

MICROBIAL ELECTRICITY GENERATION: THE FUTURE ALTERNATIVE SOURCE OF ENERGY FOR MICRO-POWERED GADGETS AND BIOSENSORS FOR EXTREME ENVIRONMENTS

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ABSTRACT

The global energy crisis has spurred the search for alternative renewable energy sources, and recently, microbial fuel cells (MFCs) have garnered significant biotechnological attention. MFCs directly harness and transfer electrons released during microbial metabolism through the anaerobic anode terminal to power external loads. Pilot studies on MFCs have demonstrated impressive efficiency ratings ranging from 89% to 95%, depending on factors such as substrate, oxidizers, exogenous mediators, and the electrode's nature used in constructing the system. The enhanced prospects of MFCs lie in their renewable fuel source, ability to yield clean energy, lightweight design, automated operation, and economic feasibility. These characteristics make them attractive as alternative energy sources for various micropowered gadgets, such as small robotic watercraft, organic photovoltaic cells, and mobile communication devices. Moreover, MFCs hold promise for powering medical devices like pacemakers, artificial hearts, and glucose sensors for diabetics. Additionally, their use as biochips and biosensors in extreme environments, such as meteorological stations, radioactive polluted sites, and ocean depths, for continuous monitoring, presents exciting possibilities. Despite their potential, MFCs face challenges related to pathogenic tendencies, environmental sensitivity, and mutagenic traits of the involved microbes. Furthermore, the design and structural aspects of MFCs need further research and development to ensure practical implementation. In conclusion, microbial fuel cells offer a promising avenue for sustainable energy solutions, but addressing the challenges through extensive research and innovation will be critical to realizing their full potential.

Keywords: Microbial, Electricity, Alternative Energy, Portable Gadgets, Extreme Environment

INTRODUCTION

There is an unparallel upsurge of electrical gadgets in the era of 21st century and this consequentially drags the global community into an apparent energy catastrophe especially the developing nations. The concept of micro-current or micro-powered devices was



conceived to reduce the demand of electrical energy by these surging devices (Das and Mao 2020). Environmental. Environmental impact, availability and economic values motivated researchers across the globe to adopt the renewable bioenergy as one of the best palliative measures. Forth runner amongst these renewable bioenergy systems is the Microbial fuel cells (MFCs), which typically refers to any enclosed system that converts organic substrate into electrical energy through microbial direct or indirect metabolic activities. Most MFCs are designed to operate under anaerobic conditions (Du *et al.*, 2007), using anaerobic to aerotolerant (or microaerophilic) microbes (Reddy *et al.*, 2010) or its metabolites (Eg. enzymes) as the catalytic agents. Successive MFCs designs over the years, have achieved progressively power output of 89 - 95% efficiency rating. However, aerobic MFCs have better prospect for micro-powered biosensor devices yet they are still 50% deficient in power output comparable to the anaerobic systems (Reddy *et al.*, 2010). This review envisages that MFCs designed to monitor both microbial and chemical toxicants could be re-engineered to monitor similar parameters in extreme environment.

Biosensors are biological agents that have a proportional consistent response to the analyst concentration. Most biosensors are incorporated into physical transducer to convert and relay the responses of biosensors into signals (Chouler and Lorenzo 2015; Chambey and Malhotra 2002). Economic and environmental vantages of biosensors are refocusing researchers' interest on the designs of biosensor for monitoring several environments; operating with biofuels (Antoni *et al.*, 2007). This review foresees the design of MFC implants that can monitor and utilize the excess glucose in diabetic patients as a sustainable source of fuel to pump insulin into the patient's system.

Most biofuels (as hydrogen, ethanol, methane, and butanol) utilize microbial byproducts as substrates (Antoni *et al.*, 2007) to readily synthesize bioenergies. The challenges of electricity generation from these biofuels necessitated the direct tapping of electrons from



microbial cells to generate electricity in the form of microbial transformer popularly known as microbial fuel cells (MFCs). This exceptional microbial transformer has the capacity to transform organic matters (domestic, animal and human wastes) into electricity through the metabolic breakdown of biomass. Allen and Bennetto (1993) described MFCs as devices that operate on the principles of the catalytic activities of microbes on chemical constituents of biomass in which its reducing metabolite (electrons) are tapped to power an external load with an efficiency not less than 50% (Katz *et al.*, 2003; Lovley, 2006).

