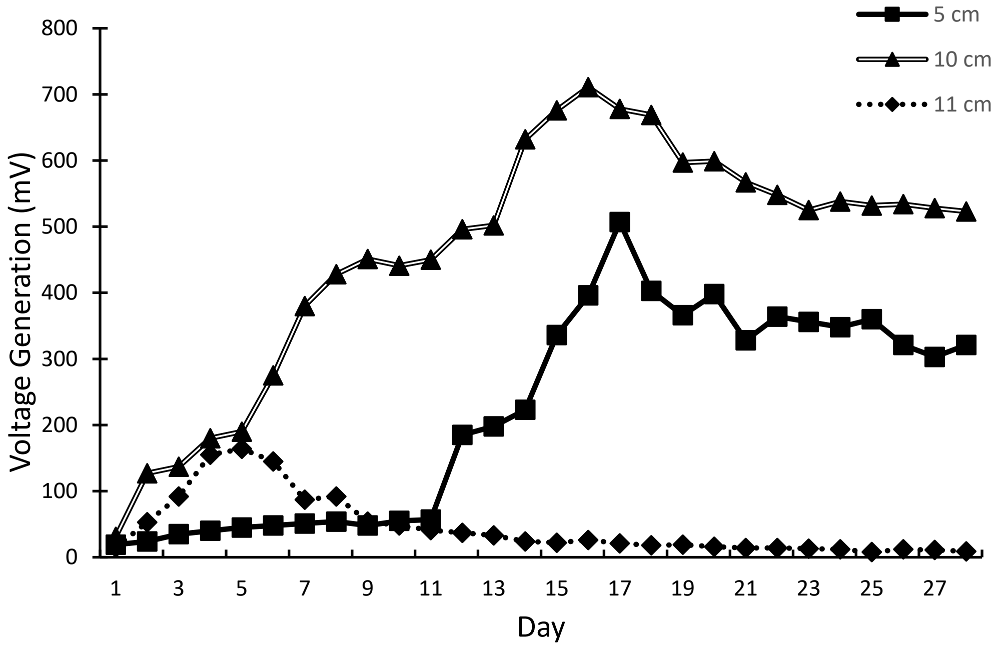

Figure 2. One month of SMFCs' voltage generation (mV) with different water depth (cm)

