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Sediment Microbial Fuel Cells: Opinion of the Factors Impeding the Deployment

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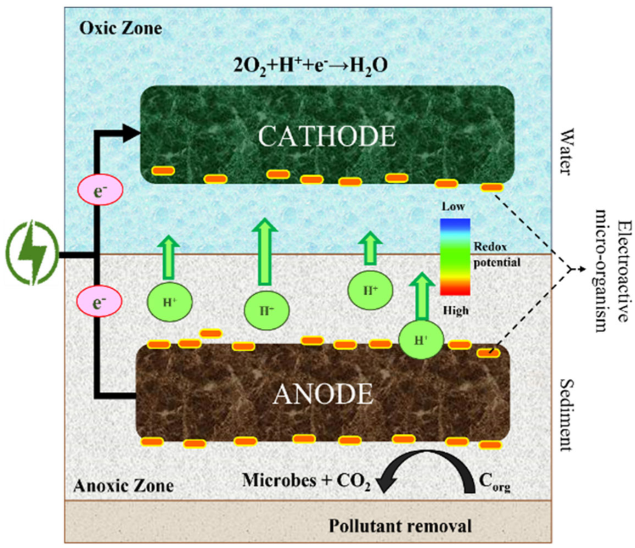
Abstract: This article explores the potential and limitations of sediment microbial fuel cells (SMFCs) and their deployment for sustainable energy production and environmental remediation. SMFCs use naturally occurring redox gradients in sediments to produce bioelectricity, making them advantageous over conventional energy sources due to their affordability, simplicity, and ability to operate in various environments with minimum maintenance requirements. However, their low-power output density restricts their practical applicability. The article discusses the controllable and uncontrollable factors that affect SMFC performance and their influence on SMFC functionality, electrode material, external resistance, electrode spacing, electrode design, electrode immersion dimensions, and catalyst. The article highlights the challenges that SMFC deployment are facing, particularly in large-scale businesses, such as the need for more scientific literature on SMFCs and inadequate focus on energy metrics.

Keywords: sediment microbial fuel cells (SMFCs), catalyst, wastewater treatment, chemical oxygen demand, microorganism

1. Introduction

The depletion of nonrenewable energy resources and the negative environmental impact of traditional energy production has led to exploring alternative energy sources. Microbes, alongside other living organisms, utilize redox processes to generate energy for growth and metabolism. The investigation of this occurrence has sparked much curiosity about the potential for energy production. Sediment microbial fuel cells (SMFCs), a class of microbial fuel cells (MFCs), is membrane-free, a technology that possesses promise in exploiting such a phenomenon. SMFCs use the naturally present redox gradients in environmentally rich sediments in the existence of fermentative bacteria at mild operating circumstances to produce bioelectricity (Zabihallahpoor et al., 2015). The energy potential (biologically mediated) develops between bacterial metabolic processes (a sequence of oxidation–reduction phenomena that create electrons (e^-) and protons (H^+)) and acceptor of electrons ailments to generate a prospective for producing bioelectricity. Microorganisms derive the energy needed to develop biomass (anabolism) from redox processes (catabolism) using electron donor–acceptor combinations (Gupta et al., 2023). However, the low-power output density of SMFC is often insufficient to continually operate ordinary electronic devices, which severely limits its practical applicability. The schematic of SMFC is illustrated in Figure 1.

Figure 1
Schematic illustration of SMFC



In the course of conventional energy sources, SMFCs have a wide range of advantages, which includes having the ability to quickly convert organic matter to energy, the potential to operate in a wide range of environments, low temperatures at which they operate, affordability, minimum levels of periodic maintenance requirements (such as frequent temporary fixes), simple design, availability of a wide range of cheap fuel sources, deploying ability to distant locations, and the absence of operational or waste-related difficulties (Thomas et al., 2013).

