Design and Configuration of Microbial Fuel Cells

Tooba Touqeer, Waheed Miran, Muhammad Waseem Mumtaz, and Hamid Mukhtar

Abstract The use of bacterial metabolism to oxidize organic matter and transfer electrons to the solid surface (electrode) leads to the development of microbial fuel cell (MFC) technology. Although MFCs have been utilized for biosensors, metals ion recovery, nutrient remediations, and synthesis of organic compounds; however, wastewater treatment and bioelectricity generation is the most generic application of MFC technology. The limitation in the commercialization of MFC is the lower power output and lack of efficient scale-ups. The MFC performance has been improved by optimizing the process parameters and various MFC reactor configurations with a focus on optimizing ohmic resistance, mass transport, and reaction kinetics. The vast research carried out on MFCs globally has led to various reactor designs. The vital components of MFC design include a group of separators, electrode materials, and reactor geometry. This chapter gives a detailed overview of conventional MFC configurations and current development in the innovative MFC designs for enhanced MFC performance and novel applications.

Keywords Microbial fuel cell · Scale-up · High-throughput system · Wastewater treatment · Bioelectricity

1 Introduction

Organic wastes and wastewater treatment are necessary for environmental protection that requires high energy [41]. Also, rapidly depleting fossil fuel resources

---

T. Touqeer · M. W. Mumtaz (✉)
Department of Chemistry, University of Gujrat, Gujrat 50700, Punjab, Pakistan
e-mail: muhammad.waseem@uog.edu.pk

W. Miran (✉)
School of Chemical and Materials Engineering, National University of Sciences and Technology, Islamabad 44000, Pakistan
e-mail: waheed.miran@scme.nust.edu.pk

H. Mukhtar
Institute of Industrial Biotechnology, Government College University Lahore, Lahore, Pakistan

A. Ahmad et al. (eds.), *Microbial Fuel Cells for Environmental Remediation*,
Sustainable Materials and Technology,
https://doi.org/10.1007/978-981-19-2681-5_3

along with a recent increase in their consumption are serious global issues [49]. These problems have urged scientists globally to find renewable energy resources and economical waste treatment technologies [64]. In this regard, the use of microorganisms to produce electricity with subsequent waste treatment has emerged as a potential technology termed microbial fuel cell (MFC) [58]. In MFC, the microorganisms act as biocatalysts and help in degrading the wastes which are ultimately converted into biocurrent/bioelectricity. This eco-friendly electrochemical device provides dual benefits, i.e., waste treatment and electricity generation [40]. MFCs have been employed for various kinds of municipal as well as industrial wastewaters for simultaneous electricity generation and wastewater treatment [16, 38]. Other applications include biosensors, metal ion recovery, nutrient remediations, and the synthesis of high-value compounds.

Generally, the MFC comprises cathode and anode chambers which are separated by a proton exchange membrane (PEM) [29]. The anodic chamber contains microbes that act as a biocatalyst to decompose waste materials. As a result, electrons are produced that are transferred to the cathodic chamber via an external circuit. The protons diffuse to the cathode through PEM and combine with electrons and O_2 to form water [15]. In most of the cases, current production is very small, so many advancements have been suggested by the scientists to get better performance by the MFCs and to find the most suitable feedstock [2], microbial consortia [26], catholyte/anolyte strength [34], and electrodes [44]. Electrochemical cell configuration is another very important domain that could improve the MFC performance [65].

The commercialization of MFCs requires the scaling-up of reactors. Various proposals which have been suggested include modifications in the design of electrodes, the design of membrane, using membrane-less reactors, and stacked systems. Some researchers have shown that a linear increase in power output can be achieved by expanding the size of MFC systems by stacking many units [69]. To get better power output, many researchers recommend minimizing the size of the MFCs system and sustaining a high feedstock supply, with optimization of the number of units for efficient performance. Another advantage of minimizing the MFC size is to explore MFC for various micro-level applications such as remote biosensors instead of bioenergy generation (which aims at offsetting the power requirements for wastewater treatment). In recent times, high-throughput MFC systems have been also designed for expediting the research in the MFC field by studying many parameters simultaneously for optimizing the MFC systems. In this chapter, we will discuss the advancements in configuration and design of MFCs which are economically feasible and that could be utilized to scale up the MFC reactor to get improved outputs. Future aspects and suggestions to further advance the MFC technology are also discussed.

2 Design and Configuration of MFCs Reactor

Cell design is a very important component in the successful operation of MFC. There is not a single standard size, configuration, or design for the MFC reactors. The configuration is entirely dependent on the researchers for a specific application. MFC performance based on reactors configuration could be controlled by various factors such as varying volumes, supply of oxygen, area of the membrane, and spacing of electrode [39]. Different reactor shapes, such as cylindrical, cubic, horseshoe, and H-shaped reactors have been proposed. Single and dual-chamber MFC reactors have been commonly studied in most MFC research projects [51]. Among the various shapes of MFC, H-shaped reactors are typically used in MFC due to the easy placement of PEM. The cell material could be glass or some type of plastic [20]. The size of the reactor varies from square centimeters to square meters having a volume of microliters to thousand liters [8]. MFC configurations based on different designs are discussed below.

