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REVIEW ARTICLE

Microbial fuel cells: a comprehensive review for beginners

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Abstract
Microbial fuel cells (MFCs) have shown immense potential as a one-stop solution for three major sustainability issues confronting the world today—energy security, global warming and wastewater management. MFCs represent a cross-disciplinary platform for research at the confluence of the natural and engineering sciences. The diversity of variables influencing performance of MFCs has garnered research interest across varied scientific disciplines since the beginning of this century. The increasing number of research publications has made it necessary to keep track of work being carried out by research groups across the globe and consolidate significant findings on a regular basis. Review articles are often the nodal points for beginners who are required to undertake an exploratory survey of literature to identify a suitable research problem. This 'review of reviews' is a ready-reckoner that directs readers to relevant reviews and research articles reporting significant developments in MFC research in the last two decades. The article also highlights the areas needing research attention which when addressed could take this technology a few more steps closer to practical implementation.

Keywords Microbial fuel cells · Microbial electrochemistry · Microbial electron transfer · Wastewater treatment · Alternate energy · Bioanode · Biocathode

Introduction

The Earth presently plays host to almost 8 billion human beings (UN DESA Population Division 2019) and the number is expected to go up further and level out by the latter half of the Twenty-first century (Gonzalo et al. 2016). Sustainability of natural resources has been a cause for concern (Buhaug and Urdal 2013) due to ambitious social and economic goals. Dwindling reserves of fossil fuels (Hallenbeck and Ghosh 2009) account for over 80% of the world's primary energy consumption (Mohr et al. 2015). Greenhouse effect, a natural phenomenon that is chiefly responsible for the habitability of earth, appears to be assuming unmanageable proportions. Unregulated release of carbon dioxide and other greenhouse gases resulting from anthropocentric activities have led to increased absorption of infrared radiation from the sun leading to above-normal surface temperatures on earth (IPCC 2014). The need to curb such emissions underlines the search for sustainable, carbon–neutral sources of energy (Arent et al. 2011; Villano et al. 2012). Reinforcing the need to shift to renewable energy, Rittman (2008) specifically outlines the potential of microorganisms as a source of energy.

Urbanization is on the rise in developing nations (Buhaug and Urdal 2013) and the resultant increase in average income has ameliorated food preferences, putting pressure on water resources (de Fraiture and Wichelns 2010). The increased demand for water has impacted water availability (Haddeland et al. 2014) and has promoted reuse of wastewater for applications such as irrigation (Toze 2006) and landscaping. However, in many developing countries, advances in sanitation infrastructure and wastewater treatment have been outpaced by population growth (Qadir et al. 2010). As a result, many of them are on the lookout for reliable and low-cost means for treatment of domestic, agricultural and industrial wastewater to make it reusable (Massoud et al. 2009). An informative and well-illustrated review article by Larsen et al. (2016) discusses the need to adopt innovative strategies for arriving at resource-efficient solutions for issues related to urban water management.

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Past and present of MFCs

Electrical effects resulting from microbial disintegration of organic compounds were first described by Potter (1911) over a hundred years ago. In the subsequent decades leading to the next century, there were only a few isolated reports of attempts to extend this fascinating discovery towards practical applications. Schröder (2011) traces the century-long history of microbial electrochemical systems from the time they were first reported, highlights significant milestones, succinctly outlines the reasons for the initial dearth of interest in taking this technology further, and finally describes the relevance and future scope of this discipline following its resurgence at the turn of the century.

Microbial Fuel Cells (MFCs) have been aptly described by Du et al. (2007) as "*bioreactors that convert the energy in the chemical bonds of organic compounds into electrical energy through catalytic activity of microorganisms under anaerobic conditions*". Figure 1 is a graphical representation of a generic two-chambered MFC comprising an anode and a cathode chamber separated by a selectively permeable membrane. The microbes' need for a compatible electron acceptor to deposit electrons is readily fulfilled by the anode of an MFC in the absence of a more suitable acceptor (Stams et al. 2006). These electrons collected by the anode are channelised across an external load (resistor) to harness usable energy. The final step of the electron transport occurs at the cathode in the presence of a terminal electron acceptor. Thus, a 'quasi-engineered' electron transport chain that mimics the bacterial respiratory chain forms the core of an MFC. Basic concepts relating to MFCs are presented in a lucidly written lecture text by Schröder (2018). The technical foundations and principles which form the basis of this technology are presented in comprehensive review articles by Logan et al. (2006) and Santoro et al. (2017). These microbe-catalysed electrochemical devices are viewed as a potential solution for wastewater management and as a source of sustainable and clean energy. To make this solution practically viable, research on microbial electrochemical technologies has primarily focused on four aspects, viz. minimizing electrochemical losses, improving performance efficiency, lowering working costs and scaling up systems for practical applications (Fig. 2).

