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Microbial fuel cells integrated in constructed wetlands: systematic review on current status, challenges, and opportunities

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Introduction: Constructed wetlands (CWs) are widely applied as low energy, nature-based wastewater treatment systems, particularly in decentralized contexts, while microbial fuel cells (MFCs) are increasingly being investigated to recover energy through bioelectrochemical processes that are favored by the redox gradients present within CWs. The integration of these two sustainable solutions is gaining increasing attention due to its potential to generate synergistic benefits. However, despite the growing number of studies on CWMFC systems, there still remains a lack of consolidated synthesis regarding system design, performance outcomes, and intensification strategies (approaches that enhance process efficiency by accelerating reaction rates, improving electron transport, and maintaining redox stratification for stable system operation). Consequently, several critical knowledge gaps persist, including limited reporting on long-term stability and durability, insufficient economic assessments, lack of standardized design and performance metrics, and underrepresentation of microbial community structure and function.
Methodology: This review covers CW-MFC studies published between 2010 and 2026 across several regions of the world and includes laboratory, mesocosm, pilot, and full-scale systems, focusing on system design, operational strategies, microbial processes, treatment, and energy recovery performance.
Results: Most CW-MFC studies are at laboratory and pilot scale, with limited full-scale applications, and their performance depends primarily on reactor and flow regime configurations, electrode materials and their positioning, substrate type, and redox gradient profile. Many studies have reported encouraging Chemical Oxygen Demand (COD) and nutrient removal efficiencies, with values reaching up to 99% COD removal, 95% Total Phosphorus (TP) removal, and 100% ammonium-nitrogen (NH4 +-N) removal. CW-MFC systems generally improve organic matter and nutrient removal compared to conventional CWs; however, the electrical energy recovered is typically low and tends to decrease with increasing system scale.
Discussion: Overall, CW-MFC systems are best regarded as sustainable, multifunctional wastewater treatment technologies rather than primary energy

recovery systems, as their practical feasibility is more constrained by long-term stability, material durability, and insufficient economic reporting rather than by treatment performance.

KEYWORDS
constructed wetlands, energy recovery, full-scale systems, microbial fuel cells, wastewater treatment

1 Introduction

The increasing demand for sustainable wastewater treatment technologies and renewable energy sources has stimulated significant research interest in systems that integrate environmental remediation with energy recovery. Within this context, constructed wetlands (CWs) and microbial fuel cells (MFCs) have emerged as key research areas. CWs have earned a prominent place among wastewater treatment technologies, especially in decentralized systems and rural areas. In many studies it is defined as an artificially engineered pollutant-removing composite ecosystem (Liu et al., 2024; Kadlec and Wallace, 2008; Vymazal, 2010) that combine the physico-chemical and biological processes to perform multiple functions (Calheiros et al., 2015). Likewise, CWs are described as biologically engineered systems (Ramirez-Vargas et al., 2019) that simulate natural wetland and represent a sustainable, well-established technology for treating different types of wastewater with low operational and maintenance costs (Fernandez-Gatell et al., 2022; Penacoba-Antona et al., 2022; Srivastava et al., 2020; Youssef et al., 2024).

