



Sediment microbial fuel cells for bioremediation of pollutants and power generation: a review

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Abstract

Worldwide pollution of almost all natural media by toxic compounds is a major public health issue requiring the development of advanced remediation techniques such as sediment microbial fuel cells that can treat contaminants in aquatic sediments. The principle of these fuel cells relies on an electrical connection between the anaerobic sediment and the aerobic overlying water column, an inexhaustible terminal electron acceptor. As a consequence, this technique is particularly adapted to power generation and to the remediation of persistent organic pollutants that are trapped within sediments. Here we review sediment microbial fuel cells with focus on principles of this technique, influencing parameters, applications, and challenges. We discuss sediment redox properties, electrodes, anode reduction pathways, microbial communities, exoelectrogens, and microbial electron transfer. Influencing parameters include pH, temperature, internal resistance, and the substrate nature. Applications to power generation, and water and sediment remediation are presented. Challenges are related to modelling, monitoring, electromicrobiology, sediment properties, the overlying water, scaling up, and economic aspects. We found that sediment microbial fuel cells best operate at a pH 6–9. Optimal temperatures vary widely and depend on the microbial community, with good performance reported from 10 °C to around 45 °C. A lower internal resistance generally improves the performance of the system by favouring electron transfer. Biofilm characteristics and water salinity influence the internal resistance of the system, with marine microbial fuel cells exhibiting generally lower internal resistance than freshwater systems. High contaminant concentration evolves the sediment microbial consortium towards generalist degraders, rather than electrochemically active microbes that can enhance the pollutants biodegradation rates.

Keywords Sediment microbial fuel cells · Lingering pollutants · Operating parameters · Electromicrobiology · Technology scale-up

Introduction

Pollution of aquatic ecosystems is a rising concern due to the toxic effects on living organisms (Blumer et al. 1970; Ayangbenro et al. 2017; Rathi et al. 2021). Aquatic sediments

around the world are considered a major sink for various environmental pollutants entering the ecosystem through the overlying water (Mortimer et al. 1999; Kaonga et al. 2016; Adeniji et al. 2017; Nel et al. 2018; Jesus et al. 2022). This is especially important for persistent organic pollutants that tend to adsorb and accumulate in the sediments, reaching much higher concentrations than in the overlying water column (Mayer et al. 2000; Zhang et al. 2003; Fairbairn et al. 2015). Sediment can thus contribute heavily to water pollution by acting as a long-term active source of contamination, which releases the contaminants back into the overlying water column (Björklund et al. 2000; Eggleton and Thomas 2004; Mustajärvi et al. 2017). The adsorption–desorption behaviour of contaminants in aquatic environments is complex, and the processes are regulated by the continuous interactions between water and sediments, posing a real challenge to the currently used remediation methods.

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There are currently many methods that are used for treatment of contaminated aquatic sediments. These methods are mainly physicochemical practices that are highly aggressive in nature, energy demanding, and very costly (Mulligan et al. 2001; Perelo 2010; Beolchini et al. 2022). This hinders the widespread application of common remediation approaches like dredging, electrochemical degradation, and ozonation (Perelo 2010; Azubuiké et al. 2016).

On the other hand, bioremediation is a process which takes advantage of the natural biota present in various environmental sources to convert toxic pollutants into less harmful by-products (Adams et al. 2015; Kumar and Ghosh Sachan 2021; Alfonso Murillo-Tovar et al. 2021). Hence, bioremediation provides a more sustainable approach for the treatment of contaminated soil, sediment, and water resources, being less expensive and non-invasive as compared to the commonly used physicochemical remediation techniques (Refugio 2016; Sanghvi et al. 2020). Bioremediation is significantly exploited for a variety of in situ as well as ex situ treatment schemes.

Few examples of the commonly practiced bioremediation techniques include phytoremediation, composting, bioventing, and bioleaching (Kumar et al. 2018b; Negrin et al. 2020). The fundamental basis of those bioremediation techniques involves the enhancement of the inherent abilities of indigenous microbes to degrade the contaminants through introducing oxygen and nutrients to the contaminated area, which is known as biostimulation. The deliberate introduction of selected microbes, or bioaugmentation, to bring about the required cleanup is also practiced but to a lesser extent (Wu et al. 2016; Benyahia et al. 2016). Recently, research is being pooled into optimizing the current bioremediation processes and developing more efficient and sustainable approaches for the attenuation of target contaminants.

Bioremediation of natural resources such as aquatic sediments exploits the metabolic capabilities of the naturally occurring sediment microbial communities for the degradation of the adsorbed pollutants. When microorganisms metabolize sediment contaminants using them as electron donors, they utilize a terminal electron acceptor to combine with the electrons generated as part of their energy production process. There are many electron acceptors that are commonly utilized by microbes in aquatic sediments (Ladino-Orjuela et al. 2016; Fuhrmann 2021). Microbial populations in the top layers of sediments, which are close to the oxygen-rich water, can generate more energy due to the high redox potential of oxygen. This translates into a faster microbial growth compared to utilizing other terminal electron acceptors available in deeper layers in the sediments, such as sulphates and nitrates. Ultimately, this leads to a faster removal of the pollutants (Carlton et al. 1989; Lovley 2011; Hazen 2018). In aerobic respiration, microbes dehydrogenate the electron donors and donate

the electrons to oxygen in the form of hydrogen atoms to produce water (H_2O). In the deeper sediment layers, microbes use other available terminal electron acceptors such as sulphates, nitrates, and iron and degrade the contaminants through anaerobic respiration. However, some microbial populations take advantage of the natural electron-shuttling capability of specific compounds, such as iron oxides, to transfer the electrons from the deeper layers of the sediments to the oxygen near the surface of the sediments (Lovley 2011). Yet, such a process is usually limited by the low concentration of electron shuttles within the sediments (Kappler et al. 2004).

The large diversity in the microbial populations inhabiting aquatic sediments allows for a range of microbial metabolic processes to take place, which permits the oxidation of various sediment contaminants (Kurtböke et al. 2018; Kebede et al. 2021; Yang and Chen 2021). This makes in situ bioremediation a potential treatment approach. However, the scarcity of available terminal electron acceptors hinders the continuous oxidation of contaminants and their removal from the aquatic environment (Holmer and Storkholm 2001).

Typical microbial activity enhancement practices include the addition of chemicals such as ferric iron salts, sulphates, nitrates, and methanol, which adds to the cost of the treatment and can cause further pollution. Another approach targets stimulation of the aerobic degradation of contaminants by aeration of the sediment; however, air bubbling disturbs the sediments and contributes to pollutants desorption into the water column (Lors et al. 2004; Perin et al. 2020). Such limitations raised the interest among the bioremediation community in finding a sustainable bioremediation approach that minimizes chemical amendments and sediments disturbance (Li and Yu 2015). This has led to the exploitation of the microbial electrochemical properties through providing an inexhaustible terminal electron acceptor that ensures a long-term stimulant for enhanced natural attenuation rates of contaminants trapped within the sediments (Breil et al. 2022).

One potential tool for optimized bioremediation performance of aquatic sediment contamination is the sediment microbial fuel cell technology (Mathuriya and Yakhmi 2014; Srivastava et al. 2019). The sediment microbial fuel cell technology is a subcategory of the microbial fuel cell technology, which is usually used as a power source as well as a treatment method (Logan 2008; Yan et al. 2012; Sherafatmand and Ng 2015; Hamdan et al. 2017; Kumar et al. 2018a). In a sediment microbial fuel cell, an electrical connection is established between the anaerobic sediment and the aerobic overlying water column. This can enhance the usually slow microbial metabolic rates within the sediments, allowing thus for a sustained breakdown of persistent

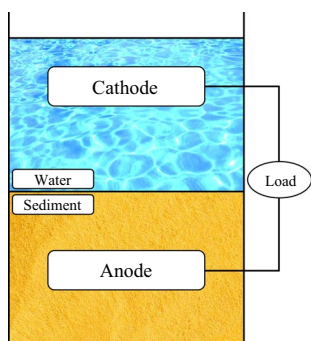


Fig. 1 A sediment microbial fuel cell showing the electrical connection between the anaerobic sediments and the oxygen-rich overlying water column. Certain microbial taxa can utilize the anode in a sediment microbial fuel cell as a terminal electron acceptor. The anode acts as a dump for electrons and facilitates their transfer to a connected cathode where the electrons eventually react with dissolved oxygen in the water. Oxygen acts as the ultimate acceptor of the electrons generated from the microbial metabolism of organic matter in the deeper sediment

complex compounds (Logan 2008). Figure 1 presents a simplified schematic of a sediment microbial fuel cell.

Recently, there has been an increased interest in using sediment microbial fuel cells for bioremediation of a multitude of persistent organic pollutants that are usually trapped within aquatic sediments, including alkanes and polycyclic aromatic hydrocarbons, in both marine and freshwater environments (De Schampelaire et al. 2008; Yan et al. 2012; An et al. 2013; Viggì et al. 2015; Sherafatmand and Ng 2015; Zhang et al. 2015; Hamdan et al. 2017; Hamdan and Salam 2021; Yang and Chen 2021). An electrode, the anode is embedded within the anaerobic sediment layer, which can be utilized by the microbes as a mediator for electron transfer to another electrode, the cathode, placed in the overlying oxygen-rich water layer. Electrons are transferred from the sediment to the overlying water, where they combine to oxygen as an ultimate inexhaustible terminal electron acceptor. By utilizing a passive and inexhaustible terminal electron acceptor, a sediment microbial fuel cell does not require chemicals amendment, nor does it require an energy input, both of which limit the feasibility and sustainability of other remediation methods. Microorganisms near the surface of the electrode can oxidize the sediment contaminants through different electron transfer mechanisms. They can directly transfer the generated electrons to the anode by using internally produced electron shuttles or indirectly by using externally added electron mediators.

The biocatalytic properties of sediment microbial fuel cells allow effective removal of persistent pollutants such as lingering petroleum hydrocarbons in aquatic sediments. The use of oxygen in the water layer as a non-exhaustible terminal electron acceptor is thermodynamically favoured over other possible natural attenuation processes in the

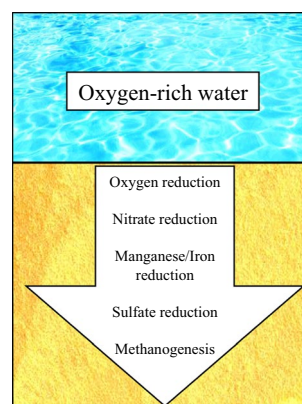


Fig. 2 Sediment redox profile in aquatic environments showing the order of reduction pathways across the depth of the sediment. The top layer of the sediment in contact with the oxygen-rich water is generally aerobic where microbial populations utilize oxygen as the terminal electron acceptor for their metabolism. Oxygen gets depleted few centimetres below the sediment surface, and a natural redox gradient is produced across the vertical profile of the sediment. Various electron acceptors become successively available across the sediment depth based on their thermodynamic properties

sediments. In addition, the system offers an added benefit of generating energy as a result of the flow of electrons between the electrodes (Chan and Li 2014). Despite the significant enhancement of the natural attenuation rates of contaminants using sediment microbial fuel cells, traditional biostimulation approaches exhibit higher bioremediation efficiencies in contaminated sediments (Bai et al. 2021; Patel et al. 2022). However, due to their lower cost, minimal required maintenance, and environmental sustainability, sediment microbial fuel cells constitute a preferred bioremediation alternative.