2.1 Configuration Based on Number of MFC Chambers

2.1.1 Single-Chamber MFCs

Natural aeration of cathode for utilizing O_2 as the ultimate electron acceptor leads to the construction of MFCs with one chamber and air cathode assembly (Fig. 1). In the single-chamber MFCs, the cathode is directly connected to PEM permitting a direct supply of oxygen to the electrode [67]. Several advantages associated with single-chamber MFC include simple operation, less internal resistance, small electrode spacing, better proton diffusion as well as an efficient cathode for O_2 reduction [70]. Since no aeration is provided by using a compressor/pump and also catholyte is not required, this configuration makes it more easily adaptable and less expensive. In addition, more power density of single-chamber cell as compared to dual-chamber MFC has been reported in earlier studies [37]. Mainly this type of configuration

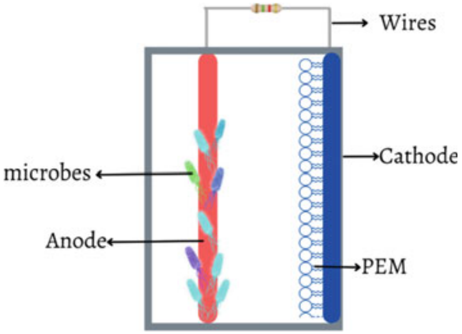

Fig. 1 Schematic presentation of a single-chamber MFC

comprises simple anodic chambers with no distinctive cathodic chamber and sometimes without any PEM. Cathode having pores on a side of the wall utilizes atmospheric oxygen and permits the protons to diffuse through the pores. The single-cell configuration is attracting researchers because of the above-mentioned advantages as well as ease of scaling-up of the system as compared to the dual-chamber MFCs [6, 37]. Carbon electrodes are used as anode in single-chamber MFC while the cathode is mostly PEM/carbon cloth hybrid or porous carbon electrodes [51]. However, cathode might be enclosed in graphite where electrolytes are added slowly which act as catholyte and avoided drying of the cathode and its membrane. Hence, fluid management is a limiting factor in such constructed cells. On the other hand, leakage of fluid, diffusion of oxygen, and evaporation are the flaws of this configuration and need to be addressed for efficient MFCs' operation. The use of different diffusion layers on the cathode surface has been proved to get better power density and oxygen diffusion [5, 71]. A comparison of a few of the studies involving single-chamber MFCs has been reported in Table 1.

2.1.2 Dual-Chamber MFCs

The two or dual-chambered MFC is also commonly used for energy generation along with wastewater treatment. It comprises anodic and cathodic compartments separated via a PEM (Fig. 2). PEM functions as a medium for the transfer of protons from the anode compartment to the cathode compartment [27]. The PEM also helps to prevent diffusion/contact of oxygen and other oxidizing agents to the anode [35].

Table 1 A comparison of single-chamber MFCs

Anode materials	Substrate	Power density	Coulombic efficiency	Microbial community	References
Graphite electrodes	Domestic wastewater	26 mW/m^2	-	*Geobacter metallireducens*	Liu et al. [36]
Carbon cloth	Artificial wastewater	-	5%	Activated sludge	Di Lorenzo et al. [12]
Toray carbon paper	Domestic wastewater	28 mW/m^2	28%	Bacteria from domestic wastewater	Liu and Logan [35]
Graphite pellets	Artificial wastewater	1.3 W/m^3	68%	Sludge collected from the treatment plant	Di Lorenzo et al. [13]
Carbon cloth	Beer brewery wastewater	483 mW/m^2 (12 W/m^3)	38%	Bacteria from domestic wastewater	Wang et al. [66]
Graphite coated stainless steel mesh	Dairy wastewater	20.2 W/m^3	26.87%	Mixed culture collected from dairy wastewater treatment plant	Mardanpour et al. [42]

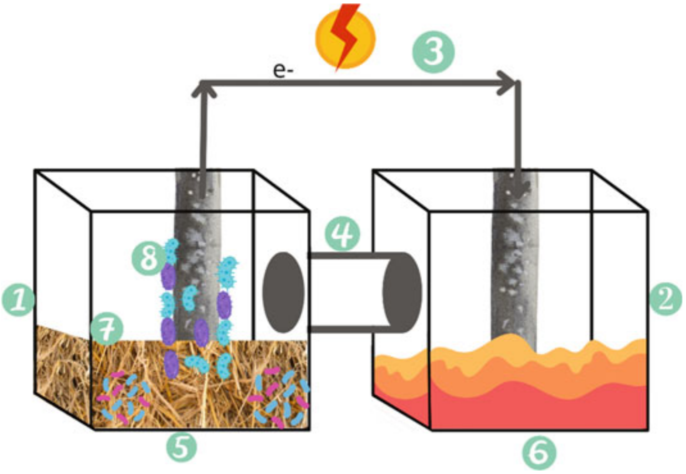

Fig. 2 Main components of dual-chamber MFC: 1. Anodic chamber with anaerobic conditions; 2. Cathodic chamber with air supply; 3. Wire for connecting electrodes; 4. Proton exchange membrane (PEM)/salt bridge; 5. Substrate to feed bacteria; 6. Catholyte; 7. Bacterial culture, and 8. Anode (with bacterial attachments)

Some problems associated with the dual-chamber microbial fuel cell are the large distance between the electrodes, which causes more internal resistance, the use of a batch process which requires regular maintenance, and enrichment of medium by some additives to get high current generation [52, 72]. These conditions for optimum power production are the hindrance to scaling up of the dual-chamber MFCs. Many studies have focused on the advancement of dual-chamber MFC to overcome the above-mentioned problems. For example, the internal resistance has been tried to reduce by having fewer distances between the two electrodes and placing them closer to the PEM but this will eventually reduce the power density by having more diffusion of O_2 from the cathodic chamber to the anodic side [18]. The continuous mode MFC has also been proposed which provides even better power density than simple bottle types dual-chamber MFC. In continuous mode dual-chamber MFC, configuration comprised a cathode hot pressed on a PEM connected with the anode and anchored with two polycarbonate plates where both chambers can be fed with feedstock in a continuous manner. Changing the electrode material in dual-chamber MFCs has also been shown to gain high MFC performance without the use of any external additives [30, 59]. Various other designs of two-chamber MFCs have also been proposed to resolve the issues related to the lower current output.

