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Review Article

Bioelectrochemical systems and their readiness for commercialisation

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Abstract

Conventional techniques for treating wastewater consume significant amounts of energy and depending on effectiveness, may result in secondary contamination. In this regard, the microbial fuel cell (MFC) technology has shown much promise as a revolutionary wastewater treatment + energy generation hybrid. This is due to the unique ability of electroactive organisms to generate direct electricity, recovering electrons from the breakdown and consumption of organic compounds in wastewater. This article critically assesses the current development of MFC technology, particularly in the last two years, focussing on the technology's economic and environmental feasibility. Even though there is a significant body of literature on MFCs with continuously increasing performance levels, the technology has not yet got fully commercialised to form part of urban planning or energy policy; this implies a lack of government consideration as a result of the absence of industrial scale research. The article presents the case for MFCs from a technology readiness level and life cycle assessment perspectives and explains why it is still premature to draw conclusions based on these two metrics.

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Keywords

Wastewater treatment, Microbial fuel cell, Bioelectricity production, Economical & environmental assessment, Technology readiness level.

Abbreviations

AD, Anaerobic Digestion; ALICE, Active Living Infrastructure: Controlled Environment; BES, Bioelectrochemical system; COD, Chemical Oxygen Demand; DC, Direct Current; DET, Direct Electron Transfer; HRT, Hydraulic Retention Time; LCA, Life Cycle Assessment; MDC, Microbial Desalination Cell; MEC, Microbial Electrochemical Cell; MFC, Microbial Fuel Cell; OPEX, Overall Operating Expenditure; Pb, Lead; PTFE, Polytetrafluoroethylene; R&D, Research and Development; TEA, Techno-Economic Assessments; TRL, Technology Readiness Level.

Introduction

There is a need to develop highly efficient technologies in order to meet water quality requirements and protect environmental biodiversity. In this regard, bioelectrochemical systems deservedly received a great deal of attention as a ground-breaking wastewater treatment method. It combines microbiology and bioelectrochemistry into a single device, which can perform the task of wastewater treatment whilst generating bioelectricity [1]. Microorganisms can remediate contaminated wastewater by consuming the organic and inorganic content, thereby leading to a reduction in its chemical oxygen demand (COD), whilst transferring electrons and releasing cations, resulting in direct current (DC) electricity generation. This inherently results in removal of harmful agents and restoration of elemental balance [2–4]. "Animal electricity", as it was originally called, was first demonstrated by Luigi Galvani in 1776, when he showed dead frog limb movement, after connecting electrodes and passing electricity through the biological tissue [5]. The first demonstration of a Microbial Fuel Cell (MFC), showing electricity generation from microorganism (*S. cerevisiae*), was first reported by Michael Cresse Potter in 1911, using glass beakers connected with a salt bridge [6]. Research development was slow, and apart from Barnett Cohen's MFC stack in 1930 [7], it was not until the late 1960s to early 1980s when researchers in Japan and Korea started focussing on enzymes, electrodes, redox mediators and materials [8–10]. After NASA's early pull-out from a space programme, which was going to look at the feasibility of MFCs as a technology for human waste treatment in space [11], scientific interest got reinvigorated in the 1990's with renewed efforts into microbial species, substrates and again redox mediators. It was the work mainly conducted by Peter Bennetto, Allen, Stirling and their collaborators, which resulted in the blueprint of the stereotypical MFC device that most labs across the globe use as their starting point in MFC research [12,13]. The direct electron transfer (DET) between a microorganisms and a conductive acceptor involves physical contact of the bacterium cell membrane or a redox-active membrane apparatus and the BES electrode. Direct extracellular electron-transfer mechanisms were reported on sediment bacteria such as *Shewanella* [14] *Geobacter* species [15] and *Rhodoferax* [16]. The discovery of long-distance direct extracellular electron transfer via nanowires was of revolutionary importance for the start of *electromicrobiology* [17].