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The widespread application of SMFCs can be observed in the provision of renewable energy sources for long-term monitoring equipment located in water bodies such as the coastline, riverbank, irrigation systems, and bay, the removal of organic compounds from sediments, and other analogous uses (Ewing et al., 2014). SMFCs have undergone testing to power low-power oceanographic instruments in off-the-grid locations and for biological remediation. Algar et al., 2020 reported that the SMFCs could also serve as a biogeochemical snorkel, allowing soil microorganisms to reach more favorable electron acceptors (i.e., oxygen). Wastewater treatment with SMFCs is a novel application, with Xu et al. (2015) demonstrating that SMFCs can effectively process wastewater while producing energy. SMFCs, in addition to providing electrical energy, may also enable the oxidation of reduction components at the anode, resulting in the removal of excess or undesirable reduction counterparts from subterranean soils over time. Consequently, SMFCs have also demonstrated an authority figure recovery system for heavy metal-polluted sludge (Abbas et al., 2017). Research on all of the above has shown to be particularly interesting in finding long-term solutions to reduce the threat posed by pollution and increase power recovery.

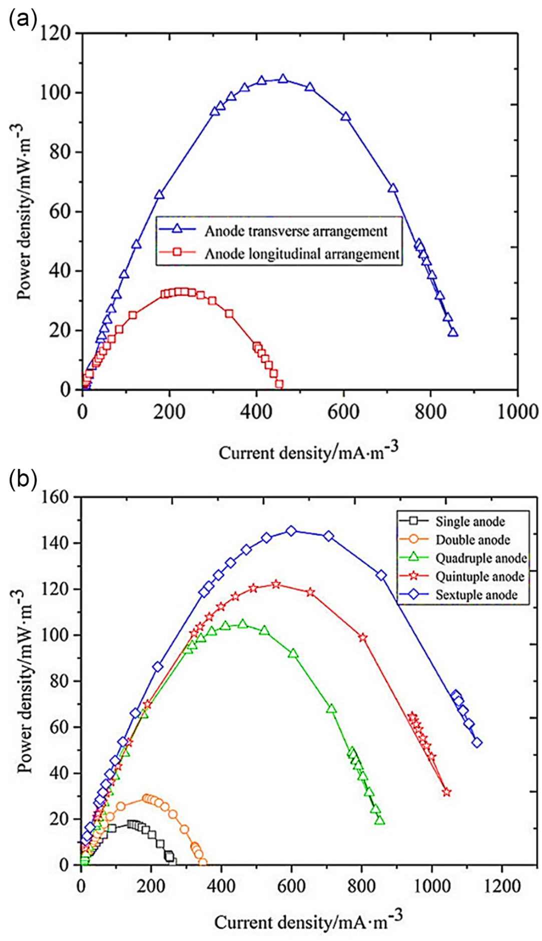
Despite their potential, SMFCs' low-power output density and the lack of research into energy metrics and wastewater treatment efficacy have limited their practicality. This article reviews the challenges and opportunities for SMFC deployment, including controllable factors such as electrode material and design and uncontrollable factors such as sedimentary traits and salinity. Further research is needed to optimize SMFC performance and overcome practical limitations.

2. Opinion regarding the challenges with SMFC deployment

Many variables influence SMFC performance, which may be categorized into controllable and uncontrolled elements that collectively determine SMFC power generation. Controllable factors include electrode material, external resistance, electrode spacing, electrode design, electrode immersion dimensions, and catalyst (Yu et al., 2021). The environment generally determines uncontrollable parameters such as salinity, pH, temperature, dissolved oxygen (DO), sedimentary traits, and substrate microorganism makeup (Zhao et al., 2016). Although SMFCs have been studied extensively for their potential to absorb energy from extracted sedimentary particles, the investigation into their practical use for the aforementioned purposes has only recently been underway. The SMFC system's potential applications are vast; nevertheless, several characteristics and challenges must be addressed prior to it can be used, especially in large-scale enterprises. Specifically, this pertains to the scientific literature that is enthusiastically on hand. Microorganisms, appropriate electrode materials, ideal SMFC designs, and process parameter optimization all affect how well an SMFC performs. Moreover, the reactor architecture, material and design of the catalyst membrane, electroactive surface area, space between electrodes, external resistance, oxygen content, and influence of the light–dark cycle often exert an impact on SMFC functionality. However, most existing research on SMFCs has primarily addressed power density in the aggregate, with only a few investigations emphasizing the energy measures that may be discovered.

