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Microbial fuel cells and treatment wetlands: what is the future outlook?

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Highlights:

- MFCs as biosensors utilizing electrical signals to monitor water quality parameters.
- Insights to propel the practical advancement of TW-MFC-based biosensor technology.
- MFC for clogging detection in Treatment Wetlands.

Keywords: Biosensor; Constructed Wetlands; Electroactive biofilm.

INTRODUCTION

Microbial fuel cells (MFC) are bioelectrochemical systems that generate electricity from the chemical energy present in organic substrates through electroactive bacteria action (Luo et al., 2023). These bacteria form an electroactive biofilm that is responsive to environmental contaminants, such as heavy metals, or changes in organic charge load, leading to alterations in metabolic pathways and reaction kinetics, which can be observed as fluctuation in the produced electrical signal output (Liu et al., 2023). In this sense, considerable research has focused on leveraging MFCs as biosensors, utilizing current or voltage signals to monitor water quality parameters (Simoska et al., 2021). MFC-based biosensors offer numerous advantages, including rapid response, simplicity of operation, real-time monitoring capabilities, and cost-effectiveness (Olias & Di Lorenzo, 2021; Safwat et al., 2023).

Over the past decade, significant research efforts have been directed toward integrating MFCs into Treatment wetlands (TWs) to improve wastewater treatment performance and promote bioelectricity production (Huang et al., 2024). Moreover, MFC could be applied in TWs as biosensor, as Xu et al. (2017) demonstrated for the first time for chemical oxygen demand (COD) monitoring. Corbella et al. (2016) applied an MFC for clogging detection, observing that the accumulation of sludge in a horizontal TW causes a drop in the current generation. This study provides a novel insight by combining bibliometric analysis with a focus on MFC biosensors in the underexplored area of TW, aiming to expand their applications beyond traditional organic matter monitoring, exploring new opportunities for continuous, in-situ monitoring.

METHODOLOGY

The bibliographic data for this analysis was retrieved from the Scopus database on the 24th April 2024 based on Ji et al. (2021). Boolean operators, and parentheses were used to create “microbial fuel cell"” AND “(“sensor" OR "biosensor")” AND “(“wastewater" OR “water”)”. The resultant original data were then limited by “document types = research articles”, “languages = English”, “year = 2013 – 2024”. In the final step, reading was done to filter and remove irrelevant manuscripts. Therefore, 154 screened journal publications were found to be sufficiently relevant. Data bibliometric analysis was performed using VOSviewer software - version 1.6.15, Leiden University, NL (van Eck & Waltman, 2009) and Bibliometrix R tool (Aria & Cuccurullo, 2017).

RESULTS AND CONCLUSIONS

Over the past decade, there has been a noticeable increase in the annual publication output on MFCs and biosensors, highlighting the growing interest in this field. However, a decline in publications was observed during the COVID-19 pandemic (2020-2021). China, the United Kingdom, Canada, the United States, Spain, and Australia lead this research field, contributing 68.7% of the total publications with 65, 15, 9, 9, and 7 papers, respectively. Among the most productive institutions, the University of Bath, Tsinghua University and Newcastle University can be considered reference in the topic. Moreover, in the topic Jiang Y., Liu P., Huang X., Mirela Di Lorenzo and Li X. are recognized as the most relevant authors.