Microbial influence in the MFCs power efficiency is traceable to study by Potter in 1911 (Bird *et al.*, 2022), that *Escherichia coli* generates electric current, and study in 1963 utilized *Clostridium butyricum* in a similar demonstration (Bird *et al.*, 2022). Since then, several improved designs of MFCs have been documented. Ringeisen et al. (2008), designed a Mini-MFCs system for *Shewanella oneidensis to* metabolize fructose and glucose as carbon sources with a power output range of 0.3 - 0.6mV (1.3 - 2.0mA). Similarly, Cohen report indicated that as far back as 1931, 2mA was achieved when MFCs are in serial connections (Bird *et al.*, 2022).

Unfortunate limitation of MFCs having low power outputs can serve as a great prospect for micro-powered gadgets industries that requires sustainable and renewable energies (Ringeisen *et al.*, 2008; Logan and Rabaey 2012). This is also a welcomed concept for extreme environmental monitoring using micro-powered biosensor devices. One of the recent successes was the design of National Aeronautics and Space administration (NASA), USA, that developed a spacecraft that uses MFCs to power its craft sensors, provide energy and manage biowastes (Hogan and Flynn, 2012; Scott, 2012). Based on this, MFCs holds the prospect of sustainable energy for life support in this extreme environment (space planets). An Ocean bed is another major extreme environment (including icy depth, mountaintops, earth core, desert, volcanoes, Polar Regions, etc) that requires advance



biosensors devices for environmental monitoring and assessment. Operational cost and sustainability of the gadgets are the predisposing parameters that enhance the propensity of MFCs as the best choice (Logan and Rabaey 2012 Furthermore, it suggests that MFCs, originally designed to monitor both microbial and chemical toxicants, could be re-engineered to measure similar parameters in extreme environments

Microbial Fuel Cells (MFCs)

Several authors have comprehensively defined MFCs but the middling concept in the definitions is that MFC is a device that transforms organic matter to energies (e.g biofuels or Electric energy) through microbial activities. However, efficiency of MFC depends on the proportion of these energies (Bird et al., 2022). The principle is similar to the biodegradation of biomass or organic waste where microbes serve as biocatalyst or source of the catalysts. Some MFCs generate electricity, or chemical energy (fuels). Most Electricity producing MFCs are made up of anodic and cathodic chambers (Table 1) which are either separated or not separated with Proton exchange membranes (PEMs) as described by (Kim *et al.*, 2003; Rabaey & Verstraete, 2005). Table 1 presents an overview of the key components and materials utilized in Microbial Fuel Cells (MFCs). MFCs are devices that harness microbial activities to convert organic matter into energy, such as biofuels or electricity. The efficiency of MFCs depends on the proportion of these energies. The table outlines materials for the anode and cathode, chambers (anodic and cathodic), proton exchange systems, electrode catalysts, and optional folded carbon veils used in MFC designs (Du et al., 2007). Crucial materials include graphite, carbon-based materials, and platinum as catalysts. The proton exchange system allows proton movement between chambers, while electrode catalysts facilitate electron transfer reactions. These components collectively contribute to the development of sustainable energy generation and waste treatment technologies (Du et al., 2007). Microbes such as E. coli, Proteus vulgaris, Enterobacter aerogenes, Clostridium butyricum, and Clostridium perfringes have been successfully



studied in MFCs, either in pure form or as a consortium, in which hydrogen and electrical energy are major products at the anaerobic anode chamber of the system (Kim *et al.*, 2000; Park and Zeikus, 2000; He and Angenent, 2005; Lovley, 2006).

Items	Materials	Remarks
Anode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, RVC	Necessary
Cathode	Graphite, graphite felt, carbon paper, carbon-cloth, Pt, Pt black, RVC	Necessary
Anodic Chamber	Glass, polycarbonate, Plexiglas	Necessary
Cathodic Chamber	Glass, polycarbonate, Plexiglas	Optional
Proton Exchange System	Proton exchange membrane: Nafion, Ultrex, polyethylene.poly, (styrene-codivinylbenzene) salt bridge, porcelain septum, or solely electrolyte ceramics	Necessary
Electrode catalyst	Pt, Pt black, MnO2, Fe3+, polyaniline, electron mediator immobilized on anode	Optional
Folded Carbon veil	Matted PAN, pitch or recycled carbon fibers	Optional

Table 1: Basic component and materials of MFC.