Predominantly, the electrode spacing augmentation was said to be a practical approach to enhance catalytic activity; regrettably, the chemical oxygen demand (COD) and total nitrogen (TN) degradation rate is a constraint that has received the least attention (Wu et al., 2022). The power production performance of SMFCs is reported to be affected also by the anode arrangement (transverse vs. longitudinal) and the number of anodes used (single, dual, quadruple, quintuple, and sextuple). Guo et al. (2022) reported that the appropriate variety of anode configurations, employing carbon felt as an anode material and expanding the number of anodes to 6, could speed up the deterioration of the oily sludge in SMFCs. The ability to make electricity was also more effective. The power density curves of SMFCs with varied anode layouts and numbers of anodes are illustrated in Figure 2(a) and (b) (Guo et al., 2022).

Figure 2
(a) SMFC power density was obtained for different anode configurations. (b) SMFC power density obtained for varying no. of anodes



There is still room for improvement in our understanding of how the breakdown of organic compounds and the production of electricity are linked. Since the usual coulombic efficiency of SMFCs for processing wastewater is low, only a small fraction of potential pollutants are eliminated during the generation of electricity (Li & Yu, 2015). Respiratory microbial organisms in wastewater function as oxygen filters in the SMFC system, analogous to the proton exchange membrane (PEM) in the SMFC system. Accordingly, the redox potential is undoubtedly influenced by the sediment's depth (An et al., 2013). SMFCs are classified into two categories based on their sediment source: saltwater SMFCs and freshwater SMFCs. The power generated from the seawater SMFC using Pt wire electrodes was relatively minuscule (about 11 mW m^{-2}) and is yet at the very beginning stage (Abbas et al., 2019).

In general, pH is essential and is a performance determinant factor for SMFCs. The electrochemically active microorganisms that oxidize organic matter in the sediment and transfer electrons to the fuel cell's anode have a specific pH range they can tolerate and perform optimally within. If the pH fluctuates outside this range, it can adversely affect the microbial activity and the power output of the SMFC. However, the magnitude of the pH fluctuations and the specific microbial species' tolerance can vary (Jung et al., 2011). Some electrochemically active microorganisms, such as Geobacter sulfurreducens, can tolerate various pH values and perform well under slightly acidic to alkaline conditions (Logan et al., 2019). In this context, a controlled SMFC should have a steady pH of 8.

Kothapalli (2013) sought to employ Ceratophyllum demersum, a rootless nonvascular water plant-based SMFC exhibiting a pH fluctuation of 7 and a lower pH level than the controlled SMFC. Therefore, the statement may be true when the pH fluctuations are small and within the microbial species' tolerance range. However, in other cases, significant changes in pH can negatively impact the efficacy of the SMFCs (Zhao et al., 2021). One such study by Haxthausen et al. (2021) found that pH fluctuations between 6.5 and 8.5 did not significantly impact the power output of SMFCs. They observed that the SMFCs had similar performance across this pH range and suggested that the microbial community in the sediment may have adapted to a broad pH range.

A controlled SMFC has a DO content of 5 ± 1 mg L^{-1}, which has a greater power density than plant SMFC, which has a DO of 2 1 mg L^{-1} (Gonzalez Olias & Lorenzo, 2021). This is because roots produce organics, which bacteria oxidize, thereby delivering electrons to the anode, and these electrons approach the cathode, where oxygen is reduced (Chabert et al., 2015). This shed light on the idea that further plant-based SMFCs should be investigated.

There is a tangible link between pH and power in single-chamber SMFC start-ups. Temperature fluctuations during the first start-up can significantly impact the variation in power output. A rapid rise in temperature or a fast drop in temperature may result in an unexpected surge in voltage or a cutoff. This has significant consequences for enhancing the effectiveness of generating power during the early stages of SMFC start-up (Zhang et al., 2010). The pH of the cathode region fluctuates in the same way that the voltage and temperature vary dramatically during the initial phase of SMFC start-up. However, pH will recoup to some extent after that. From the second step of the SMFC start-up, a continual temperature decline in a short period will result in a continuing fall in pH, even if the temperature returns to normal (Ma et al., 2019). The features of intricacy, intense coupling, and other parameters for SMFCs cannot be put together promptly and precisely during the initial procedure. At this point, it is critical to admit the need for temperature management in conjunction with pH-level regulation for SMFC. Madheswaran et al. (2022) have already noted a precondition similar to this for the efficacy of PEMFC.