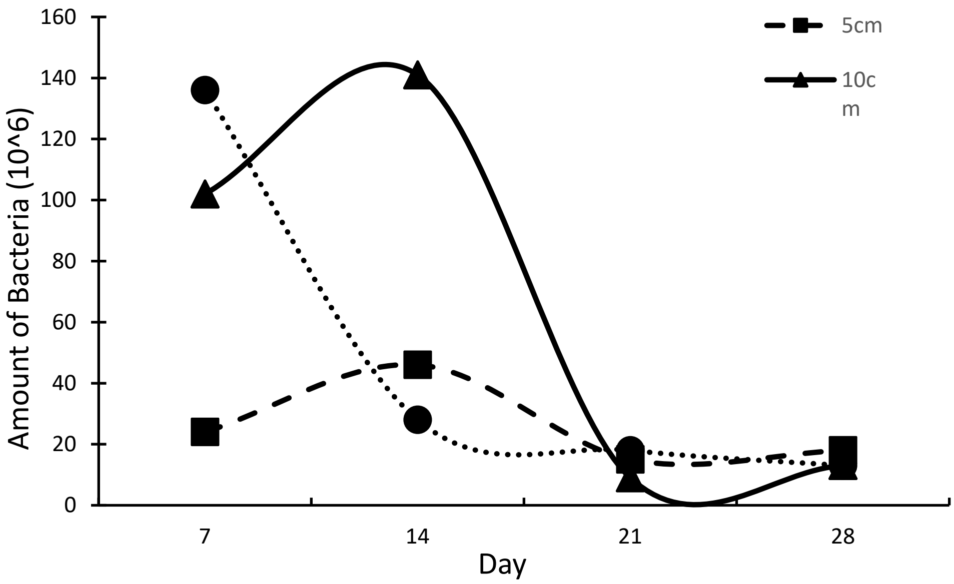

Figure 3. Number of microorganisms against weeks for different water depth

This study investigates the effect of water depth on the performance of soil microbial fuel cells (SMFCs) by analysing voltage production and microbial populations at depths of 5 cm, 10 cm, and 11 cm shown in Figure 2. The results demonstrate that a depth of 10 cm yielded the maximum voltage (711 mV) and microbial population (142 × 10^6 bacteria in day 14), which can be attributed to optimal water depth that promoted microbial activity, electron transfer, and oxygen availability for the cathodic processes [15]. The 5 cm depth demonstrated reduced voltage (507 mV) and microbial growth attributed to moisture limitations. Conversely, the 11 cm depth initially facilitated microbial proliferation of 136 × 10^6 bacteria but later experienced a significant voltage decrease from 164 mV to 9 mV due to constraints in oxygen diffusion for the cathodic processes. Sakai (2022) noted best performance at soil moisture levels of 86%, producing voltage outputs ranging from 580 to 620 mV. Moisture levels over 91% resulted in decreased power output due to constraints in oxygen diffusion, similarly to the difficulties noted in the 11 cm water depth configuration in this study [15]. The voltage outputs at various depths aligned with peaks in microbial populations shown in Figure 3, highlighting the significance of microbial activity in the efficacy of SMFCs. The reduction in voltage following peak microbial counts indicates substrate depletion or less favorable conditions over time, while the 10 cm depth consistently facilitates sustained bioelectricity production.

Electrode Spacing

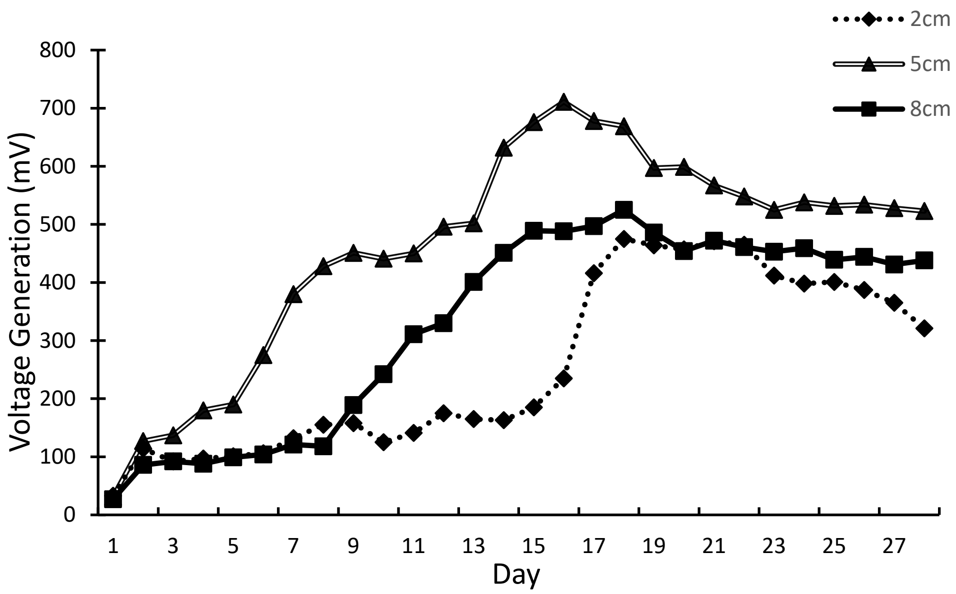

Figure 4. One month of SMFCs' voltage generation (mV) with electrode spacing (cm)

This research investigated the influence of electrode spacing (2 cm, 5 cm, and 8 cm) on bioelectricity generation in soil microbial fuel cells (SMFCs) while maintaining a constant water depth of 10 cm shown in Figure 4. The 5 cm spacing exhibited the highest peak voltage of 711 mV in day 14, the quickest voltage spike which occurred at day 6, and the most sustained output (540 mV), due to its optimal balance of minimising internal resistance and enhancing microbial activity. The 2 cm spacing, despite the closer proximity of electrodes, demonstrated a lower peak voltage of 475 mV and a delayed voltage spike at day 16, likely due to oxygen interference at the anode [17], which disrupted anaerobic microbial processes. The 8 cm spacing resulted in a moderate peak voltage of 525 mV and an earlier voltage spike observed on day 8. However, increased internal resistance hindered sustained performance [16], yielding a voltage of 450 mV. The findings aligned with Bhattacharya (2023), where electrode spacing (2cm, 5cm, and 10 cm) were investigated and 5 cm electrode spacing resulted the best voltage output among others [17]. The trends in microbial populations corresponded with voltage output, exhibiting the highest density in day 14 across all configurations similarly shown in Figure 3. The findings underscore the importance of electrode spacing in optimising SMFC performance, with a spacing of 5 cm demonstrating the greatest effectiveness in enhancing voltage generation, stability, and microbial activity.