A query submitted for the term 'microbial fuel cells' on the Web of Science™ platform of Clarivate Analytics (Fig. 3) showed a gradual increase in the number of research articles on MFCs that were published in the years 2004–2020 in scientific, peer-reviewed journals. It must be noted that this figure serves to only emphasize the growth trend and that the output of a similar query in different search engines would obviously

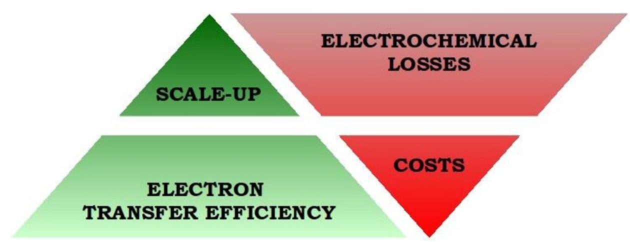
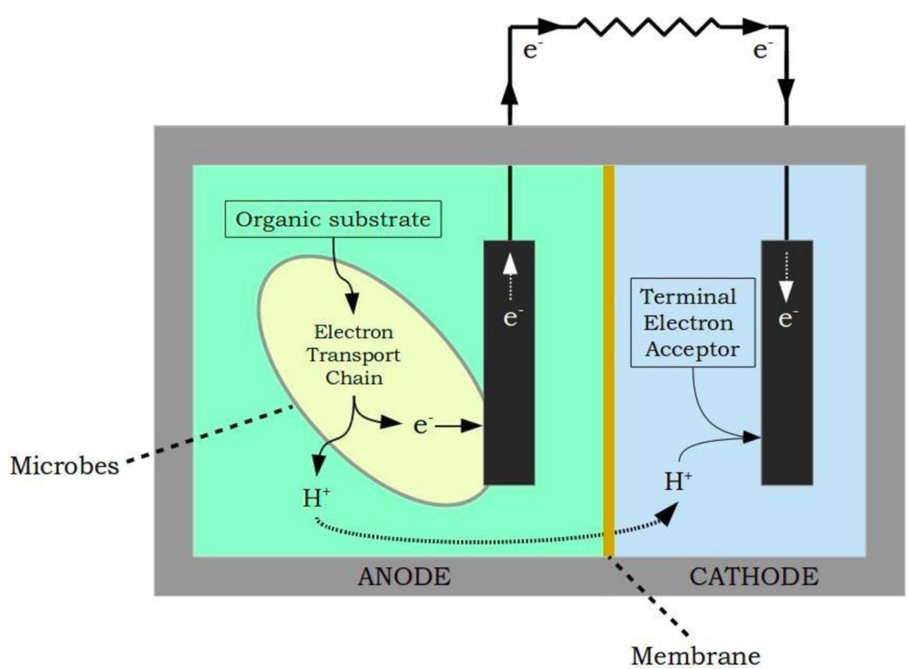


Fig. 2 Four major focus areas of MFC research

Fig. 1 Schematic of a generic two-chambered MFC



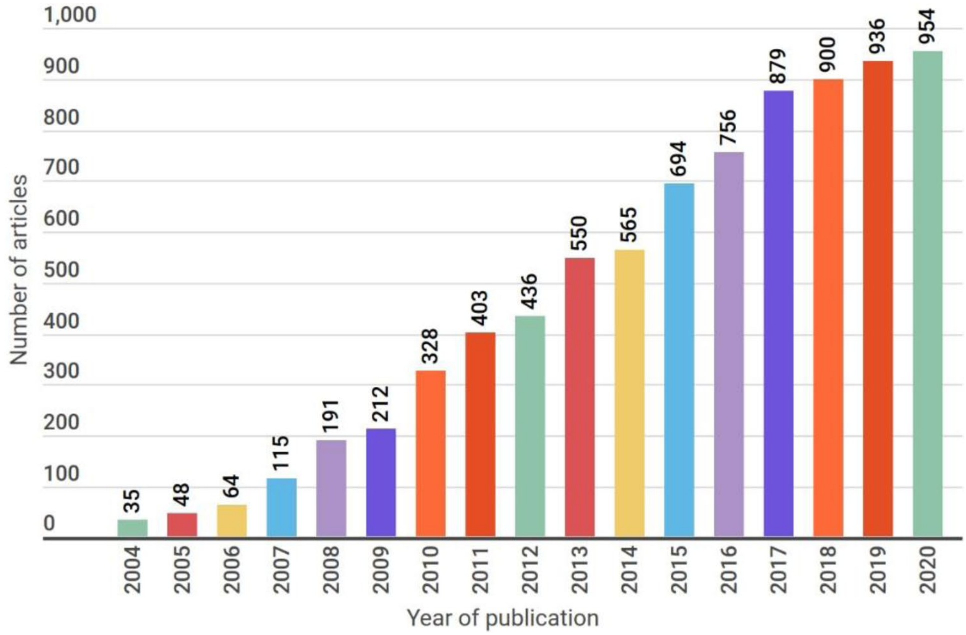


Fig. 3 Year-wise trend of publications based on a search on the Web of Science™ portal for the keyword 'microbial fuel cell' (2004–2020)

return varying numbers based on the websites and databases that are indexed by the respective algorithms.