The microbes involved in SMFCs are often called electroactive bacteria (EABs) or exoelectrogens, capable of transferring electrons to an anode electrode, thus creating a current flow. Some of the potential strains/species of microbes that can act as EABs in soil sediments include:

- Geobacter sulfurreducens: This bacterium is one of the most extensively studied EABs known for reducing Fe(III) oxides and other electron acceptors (Santos et al., 2015).
- Shewanella oneidensis: This facultative anaerobe can use a wide range of electron acceptors, including Fe(III) and Mn(IV) oxides and electrodes (Ikeda et al., 2021).
- Anaeromyxobacter dehalogenans: This bacterium is capable of dehalogenation-chlorinated organic compounds and transferring electrons to electrodes (Cabezas et al., 2015).
- Pseudomonas aeruginosa: This versatile bacterium can use a wide range of electron acceptors, including Fe(III) oxides, nitrate, and sulfate, and can also transfer electrons to electrodes (Arkatkar et al., 2021).
- Desulfovibrio spp.: These sulfate-reducing bacteria are known for their ability to transfer electrons to electrodes and are often found in anaerobic environments (Voegtlin et al., 2022).

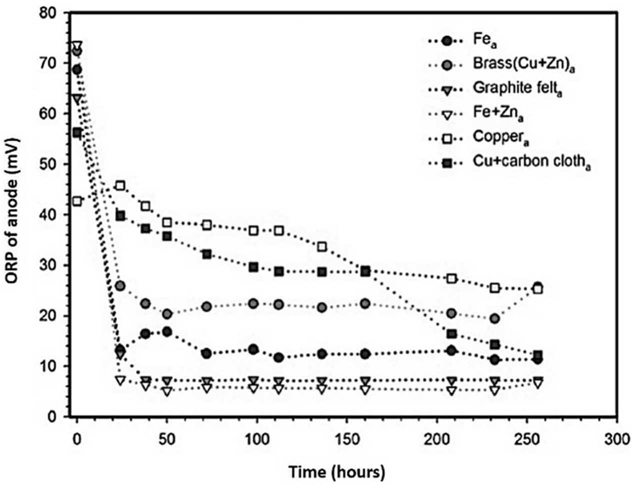
However, there are several challenges associated with using EABs for SMFCs. One major challenge is the slow growth rate of these microorganisms, which can limit the device's power output. The slow growth rate of electroactive microorganisms can be attributed to the complex metabolic pathway involved in extracellular electron transfer and requires a significant amount of energy (Naaz et al., 2023). Additionally, the environment within a SMFC can be pretty harsh, with low oxygen availability, limited nutrients, and potentially toxic substances present (Ter Heijne et al., 2010). These factors can also contribute to slower growth rates. Furthermore, the selection pressure within the SMFC may favor slower-growing, more efficient electroactive microorganisms. This means faster-growing microorganisms may be outcompeted by slower-growing, more specialized electroactive microorganisms (Saheb-Alam et al., 2019).

The slow growth rate of electroactive microbes means fewer cells are available to transfer electrons to the anode, which can slow down the electron transfer rate and limit the current output. Their slow growth rate also determines the rate at which the electroactive microbes degrade organic matter. This means there may not be enough organic matter available to sustain the microbial community, which can limit the power output of the fuel cell (Pisciotta et al., 2012). The growth rate of electroactive microbes also affects the rate at which they form biofilms on the anode surface. Therefore, as stated by Franks et al. (2010), a well-established biofilm is necessary for efficient electron transfer against the limitation of the formation of a mature biofilm.

Another challenge is the low efficiency of electron transfer from the microorganisms to the electrode, which can also limit the power output. Additionally, the composition and characteristics of the sediment matrix can also affect the performance of the SMFC, as it can influence the distribution and activity of the EABs (Mocali et al., 2013). Finally, the stability and durability of the anode material are also important consideration, as it can affect the longevity and performance of the device (Mitov et al., 2015).