The Bioelectrochemical System (BES) technology has made substantial advancements over the past 3 decades [18] by achieving significant improvements in the development of its constituent components, namely the anode and cathode electrodes and the semi-permeable separator [19,20]. Despite the technology's substantial advancement and wide deployment in numerous applications [21,22], industry and government initiatives have not yet considered BES as a serious contender for further industrial scale R&D; this is a critical factor in the eventual uptake of any technology.

Recent advancements in MFC technology are described in this study to assist in defining the readiness level of the MFC technology more accurately. In doing so, reports on life cycle assessment are critiqued within the wider context of market feasibility.

Recent advancements on MFC technology

According to Scopus, the number of publications from 2018 to 2023 increased by 2 times, when the keyword 'microbial fuel cell' was used exclusively; this demonstrates the ever-increasing interest from the scientific community. However, most of the studies are lab-based rather than in the field and commonly focus on general optimisation [23,24], anode improvement [25,26], cathode electrode and cathode catalyst development [27], membrane [28], substrate [29,30] and inoculum options [31,32]. In the last two years, studies have shown notable improvement in output performance, COD removal, power density, and coulombic efficiency [33–35]. Apart from wastewater treatment and electricity generation, biosensing [36], resource recovery [37], and hydrogen production [38] are amongst the many additional attributes of the technology. Fundamental studies focus on complex biofilm community and electrode interface as a system, and the impact of each operational and design parameter on the overall performance of the MFC [26,39]. More recently, modelling combined with AI as well as 3D fabrication of MFC bioreactors have been reported as an invaluable tool for understanding MFC potential and limitations [40,41].

Scaling-up and field work examples of MFCs

Scalability is always a critical factor in any commercialisation undertaking and how this is achieved can dictate a technology's commercial viability. For MFCs, increasing reactor volume, with concomitant increases in the cost of materials, results in decreasing performance levels, with respect to power and treatment [42]. Therefore, downsizing individual units and multiplying them in stack/cascades has been reported as an effective approach to achieving scale-up [43], especially when it comes to industrial wastewater treatment [44]. In a recent study [45], a vertical cascade of a plurality of MFCs resulted in higher power production than individual MFCs, as well as efficient COD removal. Furthermore, modular systems are more advantageous as they offer flexibility and reconfigurability, although there may be challenges with increased system complexity, which can be robustly addressed with effective engineering design.

Recently, low-power wireless sensor nodes were powered by double chamber microalgal MFCs with an energy generation capacity of 0.521 J per hour [46]. The first of its type of human-microbe interactive bio–digital interface, communicating real-time responses in an audio-visual manner, powered by MFCs, known as ALICE (Active Living Infrastructure: Controlled Environment), was also demonstrated [47]. Various examples of MFC systems at different scales/volumes have been field tested for feasibility, serving different purposes, ranging from several 10s–100s of units, treating wastewater, delivering remote power and even enhancing bio-robotics [48–51].

Technology readiness level and life cycle assessment of MFC

Technology readiness level (TRL) was designed by NASA as a measure of technology maturity for evaluating the range of technologies that were to be used for the moon landing [52]. Early stages of research or proofs of concept are at the lowest levels, whereas technological implementation and market diffusion are at the highest levels of readiness. The majority of research on MFCs, at least those with successful lab demonstrations, are commonly evaluated at TRL 4, whereas sporadic field studies range between TRLs 5–7, which are still a long way from market diffusion, i.e., TRL9; this represents a gap and a clear need for more field studies to inform the MFC technology commercialisation process.

Technology readiness is often informed by the scientific literature reporting on field data and full life cycle as well as techno-economic assessments (LCA & TEA).

LCA measures the environmental impact of a product's full life−cycle activity, whereas TEA aids in determining the economic viability of the product or activity in terms of efficiency, manufacturing and environmental stability. Given the high dependency of these evaluations in determining the fate of emerging technologies, they need to be robust, reliable and comparable.