Source from (Du et al., 2007)

Anoxic environments are prerequisite for the anodic chamber while aerobic environment (either solution or gaseous) is cathodic chamber prerequisite for the MFCs devices as illustrated by Schröder (2007). Designs of the MFCs are evolving from 2-chamber prototype to 3-chamber prototype (Arnold *et al.*, 2010), and this is to enhance the longevity of the



microbial battery. Additional chamber in 3-chambered MFCs serves as media repository that will reenforce the nutritional requirement of the microbes at the anode chamber. It was design to easily replenish nutrient through the inlet tube (Arnold *et al.*, 2010). However, two major classes of MFCs are mediator and mediatorless MFCs based on the presence or absence of mediators. Mediators are used to facilitate the electron transport from the anode to cathode when endoelectrogens (microbes with loose electrons loosely attached to the membrane) are used in MFCs (Habermann and Pommer, 1991; Cooney *et al.*, 1996; He *et al.*, 2006; Lovley 2006). While mediatorless MFCs are designed with exoelectrogens (microbes that shades its electrons into the system) consequentially, require no mediators to facilitate electron transfer Katz *et al.*, 2003). The substrates and selected microbes predetermine the type of mediators used in MFCs.

Table 2 provides an overview of various microorganisms, their respective substrates, and the operational functions within *Microbial Fuel Cells (MFCs)*. These microorganisms play crucial roles in the conversion of substrates into energy through microbial activities. *Actinobacillus succinogenes* utilizes glucose with neutral red or thionin as electron mediators, while *Aeromonas hydrophila* operates as a mediator-less MFC using acetate as its substrate. *Alcaligenes faecalis* and *Enterococcus* form self-mediate consortia and employ glucose as their substrate, achieving a maximal MFC output of 4.31Wm⁻². *Escherichia coli* requires mediators like methylene blue to metabolize sucrose effectively. (Ringeisen *et al.*, 2008; Pant *et al.*, 2010). On the other hand, *Geobacter metallireducens* and *Geobacter sulfurreducens* are mediator-less MFCs that utilize acetate. *Klebsiella pneumoniae* uses glucose with HNQ as a mediator and biomineralized manganese as an electron acceptor, while *Pseudomonas aeruginosa* relies on glucose and mediators like pyocyanin and phenazine-1-carboxamide. *Streptococcus lactis* utilizes glucose with a ferric chelate complex as a mediator, and *Shewanella sp.* operates as a mediator-less MFC using glucose and fructose. These microorganisms, in combination with various substrates and mediators,



contribute to the diverse capabilities and potential applications of MFC technology (Ringeisen *et al.*, 2008; Pant *et al.*, 2010).

Microbes	subsrate	Operation/function		
Actinobacillus	Glucose	Neutral red or thionin as electron mediator		
succinogenes				
Aeromonas Acetate		Mediator-less MFC		
hydrophila				
Alcaligenes faecalis,	Glucose	Self-mediate consortia isolated		
Enterococcus	Glucose	MFC (maximal level of 4.31 Wm ⁻²).		
Escherichia coli	Sucrose	Mediators such as methylene blue needed.		
Geobacter	Acetate	Mediator-less MFC		
metallireducens				
Geobacter	Acetate	Mediator-less MFC		
sulfurreducens				
Klebsiella pneumonia	Glucose	HNQ as mediator biomineralized		
		manganese as electron acceptor		
Pseudomonas	Glucose	Pyocyanin and phenazine-1-carboxamide		
aeruginosa		as mediators		
Streptococcus lactis	Glucose	Ferric chelate complex as mediator		
Shewanella sp	Glucose and	Mediator-less MFCs		
	fructose			
Rhodoferax	Organicacids,	Fe (III), 10 mM Fe (III) chelated with		
	glucose, fructose	nitrilotriacetic acid (FE (III)-NTA).		

TABL	E 2:	Microor	ganisms	Substrates	and o	perational f	inction
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Source: (Ringeisen et al., 2008; Pant et al., 2010).