Among the different types of articles that are published in scientific journals, review articles represent a starting point for budding researchers and a vade mecum for established scientists. In general, reviews primarily serve to fulfil the following tasks:

i. classifying the ever-growing information in a subject into relevant categories,
ii. providing references to research papers that describe significant advancements, and
iii. highlighting lacunae to be addressed by researchers.

This article has been compiled with the primary objective of aiding beginners to sift through the abundantly available scientific literature on MFCs by directing them to focused reviews and relevant breakthrough research articles highlighting significant advances in the field. The content has been divided into independent sub-sections pertaining to configuration, microbes, materials, performance characterization, scale-up and applications for the sake of convenience. The choice of references cited in this article is based entirely on their content and is not influenced by any intentional bias whatsoever.

MFC design and modeling

A wide variety of MFC configurations have been designed for specific applications and with the objective of improving performance by minimizing systemic losses. Some of the significant examples include air–cathode single-chamber MFCs (Liu and Logan 2004), flat-plate MFCs (Min and Logan 2004), upflow MFCs (He et al. 2005), tubular MFCs (Rabaey et al. 2005), membrane-electrode assembly MFCs (Pham et al. 2005), stacked MFCs (Aelterman et al. 2006), separator-electrode assembly MFCs (Ahn and Logan 2012). However, the most commonly reported are the two-chambered, 'H-shaped' MFCs which, despite their low current output, have been the most convenient for optimizing performance of new components and characterising operating conditions (Logan et al. 2006). Figure 4 (adapted) presents some of the different experimental designs that have been used in MFC studies and reported in literature.

Discussing essential aspects to be considered while designing MFCs for various practical applications, an article by Logan et al. (2015) highlights the importance of electrode configuration and source of organic substrate in determining performance. Modeling studies, which facilitate detailed analyses of factors affecting the performance of MFCs (Jadhav et al. 2020a), include mathematical modeling (Deb et al. 2020), computer simulations (Xia et al. 2018), neural network modeling (Ma et al. 2019) and electrochemical modeling (Kadivarian and Karamzadeh 2020). Given the diversity of dependent variables that can determine the performance of MFCs (Oliveira et al. 2013; Zhang et al. 2019a), analysing their influence to arrive at a valid conclusion depends to a considerable extent on the number of replicates of an experiment because repeatability is not necessarily assured (Larrosa et al. 2009).