2.1.3 Stacked MFCs

Since scaled-up MFCs are urgently required to commercialize the MFC technology, stacking arrangements of modular multiple units is an applicable solution while

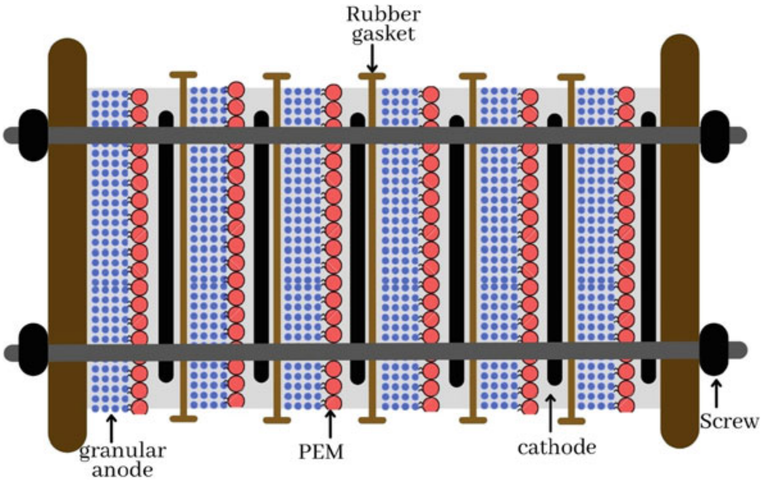

Fig. 3 Schematic presentation of stacked MFC

utilizing advanced power management systems [25]. In real applications, the multi-electrode assembly from the modular designs coupled with an electrical circuit for the storage of charge has been proposed for stacked MFCs [24]. A battery-style MFC can be formed by stacking the fuel cells (Fig. 3). The cell efficacy, i.e., power density, current, and voltage is known to be improved in stacked cells. Moreover, the Columbic efficacy of individual cell also remains unaffected. The cell stacking may be in a series or parallel manner [14]. Both methods are important and could be utilized as conventional power sources and the voltage and current requirements of electronic devices could be achieved. The design of parallel or series stacked MFC circuits is very crucial, and shape modulation and horizontal and vertical directions of the staking can considerably affect the cell efficacy [43, 57]. Efforts are in progress to further improve the MFC technology with better efficiency and feasibility, and for utilizing MFC stacks to meet the practical needs of the industry and society.

2.1.4 Configuration Based on MFC Size

MFC size is another design parameter intensively studied for commercializing the MFC technology. In this regard microliter to thousands of liter-scale MFC have been studied for various applications. The small-scale MFC manufacturing and deployment are relatively easy. In addition, they offer better prospects as a long-standing power source at distant sites for the avoidance of regular maintenance, converting waste into electricity and non-requirement of refined chemicals [4, 46]. Liter-sized MFCs have also been used for process optimizations and the development of MFC technology for practical purposes [3, 32]. Nevertheless, small-sized cells present better efficiency because of the small electrode distance which helps to avoid internal resistance. Another advantage is the small-sized electrode present provides a high surface-to-volume ratio and fast response time. Furthermore, the surface modification of small-sized electrode is far easier and more economical, and it offers better performance than large size cells [19]. Generic techniques for MFC fabrication are etching, metal deposition photolithography, and polymer molding. These could be applied for the fabrication of micro as well as macro-sized cells. Although large size MFCs provide better electrode material and microbial performance assessment, the conventional large-sized MFCs have limited performance because of large resistance and the low surface-to-volume ratio [11, 22]. High-throughput MFC systems are another domain in which investigations are being carried out for the advancement of the MFC system. Keeping in view the importance of micro-sized and high-throughput MFC systems, further discussion is provided below.

2.1.5 Micro-sized MFCs

The milliliter-scale MFCs have a huge potential for long-term power supply at remote sites where a regular change of batteries is impractical. The capability of bacteria for producing bioelectricity using indigenous resources helps in the easy deployment of micro-sized MFCs as there is no requirement for an external power source and artificial mediators [55]. With a proper supply of the carbon source, microbes' propagation and replenishing enable self-sustainable power generation. Other than milliliter-scale MFCs representation of miniatured MFCs, such MFCs are also designed for on-chip power production and fast screening of optimum operating conditions. The micro-sized MFC offers very unique features, such as a large surface area-to-volume ratio, shorter electrode distance, faster response time, and lower Reynolds number, along with various choices of design in constructing MFCs. The fabrications of miniature MFC devices are known to have high precision and have less cost when microfabrication processes are utilized. Also, the materials utilized for fabricating this type of MFCs are usually of inert character and have suitability for microbial research. The miniatured MFCs having carbon-based anodes [56] or improved designs having cloth electrode shows high efficiency than large-scale MFCs in terms of volumetric current and power densities [68]. The current milliliter-scale MFCs still have an issue of lower volumetric power densities and coulombic efficiencies because of the higher internal resistance. Nevertheless, such MFC systems have huge potential in the fast screening of electrochemically active strains and electrode materials [23].