Addition Substrate

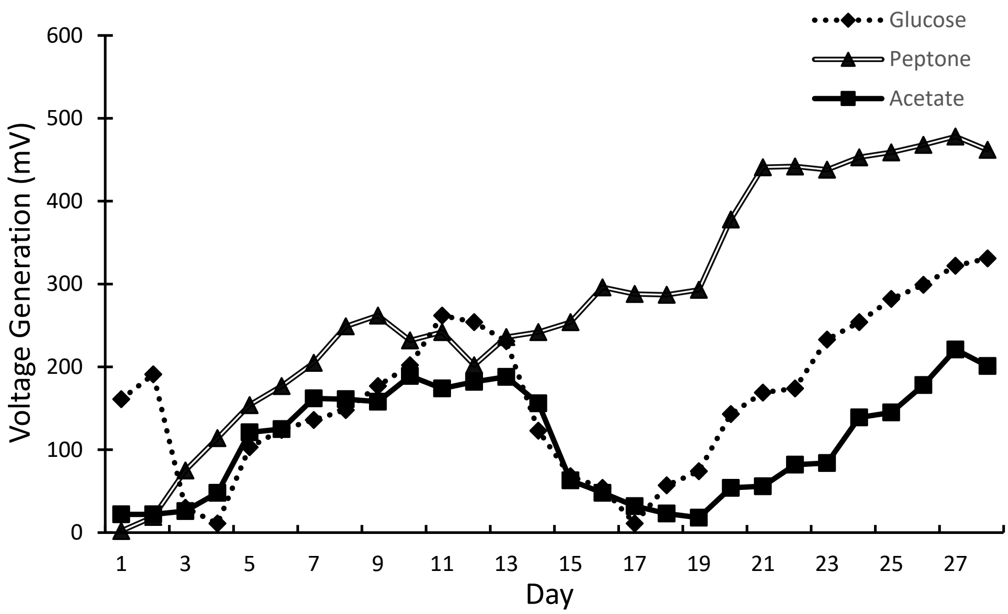

Figure 5. One month of SMFCs' voltage generation (mV) with different addition substrate

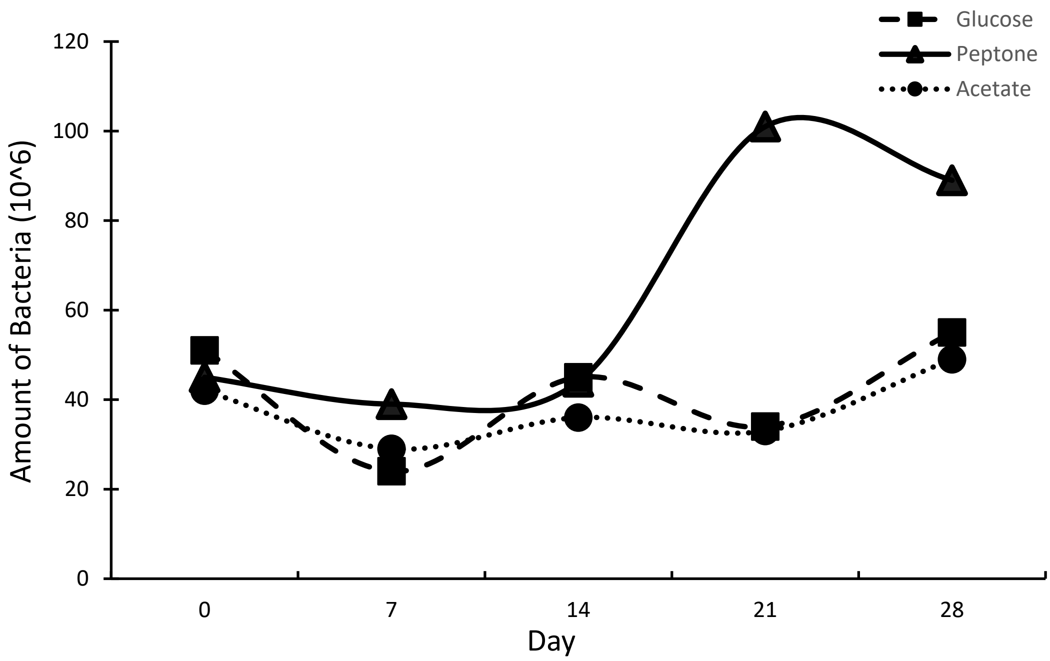

Figure 6. Number of microorganisms against weeks for different addition substrates