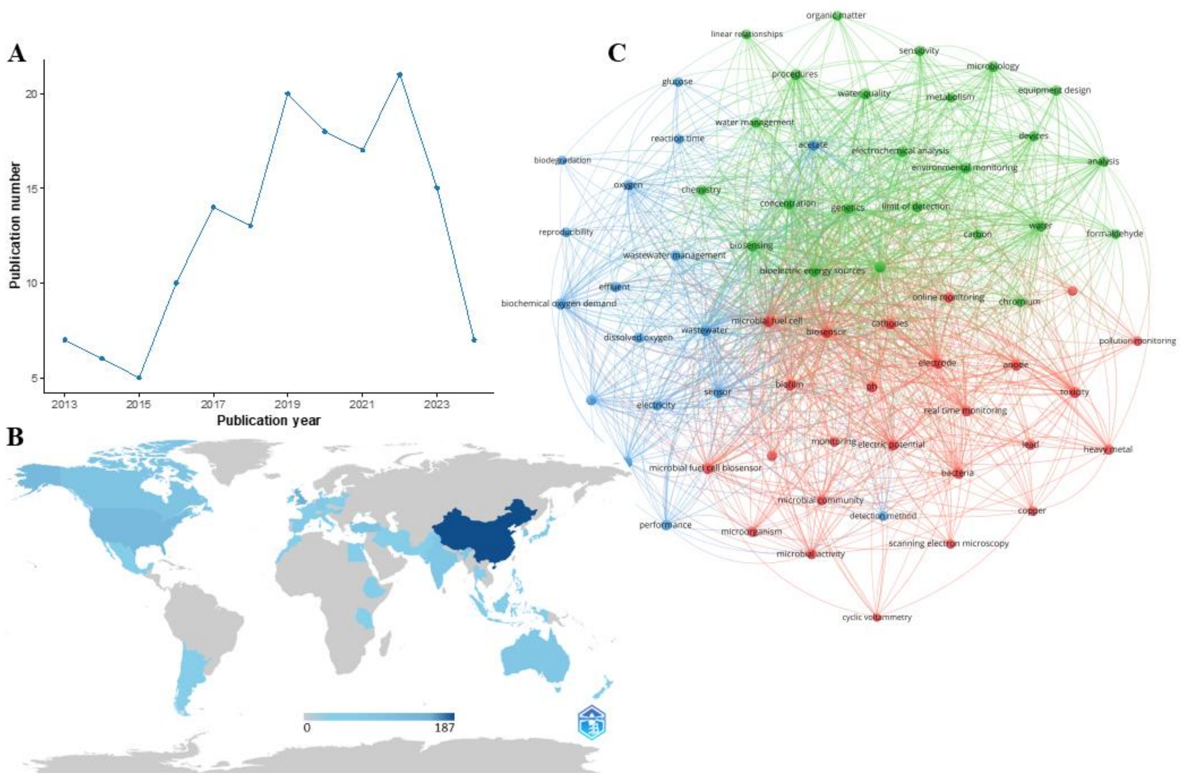

Figure 1 – (A) Number of publications between 2013 – 2024; (B) Countries scientific production; (C) Co-occurrence keyword network visualization map by VOSviewer.

The analysis of keywords is crucial for identifying key topics and research directions within a specific field. As shown in Figure 1, the keywords formed a co-occurrence network where they are grouped into three clusters, each represented by a distinct color, red, green and blue. The most frequently cited keywords reveal an emphasis on MFC biosensors (Huang et al., 2024), primarily related to organic matter (BOD – biochemical oxygen demand, COD), toxicity (heavy metals, formaldehyde), and dissolved oxygen detection in wastewater treatment. This aligns with Simoska et al. (2021), who also highlight the application of MFC sensors BOD, toxicity, dissolved oxygen, corrosion, and pathogen detection.

Standard analytical methods for detecting and quantifying toxic compounds are time-consuming, costly, and complex. They require skilled personnel and are unsuitable for real-time or in-situ monitoring (Nong et al., 2024). In contrast, MFC biosensors offers an alternative due to their ability to monitor a wide range of pollutants faster than traditional methods, with simpler operation, no need for additional reagents, and compatibility with online, long-term, and in-situ applications (Spurr et al., 2021).

Notably, the keyword "*constructed wetland*" has garnered increasing attention in the field. The Table 1 presents the manuscripts that includes the MFC as a biosensor in TW. The current studies have mainly focused organic matter monitoring (Corbella et al., 2019; Lu et al., 2021; Xu et al., 2017, 2020), clogging (Corbella et al., 2016) and pollutants (Xu et al., 2020). The results indicates a good performance in monitoring those targets in TW. However, MFC-based biosensors possess the potential to monitor additional environmental parameters (Fig.1C), suggesting an opportunity to expand the MFC based biosensor in TW field. Given the increasing use of TWs for the removal of a broad spectrum of pollutants, such as antibiotics, pesticides, heavy metals, and microplastics, monitor they is crucial. TW-MFC biosensor systems could provide fast, continuous, in-situ, non-invasive monitoring of parameters like oxygen level, heavy metals (Pb, Cr, Cu), antibiotics, and endocrine-disrupting chemicals (EDCs).

TW configuration	**Target**	**Feeding sample**	**Sensnsing Range**	**Coefficient of determination (R^2)**	**Reference**
HSSF	Solid accumulated (clogging)	Sludge	21.5 – 252.0 kgTS/m^{3}TW.year	R^2 = 0.93 – 0.95	(Corbella et al., 2016).
VF	COD	SS	0 – 1000 mg/L	R^2 = 0.9710 (0 – 500 mg/L); R^2 = 0.9245 (500 – 1000 mg/L)	(Xu et al., 2017)
HSSF	COD	DW	0 - 200 mg /L	R^2 = 0.84 – 0.9514	(Corbella et al., 2019)
VF	COD, herbicide, Cu^{2+} and NO_3^-	SS	0 – 200 ppm	N/A	(Xu et al., 2020)
VF	COD	SS	50 - 1000 mg/L	R^2 > 0.97	(Lu et al., 2021)

Table 1 – MFC based biosensor applied in TW. Note: TW – Treatment Wetland; HSSF – horizontal; VF – Vertical Flow; COD – Chemical Oxygen Demand; Cu – cooper; NO_3^- - nitrate; SS – Synthetic solution; DW – Domestic Wastewater; TS – total solid; ppm – particle per million; N/A – Not available.