Although LCA and TEA studies will identify important environmental and economical hotspots of a technology, premature assessments on a non-standardised lab-scale system, subject to local lab practice and material choice, may well conclude that the subject technology is either too expensive or largely inefficient. Moreover, the impact of the construction and operational phases of a single unit will most likely have a bigger environmental burden than a pilot-scale system in terms of impact-benefit and cost-benefit perspectives [53]. Despite the genuine intentions of understanding environmental and economic performance metrics, premature conclusions from assessments performed on inconsistent approaches (amongst international labs − also Table S1) may hinder the MFC R&D before it reaches scale-up, by biasing the interest of stakeholders and investors and therefore subsequently the TRL advancement of such a benevolent technology.

Table 1 below summarises the literature reporting on LCA specifically for MFCs, and Table S1 (See Supplementary Information) shows the criteria matrix for the different examples being included. A TRL-based table has not been attempted in this report due to the inconsistency in the comparison criteria as found in the current literature.

Common findings observed amongst LCA studies are included in Table 1, such as the need for better membrane materials and binders. In addition, pumping, so far an inevitable requirement, was often categorised as the greatest contributor to the environmental burden of these systems. Thus, a self-sustainable MFC installation/product or pumping powered by a renewable energy, could drastically reduce the environmental impact of the subject BES systems. In addition, the discovery of new materials offering better bacterial adhesion, higher surface areas and lower current collector losses, will result in increasing power density levels, which will change assessment findings and general opinion. Special considerations should be taken to unify as much as possible future LCA parameters, such as volume and quality of treated wastewater, which will also affect the retention time and energy consumption. More importantly, the differences between objectives (e.g. cradle-to-gate vs. cradle-to-grave) should be taken into consideration when comparing LCA studies.

A review on LCA and TEA [58] concluded that the overall operating expenditure (OPEX) of some specific examples of wastewater treatment MFCs comes to €1700−€2300/yr, which is low compared to existing processes. MFCs usually have high capital/constructing costs compared to established treatment systems, especially at large scales, and this is clearly a result of expensive lab-based prototyping. A TEA of nanomaterial-enhanced MFCs showed improved performance levels at high cost, which is expected from non-commercial materials [59]. The vast majority of MFC R&D is still lab-based, which means that inevitably, expensive materials are employed in proving a concept, before progressing to prototyping and beyond; when such examples are considered in LCA and TEA studies, then the result is likely to be unfavourable for the technology. Chin et al. [54] found that the environmental impact of single chamber flat type MFCs was higher when compared with other single chamber (air cathode; U-type) and double chamber MFCs (H-type; modularised MFCs), mainly due to high retention times. The operational stage of MFCs was found to give 60−90% higher environmental load compared to the construction stage, even though this is not 100% representative of field systems.

Numerous studies have found that MFCs lessen the environmental burden compared to the pollution created by conventional treatment units. Cetinkaya et al. [57] conducted a life cycle analysis of MFC-based biosensors for the purpose of detecting the toxicity of Pb^{2+} and discovered that the system had very little negative effect on both human health and the environment. Dhanda et al. [60] conducted an economic analysis of the graphene- and biochar-based cathode catalysts in MFCs to generate electricity. They claimed that biochar materials are regarded as inexpensive catalysts and that prior studies had suggested that they were suitable for large-scale MFCs. However, when the reactor volume was expanded beyond 50 mL, the economic analysis revealed that the costs of biochar and graphene as cathode catalysts were pretty much on a par. The study of Gupta et al. [61] reported that MFCs are more economically viable and profitable when energy and resource recovery is taken into account compared to the other conventional commercialised bioreactors for wastewater treatment.

Speight [62] carried out a survey of private UK and municipal US water utilities and found that the factors which best helped to drive innovation and the introduction of new technologies, were (i) a supportive culture of innovation within the water companies themselves; (ii) a regulatory regime which valued and promoted innovation; (iii) the capital available for research and innovation activities; and (iv) the backing of the public to make changes. Furthermore, Speight noted that private sector businesses, focused too much on financial considerations, whereas public-owned utilities, focused too much on political considerations; both

Table 1

Recent life cycle assessments [55,56].