The oxidation–reduction potential (ORP) of SMFCs is a measure of the tendency of the anode to accept electrons and the cathode to donate electrons. In SMFCs, microorganisms use organic matter as the electron donor and transfer electrons to the anode, which creates a potential difference between the anode and cathode. The ORP of the system is related to the electron transfer between the anode and cathode and can provide insight into the microbial community's ability to utilize organic matter and transfer electrons (Wang et al., 2012). Monitoring ORP can help optimize SMFC performance and understand microbial community dynamics. This is because the ORP of the catalyst can significantly affect the performance of the SMFC. If the ORP of the catalyst is too high or too low, it can lead to reduced power output or even complete failure of the SMFC. The ORP can also affect the microbial community in the sediment (Wang et al., 2021). If the ORP is too high, it can create an unfavorable environment for certain microorganisms, reducing microbial activity and power output. On the other hand, if the ORP is too low, it can create an environment conducive to the growth of certain types of microorganisms, such as sulfate-reducing bacteria, which can consume electrons and reduce the power output of the SMFC (Eaktasang et al., 2016). Therefore, it is crucial to carefully choose the catalyst and control the ORP in SMFCs to optimize power output and maintain a healthy microbial community. Figure 3 displays the results of an ORP experiment conducted by Haque et al. (2014) on a single-chamber SMFC with anodes made of Fe, Fe/ZN, brass (Cu/Zn), and copper, respectively, Cu/carbon cloth, and graphite felt.

Figure 3
ORP of various anode materials experimented using single-chambered SMFC



The discrepancies are likely due to small-scale physicochemical and biological uncertainty in the catalytic environment. There needs to be more research on this subject.

There is also no sophisticated monitoring tool for remote tracking of minute changes in variables throughout the start-up process of SMFCs. This would result in the loss of vital data during the detection process and the use of an extensive sum of material and human capital, disrupting the rigorous research of SMFC. It can frequently be problematic for the SMFC system to identify specific parameters continuously due to its more complicated ambient circumstances, higher coupling, and nonlinear features than MFC (Fan et al., 2015). Computational approaches are crucial in constructing fuel cells that work well under various operating circumstances. Nevertheless, due to the absence of exact mathematical modeling of MFC and the fact that standard techniques are only relevant to the requirement for a constant parameter and slow transition, applying them to SMFC is challenging. The neural network has a highly nonlinear adaptation ability, can map autonomously complicated nonlinear correlations, and has high resilience, memory, nonlinear mapping tendency, and self-learning potential (Li & Wibowo, 2017). Therefore, finding an appropriate neural network to match the nonlinear relationship between different parameters in the start-up phase is essential.

Despite research dedicated to enhancing the electrical performance of SMFCs through bettering electrode materials, optimizing electrode architecture, the functionality of several electrode constituents, and so on, only inconsequential progresses in energy harnessing and contamination managing have been attained. The impacts of material and design studies on the methodology of in situ sediment treatment and water contamination based on SMFCs must be examined more thoroughly (Kim et al., 2021).

While limited studies have investigated the combined effect of SMFCs on bioremediation and coulombic efficiency, some reports suggest that the presence of SMFCs can enhance the efficiency of bioremediation processes. For example, a study by Hamdan and Salam (2020) reported that using SMFCs in treating petroleum-contaminated soil resulted in the efficient removal of petroleum hydrocarbons and increased power output. The authors attributed this to the ability of EAB in SMFCs to stimulate the degradation of petroleum hydrocarbons in the soil by transferring electrons to the anode electrode. The electrons can then be harvested as electrical power.

In another study, Liu et al. (2020) investigated using SMFCs in conjunction with constructed wetlands to treat wastewater. The authors reported that operating SMFCs improved treatment efficiency and increased coulombic efficiency, as the electrochemical reactions in the SMFCs helped to facilitate the removal of organic pollutants from the wastewater. A few more literature references that discuss the combined effect of SMFCs on bioremediation and coulombic efficiency are studied by Sherafatmand and Ng (2015), who found that the SMFCs enhanced the removal of PAHs and the coulombic efficiency increased with increasing concentrations of PAHs; Li et al. (2022) found that the combination of SMFCs and biochar significantly enhanced the removal of petroleum hydrocarbons and increased the coulombic efficiency, indicating that the addition of biochar could improve the performance of SMFCs.