Principles of sediment microbial fuel cells

Natural sediment redox characteristics

Natural redox gradients are usually spontaneously established in the sediment layer below the sediment–water interface in aquatic environments. This is due to the separation of the microbial redox reactions throughout the sediment layer (Fig. 2) (Rosenberg et al. 2001; Vink 2002; Aharon and Fu 2003). Oxygen, which is present in the water, diffuses through the top sediment layer, allowing the topmost sediment layer to undergo aerobic processes (Brodersen et al. 2019; Versteegh et al. 2021). However, oxygen gets gradually depleted with the increase in the depth of the sediment layer. This forms an anoxic environment where organic compounds are either oxidized using other terminal electron acceptors like nitrates, sulphates, and iron oxides or degraded through fermentative processes or methanogenesis (Lovley and Phillips 1986; Hansen et al. 1998; Chan

and Li 2014; Asaoka et al. 2018). The anaerobic processes are much slower than oxygen reduction pathway due to the lower oxidation power offered by the corresponding terminal electron acceptors.

Anaerobic processes can be also hindered by the limited availability and replenishment of the anaerobic terminal electron acceptors in the aquatic environment. This can sometimes halt the natural degradation process of organic compounds. However, a multitude of naturally occurring sediment microbial populations developed mechanisms to overcome this limitation and to sustain continuous growth, mainly through the process of extracellular electron transfer (Kumar et al. 2017). The presence of electron shuttles within the sediments allows several microbial populations to export their internally generated electrons to the extracellular medium, where the shuttles can carry the electrons to the oxygen-rich layer. This practically allows the use of oxygen as a terminal electron acceptor even by microbes located deeper within the sediments (Doyle and Marsili 2015; Yang and Chen 2021; Li et al. 2021). In theory, the mediated electron transfer process can significantly accelerate the natural degradation process of organic compounds adsorbed onto the sediments. However, the process is extremely hindered by the low concentration of electron mediators within the sediment layer. Sediment microbial fuel cells thus turned out to be an appealing solution to overcome the lack of proper electron transfer from the deeper sediments to the overlying oxygen.

Anode reduction pathway in sediment microbial fuel cells

Deployment of sediment microbial fuel cells is usually performed at the bottom of an aquatic environment, where the sediment electrode is placed several centimetres below the sediment–water interface where oxygen is lacking (Logan 2008). Organic compounds can thus be oxidized by the naturally occurring microbes, which dump their electrons onto the electrode, ultimately utilizing oxygen in the water as a terminal electron acceptor through the connection made across the two distant electrodes (De Schamphelaire et al. 2008; Donovan et al. 2013; Jung et al. 2014; Sherafatmand and Ng 2015). Thus, using this bridged artificial connection, the sediment electrode can be used by nearby microorganisms as a strong terminal electron acceptor, enhancing the rate of the oxidation of contaminants. Previous studies have reported that the natural redox potential between the oxygen-rich water and the anoxic sediment layer is usually below 800 mV (Schulz 2006; Lowy et al. 2006). However, this potential is sometimes not sufficient for driving the oxidation of many persistent pollutants, especially due to overpotential being a major parameter in operating sediment microbial fuel cells (Noori et al. 2018). This limits the practical

application of sediment microbial fuel cells for bioremediation, especially that an external voltage is needed to provide the required redox potential for oxidation of some persistent compounds.

Exoelectrogens

An electrochemically active microorganism, also known as an exoelectrogen or an electricigen, is a microorganism that is capable of transferring the electrons generated by the oxidation of electron donors to the extracellular medium (Chan and Li 2014). This extends the capability of the involved microorganisms to using insoluble extracellular electron acceptors, overcoming thus the limited availability of soluble terminal electron acceptors (Logan 2008). Commonly utilized external terminal electron acceptors are strong oxidizers such as ferric iron oxides and manganese oxides (Thamdrup 2000; Lovley 2008a; Mohan et al. 2019). To better understand the mechanisms involved in the sediment microbial fuel cells operation, microbial electrochemical properties must be also understood.

Many microorganisms with electrochemical properties were identified in the literature, of which numerous were observed as a part of the microbial community inhabiting the electrodes in microbial fuel cells in general and in sediment microbial fuel cells in specific. Multiple bacterial groups belonging to *Firmicutes*, *Acidobacteria*, and *Proteobacteria*, as well as yeast, fungi, and microalgae, were reported for their involvement in current generation in sediment microbial fuel cells. Species such as *Shewanella spp.*, *Aeromonas hydrophila*, *Clostridium butyricum*, *Geobacter spp.*, *Rhodospirillum rubrum*, and *Enterococcus gallinarum*, are common examples (Logan 2008; Yu et al. 2017; Jothinathan et al. 2018b; Verma et al. 2021). During the extracellular reduction of ferric oxides, the exoelectrogens actively express genes involved in the extracellular transport of electrons. For example, the extracellular respiration of *Geobacter* involves active expression of conductive pili that can directly dump electrons onto insoluble ferric iron (Lovley 2008a). *Geobacter*, which is a model bacterium in the microbial fuel cell community, is a motile bacterium that can search for new insoluble natural ferric oxides to be used as electron acceptors (Childers et al. 2002; Tamta et al. 2020). However, if an anode is placed within the anaerobic sediment, *Geobacter* can use it as a dump for electrons. This permits the growth of this exoelectrogenic bacterium as a biofilm on the electrode, thus facilitating the optimized use of the anode as a terminal electron acceptor.

Many known exoelectrogenic bacterial species can easily transfer electrons to an external electrode. *Rhodospirillum rubrum*, *Geobacter sulfurreducens*, *Pseudomonas aeruginosa*, *S. spp.*, *Escherichia coli*, and even some pathogenic bacterial strains, such as *Ochrobactrum anthropi* and

Klebsiella pneumonia, were all previously reported for their efficient use of an external electrode as a terminal electron acceptor (Bond and Lovley 2003; Jothinathan et al. 2018a; Semenc et al. 2018; Feng et al. 2018; Zou et al. 2019). Hence, it is important to understand specific characteristics of exoelectrogenic bacteria for a better optimization of sediment microbial fuel cells for bioremediation.

Microbial communities in sediment microbial fuel cells

In a typical sediment microbial fuel cell, the anode allows for a consortium of naturally occurring microbial communities to evolve and inhabit the anode that provides an unlimited sink for electrons (De Schampelaire et al. 2008; Li and Yu 2015; Hamdan et al. 2017; Hamdan and Salam 2020a, 2021). The evolution of the microbial community at the anode level is driven by a combination of environmental parameters, the indigenous microbial population, and the type and concentration of contaminants within the sediment (Song and Jiang 2018). To ensure the stability of a field-operated sediment microbial fuel cell, the system must host an adequate anodic microbial biofilm to maintain a proper performance.

Exoelectrogens are usually not the only microbes involved in the removal of contaminants in sediment microbial fuel cells. Hence, identifying the other microbial communities and understanding the synergy among the microbial consortium is essential to optimize and apply sediment microbial fuel cells for enhanced bioremediation in aquatic contaminants (Sajana et al. 2017). The interaction between the microbes and the anode in sediment microbial fuel cells is divided into two stages. First, exoelectrogens contribute to the direct breakdown of target contaminants by utilizing the anode as a terminal electron acceptor. Second, non-exoelectrogenic microbes can stimulate exoelectrogens by breaking the complex sediment organic matter down into simpler forms that can be utilized by the exoelectrogens inhabiting the anode (Lovley 2008b). This further stimulates the exoelectrogenic bioremediation capability of the anodic microbial community.

In general, microbial populations in sediment microbial fuel cells show different characteristics based on the source of the sediment (Song et al. 2019a; Yang and Chen 2021). The majority of the exoelectrogenic bacteria belong to two major classes within the phylum *Proteobacteria*, which are *Deltaproteobacteria* and *Gammaproteobacteria* (De Schampelaire et al. 2010; Deng et al. 2014; Wang et al. 2015). Members of *Deltaproteobacteria* are ubiquitous in marine sediments, of which many were identified as direct utilizers of the anode as a terminal electron acceptor in sediment microbial fuel cells while using organic matter or sulphur as electron donors. Notable examples are *Desulfobulbus* and *Desulfocapsa* (Finster et al. 1998;

Lam et al. 2018; Daghighi et al. 2018; Langwig et al. 2022). *Geobacter* represents another bacterial group that is capable of direct utilization of the anode as a terminal electron acceptor in sediment microbial fuel cells within the class *Deltaproteobacteria* and is dominant in freshwater sediment microbial fuel cells (Hamdan and Salam 2021). *Shewanella*, a widely distributed marine bacterium belonging to *Gammaproteobacteria*, is also known for its capability of direct anode utilization as a terminal electron acceptor (De Schampelaire et al. 2008; Jung et al. 2014; Chan and Li 2014; Lam et al. 2019). Studies also indicated that even within the same sediment microbial fuel cell, the anode shows variation in the microbial composition along its length, with deeper sections showing a higher microbial diversity (De Schampelaire et al. 2008). Such observations show that understanding the interactions among the microbial populations in sediment microbial fuel cells is essential for maintaining a dominant exoelectrogenic community. Efforts to assess the sediment microbial ecology and its electrochemical potential, as well as microbial interactions in sediment microbial fuel cell systems, are still lacking in the literature.

Given the importance of the anode microbial community as an essential component for successful implementation of sediment microbial fuel cells for bioremediation, studies are overlooking the cathode as an optimizable parameter. Cathodes can be a limiting factor in many sediment microbial fuel cells because they are important determinants of the rate of oxygen reduction in the overlying water, which can inhibit proper performance of the system (Zhao et al. 2006). Oxygen availability at the level of the cathode can thus dictate the success or the failure of the sediment microbial fuel cell. Various designs incorporate high surface area cathodes to avoid this limitation. Some researchers are also incorporating photosynthetic biocathodes as part of their sediment microbial fuel cell design, which can enhance the oxygen reduction rate. Photosynthetic biocathodes can directly affect the oxygen availability for enhanced sediment microbial fuel cells performance through in situ generation of oxygen at the cathode level, which is much higher than the achievable rate under physical aeration of the cathodic compartment (Commault et al. 2014; Yang et al. 2018b; Jiang and Zeng 2019). For example, De Schampelaire et al. (2008) were able to use a biocathode to sustainably increase the cathodic potential of sediment microbial fuel cells. In addition, certain microbes can even directly accept the electrons at the cathode level to catalyse the oxygen reduction process (Dubé and Guiot 2015). The aerobic environment at the level of the cathode allows for various microbes to inhabit the electrode. Only few studies raised concerns about the ability of the cathode to serve as a medium for biofilm growth that affects the overall performance of the sediment microbial fuel cells (Wang et al. 2012; Commault et al. 2014). Information about

the cathodic microbial characteristics and composition in sediment microbial fuel cells is still extremely limited.