Current microfabrication techniques offer improved design of MFCs having submicroliter reactor volume that enables improved biofilm growth at anodic electrode [53] and a quick startup [10]. Most of the miniatured MFC devices used similar design configurations as of the conventional dual-chamber MFC, i.e., they have anodic and cathodic chambers parted by a PEM. Polydimethylsiloxane (PDMS) and silicon are extensively utilized in such MFCs owing to the flexible designs they offer in microfabrication. Because of the smaller reactor volume, miniatured MFCs are usually provided with the electrolyte replenishing system for continuous or periodic exchange, and hence allow sustained operations [9, 54]. For instance, Fig. 4a

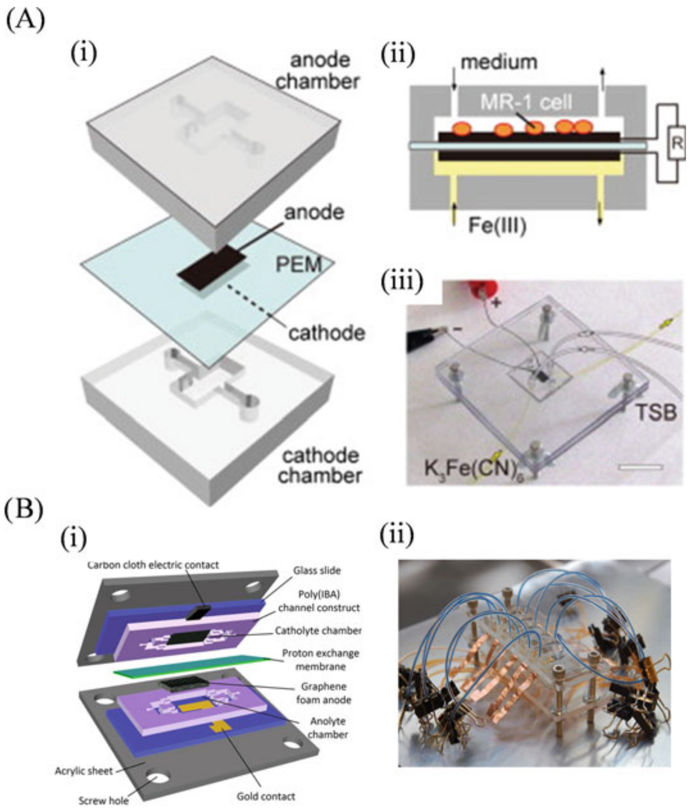

Fig. 4 **A** The design and assembly of a micro-MFC (i) the single MFC parts, (ii) a cross-sectional view of the MFC, and (iii) a picture of a PDMS micro-MFC. The scale bar is 2 cm. Adopted from [54]. **B** Microfluidic MFC design, showing (i) schematic of the device parts for the microfluidic MFC. (ii) Photograph of a ~1 × 1 × 3 inch^3 array of six microfluidic MFCs. Adopted from [28]

shows a micro-sized MFC system with a 4 μl chambers volume that has microfluidic flow cells for both anodes and cathodes [54]. Reproducible bioelectricity production and improved power densities were established. Further micro-sized improved MFC designs (Fig. 4b) allow the sustaining of a higher level of nutrient utilization, minimized the consumption of substrates, and reduced the response time of bioelectricity generation because of the fast mass transport [28].

Yet there are shortcomings in such MFC systems and to resolve these issues such as lower power of miniaturized MFCs, a combination of multiple MFCs in series or parallel can be utilized which help in achieving larger current and power output. Also, there is a reversal of voltage issue in these network systems which is required to be resolved for the long-term operation of MFC-based sensor networks and/or environmental toxin monitoring systems. A comparison of different micro-sized MFCs is provided in Table 2.

Table 2 A comparison of micro-scaled MFCs

Cell material	Microbes	Volume of anodic chamber	Anode material	Electrode distance	Power density	Columbic efficiency (%)	Refs.
Silicon	*Saccharomyces cevevisiae*	16 μL	Gold	160 μm	0.5 W/m^3	0.027	Chiao et al. [7]
Gortex	*Shewanella purtrefaciens*	10 μL	Gold with SAM	100 μm	–	–	Crittenden et al. [10]
PDMS/silicon	*Shewanella oneidensis* MR-1	1.5 μL	Gold	100 μm	15.3 W/m^3	2.8	Qian et al. [53]
Plastic	*Shewanella oneidensis* DSP-10	1.2 ml	Graphite felt	175 μm	660 W/m^3	8.3	Ringeisen et al. [56]
Plastic	Mixed bacterial culture	2.5 ml	Carbon cloth	1.7 cm	1010 W/m^3	71	Fan et al. [17]

2.1.6 High-Throughput MFCs

High-throughput MFCs are recently developed and used for the evaluation and microbial enrichment in different process conditions. In recent times [48], a 128-channel potentiostat is developed that connects with the printed circuit board. The entire array of channels was dipped in the anolyte medium, while a common reference electrode was used to carry out a high-throughput investigation for checking the effects of anode potentials on electroactive bacterial biofilms (Fig. 5a). Earlier, Zhou et al. developed a well-plate high-throughput colorimetry-based assay for the monitoring of bacterial respiration, which can show the presence of electroactive microbes associated with extracellular electron transfer (EET) capability [73]. Also, paper-based electrofluidic arrays having 6, 8, 64, and 96 wells via the fabrication method of wax printing have also been developed [21, 62, 63]. These designs help in eliminating the issues of small MFC devices such as large internal resistance, complicated assembling, and lower sample accessibility. One of the high-throughput-developed MFC reactors having 96-well plate showed these characteristics as well [60]. Additionally, it enables longer operational capability and reusability which helps in selective enrichments of EET-capable microbial culture. Also, such designs have better strength; therefore, they can be used for fieldwork which enables high-throughput in situ operations. The well plate connected to the potentiostat by electrical connections was similar to that described earlier [47]. Since the most widely studied application of MFCs is wastewater treatment, the microbial culture needs to be enriched for the specific wastewater treatment and to improve MFC performance. In this regard, preconditioning of consortia can be done using high-throughput systems which can help in achieving an easy scale-up process [1, 31]. For instance, a new 96-well MFC developed array (Fig. 5b) helped in the screening, selection, and sources of enriched EET culture by high-throughput [61]. The high-throughput MFC systems are still in their infancy, and continuous efforts are in progress to make them more reliable and useful for screening various optimization parameters.