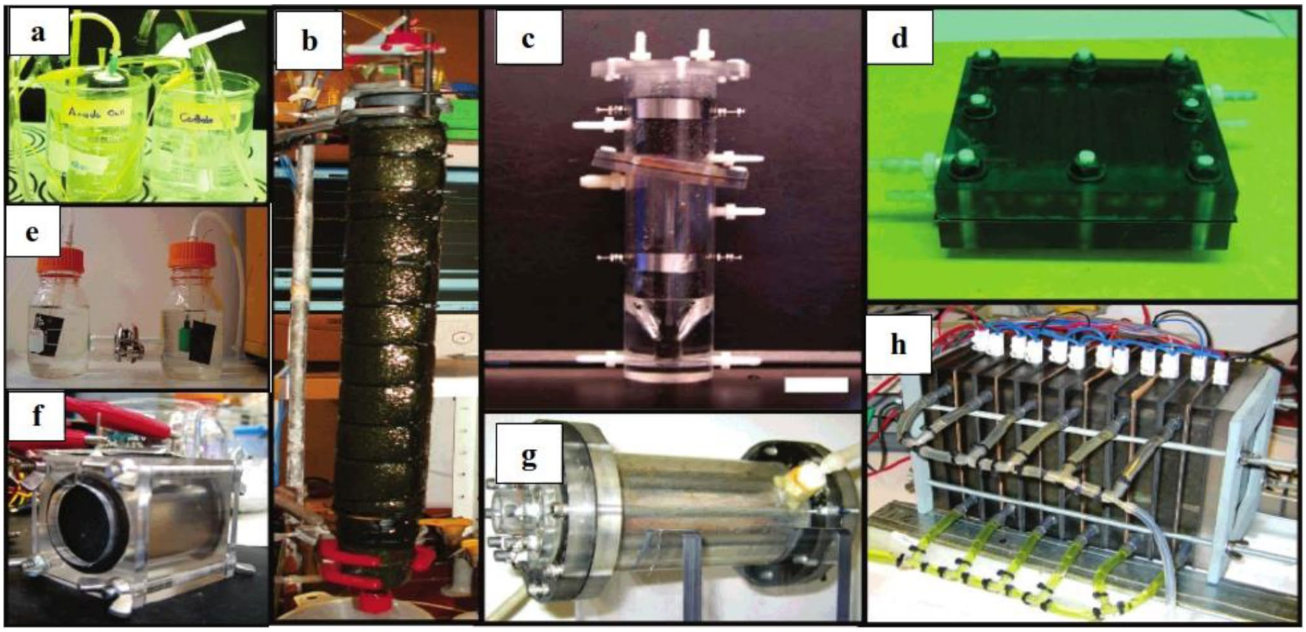


Fig. 4 Different designs used in MFC studies: **a** salt bridge MFC; **b**, **c** upflow MFCs; **d** flat-plate MFC; **e** h-shaped MFC; **f**, **g** single-chamber MFCs; **h** stacked MFC (The figure has been reprinted (adapted) with permission from Logan BE, Hamelers B, Rozendal R, et al. (2006) Microbial fuel cells: Methodology and technology. Environmental Science & Technology 40:5181–5192. https://doi.org/10.1021/es0605016. Copyright © 2006 American Chemical Society.)

Electroactive microbes

Microbes play a key role in an MFC by catalysing the release of electrons from energy rich bonds of organic substrates under anoxic conditions. Review articles by Pant et al. (2010b) and Pandey et al. (2016) describe different pure substrates and types of wastewater that have been used as a carbon source for microbes in MFCs. The electrons released in this process of oxidation travel through versatile microbial electron transport chains (Fredrickson et al. 2008; Kracke et al. 2015) which comprise serially arranged conductive protein complexes, cytochromes, nanowires and redox proteins (Costa et al. 2018) before being donated to the anode of the MFC. Schröder explains the fundamental mechanisms and energy considerations of anodic electron transfer in a classic review (2007). Electron transfer between microbes and the electrode (Lovley 2012; Kumar et al. 2017) can be either indirect—mediated by naturally produced or artificially added redox shuttles (Martinez and Alvarez 2018)—or by direct extracellular electron transfer (Yang et al. 2012) (Fig. 5). Glasser et al. (2017) provide valuable insights into endogenous extracellular electron shuttles while Lovley (2017) describes the processes associated with direct interspecies electron transfer which enables long-distance transport of electrons in bioelectrochemical systems. Dynamics of electron transfer within microbes (intra), between microbial species (inter), and at the microbe-electrode interface have been detailed in a review article by Zheng et al. (2020).

Mixed consortia of electrogenic and electrotrophic microbes (Logan 2009; Logan et al. 2019) are known to contribute more effectively to production of current in MFCs as compared to pure cultures of bacteria. This difference could be attributed to synergistic interactions between syntrophic microbial species resulting in effective utilization of available substrates (Kiely et al. 2011) by the formation of electrochemically active biofilms (Borole et al. 2011; Babauta et al. 2012; Reguera 2018; Kiran and Patil 2019). Growth and performance of electroactive biofilms can be enhanced (Li et al. 2018a) by selectively controlling growth conditions (Doyle and Marsili 2015, 2018), using synthetic biology (Glaven 2019) and adopting engineering approaches (Angelaalincy et al. 2018; Chiranjeevi and Patil 2020). Communities of microbial consortia have also been profiled and characterized using 'omics' technologies (Rittmann et al. 2008; Lacerda and Reardon 2009; Moran et al. 2013; Franzosa et al. 2015; Kouzuma et al. 2018), flow-cytometric approaches (Koch et al. 2014), computational tools (Haft and Tovchigrechko 2012; Segata et al. 2013) and statistical analysis (Buttigieg and Ramette 2014) to obtain insights from a structural and functional perspective (Zhi et al. 2014).