Electrodes

To ensure practicality and feasibility of sediment microbial fuel cells for bioremediation, electrodes, which are the major component, should be cost-effective and durable (Mustakeem 2015). Electrical conductivity is also a major contributor for maintaining a stable operation of sediment microbial fuel cells. Copper, a highly conductive metal, is usually avoided due to its toxic effects on biofilm growth as well as due to the corrosion of the metal (Wu et al. 2019). Stainless steel was used in multiple studies as an electrode material due to its non-corrosive nature. However, although the efficiency of microbial electron transfer to stainless steel electrodes is generally efficient, the low surface area to volume ratio of these electrodes constitutes a major limitation for their use (De Schamphelaire et al. 2008; Wei et al. 2011). Carbon-based electrodes thus came into competition by offering a versatile and durable material that is non-toxic, resistant to corrosion and biofouling, inexpensive, and provides a high surface area for microorganism to flourish (De Schamphelaire et al. 2008; Wei et al. 2011). Carbon-based electrodes are therefore commonly used in recent sediment microbial fuel cells studies, including graphite rods/plates, carbon cloth, carbon paper, and carbon fibre. Those with a higher surface area per volume are usually preferred and are more effective in sediment microbial fuel cells.

Performance of carbon-based electrodes in sediment microbial fuel cells can be also improved through various chemical and physical modifications (Wei et al. 2011). Nonetheless, some challenges like overcoming electrode passivation due to deposition of sulphur and other materials are still to be addressed in the literature. Namely, the long-term effect on the anodic biofilm growth is not well investigated (Prakash et al. 2018; Peixoto et al. 2019). Guo et al. (2022) showed a significant variation in the efficiency of oily sludge degradation in sediment microbial fuel cells operated using different carbon-based anode material. The degradation ranged from 13.11% for carbon plate to 17.04% for carbon felt and was translated into similar variations in the voltage and power density of the reactors. In another study, simple modification of carbon felt anodes by graphene oxide coating significantly improved the power density of sediment microbial fuel cells used for removal of chemical oxygen demand and ammonia in marine systems by a factor of 4.5, approaching a power density of 132 mW/m² (Yang et al. 2022). Hence, such studies offer insights on the importance of anodes as an optimizable parameter in sediment microbial fuel cells.

Often, the low oxygen reduction rate at the cathode in sediment microbial fuel cells poses a major limitation to

the performance of the system (Guo et al. 2019). Carbon-based cathodes are usually preferred due to the same advantages observed in the case of the anodes. There is a wide variety of cathode setups that were practiced in sediment microbial fuel cells, all of which were aimed at increasing the availability of oxygen for reduction. Examples include using partially submerged rotating cathodes and coupling of platinum as a catalyst (Wang et al. 2012; Zhou et al. 2018). These setups increase both the complexity of the system and the cost of operation. With the endeavours of scaling up sediment microbial fuel cells for bioremediation of contaminated sites, the current understanding and optimization of cathodes should be further addressed in future studies.

Yet, few studies examined cathodes for potential enhancement of the efficiency of sediment microbial fuel cells. For example, by integration of a rotating cathode that is partially submerged in the overlying water, Guo et al. (2019) showed a significant increase in the maximum power density generated sediment microbial fuel cells, reaching 47.3 mW/m². This was a significant improvement compared to the control in which the cathode was fully submerged in water, contributing to a maximum power density of only 26.5 mW/m². In another study, cathodes modified by addition of biochar-based oxygen releasing beads resulted in a 2.3 times improvement in the power density of sediment microbial fuel cells operated for treatment of copper pollution in sediments, reaching up to 66.5 mW/m². Such results further indicate the importance of addressing the cathode limitation in sediment microbial fuel cells as a key for significant enhancements of sediment microbial fuel cells efficiency, including both power production and bioremediation.

Overall, the performance of sediment microbial fuel cells is strongly correlated with the anode and cathode properties. Cathode properties thus affect the performance of the system in various environmental settings. At the anode level, mass transfer of electron donors can significantly impact the oxidation of the pollutants in the sediments. Unlike regular microbial fuel cells where mass transfer is not a limitation because of the liquid nature of the medium, the solid sediment matrix in sediment microbial fuel cells hinders the efficient microbial utilization of electron donors farther away from the anode (Donovan et al. 2008). For example, in one study, sediment microbial fuel cells were shown to favour the degradation of molecules with a higher polarity compared to less polar ones because of their higher mobility within the sediment. In addition, the study demonstrated that sediment microbial fuel cells were less efficient in the removal of complex organic matter compared to simple organic matter, mainly due to limitations in mass transfer of the complex organic matter within the sediment layer (Xu 2015; Xia et al. 2015). The mass transfer limitation is thus especially important when targeting trace organic pollutants.

In this case, a significant removal of the target pollutant(s) would require a significantly large surface area of the anode, rendering the system implementation inadequate.

Microbial electron transfer

Electrochemically active microbes can transfer the electrons to the extracellular medium, specifically the anode in the case of sediment microbial fuel cells, via different mechanisms. These mechanisms can be either direct or mediated. Four major mechanisms are responsible for the microbial electron transfer to the anode in sediment microbial fuel cells and are presented in Fig. 3.

The various electron transport mechanisms utilized by bacteria highlight the importance of understanding the interactions between the microbial biofilm and the anode, as well as the inter-microbial interactions, which affect the overall performance of the sediment microbial fuel cells. These microbial interactions are well studied in microbial fuel cells; however, such knowledge is still limited in sediment microbial fuel cells. Most studies only report the relative composition of the sediment and anode biofilm at the end of the experiments. To better understand the applicability and performance of sediment microbial fuel cells for bioremediation of specific pollutants, future research must report the evolution of the microbial biofilm throughout the progress of contaminants removal.

Electron transfer via self-produced electron shuttles Bacterial species such as *Pseudomonas aeruginosa*, *Geothrix fermentans*, *Shewanella oneidensis*, and *Lactococcus lactis*, have the ability to produce their own electron shuttles, enabling them to shuttle the internally generated electrons to an external insoluble terminal electron acceptor (Glasser et al. 2017). There are many self-produced electron shuttles that were identified in bacteria (Watanabe et al. 2009). Flavins and quinones are famous examples of such shuttles, which

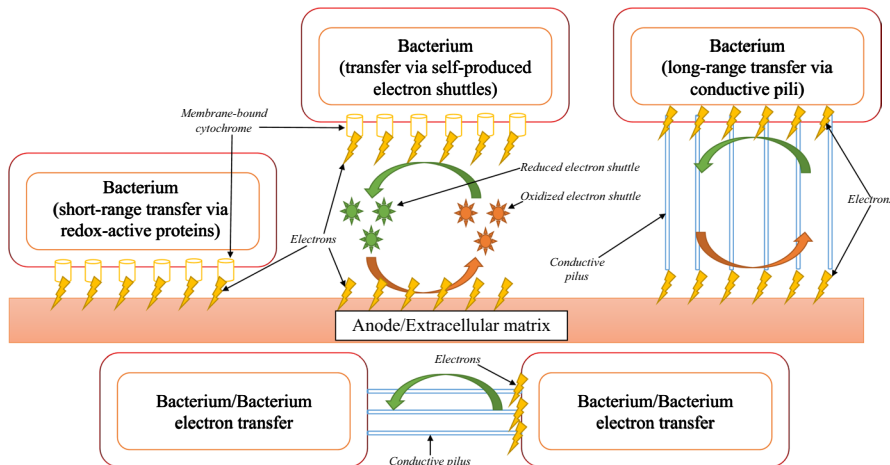
are small soluble molecules that are produced by bacterial cells and are excreted into the extracellular medium.

These shuttles diffuse between the cells while carrying the electrons generated from the bacterial metabolism to extracellular electron acceptors, mainly to iron oxides and manganese oxides near the bacterial surface (Zou et al. 2021; Tolar et al. 2023). This process enables microbial respiration and growth in low-oxygen environments by providing alternative electrons sink.

One well-known example of microbial species with self-produced electron shuttles is *Shewanella*, which is widespread in marine sediments. *Shewanella* produces flavins as well as other metabolites to facilitate the electron shuttling to the extracellular medium (von Canstein et al. 2008; Marsili et al. 2008). In one study, removing riboflavin from *Shewanella* sp. and *S. oneidensis* biofilm significantly reduced the electrons transfer rate to the electrode (Marsili et al. 2008). Another example is *Geobacter fermentans*, which was shown to produce riboflavin to mediate the electron transfer to externally added ferric iron in the growth medium (Mehta-Kolte and Bond 2012; Umar et al. 2021). Hence, this natural shuttling capability of various microbial taxa can play major role in the operation of sediment microbial fuel cells.

Redox-active proteins Redox-active proteins are another means utilized by bacteria for direct short-range electron transfer. Redox-active proteins usually act as shuttles that facilitate the transfer of electrons across the cell membrane to an external electron acceptor (Brutinel and Gralnick 2012; Kaneko et al. 2020). Dissimilatory metal-reducing bacteria utilize redox-active proteins to reduce iron oxides in the extracellular medium (Carlson et al. 2012; Mehta-Kolte and Bond 2012). A well-known protein produced by such bacteria is C-type cytochrome, which carries electrons from the intracellular medium to an external electron acceptor outside the cell, namely to iron minerals (Leung

Fig. 3 Mechanisms of microbial electron transfer to the extracellular medium. Four mechanisms dictate microbial electron transfer: electron transfer via self-produced electron shuttles, electron transfer via redox-active proteins, long-range electron transfer via conductive bacterial pili, interspecies electron transfer. The ability of certain microbial taxa to transfer the electrons generated as part of their metabolism to the extracellular medium provides the basis of operation of sediment microbial fuel cells



et al. 2021; Xie et al. 2021). For example, *G. sulfurreducens* expresses many types of cytochromes that protrude from the outer membrane. These cytochromes are used to directly transfer the electrons from the intracellular medium to an external terminal electron acceptor such as elemental sulphur, metal ions, and anodes in sediment microbial fuel cells (Hernandez-Eligio et al. 2018; Dantas et al. 2018; Zhang et al. 2021; Kai et al. 2021). Redox active proteins can therefore be particularly important in enhancing sediment microbial fuel cells performance.

Long-range electron transfer via conductive bacterial pili Conductive bacterial pili, also known as nanowires, are surface filamentous structures present in certain bacteria. These nanowires act as cellular extensions that facilitate the transfer of electrons to an extracellular electron acceptor over a relatively long distance (Yang et al. 2021). Conductive bacterial pili are simply modified extensions of the bacterial cell membrane, which can reach several micrometres in length and up to 10 nm in diameter (Lovley and Yao 2021). This facilitates the exchange of electrons between a wide range of bacteria and their extracellular environment, including sediment and soil environments.