3 Conclusions and Future Prospects

Various designs and configurations have been developed for MFCs to improve their performance and achieve commercialization of this emerging biotechnology. The designs and configurations include single chamber, dual chamber, stacked, micro-sized, large scale, and high throughput MFC systems. There is significant progress in the MFC research owing to various designs; however, many commercialization challenges are still being addressed and need further research. In addition to improving the power densities under real conditions, the capital and running costs linked with materials such as electrodes must be further reduced. For this, costly anodic and cathodic electrodes and catalyst layers on the cathode should not be used, as these costs add largely to the cost of MFC construction. Further scaling up is required with high surface area anodes and cathodes, which can help in achieving larger power

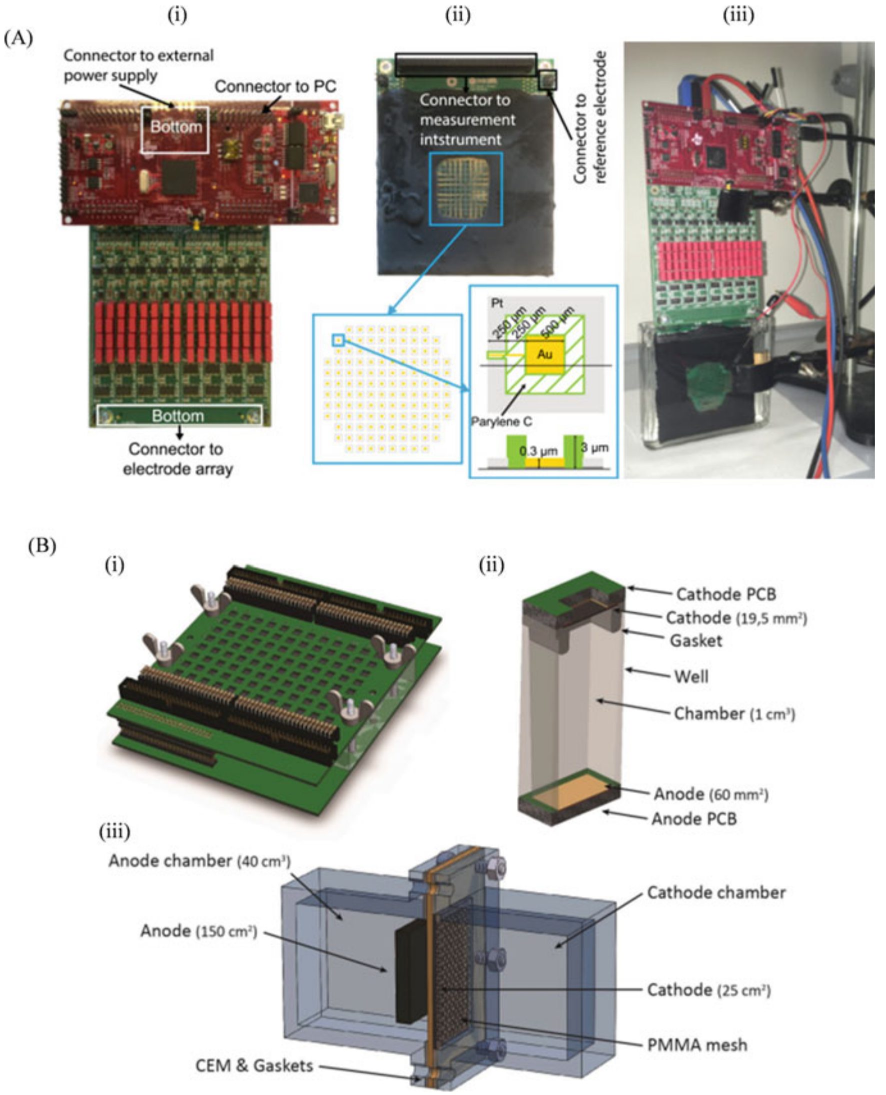

Fig. 5 **A** High-throughput bioelectrochemical system (i) a potentiostat having 128 channels connected to the computer (top view), (ii) 128 gold WE (0.5×0.5 mm^2) and platinum CE's scheme, and (iii) a complete bioelectrochemical system having 128-electrode array which is immersed in an electrolyte having a single RE. Adopted from [48]. **B** 3-D view of a 96-well MFC system including (i) the complete plate, (ii) cross-sections of individual wells, and (iii) a schematic of large-scale MFC. Adopted from [61].

densities. In the current scenario, because of lower bioelectricity production, expensive materials, and the continuously decreasing cost of renewable energy, it is less likely that bioelectricity produced from MFCs will outplay existing technologies. Therefore, applications other than bioelectricity production should also be considered and explored. Further, research is required in exploring the device configurations for minimizing the internal resistances for the improvement of micro-sized MFCs. Similarly, the high-throughput MFC systems for studying the impact of electrode's potential and external load for controlling bacterial metabolism are vital for understanding MFC operations. Currently, there are limited studies about high throughput MFC systems for EET capable microbial species and communities and it has huge potential for making a breakthrough in the commercialization of MFC technology. High throughput MFCs can be effectively utilized for various applications such as genetic engineering, screening of phenotypes, and mutants development studies for both microbial communities and single cultures [61]. With the recent discovery of human pathogens having EET capability [35, 45, 50], these systems can be very useful for evaluating the current production mechanism and the importance of EET-capable pathogens in human health, which can open a spectrum of new research areas.