Configuration of MFC/ other reactors	Applications	Remarks & Conclusions	Impact factors*																	Ref.
			Climate change/Global warming	Ozone depletion	Particulates formation	Photochem	Photochemical	Acidification	Eutrophication	Human toxicity	Ecotoxicity	Resource scarcity	Health damage	Ecosystem damage	Resources damage	GHG emissions	Abiotic depletion	Respiratory Inorganics	Ionizing Radiation	
Air-cathode, H-type, U-type, flat, and modularized MFCs compared with other BES	Wastewater treatment, Electricity generation and Resource Recovery	(i) Membrane distillation integrated MFC and double chamber air-cathode are the most environmentally friendly. (ii)MFC H-type in lab scale is 3 times more environmentally damaging than pilot-scale modularized MFC. (iii) Value added by-products and electricity generation reduce the impact generated from the systems.	✓		✓			✓	✓	✓	✓	✓								[65]
Air-cathode, H-type, U-type, flat, and modularized .	Wastewater treatment and Electricity generation	(i)High HRT (flat MFC) has increased environmental burden. (ii)OPEX more energy intensive than construction costs (electricity consumption).	✓		✓			✓	✓			✓	✓							[66]
MDC	Wastewater treatment Seawater desalination	(i) MDC currently has negative env. impact due to low power density, binder selection, and ion-exchange membrane fabrication. (ii) Cathode & desalination chamber manufacturing has significant environmental impact.	✓	✓			✓	✓	✓	✓	✓					✓	✓	✓		[67]
MFC, compared with MEC, MDC, and AD		(i) MEC shows better environmental performance due to value-added by-products. (ii)PTFE and membrane fabrication identified as environmental hotspots. (ii)MFC environmental impact compensated by increasing power.	✓	✓			✓	✓	✓	✓	✓					✓	✓	✓		[68]
Air cathode MFC	Biosensing of Pb^{+2}	(i)HRT key factor for electricity generation performance in the system. (ii)Low human health and environment impact; emissions to air, water, and soil are negligible.	✓	✓		✓				✓			✓	✓	✓				✓	[69]

*Some impact factors may have sub-classifications or were performed using different methods. Please refer to Supplementary Table S1 for more detail.

are imperfect when considered in isolation but would form a powerful innovation strategy if considered in tandem.

Conclusion/future perspectives

Although LCA and TEA can integrate data for the full potential of MFC, assumptions/conclusions derived from these studies serve as a double-edged sword for premature technologies. These useful tools help identify bottlenecks, and consequently take actions to improve the critical issues and overall performance. Such feedback cycle is essential for every technology's development. Nevertheless, early (or perhaps premature) assumptions of the overall feasibility of MFCs using lab-scale LCA and TEA can also hinder the path of this technology towards large-scale process at the industrial level, since they will serve as bias for stakeholders to divest away from the research needed for such a technology. Hence, decisions on technology development must be made with patience and full information at hand, at a much more mature stage of larger-scale research, rather than in a haste due to the race for '*being first*'.

On the other hand, hybridisation of technologies has proven to be a more effective strategy than rejection or full replacement of conventional methods. For instance, anaerobic treatment technologies may have lower treatment costs, but they are typically only appropriate for high-strength wastewater streams needing sizable workspace that ends up being an expensive cost; this is in addition to the input being strictly within narrow parameters to avoid affecting the balance of the microbial community. Additionally, the generation of sludge resulting from the operation needs further treatment. The MFC technology feasibly tackles these issues as both high and low strength operation can be done within a smaller footprint without any secondary sludge production, and it comes with the significant benefit of electricity generation. Thus, wastewater treatment systems will benefit from MFC-anaerobic wastewater treatment unit hybridization. Similarly, remote locations deprived of electricity for lighting or charging essential devices can be served a lot better by a MFC-photovoltaic hybrid. These are opportunities which have been largely unexplored, but which can offer huge benefits to humanity and our environment.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ioannis Ieropoulos reports financial support was provided by Bill & Melinda Gates Foundation. Ioannis Ieropoulos has patent #US20140057136A1_1 issued to University of the West of England and University of Southampton. Ioannis Ieropoulos has patent #WO2016120641A1_2 issued to University of the West of England and University of Southampton. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coelec.2024.101540.

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