This mode of microbial electron transfer was first observed in *G. sulfurreducens*, in which a dense network of pili was observed to have metallic properties, rendering the overall biofilm conductive (Walker et al. 2018; Lee et al. 2019; Ye et al. 2022). The metallic characteristics of the conductive pili extend beyond simple electrical conductivity. These pili in *Geobacter* are actively expressed in the presence of insoluble electron acceptors, including manganese (IV) and ferric iron. However, in the case of the presence of soluble forms of these electron acceptors, the conductive pili are not expressed (Abbas et al. 2017). These observations, along with other related findings, suggested that *G. sulfurreducens* use their conductive pili as nanowires for long-range dumping of electrons onto external insoluble terminal electron acceptors (Filman et al. 2018). The properties of nanowires were ultimately correlated with the highest current densities when utilizing *Geobacter* as the exoelectrogenic microbial community in microbial fuel cells (Nevin et al. 2008). Other bacteria that can produce conductive pili are strains of *Synechocystis*, *Pelotomaculum thermopropionicum*, and *Methanothermobacter thermautotrophicus* (Gorby et al. 2006; Sure et al. 2016; Gahlot et al. 2020). Therefore, the variety of microbial taxa that can utilize nanowires can play a key role in dictating the performance of sediment microbial fuel cells.

Interspecies electron transfer Interspecies electron transfer involves microbial species exchanging electrons when some of them are not able to directly utilize the available substrates for metabolism and energy production. This is

mainly apparent when the normal respiratory pathway, such as respiration or fermentation, is not possible (Stams et al. 2006). This was well-observed in many soil and sediment microbial communities which interact as a consortium in order to establish such metabolic pathways.

Several mechanisms of interspecies electron transfer were identified, including direct physical contact between cells, electron shuttles, and nanowires or conductive pili (Malvankar and Lovley 2014; Gahlot et al. 2020). Interspecies electron transfer was previously observed in a mixture of *G. sulfurreducens* and *Geobacter metallireducens*, in which the conductive pili contributed to the mutual growth of both species (Ueki et al. 2018). Non-metal-reducing bacteria were also noted for their direct inter-species electron transfer. For example, this was observed in co-cultures of *Pelobacter carbinolicus* and *G. sulfurreducens*, *G. metallireducens*, and *Methanosarcina barkeri*, as well as a wide range of other bacterial species (Rotaru et al. 2012, 2014; Dubé and Guiot 2015). Electron shuttles are usually produced by certain bacterial species, which would diffuse within the sediment or soil matrix, ultimately being picked up by other bacteria that accept these shuttled electrons as a component of their own metabolic or respiratory pathway (Glasser et al. 2017). However, other species will utilize conductive pili such as nanowires to facilitate the electron transfer to other bacteria over longer distances, thus establishing a redox gradient that can involve multiple bacterial species.

Some bacterial groups can establish direct contact for electron transfer between cells, mainly by formation of cytoplasmic connections through nanotubes, which increases the metabolic capabilities of the microbial biofilm (Boopathi et al. 2021). This process of interspecies electron transfer can therefore result in an elaborate coordination among the bacteria to completely oxidize a substrate that would not have been completely oxidized otherwise.

Interspecies electron transfer has been shown to play an important role in bioremediation of various environmental pollutants, such as polycyclic aromatic hydrocarbons (Hao et al. 2020). Hence, better understanding of interspecies electron transfer is particularly important for improving the bioremediation efficiency as well as the power production in sediment microbial fuel cells.

Operating parameters

Studies targeting sediment microbial fuel cells for bioremediation tend to overlook major operating factors that contribute to the successful implementation of the system. Most studies have focused on the applicability of sediment microbial fuel cells in the bioremediation of specific pollutants, the impact of anode and cathode modifications on the system performance, and the stimulation of the anodic microbial

population with external supplements. However, literature tends to overlook other important operating parameters such as pH, temperature, internal resistance, and characteristics of target pollutants.

pH

The pH in bioelectrochemical systems such as sediment microbial fuel cells plays an important role in shaping the microbial biofilm, which affects the removal of the target contamination (Guo et al. 2020; Wang et al. 2022). Changes to the pH of a sediment microbial fuel cell could lead to the alteration of the proton and electron shuttling, ultimately leading to failure of proper formation of the anode biofilm (He et al. 2008; Abbas et al. 2017). Typically, sediment microbial fuel cells are operated under slightly acidic condition because of the microbial acidophilic pathways. This is due to the high internal proton gradient formed during the microbial metabolism (Abbas et al. 2017; Algar et al. 2020; Liu et al. 2022). This aids in the electron transfer from inside of the bacterial cells to the external medium. pH of sediment microbial fuel cells is usually influenced by the initial pH of the sediment and water, mainly because the generation of protons and their consumption occur simultaneously as they diffuse from the anode to the cathode. Bacteria normally require a neutral medium for a maximized sediment microbial fuel cells performance. However, since the local pH within a sediment microbial fuel cells is affected by the anodic and cathodic processes, bacteria can adjust their intracellular pH by producing internal buffers that resist the external changes, which maintains a proper performance of the system (Kelly and He 2014). In some cases, there might be an imbalance between the generation of protons at the anode level and their consumption at the cathode level, which requires the addition of external buffers like glucose and phosphate to maintain a neutral operating pH (Sajana et al. 2014). It was found that pH values between 6 and 9 are optimal for sediment microbial fuel cells operation (An et al. 2013).

Several studies have addressed the effect of pH on the performance of sediment microbial fuel cells. In one study, a decrease in the pH from 8.5 to 6.5 of the feed water to sediment microbial fuel cells operated for the removal of chemical oxygen demand and total nitrogen led to higher removals of these contaminants (Sajana et al. 2013a). In another study, the power density of sediment microbial fuel cells was maximized at a neutral pH of 7 (Fadzli et al. 2021). Furthermore, in SMCFs operated for in situ remediation of aquaculture water, a feed water pH of 7.6 to 8.5 was found to be optimum for chemical oxygen demand and total nitrogen removal as well as for power density of the sediment microbial fuel cells (Sajana et al. 2014). Such results indicate that the optimal range of pH for various applications of sediment

microbial fuel cells can vary significantly depending on the target substrate, the microbial community structure, and the water and sediment characteristics, all having an effect on the electrochemical conditions of the system.

A specific pH can thus affect the efficiency and power production in sediment microbial fuel cells through resulting changes to the microbial community structure, metabolic pathways, and solubility and bioavailability of substrates and organic matter. Additionally, pH can affect the thermodynamics of the electrochemical reactions, including the electron transfer processes. Hence, for efficient implementation of sediment microbial fuel cells for bioremediation, the pH must be optimized for specific applications, such as for different sites or different target contaminants. Therefore, it is important for future studies to further investigate pH as a variable affecting the performance of sediment microbial fuel cells.

Temperature

Temperature plays a vital role for proper operation of sediment microbial fuel cells. A change in the operating temperature could affect various aspects of a sediment microbial fuel cell, including the mass transfer rates, the kinetics, and the development of various bacterial species in the anode biofilm (Acosta-González and Marqués 2016; Ye et al. 2016; Abbas and Rafatullah 2021). Several studies reported enhanced performance of sediment microbial fuel cells, both in terms of contaminant removal and power production, with an increase in the operating temperature, probably due to enhancement in the microbial metabolic pathways combined with an increase in sediment conductivity leading to a lower internal resistance (Sajana et al. 2014; Alipanahi et al. 2019; Moqsud and Khong 2021).

Optimal operating temperatures of sediment microbial fuel cells are in the range of 30–45 °C. This range ensures a proper formation of the anode biofilm, leading to a sustained and stable operation (Abbas et al. 2017). However, due to the diversity in the microbial species growing within the anode biofilm, each having its own optimal temperature range, higher temperatures could sometimes lead to the denaturing of microbial enzymes required for anode reduction and contaminants oxidation. This might ultimately lead to biofilm inactivation (Abbas et al. 2018). Therefore, the initial operating temperature of a sediment microbial fuel cell has a significant impact on the development and relative distribution of anode microbial cells, which can later tolerate temperature changes by adjusting their metabolic activities. This can lead to a better long-term performance once the biofilm has been established.

In one study, an increase in the temperature of sediment microbial fuel cells from 10 to 35 °C was accompanied by a significant improvement in the maximum power density

from 0.65 to 0.9 mW/cm², which was attributed in part to the presence of mesophilic bacterial communities within the sediments (Alipanahi et al. 2019). In another study, lowering the temperature from 28–30 to 21–25 °C did not result in a significant drop in the removal efficiency of chemical oxygen demand and total Kjeldahl nitrogen using sediment microbial fuel cells. In addition, the decrease in the temperature did not affect the open-circuit voltage (Sajana et al. 2013b). Zhao et al. (2017) showed that sediment microbial fuel cells power output was significantly inhibited below a temperature of 20 °C. Furthermore, Hong et al. (2009) observed prolonged power production in sediment microbial fuel cells operated at 20–35 °C and reported a decreased power output at lower temperatures of around 10 °C.

The mentioned studies demonstrate that operating temperatures have a significant impact on the performance of sediment microbial fuel cells. In general, higher temperatures result in a significant increase in power outputs due to thermodynamic enhancements of the microbial and chemical processes within the sediment. This includes increased rates of electrons transfer and microbial growth. However, the performance of sediment microbial fuel cells operated under different temperatures is mostly affected by the original sediment microbial community. Indeed, the anode microbial community establishes itself based on the original sediment community and exhibits different tolerances to temperature conditions.

Internal resistance

Internal resistance of sediment microbial fuel cells is an additional key factor that affects the efficiency of sediment microbial fuel cells for bioremediation purposes. Internal resistance is a function of several other sediment microbial fuel cells design parameters, mainly the distance between the electrodes and the conductivity of the sediment and the water (Sajana et al. 2014). A higher conductivity, such as in the case of marine sediment microbial fuel cells, will decrease the internal resistance. This results in a better electrochemical performance by facilitating the movement of electrons and protons within the system (Chen et al. 2016). For optimal results, the two electrodes must be as close as possible to each other to lower the internal resistance. However, electron losses were previously reported to be a limitation when the electrodes were very close to one another, resulting in lower overall performance (Donovan et al. 2013; Abbas et al. 2017). One approach to overcome the limitation of internal resistance in sediment microbial fuel cells is the modification of the anode material, such as the addition of conductive carbon nanotubes to the anode material. For example, Zhu et al. (2015) used carbon nanotube-modified graphite felt as the anode material, which significantly increased the power density by a factor of 1.6 times compared to unmodified graphite felt anodes in sediment

microbial fuel cells. Another approach is to increase the size and surface area of the anode, which generally improves the power density of sediment microbial fuel cells (Hsu et al. 2013).

Furthermore, as indicated earlier, operation conditions of sediment microbial fuel cells, such as pH, temperature, salinity, and even biofilm composition, all have a significant impact on the internal resistance of sediment microbial fuel cells. Hence, these parameters are strongly correlated with the internal resistance in sediment microbial fuel cells and require optimization depending on the target application of the system. Future studies therefore should focus on optimization of distance between the anode and the cathode in sediment microbial fuel cells as well as on other factors affecting the internal resistance of sediment microbial fuel cells to ensure a maximal rate of electron acceptance throughout the system.