References

1. AlSayed A, Soliman M, Eldyasti A (2020) Microbial fuel cells for municipal wastewater treatment: from technology fundamentals to full-scale development. Renew Sustain Energy Rev 134:110367
2. Angosto J, Fernández-López J, Godínez C (2015) Brewery and liquid manure wastewaters as potential feedstocks for microbial fuel cells: a performance study. Environ Technol 36(1):68–78
3. Babanova S, Jones J, Phadke S, Lu M, Angulo C, Garcia J, Carpenter K, Cortese R, Chen S, Phan T, Bretschger O (2020) Continuous flow, large-scale, microbial fuel cell system for the sustained treatment of swine waste. Water Environ Res 92(1):60–72. https://doi.org/10.1002/wer.1183
4. Chen S, Patil SA, Brown RK, Schröder U (2019) Strategies for optimizing the power output of microbial fuel cells: transitioning from fundamental studies to practical implementation. Appl Energy 233:15–28
5. Cheng S, Liu H, Logan BE (2006) Increased performance of single-chamber microbial fuel cells using an improved cathode structure. Electrochem Commun 8(3):489–494
6. Cheng S, Logan BE (2011) Increasing power generation for scaling up single-chamber air cathode microbial fuel cells. Biores Technol 102(6):4468–4473. https://doi.org/10.1016/j.biortech.2010.12.104
7. Chiao M, Lam KB, Lin L (2006) Micromachined microbial and photosynthetic fuel cells. J Micromech Microeng 16(12):2547
8. Choi S, Chae J (2013) Optimal biofilm formation and power generation in a micro-sized microbial fuel cell (MFC). Sens Actuat A 195:206–212
9. Choi S, Lee H-S, Yang Y, Parameswaran P, Torres CI, Rittmann BE, Chae J (2011) A μL-scale micromachined microbial fuel cell having high power density. Lab Chip 11(6):1110–1117. https://doi.org/10.1039/C0LC00494D
10. Crittenden SR, Sund CJ, Sumner JJ (2006) Mediating electron transfer from bacteria to a gold electrode via a self-assembled monolayer. Langmuir 22(23):9473–9476

11. Dewan A, Beyenal H, Lewandowski Z (2008) Scaling up microbial fuel cells. Environ Sci Technol 42(20):7643–7648
12. Di Lorenzo M, Curtis TP, Head IM, Scott K (2009) A single-chamber microbial fuel cell as a biosensor for wastewaters. Water Res 43(13):3145–3154
13. Di Lorenzo M, Scott K, Curtis TP, Head IM (2010) Effect of increasing anode surface area on the performance of a single chamber microbial fuel cell. Chem Eng J 156(1):40–48
14. Dizhou L, Meiying X, Yonggang Y (2020) Research progress of series and parallel stack of microbial fuel cells. Environ Chem 8:2227–2236
15. Du Z, Li H, Gu T (2007) A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. Biotechnol Adv 25(5):464–482
16. Fadzli FS, Bhawani SA, Adam Mohammad RE (2021) Microbial fuel cell: recent developments in organic substrate use and bacterial electrode interaction. J Chem 2021
17. Fan Y, Hu H, Liu H (2007) Enhanced Coulombic efficiency and power density of air-cathode microbial fuel cells with an improved cell configuration. J Power Sour 171(2):348–354
18. Fan Y, Sharbrough E, Liu H (2008) Quantification of the internal resistance distribution of microbial fuel cells. Environ Sci Technol 42(21):8101–8107
19. Feng Y, He W, Liu J, Wang X, Qu Y, Ren N (2014) A horizontal plug flow and stackable pilot microbial fuel cell for municipal wastewater treatment. Biores Technol 156:132–138
20. Flimban SG, Ismail IM, Kim T, Oh S-E (2019) Overview of recent advancements in the microbial fuel cell from fundamentals to applications: design, major elements, and scalability. Energies 12(17):3390
21. Gao Y, Hassett DJ, Choi S (2017) Rapid characterization of bacterial electrogenicity using a single-sheet paper-based electrofluidic array. Front Bioeng Biotechnol 5:44. https://doi.org/10.3389/fbioe.2017.00044
22. Hiegemann H, Littfinski T, Krimmler S, Lübken M, Klein D, Schmelz K-G, Ooms K, Pant D, Wichern M (2019) Performance and inorganic fouling of a submergible 255 L prototype microbial fuel cell module during continuous long-term operation with real municipal wastewater under practical conditions. Bioresour Technol 294:122227
23. Hou H, Li L, Cho Y, de Figueiredo P, Han A (2009) Microfabricated microbial fuel cell arrays reveal electrochemically active microbes. PLoS ONE 4(8):e6570–e6570. https://doi.org/10.1371/journal.pone.0006570
24. Ieropoulos I, Greenman J, Melhuish C (2008) Microbial fuel cells based on carbon veil electrodes: stack configuration and scalability. Int J Energy Res 32(13):1228–1240. https://doi.org/10.1002/er.1419
25. Jadhav D, Mungray AK, Arkatkar A, Kumar S (2021) Recent advancement in scaling-up applications of microbial fuel cells: from reality to practicability. Sustain Energy Technol Assess 45:101226. https://doi.org/10.1016/j.seta.2021.101226
26. Jadhav DA, Ghangrekar MM (2020) Optimising the proportion of pure and mixed culture in inoculum to enhance the performance of microbial fuel cells. Int J Environ Technol Manag 23(1):50–67
27. Jia Q, Wei L, Han H, Shen J (2014) Factors that influence the performance of two-chamber microbial fuel cell. Int J Hydrogen Energy 39(25):13687–13693
28. Jiang H, Ali MA, Xu Z, Halverson LJ, Dong L (2017) Integrated microfluidic flow-through microbial fuel cells. Sci Rep 7(1):41208. https://doi.org/10.1038/srep41208
29. Kim IS, Chae KJ, Choi MJ, Verstraete W (2008) Microbial fuel cells: recent advances, bacterial communities and application beyond electricity generation. Environ Eng Res 13(2):51–65
30. Kuchi S, Sarkar O, Butti SK, Velvizhi G, Mohan SV (2018) Stacking of microbial fuel cells with continuous mode operation for higher bioelectrogenic activity. Biores Technol 257:210–216
31. Li W-W, Yu H-Q, He Z (2014) Towards sustainable wastewater treatment by using microbial fuel cells-centered technologies. Energy Environ Sci 7(3):911–924
32. Liang P, Duan R, Jiang Y, Zhang X, Qiu Y, Huang X (2018) One-year operation of 1000 L modularized microbial fuel cell for municipal wastewater treatment. Water Res 141:1–8
33. Light SH, Su L, Rivera-Lugo R, Cornejo JA, Louie A, Iavarone AT, Ajo-Franklin CM, Portnoy DA (2018) A flavin-based extracellular electron transfer mechanism in diverse gram-positive bacteria. Nature 562(7725):140–144. https://doi.org/10.1038/s41586-018-0498-z