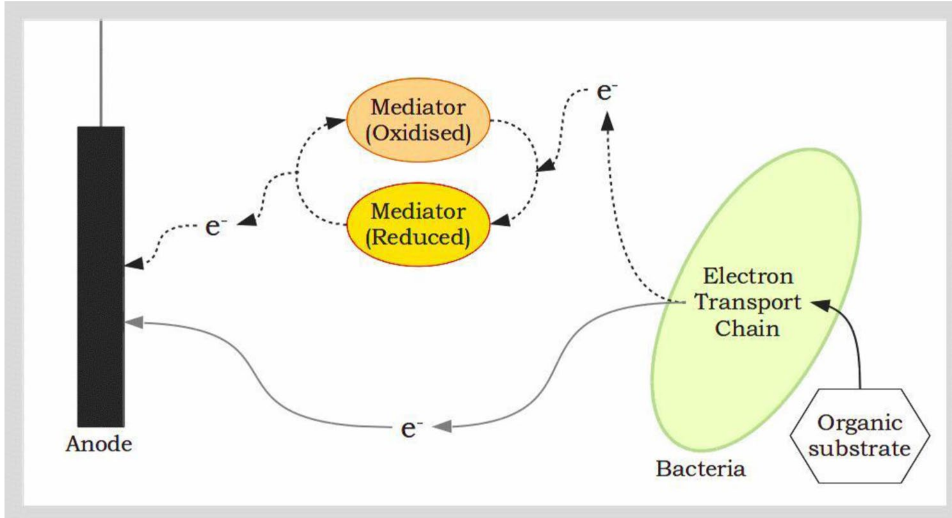


Fig. 5 Direct (solid lines) and indirect (dotted lines) electron transfer from bacteria to the anode

Electrodes and separators

Efficient electrode materials in MFCs must essentially be biocompatible, electrically conductive, non-corrosive and electrochemically stable. Wei et al. (2011), in their detailed review article, analyse the advantages and disadvantages of different materials used as electrodes in MFCs and discuss the prospects of electrode development. Assessing the performance of electrodes and separators (Hamelers et al. 2010) and use of low-cost materials such as ceramics (Winfield et al. 2016), ligno-cellulosic material (Mehta et al. 2020) and biochar (Chakraborty et al. 2020a) without significantly compromising on efficiency is important for design of efficient MFCs. Breheny et al. (2019) discuss critical aspects for improvement of bioelectrodes in MFCs and Pasternak et al. (2020) present a new dimension for enhancing performance of microbial electrochemical systems using surfactants.

Anodes serve as the substratum for biofilm formation and also function as current collectors in MFCs. Among different materials that have been reported, carbon is most preferred for anodes because of its versatility, non-reactivity, high electrical conductivity and biocompatibility (Logan 2008). While carbon cloth and carbon felt provide more room for colonization of microbes by virtue of being more porous compared to graphite sheets or carbon paper, the innovative introduction of graphite brush anodes (Logan et al. 2007) enabled the incorporation of larger surface area of electrodes for a given volume of the reactor. The high conductivity and surface area provided by nanomaterials resulted in their use in the anode chamber of MFCs (Liu et al. 2020). Gnana kumar et al. (2013) describe the features of anode materials used in MFCs and different processing techniques that can improve efficiency of bacterial adhesion, electron capture and transfer. A comparative account of conventional and modified anodes (Cai et al. 2020) opens up a new window for understanding the characteristics of anode materials and paves the way for development of next generation MFC anodes.

Cathodes provide a common interface for the culmination of the microbial electron transfer process in an MFC resulting in the confluence of electrons, protons and the terminal electron acceptor. On account of their complex role, cathodes have been considered as a critical point to determine the efficiency of MFCs (Rabaey and Keller 2008). Based on the type of electron acceptor used (He et al. 2015), cathodes can be classified as chemical or biological. Oxygen is often preferred as a terminal electron acceptor due to its ubiquity and propensity to get reduced to water. However, poor kinetics of the oxygen reduction reaction led to the use of expensive, precious-metal catalysts such as platinum at the cathode. Studies that focused on reduction of operating costs (Zhang et al. 2009) eventually led the way to development of more economical, alternate cathode materials based on carbon (Peera et al. 2020) and nanocomposites (Dessie et al. 2020) devoid of precious metals for improving efficiency of the oxygen reduction reaction (Yuan et al. 2016). Erable et al. (2012) describe the application of microbes to catalyse the rate-limiting oxygen reduction reaction at the cathode. Biocathodes (He and Angenent 2006), comprising electrotrophic microbes that can directly accept electrons from the electrode (Lovley 2011), can overcome many of the shortcomings encountered using chemical cathodes and are now being actively pursued as a topic of research interest (Song et al. 2019).

A separator in an MFC is a physical barrier that allows charges to pass through but serves as a hurdle to prevent direct electrical contact between the anode and cathode. In the early years, proton exchange membranes such as Nafion® were used in MFCs to selectively allow only protons to the cathode chamber of an MFC (Rahimnejad et al.