Target substrate

The type and the level of contamination within the sediments determine the successful use of sediment microbial fuel cells for bioremediation purpose. Sediment microbial fuel cells might not be capable of significantly enhancing the natural removal rates of certain persistent pollutants due to the absence of specific microbes capable of degrading those compounds (Kim and Kwon 2010; Das and Chandran 2011; Hamdan and Salam 2021). Additionally, the concentration of the target substrate in the sediment might also hinder the proper performance of the sediment microbial fuel cell. Low abundance of electron donors limits the sustained growth of the anode biofilm. This becomes significant when the contaminants have low solubilities, which limits their bioavailability for microbial degradation. In recent studies that we performed on the bioremediation of polycyclic aromatic hydrocarbons in marine sediments using sediment microbial fuel cells, we measured an enhanced removal of low and medium molecular weight polycyclic aromatic hydrocarbons such as naphthalene and phenanthrene as compared to natural attenuation controls, while we did not observe a major improvement in the removal of high molecular weight polycyclic aromatic hydrocarbons such as benzo[a]pyrene (Hamdan et al. 2017; Hamdan and Salam 2021). In another study, we reported the inefficiency of sediment microbial fuel cells in mitigating high pollution levels of crude petroleum oil in marine sediments (Hamdan and Salam 2020a). These results demonstrate the effect of pollutant type and contamination level on sediment microbial fuel cells performance, requiring system optimization for enhanced removal rates of the contaminant.

Applications

Power generation

Due to their low current production capabilities, sediment microbial fuel cells were mainly investigated for operating low power-consuming aquatic instruments such as remote environmental sensors. Most of these applications were focused in marine environments where the higher conductivity is translated into a better energy recovery (Gambino et al. 2021; Bose et al. 2022). Sediment microbial fuel cells application in power generation facilitates environmental monitoring in aquatic ecosystems, such as the monitoring of pH and temperature in remote and hard-to-access locations (Yang et al. 2018a; Wang and Jiang 2019). Yet, in most cases, the low energy potential provided by the sediment microbial fuel cells is not sufficient and consistent to maintain a continuous operation of the sensors. Therefore, to overcome this limitation, power control circuits can be used to store the power and supply a continuous voltage to the operated sensors.

The advantage of sediment microbial fuel cells over traditional batteries is in being a maintenance-free system (Zhang et al. 2011). In one study, multiple small sediment microbial fuel cells connected together provided a significantly higher power output than a single larger sediment microbial fuel cell. The system was suggested for operating aquatic equipment having a high energy demand (Ewing et al. 2014). Another study reported the successful long-term operation of sediment microbial fuel cells as a power supply for commercial electronic devices (Yang et al. 2015). In addition, sediment microbial fuel cells were reported to be successfully utilized to power a variety of devices, including a hydrophone, temperature sensors, environmental sensors, an underwater ultrasonic receiver, and a wireless telecommunication sensor (Wotawa-Bergen et al. 2010; Donovan et al. 2011, 2013; Zhang et al. 2011; Thomas et al. 2013).

Studies that employ sediment microbial fuel cells for bioremediation purpose apply continuous monitoring of the power output of the system. This is done to monitor the biodegradation process and the performance of the system. In one of our recent studies, we used marine sediment microbial fuel cells for the removal of low molecular weight polycyclic aromatic hydrocarbons at relatively low concentrations of 10–20 mg/kg of dry sediment, in the presence and absence of inhibition of sulphate-reducing bacteria. The high abundance of sulphate-reducing bacteria in the marine sediment limited the enrichment of anode reducers, which resulted in a lower bioremediation performance. Throughout the experiments, we monitored the sediment microbial fuel cells voltage and recorded the

highest voltage of 0.57 mV in sediment microbial fuel cells operated under sulphate reduction inhibition, compared to a slightly lower voltage of 0.33 mV measured in conventional sediment microbial fuel cells operated without inhibition of sulphate-reducing bacteria (Hamdan et al. 2017). Furthermore, under both operating conditions, we observed a lag phase of one week during which a negligible voltage was recorded. This was followed by a consistent rise in voltage reaching a maximum value after four weeks of sediment microbial fuel cells operation, then a gradual drop to zero after twelve weeks as shown in Fig. 4. This trend was correlated with the gradual establishment of microbial activities as biodegradation progressed, and the ultimate exhaustion of substrate within the sediments over time. The higher voltage recorded under inhibition of sulphate-reducing bacteria was correlated with the absence of competition for substrate between the highly abundant sulphate-reducing bacteria and the rarer electrochemically active anode reducers in the marine sediment.

In another related study, we studied the effect of iron stimulation on the performance of marine sediment microbial fuel cells in the bioremediation of high molecular weight polycyclic aromatic hydrocarbons (Hamdan and Salam 2021). We measured extremely low voltages in conventional sediment microbial fuel cells operated without iron stimulation. Voltage values reached around 0.12 mV in conventional sediment microbial fuel cells where sulphate-reducing bacteria were inhibited, indicating a limited contribution of anode reduction to the removal of the contaminants. However, iron-stimulated sediment microbial fuel cells reached much higher voltages, peaking at 4 and 6 mV after 15 and 20 weeks, respectively, in the absence and presence of sulphate reduction inhibition. The significant enhancement in the voltage generated under iron stimulation, namely under inhibition of sulphate-reducing bacteria, was directly correlated with the activity of the electrochemically active anodic microbial biofilm. Voltage profiles are presented in Fig. 5.

In further investigations we conducted on the bioremediation of crude petroleum oil in heavily contaminated marine sediments using iron-stimulated sediment microbial fuel cells, we recorded a maximum voltage of only 0.05 mV. This is negligible as compared to the voltage reported in our previous study on low-level contamination with polycyclic aromatic hydrocarbons (Figs. 5 and 6) (Hamdan and Salam 2020a). The low power production in this case was attributed to a limited presence of anode reducers and to the evolution of the sediment and the anode microbial communities towards high abundance of generalist petroleum hydrocarbon degraders. These results highlight the impact of the contamination type and level, as well as the sediment characteristics in defining sediment microbial fuel cells performance, as they can significantly shift the microbial community away from efficient anode reduction.

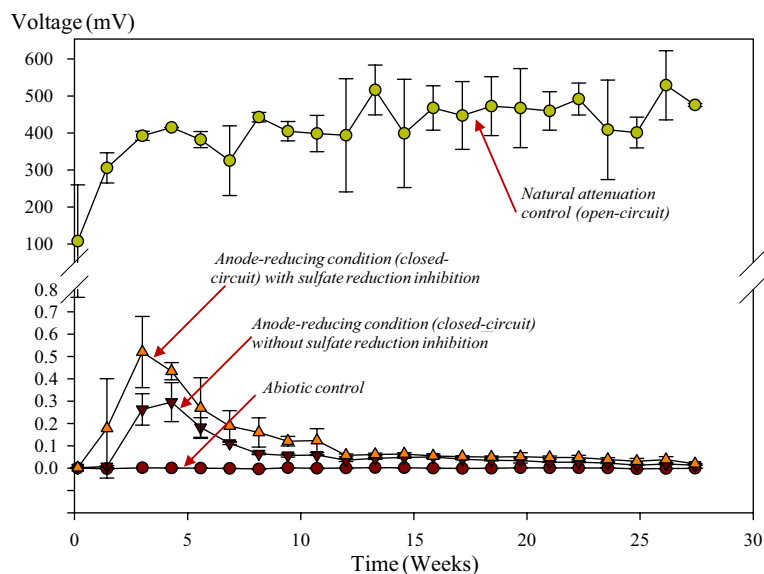


Fig. 4 Voltage profile in marine sediment microbial fuel cells operated for the bioremediation of polycyclic aromatic hydrocarbons. Error bars represent ± 1 standard error of the mean unit. Abiotic controls show negligible voltage compared to the other operating conditions. A high open-circuit potential, fluctuating around 450 mV, is recorded in natural attenuation controls consisting of sediment microbial fuel cells operated with no electrical connection between the anode and the cathode, and mimicking the natural degradation process of organic matter in sediment. Conventional sediment micro-

bial fuel cells consisting of a closed-circuit between the anodic and cathodic compartments provide anode reducing conditions. In this case, and in the presence and absence of sulphate reduction conditions, a lag phase of minimal voltage is observed followed by an increase in the voltage to maximum values, then a gradual decrease in voltage to around zero. Results indicate a successful implementation of the system, with inhibition of sulphate reduction enhancing the efficiency of power production. Adapted with permission of Elsevier from Hamdan et al. (2017)

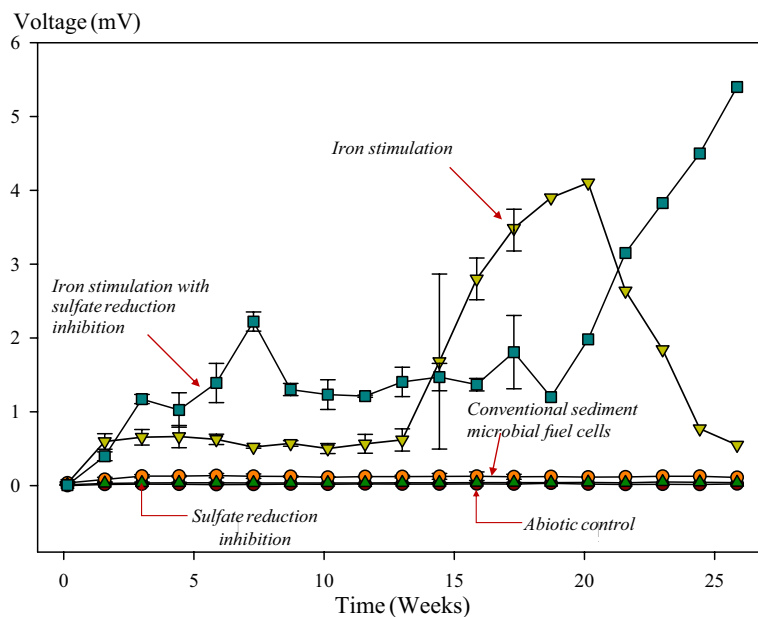


Fig. 5 Voltage profiles in closed-circuit sediment microbial fuel cells operated for bioremediation of a mixture of low and high molecular weight polycyclic aromatic hydrocarbons, under various redox conditions. Error bars represent ± 1 standard error of the mean unit. Iron-stimulated sediment microbial fuel cells, with and without inhibition of microbial sulphate reduction, show significantly high voltages compared to negligible voltages under all other operating conditions,

indicating a major contribution of iron stimulation. Conventional sediment microbial fuel cells operated with and without sulphate reduction inhibition show minimal power outputs, indicating that the microbial community failed to evolve to electrochemically active bacteria. Adapted with permission of Elsevier from Hamdan and Salam (2021)