34. Linke L (2018) Optimization of electrolytes and electrodes to improve performance of microbial fuel cells (MFC) and microbial desalination cells (MDC). National University of Singapore (Singapore)
35. Liu H, Logan BE (2004) Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane. Environ Sci Technol 38(14):4040–4046
36. Liu H, Ramnarayanan R, Logan BE (2004) Production of electricity during wastewater treatment using a single chamber microbial fuel cell. Environ Sci Technol 38(7):2281–2285
37. Logan B, Cheng S, Watson V, Estadt G (2007) Graphite fiber brush anodes for increased power production in air-cathode microbial fuel cells. Environ Sci Technol 41(9):3341–3346. https://doi.org/10.1021/es062644y
38. Logan BE, Rossi R, Ragab A, Saikaly PE (2019) Electroactive microorganisms in bioelectrochemical systems. Nat Rev Microbiol 17(5):307–319. https://doi.org/10.1038/s41579-019-0173-x
39. Logan BE, Wallack MJ, Kim K-Y, He W, Feng Y, Saikaly PE (2015) Assessment of microbial fuel cell configurations and power densities. Environ Sci Technol Lett 2(8):206–214
40. Lovley DR (2008) The microbe electric: conversion of organic matter to electricity. Curr Opin Biotechnol 19(6):564–571. https://doi.org/10.1016/j.copbio.2008.10.005
41. Maktabifard M, Zaborowska E, Makinia J (2018) Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. Rev Environ Sci Bio/Technol 17(4):655–689. https://doi.org/10.1007/s11157-018-9478-x
42. Mardanpour MM, Esfahany MN, Behzad T, Sedaqatvand R (2012) Single chamber microbial fuel cell with spiral anode for dairy wastewater treatment. Biosens Bioelectron 38(1):264–269
43. Mateo S, Cantone A, Cañizares P, Fernández-Morales F, Scialdone O, Rodrigo M (2018) On the staking of miniaturized air-breathing microbial fuel cells. Appl Energy 232:1–8
44. Miran F, Mumtaz MW, Mukhtar H, Akram S (2021a) Iron oxide-modified carbon electrode and sulfate-reducing bacteria for simultaneous enhanced electricity generation and tannery wastewater treatment. Front Bioeng Biotechnol 9
45. Miran W, Naradasu D, Okamoto A (2021b) Pathogens electrogenicity as a tool for in-situ metabolic activity monitoring and drug assessment in biofilms. iScience 24(2):102068. https://doi.org/10.1016/j.isci.2021.102068
46. Mirhosseini A, Salvacion M, Chen S, Babanova S, Bretschger O (2016) Influence of anode configuration on flow distribution and performance in tubular microbial fuel cells. In: ECS Meeting Abstracts, vol 36. IOP Publishing, p 1841
47. Mohamed A, Ha P, Peyton B, Mueller R, Meagher M, Beyenal H (2019) In situ enrichment of microbial communities on polarized electrodes deployed in alkaline hot springs. J Power Sour 414:547–556. https://doi.org/10.1016/j.jpowsour.2019.01.027
48. Molderez T, Prévoteau A, Ceyssens F, Verhelst M, Rabaey K (2020) A chip-based 128-channel potentiostat for high-throughput studies of bioelectrochemical systems: optimal electrode potentials for anodic biofilms. Biosens Bioelectron 174:112813. https://doi.org/10.1016/j.bios.2020.112813
49. Muttitt G, Kartha S (2020) Equity, climate justice and fossil fuel extraction: principles for a managed phase out. Clim Policy 20(8):1024–1042. https://doi.org/10.1080/14693062.2020.1763900
50. Naradasu D, Guionet A, Miran W, Okamoto A (2020) Microbial current production from Streptococcus mutans correlates with biofilm metabolic activity. Biosens Bioelectron 162:112236. https://doi.org/10.1016/j.bios.2020.112236
51. Obileke K, Onyeaka H, Meyer EL, Nwokolo N (2021) Microbial fuel cells, a renewable energy technology for bio-electricity generation: a mini-review. Electrochem Commun 125:107003. https://doi.org/10.1016/j.elecom.2021.107003
52. Powell E, Evitts R, Hill G, Bolster J (2011) A microbial fuel cell with a photosynthetic microalgae cathodic half cell coupled to a yeast anodic half cell. Energy Sour Part A: Recov Utiliz Environ Effects 33(5):440–448