This research investigated the effects of various substrates addition, peptone, glucose, and acetate, on bioelectricity generation in soil microbial fuel cells (SMFCs) utilising rice washing wastewater (RWW) shown in Figure 5. Peptone exhibited the highest peak voltage of 478 mV on day 27 and a sustained output of 430 mV, signifying its enhanced capacity to facilitate microbial activity and electron transfer. Glucose and acetate demonstrated reduced peak voltages of 331 mV and 221 mV, respectively, and undergo temporary rapid voltage declines after day 13 due to burrowing activity and methane gas emissions from microbial decomposition. The activities enhanced pore size in the compacted dirt block, facilitating oxygen diffusion into the anode region and disrupting the anaerobic conditions required for optimal electron production. The expansion of the soil block resulted in increased water depth, which submerged the cathode and limited oxygen diffusion necessary for cathodic reactions, thereby reduce the quantity of electrons generated and transferred [18]. Once the soil structure stabilized, the voltage output returned to normal levels, with glucose and acetate maintaining outputs of 320 mV and 210 mV, respectively. Trends in microbial populations shown in Figure 6 were correlated with voltage production, thereby reinforcing the relationship between microbial activity and electron generation.

CONCLUSION

This study shows that optimal water depth level and electrode spacing are required for microbial activity and performance of Soil Microbial Fuel Cell (SMFC). However, additional substrate of the other ingredient such as peptone, glucose and acetate that were have investigated in this study should be considered to ensure sustained bioelectricity production. Throughout the study, it was found that the SMFC with 10 cm water depth, 5 cm electrode spacing and using only rice washing water (RWW) as substrate without any addition of other substrate was the best condition with the maximum voltage output of 711 mV. Moreover, with TBC analysis, this setup has proven that the more the number of microorganisms in the fuel cell, the higher the voltage output (mV) as it has the highest amount of microorganisms up to 141×10^6 of microorganisms at its highest voltage output's peak. For future recommendation, studies are encouraged to explore alternative, low-cost, and sustainable electrode materials such as biochar, graphite felt, or stainless steel mesh to enhance electrical conductivity and microbial colonization. Additionally, microbial community analysis using metagenomic or 16S rRNA sequencing is recommended to identify key electrogenic species, which could support the development of more efficient microbial consortia for improved SMFC performance.

Acknowledgement

This research is fully supported by Universiti Teknologi Malaysia and supervisor, Assoc Prof Dr Umi Aisah from Universiti Teknologi Malaysia, Skudai, Malaysia (UTM)

References

[1] C. Yu, M. Moslehpour, T. K. Tran, L. M. Trung, J. P. Ou, and N. H. Tien, "Impact of non-renewable energy and natural resources on economic recovery: Empirical evidence from selected developing economies," *Resour. Policy*, vol. 80, p. 103221, Jan. 2023, doi: 10.1016/j.resourpol.2022.103221

[2] V. Smil, "A Global Transition to Renewable Energy Will Take Many Decades," SCI AM. Accessed: May 15, 2024. [Online]. Available: https://www.scientificamerican.com/article/a-global-transition-to-renewable-energy-will-take-many-decades/

[3] N. Vig, K. Ravindra, and S. Mor, "Environmental impacts of Indian coal thermal power plants and associated human health risk to the nearby residential communities: A potential review," *Chemosphere*, vol. 341, p. 140103, Nov. 2023, doi: 10.1016/j.chemosphere.2023.140103.

[4] S. Chibueze Izah, A. Omozemoje Aigberua, and A. Lal Srivastav, "Microbial fuel cells," in *Artificial Intelligence for Renewable Energy Systems*, Elsevier, 2022, pp. 105–129. doi: 10.1016/B978-0-323-90396-7.00014-6.

[5] W. Yao, X. Han, Y. Huang, Z. Zheng, Y. Wang, and X. Wang, "Analysis of the influencing factors of the dust on the surface of photovoltaic panels and its weakening law to solar radiation — A case study of Tianjin," *Energy*, vol. 256, p. 124669, Oct. 2022, doi: 10.1016/j.energy.2022.124669.