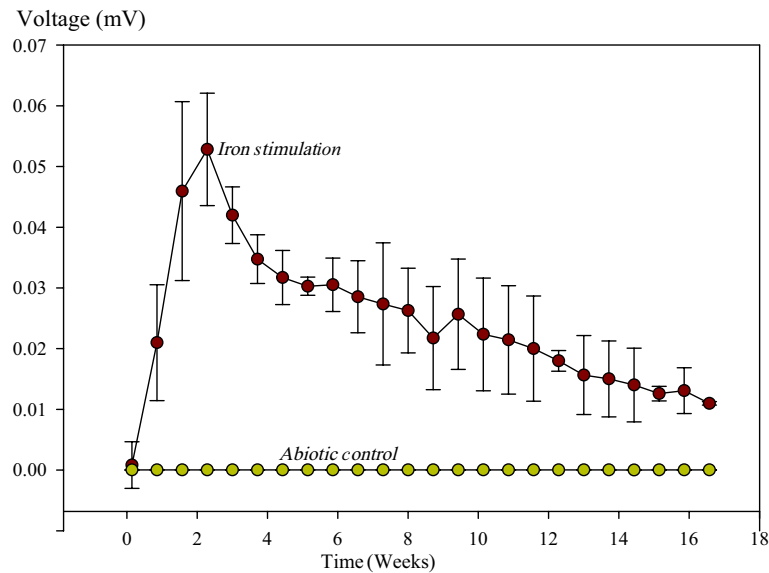


Fig. 6 Voltage profiles of sediment microbial fuel cells operated for bioremediation of crude oil under iron stimulation. Error bars represent ± 1 standard error of the mean unit. Low-voltage values are recorded reaching a maximum of around 0.05 mV. The sediment microbial fuel cells in this study showed negligible presence of electrochemically active bacteria in both the sediment and anode bio-

films, even under iron stimulation. Biofilms evolved towards generalist hydrocarbon degraders, which was mainly due to the high levels of oil contamination in the sediments, at a concentration of around 1 g of crude oil per kg of sediment. Adapted with permission of Elsevier from Hamdan and Salam (2020a)

Water bioremediation

Overall, there are several limitations to using a sediment microbial fuel cell as a power production tool, mostly due to the low power generation in most environmental settings. This is especially important in areas where a sustained operation is not possible due to low sediment conductivity, such as in freshwater environments, or due to a low concentration of sediment organic matter (Chen et al. 2016). As a result, research is being oriented more towards other environmental applications of the sediment microbial fuel cell technology, including treatment of polluted effluents and bioremediation of freshwater systems (Hamdan and Salam 2020a, 2021). For example, in one study, significant removal of chemical oxygen demand in wastewater was achieved using a modified version of the sediment microbial fuel cell technology. In this case the concentration of chemical oxygen demanding material was reduced from 330 mg/L to around 125 mg/L within a day (Erable et al. 2011). Zhang and Angelidaki (2012) reported total nitrogen removal of 77% from a eutrophic lake using sediment microbial fuel cells. Sajana et al. (2013a, b) used sediment microbial fuel cells for in situ reclamation of aquaculture water and achieved chemical oxygen demand and total nitrogen removal of 84.4% and 49%, respectively. Xu et al. (2018) showed promising phosphorus removal efficiencies in the water column in sediment microbial fuel cells. In another study, sediment microbial fuel cells achieved a removal of 95.8% of ammonia and

82.1% of chemical oxygen demand in mariculture wastewater (Yang et al. 2022). Sediment microbial fuel cells were also tested in the treatment of phosphorus in lakes, which is a major contributor to water pollution around the world. In one study, sediment microbial fuel cells successfully reduced the release of phosphorus into the overlying water, decreasing its concentration from 0.14 to 0.05 mg/L (Yang et al. 2022). In another study using sediment microbial fuel cells for sediment phosphorus immobilization for limiting the release of phosphorus from the sediment into the overlying water column in lakes, 94% reduction in phosphorus concentration in the overlying water was achieved (Haxthausen et al. 2021). These studies demonstrate the versatility of sediment microbial fuel cell technology to different environmental applications.

Sediment bioremediation

The diversity in the indigenous sediment microbial structure allows the removal of a wide range of sediment contaminants as the sediment microbial fuel cell biofilm evolves. For example, Williams et al. (2010) stimulated metal-reducing microbial populations using sediment microbial fuel cells for the attenuation of uranium in contaminated groundwater sediment. Sediment microbial fuel cells were also reported for enhanced bioremediation of several heavy metals and organic matter from contaminated sediment (Wu et al. 2017; Zhu et al. 2019). Furthermore, a lot of research focused on

understanding the use of sediment microbial fuel cells for the removal of organic contaminants from polluted sediments (Yang et al. 2015; Abbas and Rafatullah 2021). This is especially important for aquatic petroleum hydrocarbon pollution due to the variety of polluting sources contributing to the daily increase in the contamination.

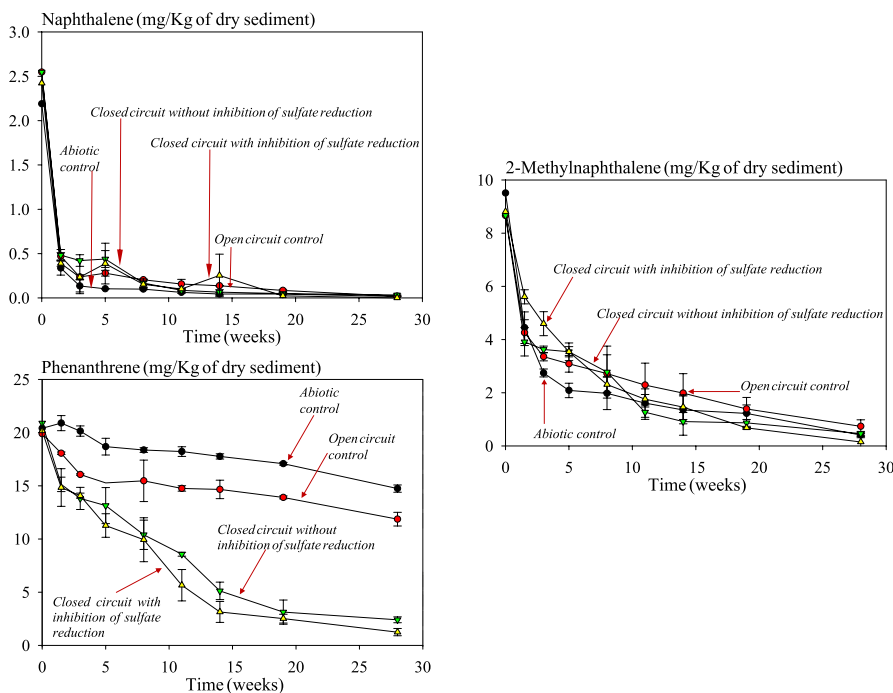
Naturally occurring microorganisms in aquatic sediments can attenuate petroleum hydrocarbon deposited in the sediments (McGenity et al. 2012). The sediment microbial structure has a major impact on the fate of the individual hydrocarbons and the success of sediment microbial fuel cell technology for the bioremediation of petroleum hydrocarbons at contaminated sites. Yan et al. (2012) reported enhancement in the removal of phenanthrene and pyrene in freshwater sediment microbial fuel cells and measured respective removal efficiencies of $96.14 \pm 1.28\%$ and $92.13 \pm 3.29\%$, respectively. Sherafatmand and Ng (2015) showed high removal rates for naphthalene, acenaphthene, and phenanthrene in lake sediment using sediment microbial fuel cells. Xia et al. (2015) demonstrated the role of sediment microbial fuel cells in enhancing the biodegradation of alkanates and phthalates polar compounds in heavily contaminated sediments. Yan et al. (2015) demonstrated the ability of sediment microbial fuel cells to oxidize a mixture of low molecular weight polycyclic aromatic hydrocarbons in contaminated sediments. Yang et al. (2015) demonstrated the efficiency of sediment microbial fuel cells in reducing total organic carbon in heavily contaminated sediment containing heavy metals, polycyclic aromatic hydrocarbons, and polybrominated diphenyl ethers. In addition, Viggi

et al. (2015) measured enhanced degradation rates of total petroleum hydrocarbons in crude oil polluted sediment using a variation of the sediment microbial fuel cell technology termed “Oil-Spill Snorkel”.

In one recent study, we measured high removal rates of phenanthrene in marine sediment microbial fuel cells, reaching up to 93.8% as compared to only 40.3% in the natural attenuation controls (Hamdan et al. 2017). An enhanced removal of the contaminant was observed in sediment microbial fuel cells operated under sulphate reduction inhibition. In this case, biodegradation constant of phenanthrene increased from 0.0021/day measured in the natural attenuation control to 0.0168/day in those SFMCs. On the other hand, the lower molecular weight polycyclic aromatic hydrocarbons, naphthalene and 1-methylnaphthalene, were mostly removed by volatilization and showed no significant difference in their removal rates across the different operating conditions. Figure 7 shows the degradation profiles of the polycyclic aromatic hydrocarbons.

In another study, we observed a significant removal of a range of low and high molecular weight polycyclic aromatic hydrocarbons in iron-stimulated sediment microbial fuel cells operated under different redox conditions. The highest removal rates of the highly persistent contaminants pyrene and benzo[a]pyrene were 36.87% and 40.85%, respectively, and were measured in the open-circuit iron-amended sediment microbial fuel cells operated in the absence of anode reduction and under inhibition of sulphate reducers. We concluded that amendment of contaminated sediment with ferric iron could constitute a better bioremediation strategy

Fig. 7 Biodegradation profile of low molecular weight polycyclic aromatic hydrocarbons in marine sediment microbial fuel cells. Error bars represent ± 1 standard error of the mean unit. Naphthalene and 2-methylnaphthalene show no significant differences in their removal among the different treatments, their high volatility being the major pathway for their decay. Phenanthrene removal is enhanced under anode reduction conditions in closed-circuit sediment microbial fuel cells and is slightly higher under inhibition of sulphate reduction compared to the abiotic controls and the natural attenuation controls. Adapted with permission of Elsevier from Hamdan et al. (2017)



than using sediment microbial fuel cells (Hamdan and Salam 2021). Figure 8 shows the decay profiles of pyrene and benzo[a]pyrene.