Various classifications of MFCs have been documented based on the substrate, environment, or structural designs (Liliana Alzate-Gaviria, 2011; Rabaey and Verstraete, 2005; Logan, 2008; Tsuru and Hirata, 2013). Prominent among them include biomass/Wastewater MFCs (designed to manage waste and generate energy), tubular or



square type MFCs (based on the structural design of tubes or squares), upflow MFCs (based on structural design), and benthic unattended generator MFCs (based on the environment) (Liliana Alzate-Gaviria, 2011; Rabaey & Verstraete, 2005; DeLong and Chandler 2002; Tsuru & Hirata, 2013). Microbes in MFCs employ three major theories of electron transfer mechanisms: direct transfer (mediatorless), electron shuttling (mediators), and microbial nanowires (Nawaz *et al.*, 2020).

Notably, significant advancements and patent filings for MFC devices have been observed since 2001. Fig. 1 presents a fascinating glimpse into the historical development of Microbial Fuel Cells (MFCs) as depicted by the biannual increase in patents captured in the Google Scholar Patent Database. The chart reveals a noteworthy surge in MFCs patents between the years 2004 and 2005, signifying a period of intensified interest and research activity in this innovative energy technology. During this time, scientists, researchers, and inventors were likely exploring the potential applications and benefits of MFCs, leading to an influx of novel ideas and patented inventions.

As the MFCs technology continued to evolve and mature, the number of patents steadily increased, reaching a remarkable milestone of over 5,000 registered MFCs patents by approximately 2014-2015. This exponential growth highlighted the growing confidence in MFCs as a viable alternative energy source and reflected the mounting belief in its potential to revolutionize energy generation and environmental management.

However, it is intriguing to note that after the peak period in 2014-2015, there was a decline in the number of MFCs-related patents. Several factors might have contributed to this shift in the trend. Challenges encountered during real-world implementation, such as the power output limitations of MFCs for larger-scale applications, could have dampened the enthusiasm for further patenting. Additionally, researchers and industries may have started



exploring other renewable energy options or shifted their focus to different sustainable technologies (Fig. 1).

Despite the recent decline in patents, the historical trajectory of MFCs remains noteworthy, and the chart underscores the importance of understanding the factors that influence the ebb and flow of interest in this cutting-edge technology. Continued research, development, and innovation in the field are crucial for harnessing the full potential of MFCs and cementing their role as a viable and environmentally friendly energy solution for the future. It is important to note that MFCs efficiency increases with miniaturizating or stacking of the system, such that the surface area to volume ratio increases and this reduced the methanogenesis in the system.



Fig. 1: Binnaual increase in MFCs patents captured in Google Scholar Patent Dataabase

On the other hand, MFC biosensor patents in chart (Fig. 2) illustrates the biannual increase in patents related to Microbial Fuel Cells (MFCs) biosensors, as captured in the Google



Scholar website. The graph showcases a significant rise in MFCs biosensors patents starting around 2007, indicating a pivotal moment when researchers recognized the potential of combining MFCs technology with biosensors. Subsequent years saw a continued growth in patents, demonstrating sustained interest and dedication to advancing MFCs biosensors. This upward trend reflects the increasing recognition of MFCs biosensors as a promising technology with diverse applications in environmental monitoring, medical diagnostics, and industrial processes. The chart's trajectory highlights the transformative impact of MFCs biosensors, offering sustainable energy solutions alongside precise and efficient monitoring capabilities. As the number of patents continues to increase, it underscores the field's potential for further research and commercialization, contributing to a more sustainable and technologically advanced future.



Fig. 2: Binnaual increase in MFCs biosensors patents captured in Google Scholar website



Micro-Powered Gadgets and Prospect of MFCs

Advances in the medical sciences

Recently, the use of biofuel cells as alternative source of energy to power implants against the conventional abiotic (chemical) batteries are gaining popularity. These biofuel cells are competitively preferred to chemical batteries, because they are designed to draw energy from the patient and run infinitely as long as the patient lives. But implants with chemical batteries require periodic surgery to recharge battery, which have unpredictable negative impact. Surging number of implants have been designed to operate with micro-current such as biofuel cell powered pacemaker that uses glucose from the patient's blood to function indefinitely. [Birds *et al.*, 2022).

Also, Kerzenmacher *et al.* (2007) believed that their conceptualized biofuel using mountable glucose cell to harvest micro-power of about 1.1 mW/cm² have a promising prospect for autonomous and sustainable long-term medical implants and sensors. Han et al., (2010) designed an operational medical MFC implant that would be place in the large intestine of human to generate 7-10mV daily (in 60 operational days) from the activities of microorganisms found in the colon. No doubt, voltage rate is adequate for most implants and biosensor functions. Non-implant micro-powered medical devices could be operated successively within MFCs 100mV capacity output generated from patients' system (Amar et al., 2015).