Moreover, Corbella et al. (2019) suggested the application of MFC-based biosensors to detect the clogging in horizontal configuration. At the current stage, there is no in-situ and continuous available method to evaluate the clogging in TW. Then, it is necessary to spread this device to other TW configurations. For example, in French TW systems, as clogging progresses, oxygen diffusion within the filter drops. Then, it is hypnotized that this change could be detected through the oxygen reduction reaction in the MFC biosensor cathode. This expanded monitoring capability could improve TW management, enabling more precise and real-time pollutant tracking, reducing operational failures, and enhancing overall treatment efficiency. Up to now, there is no in-situ and continuous available method to evaluate the clogging in TW.

Despite these advantages, MFC-based biosensors face challenges to detect low or high concentration and require calibration. Furthermore, the presence of interfering substances can affect sensor accuracy. Nonetheless, MFC biosensors have the potential to act as early warning systems in TWs, helping to prevent treatment failures. With further research into synergistic TW-MFC based biosensor systems, this approach holds the potential to transform the in situ and continuous monitoring of pollutants and state, contributing to the future of sustainable wastewater treatment trough TW.

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REFERENCES

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics*, *11*(4), 959–975.

Corbella, C., García, J., & Puigagut, J. (2016). Microbial fuel cells for clogging assessment in constructed wetlands. *Science of the Total Environment*, *569*, 1060–1063.

Corbella, C., Hartl, M., Fernandez-Gatell, M., & Puigagut, J. (2019). MFC-based biosensor for domestic wastewater COD assessment in constructed wetlands. *Science Of The Total Environment, 660*, 218–226.

Huang, M., Zhao, L., Chen, D., Liu, J., Hu, S., Li, Y., Wang, Z., Yang, Y., & Moreira, M. T. (2024). Bibliometric analysis and systematic review of electrogenic bacteria in constructed wetland-microbial fuel cell: Key factors and pollutant removal. *Journal of Cleaner Production*, *451*, 142018.

Ji, B., Zhao, Y., Vymazal, J., Mander, Ü., Lust, R., & Tang, C. (2021). Mapping the field of constructed wetland-microbial fuel cell: A review and bibliometric analysis. *Chemosphere*, *262*, 128366.

Liu, S.-H., Zhu, T.-J., & Lin, C.-W. (2023). Biotoxicity monitoring of Bisphenol A using microbial fuel cell sensors: Optimizing the response of sensor's voltage changes to toxicity and assessing the impact on the application to river water monitoring. *Biochemical Engineering Journal*, *200*, 1369–1703.

Luo, J., Tian, W., Jin, H., Yang, J., Li, J., Wang, Y., Shen, W., Ren, Y., & Zhou, M. (2023). Recent advances in microbial fuel cells: A review on the identification technology, molecular tool and improvement strategy of electricigens. *Current Opinion in Electrochemistry*, *37*, 101187.

Lu, R., Chen, Y., Wu, J., Chen, D., Wu, Z., & Xiao, E. (2021). In situ COD monitoring with use of a hybrid of constructed wetland-microbial fuel cell. *Water Research*. 210, 117957.

Nong, Y., et al. (2024). Low temperature acclimation of electroactive microorganisms may be an effective strategy to enhance the toxicity sensing performance of microbial fuel cell sensors. *Water Research*, 256, 121566

Olias, L. G., & Di Lorenzo, M. (2021). Microbial fuel cells for in-field water quality monitoring. *RSC Advances*, *11*(27), 16307–16317.

Safwat, S. M., et al. (2023). Dual-chamber microbial fuel cells as biosensors for the toxicity detection of benzene, phenol, chromium, and copper in wastewater: Applicability investigation, effect of various catholyte solutions, and life cycle assessment. *Process Safety and Environmental Protection*, *170*, 1121–1136.

Simoska, O., et al. (2021). Recent trends and advances in microbial electrochemical sensing technologies: An overview. *Current Opinion In Electrochemistry*, *30*, 100762.

Spurr, M. W., et al. (2021). No re-calibration required? Stability of a bioelectrochemical sensor for biodegradable organic matter over 800 days. *Biosensors and Bioelectronics*, *190*, 956–5663.

van Eck, N. J., & Waltman, L. (2009). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538.

Xu, L., Yu, W., Graham, N., & Zhao, Y. (2020). Revisiting the bioelectrochemical system based biosensor for organic sensing and the prospect on constructed wetland-microbial fuel cell. *Chemosphere*, *264*, 128532.

Xu, L., Zhao, Y., Fan, C., Fan, Z., & Zhao, F. (2017). First study to explore the feasibility of applying microbial fuel cells into constructed wetlands for COD monitoring. *Bioresource Technology*, *243*, 846–854.