2014). Eliminating the use of a proton-specific, separating membrane in MFCs (Jang et al. 2004) was a significant breakthrough for reducing operation costs, but it brought along the twin drawbacks of oxygen diffusion into the anoxic anode chamber and short circuiting of electrons between the anode and cathode, both of which when unregulated have a detrimental impact on performance efficiency. In subsequent years, expensive membranes were substituted with alternatives like Zirfon® (Pant et al. 2010a; Pasupuleti et al. 2016) and low-cost materials having more general transport properties such as ion exchange membranes (Leong et al. 2013), ceramic filtration membranes (Yang et al. 2016a), polymeric membrane separators (Bakonyi et al. 2018), sand/activated carbon separators (Gao et al. 2018), silk fibroin membranes (Pasternak et al. 2019) and polystyrene (Mathuriya and Pant 2019).

Performance characterization

Electrochemical techniques and tools are used to analyze the effect of modifications made to MFCs with the objective of minimizing electrochemical losses and enhancing performance efficiency. Rimboud et al. (2014) present a detailed perspective on the factors to be considered while designing anodes for microbial electrochemical systems. Electroactivity of biofilms has been characterized using techniques such as cyclic voltammetry (Gimkiewicz and Harnisch 2013), electrochemical impedance spectroscopy (ter Heijne et al. 2015), confocal resonance Raman microscopy (Virdis et al. 2016), interdigitated electrode array (Yates et al. 2018) and other methods. Technical aspects such as internal resistance (Zhang and Liu 2010) and anode potential (Aelterman et al. 2008; Wagner et al. 2010; Zhu et al. 2013) have to be understood and commonly encountered issues such as power overshoot (Watson and Logan 2011; Winfield et al. 2011) and voltage reversal (Kim et al. 2020) must be analysed to minimise losses and enhance performance of MFCs. Tutorial articles provide the necessary support to beginners to understand fundamental concepts in electronic circuitry (Sánchez et al. 2020), choice of electrode configurations and operating conditions for electroanalysis (Zhao et al. 2009) and nuances of techniques such as cyclic voltammetry (Harnisch and Freguia 2012; Elgrishi et al. 2018) and electrochemical impedance spectroscopy (He and Mansfeld 2009). Other useful reviews outline performance indicators (Sharma et al. 2014) and terms used to describe performance of microbial electrochemical systems (Wang and He 2020). Challenges encountered due to the diverse configurations of MFCs and different techniques available for characterizing activity of electroactive microbes can be addressed by having a standardized framework (Harnisch and Rabaey 2012) and fundamental guidelines to plan experiments, analyse observations and report results in a more meaningful manner (Logan 2012).

Scaling up

Schröder (2011) reported that the performance of MFCs improved by close to three orders of magnitude—from few μA/cm^2 to over 1 mA/cm^2—during the first decade of this century. Microscale (Wang et al. 2011; Choi 2015) and microfluidic (Yang et al. 2016b; Parkhey and Sahu 2020) MFCs have shown enhanced performance in terms of power production. Although μL and mL scale laboratory experiments provide cues and clues regarding different mechanisms involved in the functioning of MFCs, systemic understanding obtained from such studies must be transferred and translated (Janicek et al. 2014; Butti et al. 2016) to enable setting up of pilot-scale systems (Logan 2010). Knowledge of the different components and processes involved is critical to make upscaling of MFCs practically feasible (Logan et al. 2015). Significant progress has been achieved over the past decade in developing scaled-up MFC systems for practical applications (Gajda et al. 2018; Abdallah et al. 2019; Jadhav et al. 2020b).

Applications

The primary application of MFCs is wastewater treatment with concomitant production of electricity (Pant et al. 2012). Lefebvre et al. (2011) describe energetics of MFCs with the objective of developing a self-sustaining domestic wastewater treatment process (Oh et al. 2010). Harnessing the potential of MFCs as a power source (Wang et al. 2015) and for production of valuable products by microbial electrosynthesis (Rabaey and Rozendal 2010; Harnisch and Urban 2018) requires an in-depth understanding of factors that limit performance (Sleutels et al. 2012) along with the principles of energy capture and storage (Sun et al. 2016).

Evolution of microbes has favoured the diversification of MFCs into a number of technologies (Schröder and Harnisch 2017) with varied applications (Schröder et al. 2015), resulting in the more generic term ‘microbial electrochemical cells’ (MXCs) (Fig. 6). Table 1 presents an overview of the multifarious applications of microbial electrochemical technologies and provides references to recently published review articles. Torres (2014) emphasizes on the need to “*identify, understand and predict*” different phenomena that govern the performance of such systems.