In addition, in another related study, we used sediment microbial fuel cells for the bioremediation of heavily contaminated sediment with crude petroleum oil at 1 g/kg of sediment. We observed no significant differences in the removal of total petroleum hydrocarbons among the different treatments as compared to the natural attenuation controls (Hamdan and Salam 2020a). The initial concentration

of total petroleum hydrocarbons in the contaminated sediments was 10,586 mg/mg hopane, which dropped to 8553 ± 636 , 8978 ± 242 , and 8236 ± 453 mg/mg hopane, respectively, in the natural attenuation controls, the iron-stimulated natural attenuation controls, and the iron-stimulated sediment microbial fuel cells (Fig. 9). The results were correlated with the evolution of the sediment and anode microbial communities towards generalist hydrocarbon degraders. Indeed, the high contamination level

Fig. 8 Biodegradation profile of high molecular weight polycyclic aromatic hydrocarbons in marine sediment microbial fuel cells. Error bars represent ± 1 standard error of the mean unit. Iron stimulation contributed to higher removal rates of pyrene and benzo[a]pyrene, irrespective of the anode availability as a terminal electron acceptor and of the inhibition of microbial sulphate reduction. Adapted with permission of Elsevier from Hamdan and Salam (2021)

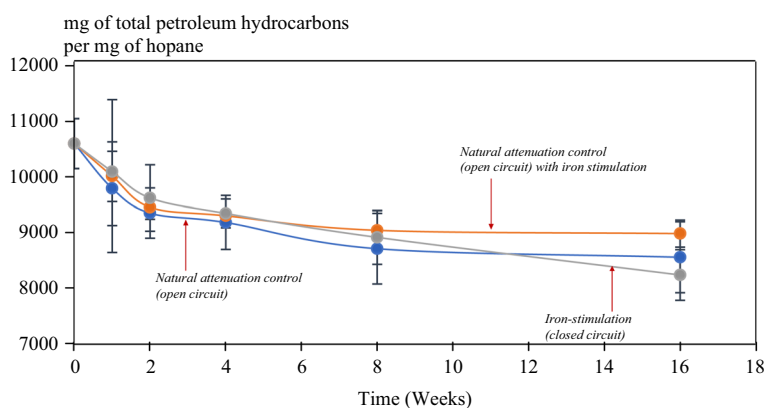
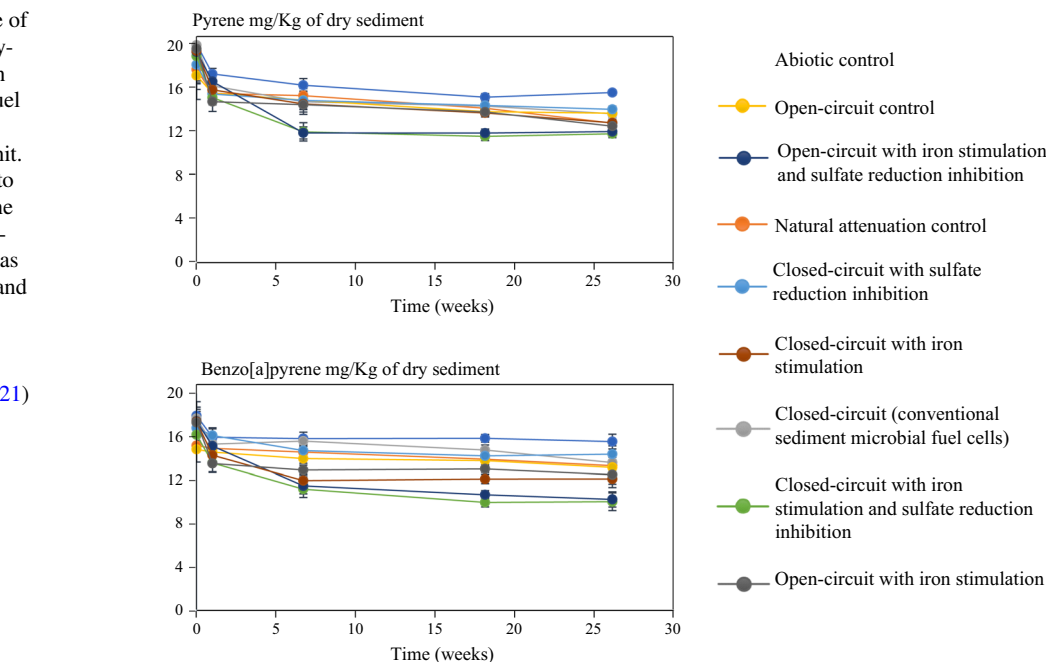


Fig. 9 Biodegradation profiles of total petroleum hydrocarbons in marine sediment microbial fuel cells operated under heavy sediment contamination levels. Error bars represent ± 1 standard error of the mean unit. No major improvement in the biodegradation of crude oil is observed in iron-stimulated sediment microbial fuel cells as compared to the controls, which indicated that the operation of sediment microbial fuel cells for bioremediation can be limited in the case of

heavy contamination levels. This is attributed to the failure of the sediment and anode microbial communities in iron-stimulated sediment microbial fuel cells to evolve to electrochemically active bacteria. Instead, microbial communities evolved towards generalist hydrocarbon degraders, explaining the similarity in the removal rates of petroleum hydrocarbons across the different treatments. Adapted with permission of Elsevier from Hamdan and Salam (2020a)

prevented the establishment of an electrochemically active microbial biofilm, even under anode reduction conditions.

Studies on the applicability of sediment microbial fuel cells as a bioremediation technology were mainly conducted in laboratory scale experiments and targeted the removal of individual groups of contaminants. In such settings, the control of the sediment microbial fuel cell system is relatively easy and the complex interactions between different groups of contaminants, as they occur in the natural environment, are excluded. Accordingly, field scale testing of the potential use of sediment microbial fuel cells for pollution remediation is necessary. This would permit a proper understanding of the effect of physicochemical interactions occurring in natural environments on the operation of sediment microbial fuel cells at contaminated sites.

Perspective

To ensure a better understanding of the sediment microbial fuel cell technology for its scale-up to field bioremediation applications, certain aspects of the system must be considered in future studies. This would permit an improved optimization of the system for field bioremediation applications, a proper monitoring of the process and predictive maintenance, and a better overall control over the system operation. The following points present major considerations for a successful implementation of sediment microbial fuel cells as a bioremediation technology at contaminated sites:

1. Modelling sediment microbial fuel cells operation for the prediction of the removal rates of contaminants under specific environmental conditions
2. Adequate monitoring of the sediment microbial fuel cells to better understand the system as a collective unit of operation
3. Proper understanding of the electromicrobiology of sediment microbial fuel cells, especially in terms of the microbial dynamics
4. Assessment of the impact of sediment characteristics on the performance of sediment microbial fuel cells
5. Assessment of the impact of the characteristics of the overlying water on sediment microbial fuel cells performance
6. Field scale testing of sediment microbial fuel cells for the bioremediation of contaminated environments
7. Estimation of the cost of sediment microbial fuel cells for field scale applications

Modelling

Modelling the effect of different parameters on the performance of sediment microbial fuel cells is essential for the

proper field scale implementation of this technology. Those include among other parameters the sediment characteristics, pollutants properties, and dynamics and evolution of microbial communities within the sediment layer and in the anode biofilm.

The bioavailability of contaminants in polluted sediment is influenced by their chemical nature and physical properties, as well as the characteristics of the sediment. Pollutants with low solubility tend to adsorb onto the sediment, which limits the rate at which they can be mineralized by the electrochemically active biofilm in a sediment microbial fuel cell. Modelling of the sorption–desorption processes and transport mechanisms of the pollutants within the sediment layer, would help determining their availability for microbial degradation and the overall efficacy of sediment microbial fuel cells in specific contaminated sites.

In one study, the degradation of the sediment organic matter content was modelled using empirical data on the degradation rate constants, temperature sensitivity, and complexity of the organic matter (Shang 2023). This ultimately helps in the prediction of contaminants availability for microbial degradation, as the sediment organic matter might have strong adsorption and chelating effects on them. In another study, Monga et al. (2014) developed a model that simulates the microbial degradation of organic matter within soil pore spaces and the consequent mineralization rates of target contaminants. Several other models were also developed to predict the behaviour of natural organic matter in sediment and soils, and more accurate models continue to be developed as well (Clay et al. 2021).

Furthermore, the modelling of microbial growth kinetics, rates of electron transfers, and interactions among different microbial taxa contribute to predicting the performance of sediment microbial fuel cells in actual contaminated sites. For example, Dziegielowski et al. (2023) developed a model that predicts the electrochemical behaviour of sediment microbial fuel cells in different soils. In another study, Ojeda et al. (2008) modelled the relative contribution of the various microbial reactions in the removal of organic matter in wastewater.

The performance of sediment microbial fuel cells depends on a complex system of parameters. Modelling these parameters based on laboratory and field scale empirical data would provide useful indications on optimal design and operational conditions of sediment microbial fuel cells and a guide to effective scale-up strategies for their use in bioremediation.

Monitoring

A proper monitoring of a sediment microbial fuel cell operation is essential to check the progress of the bioremediation process and define its limitations, as well as to optimize the

technology for successful field implementation. There is usually a lack of a comprehensive understanding of the combined interactions among the numerous parameters involved in the operation of a sediment microbial fuel cell, such as the concentration of the target pollutant, the power output, and the concentration of specific terminal electron acceptors. A proper monitoring of those parameters which influence each other during the sediment microbial fuel cell operation, would ensure a better understanding and control of the system. Namely, this would allow a better understanding of the microbial reactions taking place within the sediment compartment, as determined by the established microbial communities at different stages of the bioremediation process. Sediment microbial fuel cells can be monitored for their electrical, chemical, and microbiological aspects.

Electrical monitoring involves the use of a multimeter or a data logger to determine the voltage of the cells. This allows for the measurement of the system current output and power density. The voltage nonetheless can vary significantly among similar sediment microbial fuel cells due to variations in the operating conditions, such as the internal resistance, the shape, type, size, and configuration of the electrodes, as well as the microbial community structure. Hence, a proper monitoring of the voltage permits a better comprehension of the performance of the sediment microbial fuel cells.

Chemical monitoring is also important because it provides an important insight into the biochemical processes taking place within a sediment microbial fuel cell. This includes insights of the microbial community structure and function, as well as the biodegradability of the target substrates. Chemical monitoring may range from the monitoring of simple parameters to overly complex analyses. Simple parameters include pH, organic content, conductivity, and dissolved oxygen. Complex analyses include the determination of the concentration of target substrates and their biodegradation by-products, which can be time-consuming and expensive. For example, measurement of petroleum hydrocarbons requires the use of expensive equipment and laborious methodologies for their extraction and measurement. Those include accelerated solvent extraction, high-performance liquid chromatography, and gas chromatography-mass spectrometry.

Furthermore, microbial monitoring constitutes an important parameter in the operation of a sediment microbial fuel cell and can provide valuable information about the microbial dynamics in the system. Knowledge of the active microbial communities in a sediment microbial fuel cell often explains the observed trends in the data acquired during operation, such as the power outputs and the biodegradation rates. Microbial monitoring requires implementation of molecular biology techniques such as DNA extraction, polymerase chain reaction, and DNA sequencing. It also requires

solid knowledge of bioinformatics to analyse the immense amount of data obtained from microbial analyses. In addition, microbial monitoring allows the identification of new microbial taxa or previously unknown associations between certain microbial taxa and certain metabolic processes, such as the ability to degrade specific pollutants.

One major limitation in microbial monitoring is that it often requires sacrificing an entire sediment microbial fuel cell to isolate and extract the sediment and the anode microbial biofilms. Hence, it is difficult to provide information about the temporal dynamics of the sediment microbial fuel cells microbial communities throughout the bioremediation process, which is a key factor in optimizing the sediment microbial fuel cells for bioremediation. Obtaining such information requires an experimental setup that accounts for frequent sampling events, which would require a substantial increase in the number of replicate sediment microbial fuel cells. To our knowledge, no studies on the use of sediment microbial fuel cells for bioremediation have performed periodic sacrificing of the entire system. Chemical and biological monitoring usually considered a single-point measurement conducted at the end of the experiments. In our studies, however, we reported useful information about the sediment and anodic microbial communities and their evolution in marine sediment microbial fuel cells, through periodic sampling and analysis of the entire system (Hamdan and Salam 2020a, 2021). This enabled a proper correlation between the most abundant microbial taxa at each stage of operation of the sediment microbial fuel cells with the biodegradation profile of the target pollutants and the sediment microbial fuel cells electrical profiles. However, proper microbial monitoring in sediment microbial fuel cells is still a major limitation due to the high cost of molecular biology analysis.