Microbial Fuel Cell Type Biosensor

Contrary to the assumptions that MFCs are contemporary technology for biosensors devices, Karube *et al.*, (1977) designed MFCs biosensor device using hydrogen from *Clostridium butyricum* immobilized on electrodes to monitor BOD and recently more efficient MFC biosensors for monitoring BODs are reported Lei *et al.*, 2006). Also, Logan *et al.* (2008) used MFCs to monitor COD, while Lorenzo *et al.* (2009) effectively monitored BOD and optical density (OD). In fact, Peixoto et al. (2011) demonstrated a direct correlation between



MFCs and BOD, suggesting its potential application as a BOD indicator Dai and Choi (2013). Lei *et al.*, (2006) argued that the stability of MFCs biosensors are adversely affected by electron mediators which were incorporated to enhance the electron transfer ability. Consequently mediator-less MFCs were exploited for BOD real-time assessment (Chang *et al.*, 2005).

Conceptualization of MFCs for toxicant monitoring was demonstrated in 2007 (Kim *et al.*, 2007a) and since then, several improvements have been speculated and tried by different studies (Kim *et al.*, 2007a; Patil et al., 2010; Kim et al., 2007b). However, Patil *et al.* (2010), noted that possibility of microbial biosensors to acquire resistance to toxicants, could be eliminated by immobilized enzyme technology and Kim *et al.* (2007b) suggested the use of pre-cultured electrochemically-active bacteria.

Challenges of universal application of MFCs as biosensors are not only peculiar to socioeconomic demography of the intended community of deployment (Chouler and Lorenzo, 2015), but also to the purpose, specificity, location and efficiency. Utilization of MFCs in developing countries for monitoring aquatic qualities and environment are faced with simplicity factor. Di Lorenzo *et al.* (2014) argued for a single chamber MFCs system with non-expert maintenance design, and Feng *et al.* (2013) advocates for simple input and output MFCs systems. Other studies proffer alternative inexpensive MFCs materials, such latex condom (Winfield *et al.*, 2013), ceramics (Behera *et al.*, 2014) and pre-fabricated latex glove (Windfield *et al.*, 2014) as MFCs membrane; while banana and sewage sludges served as good MFCs catalysts (Yuan *et al.*, 2014).

Microbial fuel Cell for Agriculture and Environmental Health

Another interesting development of MFCs is the design of a self-powered artificial grass eater robot called Gastronome or Chew-Chew or Gastrorobot. The self-powered herbivorous robot directly transforms grass (carbohydrate fuel) to electricity to operate in semi



autonomous mode and as well control weeds and grass in field or lawns (Shukla *et al.*, 2004). Soil and environment could be successful monitored with miniature sized or microscale MFCs biosensors that are efficient and rapid detectors of trace quantity of toxins such as formaldehyde (Da'vila *et al.*, 2011). Automated MFC powered ultrasonic sound devices are gaining popularity as farms pests and domestics nuisance (rodents and insects) control measures as the economic and health attributes outweigh the convectional chemical and physical methods.

Microbial Fuel Cells for portable digital commuication devices

Ideally, electric devices are advancing towards microchip size, thus they requires microcurrent to operate. Presently, MFCs are found to discharge 7 - $10mV(100\mu A max)$ daily (Han *et al.*, 2010) and most electric portable devices are designed to operate within or below this voltage. Micropower concept are solely intended to manage global energy crisis. Some of the suggestive portable micro-current devices that could run on MFCs include minilaptops, digital cameras, cell phones (Tsuru and Hirata 2013), bluetooth peripherals, ipods, ipads, etc. Others are designed to manage and maintain telecommunication gadgets at remote areas including outer space, weather stations and as well extreme environments monitoring devices [Birds *et al.*, 2022; Katz *et al.*, 2003; Lovley 2006).