[6] P. P. A. Amit, "A Review on Soil Based Microbial Fuel Cell," *Int. J. Sci. Techonlogy Manag.*, vol. 10, no. 11, 2021, [Online]. Available: http://www.ijstm.com/images/short_pdf/1637843744_J128.pdf

[7] S. Z. Abbas, J.-Y. Wang, H. Wang, J.-X. Wang, Y.-T. Wang, and Y.-C. Yong, "Recent advances in soil microbial

fuel cells based self-powered biosensor," *Chemosphere*, vol. 303, p. 135036, Sep. 2022, doi: 10.1016/j.chemosphere.2022.135036.

[8] D. Vidhyeswari, A. Surendhar, and S. Bhuvaneshwari, "General aspects and novel PEMss in microbial fuel cell technology: A review," *Chemosphere*, vol. 309, p. 136454, Dec. 2022, doi: 10.1016/j.chemosphere.2022.136454.

[9] G. G. Gagliardi *et al.*, "Microbial fuel cells with polychlorinated biphenyls contaminated soil as electrolyte: energy performance and decontamination potential in presence of compost," *J. Power Sources*, vol. 613, p. 234878, Sep. 2024, doi: 10.1016/j.jpowsour.2024.234878.

[10] M. Mashkour, M. Rahimnejad, M. Mashkour, and F. Soavi, "Increasing bioelectricity generation in microbial fuel cells by a high-performance cellulose-based membrane electrode assembly," *Appl. Energy*, vol. 282, p. 116150, Jan. 2021, doi: 10.1016/j.apenergy.2020.116150.

[11] K. S. Maan, P. Gajbhiye, A. Sharma, and A.-A. Al-Gheethi, "Efficient anode material derived from nutshells for bio-energy production in microbial fuel cell," *J. Environ. Manage.*, vol. 364, p. 121422, Jul. 2024, doi: 10.1016/j.jenvman.2024.121422.

[12] Z. Zafar, S. Naz, N. H. Malik, F. Ahmed, and N. Ali, "Bioelectrogeneic performance of air-cathode microbial fuel cells with diesel contaminants," *Fuel*, vol. 355, p. 129407, Jan. 2024, doi: 10.1016/j.fuel.2023.129407.

[13] A. Nandy *et al.*, "Influence of carbon-based cathodes on biofilm composition and electrochemical performance in soil microbial fuel cells," *Environ. Sci. Ecotechnology*, vol. 16, p. 100276, Oct. 2023, doi: 10.1016/j.ese.2023.100276.

[14] H.-U.-D. Nguyen, D.-T. Nguyen, and K. Taguchi, "A compact, membrane-less, easy-to-use soil microbial fuel cell: Generating electricity from household rice washing wastewater," *Biochem. Eng. J.*, vol. 179, p. 108338, Feb. 2022, doi: 10.1016/j.bej.2022.108338.

[15] Y. Sakai, C. M. Nielsen, Y. Sato, S. Kato, and Y. Kansha, "Evaluation of the Dependence of Microbial Fuel Cells on Soil Composition and Water Content," *J. Ital. Assoc. Chemcial Eng.*, vol. 94, 2022, doi: https://doi.org/10.3303/CET2294103.

[16] I. M. Simeon, A. Weig, and R. Freitag, "Optimization of soil microbial fuel cell for sustainable bio-electricity production: combined effects of electrode material, electrode spacing, and substrate feeding frequency on power generation and microbial community diversity," *Biotechnol. Biofuels Bioprod.*, vol. 15, no. 1, p. 124, Nov. 2022, doi: 10.1186/s13068-022-02224-9.

[17] R. Bhattacharya *et al.*, "Bioremediation and bioelectricity from Himalayan rock soil in sediment-microbial fuel cell using carbon rich substrates," *Fuel*, vol. 341, p. 127019, Jun. 2023, doi: 10.1016/j.fuel.2022.127019.

[18] M. Müller-Inkmann and H.-C. Fründ, "Glucose amendment influences restructuring of compacted soil blocks – Results of a field experiment with varying soil-site conditions," *Soil Tillage Res.*, vol. 211, p. 105025, Jul. 2021, doi: 10.1016/j.still.2021.105025.