53. Qian F, Baum M, Gu Q, Morse DE (2009) A 1.5 μL microbial fuel cell for on-chip bioelectricity generation. Lab Chip 9(21):3076–3081. https://doi.org/10.1039/B910586G
54. Qian F, He Z, Thelen M, Li Y (2011) A microfluidic microbial fuel cell fabricated by soft lithography. Biores Technol 102:5836–5840. https://doi.org/10.1016/j.biortech.2011.02.095
55. Ren H, Lee HS, Chae J (2012) Miniaturizing microbial fuel cells for potential portable power sources: promises and challenges. Microfluid Nanofluid 13(3):353–381. https://doi.org/10.1007/s10404-012-0986-7
56. Ringeisen BR, Henderson E, Wu PK, Pietron J, Ray R, Little B, Biffinger JC, Jones-Meehan JM (2006) High power density from a miniature microbial fuel cell using Shewanella oneidensis DSP10. Environ Sci Technol 40(8):2629–2634. https://doi.org/10.1021/es052254w
57. Shin S-H, Choi Y-j, Na S-H, Jung S-h, Kim S-h (2006) Development of bipolar plate stack type microbial fuel cells. Bull Korean Chem Soc 27(2):281–285
58. Sivasankar V, Mylsamy P, Omine K (2018) Microbial fuel cell technology for bioelectricity. Springer
59. Srikanth S, Kumar M, Singh D, Singh M, Das B (2016) Electro-biocatalytic treatment of petroleum refinery wastewater using microbial fuel cell (MFC) in continuous mode operation. Biores Technol 221:70–77
60. Syzdlowski L, Ehlich J, Shibata N, Goryanin I (2021) High-throughput screening and selection of PCB-bioelectrocholeaching, electrogenic microbial communities using single chamber microbial fuel cells based on 96-well plate array. bioRxiv
61. Szydlowski L, Ehlich J, Goryanin I, Pasternak G (2022) High-throughput 96-well bioelectrochemical platform for screening of electroactive microbial consortia. Chem Eng J 427:131692
62. Tahernia M, Mohammadifar M, Gao Y, Panmanee W, Hassett D, Choi S (2020) A 96-well high-throughput, rapid-screening platform of extracellular electron transfer in microbial fuel cells. Biosens Bioelectron 162:112259. https://doi.org/10.1016/j.bios.2020.112259
63. Tahernia M, Mohammadifar M, Hassett D, Choi S (2019) A fully disposable 64-well papertronic sensing array for screening electroactive microorganisms. Nano Energy 65:104026. https://doi.org/10.1016/j.nanoen.2019.104026
64. Tan WH, Chong S, Fang H-W, Pan K-L, Mohamad M, Lim JW, Tiong TJ, Chan YJ, Huang C-M, Yang TC-K (2021) Microbial fuel cell technology—A critical review on scale-up issues. Processes 9(6):985
65. Tang RCO, Jang J-H, Lan T-H, Wu J-C, Yan W-M, Sangeetha T, Wang C-T, Ong HC, Ong ZC (2020) Review on design factors of microbial fuel cells using Buckingham's Pi Theorem. Renew Sustain Energy Rev 130:109878
66. Wang X, Feng Y, Lee H (2008) Electricity production from beer brewery wastewater using single chamber microbial fuel cell. Water Sci Technol 57(7):1117–1121
67. Watanabe K (2008) Recent developments in microbial fuel cell technologies for sustainable bioenergy. J Biosci Bioeng 106(6):528–536
68. Yang Y, Liu T, Tao K, Chang H (2018) Generating electricity on chips: microfluidic biofuel cells in perspective. Ind Eng Chem Res 57(8):2746–2758. https://doi.org/10.1021/acs.iecr.8b00037
69. Yang Y, Lu Z, Lin X, Xia C, Sun G, Lian Y, Xu M (2015) Enhancing the bioremediation by harvesting electricity from the heavily contaminated sediments. Biores Technol 179:615–618
70. Yano M, Tomita A, Sano M, Hibino T (2007) Recent advances in single-chamber solid oxide fuel cells: a review. Solid State Ionics 177(39–40):3351–3359
71. Zhang X, Cheng S, Huang X, Logan BE (2010) Improved performance of single-chamber microbial fuel cells through control of membrane deformation. Biosens Bioelectron 25(7):1825–1828
72. Zhang Y, Min B, Huang L, Angelidaki I (2011) Electricity generation and microbial community response to substrate changes in microbial fuel cell. Biores Technol 102(2):1166–1173
73. Zhou S, Wen J, Chen J, Lu Q (2015) Rapid measurement of microbial extracellular respiration ability using a high-throughput colorimetric assay. Environ Sci Technol Lett 2(2):26–30. https://doi.org/10.1021/ez500405t