Microbial Fuel Cell for Monitoring Extreme Environment

Recent MFC monitoring devices used in the extreme environment assessment is the Benthic Unattended Generator (BUG), which have the ability to harvest electricity from oceanic beds (Greer 2007). BUGs also known as BMFCs (Benthnic Microbial Fuel cells) are designed as biosensors with economic advantage over the expensive conventional deep oceanic environment monitoring and maintenance services. Meteorological buoy was successfully powered by MFC (Tender *et al.*, 2008) and a robot that have air-cathode MFC on board have successfully monitored, processed and communicated as sensoring devices (Ieropoulos *et al.*, 2008; Ren *et al.*, 2012) in nano-dimensions. Nanotechnology is rapidly



evolving the MFCs designs into encapsulation and microscale dimensions for efficiency and competitive merits. Remote and harsh locations (extreme environments), could be economically powered with MFCs when conventional electricity is unavailable (Chaudhuri and Lovley 2003; Gregory and Lovley 2005). Nanotechnology has achieved good immobilization and performance by enhancing conductivity, catalytic activities and compatibility of MFCs (Deng *et al.*, 2010). Exploration of this micro-chipping MFCs designs concepts would pose a great prospect for MFCs efficiency for extreme environment monitoring by improving the device portability and transmissibility of mined data (Slate *et al.*, 2019).

Challenges of MFCs Application in Extreme Environment

Microbial Fuel Cells (MFCs) hold immense promise for sustainable energy generation and environmental monitoring, but their application in extreme environments presents unique challenges. The harsh and unpredictable conditions in these settings, such as extreme temperatures, high salinity, low pH, and high radiation levels can adversely affect MFC performance and durability ((Slate *et al.*, 2019). Thus, redesigning and reengineering of existing MFCs would be necessary to withstand these conditions and continue to operate efficiently in such environments. Limited access to resources in remote locations requires MFC systems to be self-sustaining or require minimal external inputs (Winfield *et al.*, 2014). Electrode fouling and biofilm formation are additional challenges that can reduce electricity generation. Preventing or managing these issues becomes crucial for sustained MFC performance. Stability and durability are paramount in environments where frequent maintenance is impractical. MFCs must exhibit resilience to environmental stress and prolonged operation without compromising efficiency (Logan *et al.*, 2008; Han *et al.*, 2010).

Regulatory compliance and ethical considerations are also critical when deploying MFCs in protected or sensitive areas. Adhering to environmental regulations and addressing ethical concerns ensures responsible and sustainable use of MFC technology. By addressing these



challenges through innovative research and collaboration among experts, MFCs can realize their full potential as a transformative technology in extreme environments, contributing to a greener and more sustainable future (Slate *et al.*, 2019; Nawaz *et al.*, 2020). Maximizing energy harvesting efficiency is vital in locations with scarce organic matter. Optimizing the energy conversion process ensures MFCs generate sufficient power under challenging conditions. Miniaturizing MFC systems is essential for space exploration or weightrestricted environments. Selecting resilient materials addresses corrosion and degradation concerns (Winfield *et al.*, 2014; Han *et al.*, 2010).

CONCLUSION

Incorporating mutagenesis and rDNA technology represents a crucial approach to propel the development of more efficient Microbial Fuel Cells (MFCs). To achieve this, experts in microbial physics must collaborate with electrochemists, materials scientists, engineers, and nano-electronicists to intensify research on anodophilic and microbial biofilm signaling, aiming for superior MFC performance. Additionally, stacking MFCs in upflow mode has emerged as a potential strategy to enhance power output, presenting opportunities of great significance. This technology could find diverse applications in the defense sector, powering remote surveillance unmanned stations, medical implants, portable and handheld appliances, communication gear, biosensor devices, and environmental bioremediation of soil and wastewater, among others. However, various challenges stand in the way of seamless MFC integration into real-world scenarios. Pathogenic tendencies, environmental sensitivity, mutagenic traits of microbes, and structural MFC designs require careful consideration and extensive research to be addressed effectively. Despite these obstacles, the relentless efforts of researchers and engineers continue to make remarkable progress in the field of MFCs. The advancement of materials science, biotechnology, and system design offers promising solutions for overcoming these challenges, potentially transforming MFCs into practical energy sources and reliable monitoring tools in extreme environments.



Collaborative endeavors among interdisciplinary experts are essential to harness the full potential of MFCs in demanding settings. Continued research and innovation are key to unlocking the inherent possibilities of MFCs, paving the way for greener and more sustainable solutions in energy generation and environmental monitoring. By capitalizing on the strengths of different disciplines, MFC technology can be refined and optimized, leading to its widespread implementation and positive impact on various industries and environmental sectors.

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