3. Opinion regarding the opportunities with SMFC deployment

Sediment treatment with biological agents, sensor deployment in inaccessible regions, and wastewater degradation of pollutants are all conceivable applications of SMFC. They may be used to bioremediate cellulose and organic chemicals in sewage alongside petroleum hydrocarbons within sediments (Sherafatmand & Ng, 2015).

However, the papers reported on present energy results by the SMFC system are insignificant, although the SMFC is an excellent option for installing low-power wireless gadgets such as oceanographic mobility sensors and monitoring systems. Since it is challenging to produce energy continuously, SMFC technology also requires storage, frequently referred to as an energy management system (Donovan et al., 2013). The DC–DC converter, frequency controller, and capacitor comprise the energy control system, which uses a renewable energy source to power the remote sensor continuously (Donovan et al., 2011).

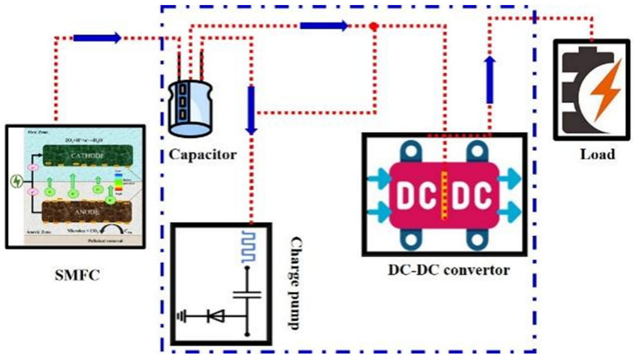
Aside from the importance of learning about application-based issues, the general scientific limits on the microorganisms that live in sediments and the water that comes from them play an important part (Kabutey et al., 2020) and require additional wide-ranging investigations. The lack of knowledge about the profound impact of the environment on bacteria is another technological barrier. In comparison to other fuel cell designs, very little is known about the electrode production methods, the expense of the electrode, or the poor electrode kinetics. Oxygen has a significant redox potential and is widely available in wetland and aquatic ecosystems in a dissolved state, making it the most practical and sustainable source for using SMFCs (Wang & Kong, 2022). Nevertheless, slow-moving ORR and severe overpotential limitations hampered the ability of the SMFCs to generate significant power (Salgado-Dávalos et al., 2021). The kinetics of cathode reduction must thus be accelerated using the proper catalysts. Platinum (Pt) enzymatic cathodes displayed good results when employed in SMFCs due to a lower barrier to activation energy to achieve ORR. Although the Pt-catalyzed cathode produced promising results, it is high cost and severe toxicity from the presence of H_2S might make it challenging to use in SMFCs, particularly in marine environments (Santoro et al., 2016). As a result, a low-cost iron-cobalt catalyst was established to substitute Pt (Ahmed et al., 2012). Electrode spacing augmentation was said to be a practical approach to enhance catalytic activity; regrettably, the COD and TN degradation rate is a constraint that has received the least attention (Sajana et al., 2014).

An eco-friendly cathode electrocatalyst for SMFC is currently designed using carbon materials generated from chitosan biopolymer due to its large surface area, low price, and solid catalytic activity. Chitosan polymers are frequently used as catalyst supports to optimize the attributes of catalyst particles due to their high sorption abilities, durability, and decreased poisoning impact of metal ions (Türker et al., 2020). Hence, in recent years, the possibility of enhancing bioelectricity using chitosan support electrodes in SMFC devices has been the focus of scientific attention. Consequently, Türker et al. (2020) presented the synthesis of smart electrocatalysts composed of chitosan polymer and palladium ions on magnetic particles to improve the power of plant-based SMFC. Plant growth results in significant metal volatilization for smart catalysts containing Cu. As a result, a magnetic feature allowed for simple separation from the aquatic environment and high-power generation.