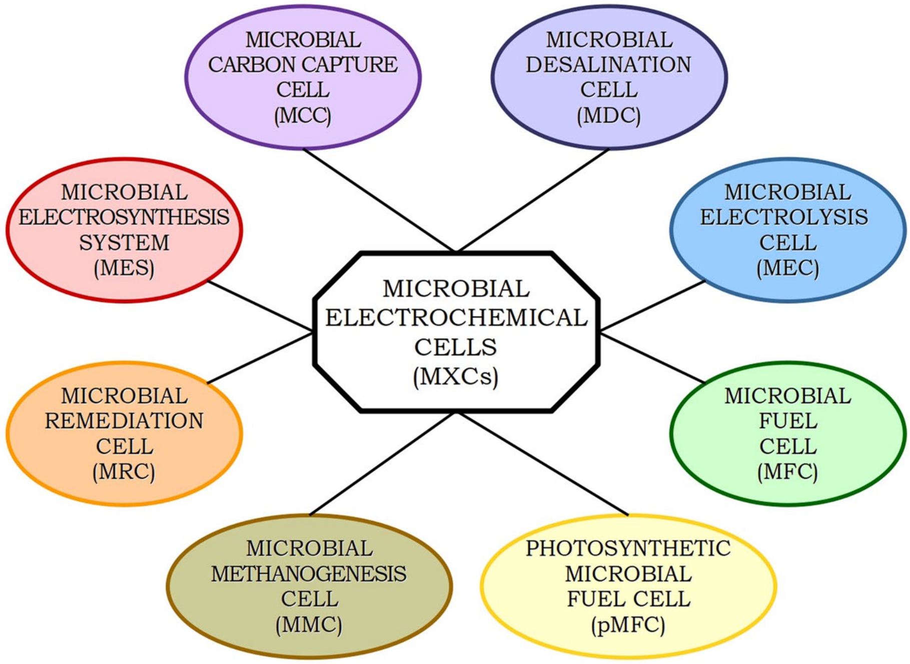


Fig. 6 Diversification of microbial electrochemical cells

Table 1 Applications of microbial electrochemical technologies

	Application	Reference
1	Electrobioremediation of recalcitrant pollutants and xenobiotics	(Sevda et al. 2018; Chakraborty et al. 2020b; Chandrasekhar et al. 2020; Wang et al. 2020b)
2	In situ remediation of groundwater and soil	(Cecconet et al. 2020; Li et al. 2020)
3	MFC-coupled hybrid systems for environmental remediation and resource recovery	(Yang et al. 2019; Zhang et al. 2019b; Elmaadawy et al. 2020; Wang et al. 2020a)
4	Energy recovery from urine and solid wastes	(Gurjar and Behera 2020; Santoro et al. 2020)
5	Recycling elements using self-sustaining photosynthetic MFCs	(Greenman et al. 2019; Mekuto et al. 2020)
6	MFC-based biosensors	(Sun et al. 2015; ElMekawy et al. 2018; Jiang et al. 2018; Sevda et al. 2020)
7	Energy harvesting and storage in combination with electrochemical capacitors and as supercapacitive MFCs	(Caizán-Juanarena et al. 2020; Soavi and Santoro 2020)
8	Carbon capture and microbial electrosynthesis of value-added products	(Roy et al. 2015; Das et al. 2019; Chu et al. 2020)
9	Platform technology for novel applications	(Butti et al. 2016; Zou and He 2018; Hoareau et al. 2019)

Conclusions

The pursuit of alternate sources of energy due to the consequences of an unabated rise in human population has directed attention of researchers towards MFCs which essentially perform a dual-role of wastewater treatment and clean energy production. The steady increase in the number of research articles published on MFCs (Md Khudzari et al. 2018) over the last 15 years is an indicator of the steadfastness and commitment of the research community. Moreover, among the several books written or compiled on MFCs, the following three which encapsulate significant advances pertaining to construction, characterization, applications and diversification of this technology deserve a mention: Microbial fuel cells (Wiley-Interscience) (Logan 2008), Microbial Electrochemical Technology: Sustainable Platform for Fuels, Chemicals and Remediation (Elsevier) (Venkata Mohan et al. 2018) and Microbial Electrochemical Technologies (Routledge/CRC Press) (Tiquia-Arashiro and Pant 2020).

However, what goes unnoticed is the increasing number of students opting for MFCs and related technologies for their projects at high school and university levels due to the societal relevance of these topics. Considering the fact that data presented in such project reports often trigger more specialized and resource intensive studies, it might be worthwhile exploring the creation of a platform to document and collate promising results from such projects. Moreover, acknowledging the efforts of these young contributors, in a noteworthy manner, in research publications resulting from these leads would encourage more exploratory studies by students.