Electromicrobiology

Electrochemically active biofilms are often affected by the thickness of the biofilm itself, with increased thickness resulting in a reduced efficiency of the anode as a terminal electron acceptor (Kondaveeti et al. 2018). Thus, more focus on the formation and functioning of the biofilm is required. By developing an optimized biofilm, an enhanced microbial-to-anode electron transfer can be achieved.

Additionally, the composition of the sediment and anodic biofilm depends on the original sediment microbial community. It is also highly dependent on the redox conditions in the sediment microbial fuel cells and the biochemical characteristics of the system. Hence, development of an efficient anode reducing population that is capable of bioremediation can be hindered by the deficiency of the original microbial community in the sediment with specific microbial species (Kim and Kwon 2010). On the

other hand, pre-seeding the anode with a known biofilm to initiate anode reduction in contaminated sediment could also fail due to competition with the indigenous sediment microbes (Pan et al. 2017).

The microbial biofilm can therefore undergo significant changes over time in a sediment microbial fuel cell, with different microbial taxa enriching at different stages of the bioremediation process. In general, generalist degraders that can oxidize easily degradable compounds appear during the initial stages of bioremediation, while more specialized taxa flourishing later as the oxidation shifts towards the more recalcitrant compounds (Hamdan and Salam 2020b, a, 2021). Maintaining an active anodic biofilm that is capable of consuming the target pollutants is an essential consideration in future research for improved efficiency of sediment microbial fuel cells.

Sediment characteristics

Sediment characteristics affect both the catalytic capabilities of the sediment microbial community, as well as the power output of the system. Sediment properties, such as particle size distribution, can have a major impact on the bioremediation performance of a sediment microbial fuel cell through affecting the solubility and availability of target substrates. This also affects the solubility of nutrients and organic matter in the sediment pore water, which in turn affects the microbial composition of the sediment. Furthermore, sediment characteristics dictate the background sediment microbial population, which can significantly affect the establishment of an electrochemically active biofilm.

Sediment conductivity is another major contributor to the performance of sediment microbial fuel cells. For example, marine sediment is much more conductive than freshwater sediment due to the higher salinity. Higher conductivity can facilitate the electron and proton transfer processes, which translates into a better bioremediation performance (Song et al. 2012; Guo et al. 2021). On the other hand, marine sediments often lack the iron-reducing microbial community that is important for proper establishment of an electrochemically active biofilm in the sediment microbial fuel cells (Hamdan et al. 2017; Wang and Tam 2019; Hamdan and Salam 2020a, 2021; Algar et al. 2020). This is due to the low concentration of iron in aquatic environments and to the extremely dominant sulphate-reducing microbial population, which is aided by the high sulphate concentration in marine ecosystems. In addition, the presence and the concentration of organic matter, nutrients, and secondary pollutants, can have a major impact on the performance of sediment microbial fuel cells by affecting the sediment microbial ecosystem (Mathuriya et al. 2018).

Overlying water

In addition to the sediment characteristics, water characteristics can affect the successful operation of a sediment microbial fuel cell (Touch et al. 2017; Xu et al. 2019). Mostly, the availability of dissolved oxygen as a terminal electron acceptor at the level of the cathode, determines the biodegradation rates of the target contaminants in the sediment (Song et al. 2019b; Abazarian et al. 2020). A low concentration of oxygen in the cathodic compartment can lead to significantly lower power outputs and a severe reduction in the biodegradation rate of target substrates (Song et al. 2020; Abazarian et al. 2020). Maintaining high concentration of oxygen in the overlying water is hence key in successful implementation of sediment microbial fuel cells for bioremediation.

Other water parameters that are also important to monitor include pH, temperature, dissolved solids, and water microbial composition, all of which affect the cathodic biofilm growth. For example, in a sediment microbial fuel cell, water temperature can affect the solubility and concentration of dissolved oxygen, the dissolution and bioavailability of substrates, and the metabolic activity of the biofilm. This means that subtle changes in temperature of the overlying water can lead to variations in the anodic biofilm and in the power output of the sediment microbial fuel cells.

Furthermore, water salinity can significantly alter the performance of sediment microbial fuel cells. A high salinity can have an inhibitory impact on many microbial groups (Tam et al. 2002; Wang and Gu 2014; Shi et al. 2015). It can also change the osmotic balance of many microbial groups. This leads to alterations in the activity of the biofilm.

Moreover, changes in the pH of the overlying water can cause changes to the sediment pH. This in turn affects the metabolic activities of the microbial biofilm, and the bioavailability of many sediment constituents and target substrates. It can also cause deposition of minerals onto the electrodes, leading to reduced performance of the system.

Scaling up

The complex nature of the sediment microbiology makes large-scale sediment microbial fuel cells operation difficult. In addition, the spatial and temporal variations of the sediment and water characteristics in aquatic environments, greatly affect the microbial structure at contaminates sites, limiting the scalability of laboratory-based findings to field applications (Seelam et al. 2018; Hamdan et al. 2019). Furthermore, the development of suitable electrodes, which are able to withstand the harsh natural environmental conditions while maintaining the feasibility and durability of a long-term bioremediation process, becomes necessary when scaling-up the sediment microbial fuel cell technology (Das 2018; Seelam et al. 2018). In addition, the diffusion of the

substrate towards the anodic area becomes increasingly difficult in the field, especially if the substrate has an extremely limited solubility in the pore water. This would reduce the microbial activity and limits the bioremediation potential of the sediment microbial fuel cells to the vicinity of the anodic area. Also, the internal resistance of sediment microbial fuel cells can increase significantly with the increase in the size of the cells (Mei et al. 2020; Kim and Simson 2022). This leads to a size limit of any scaled-up system, beyond which no further improvement in the performance of the sediment microbial fuel cells can be attained.

One strategy to overcome the scale-up limitations of sediment microbial fuel cells is by increasing the surface area of the electrodes to enhance contact between the anode and the target substrates within the sediment. The increase in the total surface area of the anode reduces mass transfer limitations of the substrates and nutrients in a sediment microbial fuel cell. It also provides a higher area for potential anode reducers to flourish (Mei et al. 2020; Abbas et al. 2022). Multiple electrodes can be also connected in parallel or in series to reduce the internal resistance of sediment microbial fuel cells and increase the surface area of the anodic compartment (Wang and Lim 2019; Yang et al. 2019). Geetanjali et al. (2019), for example, reported an enhancement in the power outputs in sediment microbial fuel cells by 18% through connecting multiple sediment microbial fuel cells in parallel and in series.

Economic considerations

Although sediment microbial fuel cells provide a promising bioremediation technology, the cost of manufacturing and operating the system can be a major limitation for future field applications. The cost of the sediment microbial fuel cell technology includes the cost of the material used, of which the electrodes are usually the most expensive, the cost of the cell construction labour, as well as the cost of the operation, monitoring and maintenance of the system (Dzięcielowski and Di Lorenzo 2022; Hirose et al. 2023). Given that field applications would require rather large designs, the cost of a single sediment microbial fuel cell can increase dramatically compared to their laboratory-based counterparts. Furthermore, the cost of the system maintenance can be substantial due to required skilled personnel, engineers, and technicians.

However, given that sediment microbial fuel cells are designed to provide a passive and robust bioremediation system, their overall cost should still be competitive as compared to alternative pollution cleanup technologies. This is important because sediment microbial fuel cells are passive by nature, and thus they do not require a lot of material to construct and substantial monitoring (Budihardjo and Syafrudin 2021). Additionally, continuous optimization

of sediment microbial fuel cells aimed at increasing their bioremediation potential and efficiency in power production would ultimately provide a competitive technology with lower operation cost.

Conclusion

The natural anoxic environment prevailing in aquatic sediments, in combination with the natural ability of many sediment microbial communities to degrade pollutants, allows sediment microbial fuel cells to be a strong candidate for future large-scale bioremediation studies. While abundant research is addressing the use of sediment microbial fuel cells for bioremediation and energy production, the state of knowledge related to this technology is still limited as compared to that of wastewater microbial fuel cells. The simple extrapolation of findings from the latter technology to sediment microbial fuel cells might not be adequate due to variations in the setup and operations of the two technologies. This is also difficult when considering the complexity of the electromicrobiology and the mass transfer limitations encountered in sediment microbial fuel cells.

Sediment microbial fuel cells thus created their own line of research that is oriented towards providing a controllable, economically feasible, and sustainable technology for bioremediation of various pollutants. While the current research is mostly focused on laboratory scale applications of sediment microbial fuel cells, future research should explore the capabilities and the scalability of the system to field bioremediation applications. This will require addressing a variety of field-related limitations such as the actual installation of the system, electrode passivation, corrosion of connections, and destruction by aquatic organisms. This will also require knowledge beyond what is possible through laboratory operation. Yet, this does not belittle the importance of laboratory experimentation in addressing the missing knowledge and optimizing the system for pilot field studies.

Hence, sediment microbial fuel cells provide a promising technology for future implementation for the purpose of bioremediation. However, the current state of knowledge of this technology is not sufficient to permit the use of sediment microbial fuel cells as a competitive alternative to the currently applied bioremediation methods. Although the technology was proven efficient in bioremediating different pollutants in aquatic sediments, results remain tied to very specific experimental conditions that are extremely difficult to reproduce in the open field. Even findings from large-sized laboratory sediment microbial fuel cells cannot be confidently transferred to the field. Laboratory sediment microbial fuel cells will always constitute closed systems that are confined to the sediment within the tested reactor and to any potential externally added stimulant. In the open

field, the harsh environmental conditions might damage the sediment microbial fuel cell itself. In addition, transport phenomena would disperse the pollutants and added chemicals into the surroundings, thus reducing the treatment efficiency.

It is important to keep in mind that the most important consideration for sediment microbial fuel cells successful implementation is the establishment of the anode biofilm, which is a function of all other operating parameters in a sediment microbial fuel cell. A very small change in any of the operating parameters of a sediment microbial fuel cell might cause a significant shift in the evolution of the anodic microbial community away from an electrochemically active biofilm that is capable of pollution degradation. This includes pH, temperature, internal resistance, target substrate type and concentration, and sediment and water characteristics.

Sediment microbial fuel cells carry a huge future potential for bioremediation of contaminated aquatic environments. However, many limitations still need to be addressed for the successful implementation of the technology. The continued research aiming at better understanding and optimizing sediment microbial fuel cells as a bioremediation method will ultimately sustain the improvement of the technology. This would require the combined efforts of multiple disciplines, including electrochemistry, biotechnology, environmental sciences, and material sciences.

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