The use of biocathodes in SMFCs can be helpful in numerous ways. The first possibility is to reduce the cost of creating and operating SMFCs. Second, contaminants in natural water might harm metal electrocatalysts or inorganic electron intermediaries. Finally, microbes can act as catalysts, facilitating electron transport. MFC reported a maximum power density of 1 Wm^{-3} employing a buoyant foam shell-reinforced carbon cloth biocathode, which should be investigated for SMFCs (Wang et al., 2012). Algal biocathode has been demonstrated to create oxygen in the cathode, which might provide an additional advantage in overcoming oxygen deficiency (Chen et al., 2012).

The future applications of SMFCs include remote monitoring of ecological factors and military tactical remote monitoring using wire-free sensors. The variable and low voltage produced by SMFC makes it impossible for a wireless sensor to be powered by it. Hence, a power management system (PMS) (see Figure 4) was created in order to store enough power in supercapacitors for sporadic usage and to improve the voltage using a DC–DC converter to the standard expected by sensors (mostly 5 V) (Zhang & Angelidaki, 2012).

Figure 4
Typical PMS of SMFC



In addition, although employing a single electrode with a larger electrochemical surface area, using several small-size electrodes in parallel as opposed to a single large electrode may be a suitable way to provide the necessary power to run wire-free sensors with SMFCs. Using tailored PMS, this electricity was used to energize a wireless temperature sensor (Bose et al., 2018).

Addressing all these will indeed offers to support the commercialization that meets the Sustainable Development Goal 7 (SDG-7) and guarantees the right approach to affordable, reliable, sustainable, and contemporary energy for everybody.

4. Conclusion

Several SMFC-related challenges, impediments, and potential have been examined. The advancement of SMFCs is intended to answer the energy concern. Shortly, SMFCs could occupy a niche among several existing technologies to provide a realistic solution to sediments, water treatment, and energy harvesting. Nevertheless, the difficulties associated with manufacture, deployment, and functionality still lie in the early stages of development. Anticorrosive carbon-based materials, such as carbon paper, carbon/graphite felt, graphite-based column/disk/plates, and so on, must be employed in SMFCs due to their excellent performance and their long-term stability in hostile environments. The electrodes provide a vast surface area for biofilm formation and more excellent ORR. Bio-cathode should also be accounted for in such a context. However, it has been shown that this considerably influences wastewater treatment and power recovery.

Promisingly, microbe–host interacting units in SMFCs have ambiguous advantages. Microbial consortia can perform synergistic functions in SMFCs, leading to improved electron transfer and higher power output. For example, Geobacter sulfurreducens, commonly found in anode biofilms, can oxidize organic matter and transfer electrons to the anode surface. At the same time, other microorganisms in the consortium can produce electron shuttles, such as flavins and quinones, to facilitate extracellular electron transfer. Biofilms can provide a favorable microenvironment for electroactive microorganisms to thrive and function optimally. The presence of extracellular polymeric substances (EPSs) in biofilms can promote the adhesion of microorganisms to the electrode surface, reduce mass transfer limitations, and enhance the formation of conductive networks. Furthermore, biofilms can protect electroactive microorganisms from environmental stressors, such as pH fluctuations and toxic compounds, thus ensuring their long-term stability and activity.

Despite the potential benefits of microbe–host interacting units in SMFCs, it has yet to be noticed in the literature. This may be due to the complexity of microbial communities and biofilms, making identifying specific microorganisms or mechanisms responsible for electron transfer challenging. Furthermore, the heterogeneity and variability of sediment environments can make it hard to generalize findings across different SMFC systems. Nevertheless, recent advances in molecular techniques and imaging technologies have allowed for better characterization and understanding of microbial communities and biofilms in SMFCs, which may lead to the developing of more efficient and sustainable electroactive systems.

Furthermore, from a social perspective, using SMFCs raises several ethical and social issues. For example, using SMFCs for energy production in remote areas may displace traditional sources of energy, such as biomass or animal waste, which are essential for local communities' livelihoods. Moreover, the potential environmental impacts of SMFCs, such as releasing harmful compounds or altering soil ecosystems, require careful assessment and monitoring.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work

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