Planning for a student project or designing a research experiment might seem to be an elementary process because of the seemingly limitless possibilities that exist to observe the effects of tweaking the diverse physico-chemical and biological variables that directly or indirectly influence MFC performance. However, it would preferable to align the scope of such investigations to the aforementioned four major objectives of MFC research—keeping electrochemical losses under check, boosting electron transfer efficiency, bringing down operational costs and upscaling systems for practical applications—so that it results in a significant contribution to the existing body of knowledge.

MFCs have been prototyped in various shapes and sizes; each new configuration presenting an improvement over the others in some aspect of performance. Alterations to MFC configurations will continue in the quest for models that can be effectively implemented on a large scale. The understanding of variables associated with MFC performance has certainly improved over the years and the inventory of materials that improve the performance of MFCs is also continually expanding. These must go hand-in-hand with efforts to curb costs of scaled-up systems. Agricultural wastes, for instance, are carbon-rich materials that can be carbonized and exploited as low-cost electrode material. However, such substitutions can imply a trade-off with performance efficiency, opening up new avenues for detailed optimization studies using statistical methods such as response surface methodology.

Carrying out mathematical modeling and computer simulations can provide a near-realistic estimate of the optimal configuration, components and operating parameters to be employed under a given set of conditions for specific applications. Designing high-throughput methods for screening performance of components and operating parameters is a challenge that is still relevant and needs attention; especially because of the inter-relationships among the physico-chemical and variables influencing MFCs.

The fact remains, however, that the biological component will always be a complex variable that cannot be precisely modelled; and thus needs more focused attention for unravelling unknown facets of bacterial metabolism and energetics specifically in the context of bioelectrochemical systems. Community dynamics of microbial consortia in electroactive biofilms powering microbial electrochemical systems are still being understood. In silico analyses of genomic and proteomic data in openly available repositories such as the National Center for Biotechnology Information (www.ncbi.nlm.nih.gov), Worldwide Protein Data Bank (www.wwpdb.org), European Bioinformatics Institute (www.ebi.ac.uk) and many others make it possible to gain insights into the mechanistic aspects of bacterial electron transfer systems and processes. Metagenomic approaches for microbial community profiling are gaining relevance as they also account for bacteria which cannot be easily cultured in laboratory conditions. Sophisticated protein modelling and visualization tools available today can uncover hitherto unknown aspects of bacterial respiratory proteins and biofilm-associated proteins (www.biofilms.biosim.pt). Protocols employed for control of biofilms, especially in the food and healthcare sectors where they are known to be a nuisance, could provide useful hints to develop methods for promoting their growth in bioelectrochemical systems.

Tutorial articles on a design of experiments approach to effectively plan experiments and on electrochemical techniques for performance characterization will help in handholding students and scientists from diverse backgrounds to set-up the working environment. Limited access to equipment for electrochemical characterization, often not affordable for school and colleges not having established routes to obtain funding, can be a major bottleneck for obtaining reliable results. Efforts to bring down costs of basic instrumentation using micro-controllers (Meloni 2016; Li et al. 2018b) would bolster the quality of results of academic projects relating to MFCs.

As evidenced by literature, what began as a fascinating phenomenon over a century ago has evolved into a fertile avenue for researchers from different disciplines to converge and contribute (Fig. 7). The journey of MFCs seems to be akin to the folk-tale of the six blind men who tried to describe an elephant; each one basing his judgement on a part of the animal that he felt with his hands. It was only when all their views were rationally consolidated that they perceived the bigger picture and came to the conclusion that an elephant is actually much more than just fan-like ears, pillar-like legs, spear-like tusks, a tube-like trunk, a rope-like tail and a wall-like body. Multidisciplinary approaches and transdisciplinary efforts have demolished traditional barriers and bridged the gaps which had prevailed in the earlier years on account of adopting a simplex approach

Fig. 7 MFC research can be classified under many subject areas

towards harnessing energy from wastewater using microbial catalysts.

The plethora of applications conceptualized, demonstrated and envisaged portray microbial electrochemical technologies as a 'magic bullet' for impending sustainability crises. However, global sustainability issues can be successfully addressed by MFCs only if the efforts are collated, structured and directed towards a common objective of practical application of these technologies. Singular efforts in multiple directions would only result in a tug-of-war between research groups of varying skills and capabilities. Rather, a collaborative approach at the regional level could optimally utilize the available pool of expertise for the output of MFCs to reach usable levels in large scale applications at affordable costs. Established groups must take the lead in their respective regions for drawing up a framework and charting a roadmap for other fledgling groups to also contribute in their respective niche areas towards a common objective of societal benefit. The untiring efforts of the International Society for Microbial Electrochemistry and Technology (www.is-met.org) in this direction will certainly go a long way in making this possible. As it has been rightly said: "*Coming together is a beginning. Keeping together is progress. Working together is success.*"

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Declarations

Conflict of interest The author declares no conflict of interest in the publication.

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