MFCs have been extensively studied for their potential to generate bioelectricity and simultaneously treat wastewater (Colares et al., 2022; Penacoba-Antona et al., 2022; Sonawane et al., 2024; Xu et al., 2016; Saeed et al., 2022). In these systems, electroactive microorganisms catalyze the oxidation of biodegradable organic matter present in wastewater at the anode, under anaerobic conditions. During this process, organic substrates are metabolized, releasing electrons and protons as by-products. The electrons are transferred to the anode and flow through an external electrical circuit to the cathode, generating an electric current, while protons migrate through the electrolyte or a proton exchange medium. At the cathode, electrons react with protons and a terminal electron acceptor, typically oxygen, to complete the electrochemical reaction. This bioelectrochemical process enables the direct conversion of chemical energy stored in wastewater into electrical energy, while simultaneously achieving pollutant removal through microbial degradation of organic matter (Sonawane et al., 2024; Xu et al., 2016). Together, these two solutions are called CW-MFC and are recognized for their combined advantages in treating wastewater from various sources and recovering electrical energy in a single treatment system (Patel et al., 2021). Figure 1 shows a diagram of a horizontal subsurface flow CW combined with an MFC. The system exploits the natural redox gradient within CWs, where oxidation and reduction reactions occur in the lower anaerobic and upper aerobic layers, respectively (Ramirez-Vargas et al., 2019; Villasenor et al., 2013). The role of wetland vegetation extends beyond supporting conventional treatment processes. Plant-associated MFC systems have demonstrated that rhizosphere-derived organic compounds can serve as substrates for electroactive microorganisms, while plant roots contribute to the establishment of redox conditions that support bioelectrochemical activity (Kuleshova et al., 2022). These interactions provide additional context for understanding the functioning of CW-MFC systems. The high cost of electrode materials, oxygen permeability of separating membranes between electrode chambers, and high external resistance are key limitations of CW-MFC systems; additionally, variability in system configurations, electrode materials, plant species, operational conditions, and performance metrics has resulted in fragmented knowledge and difficulty in cross-study comparisons (Selvaraj and Velvizhi, 2023; Treesubsuntorn and Thiravetyan, 2021; Wu et al., 2015).

The increasing interest in CW-MFC technology has led to a growing number of review articles examining different aspects of the field. Earlier reviews primarily focused on the fundamental principles of CW-MFC systems, reactor configurations, pollutant removal mechanisms, and electricity generation. More recent reviews have become increasingly specialized, reflecting the diversification of research themes and technological developments within the field. For example, Zhang et al. (2023) focused on greenhouse gas emissions and extracellular electron transfer mechanisms, while Rusyn and Gómora-Hernández (2024) reviewed CW-MFC systems as enhanced pollutant treatment technologies for green energy production, with emphasis on plant selection, microbial interactions, pollutant removal mechanisms, and strategies for improving electricity generation. Miwornunyuie et al. (2025b) examined the technological evolution of CW-MFC systems through bibliometric and patent analyses, whereas Wu et al. (2025) assessed the role of CW-MFC in simultaneous pollutant removal and carbon emission reduction. More recently, Wu et al. (2026) critically evaluated the relationship between pollutant removal and electricity generation and highlighted the need to reassess the role of CW-MFC as wastewater treatment technologies.

As shown in Table 1, recent review articles have provided valuable insights into specific aspects of CW-MFC technology, including greenhouse gas mitigation, extracellular electron transfer, plant–microbe interactions, electricity generation, carbon neutrality, and technological development. However, most of existing reviews address specific aspects or applications of CW-MFC systems. An integrated assessment encompassing system architecture, operational intensification strategies, scaling behavior, microbial ecology, treatment performance, energy recovery, and implementation readiness across multiple scales of application is still lacking.

Therefore, this review assesses the current state of CW-MFC research through a system-oriented perspective by integrating bibliometric analysis with a critical evaluation of reactor configurations, operational intensification strategies, treatment

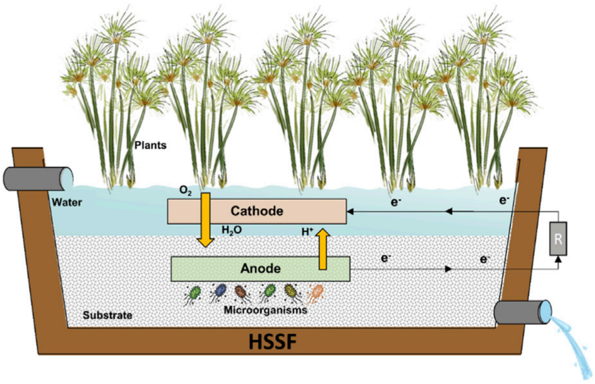

FIGURE 1
Schematic representation of a horizontal subsurface flow CW-MFC, showing anodic and cathodic zones, microbial activity, electron flow, and external resistance (R).

performance, microbial processes, energy recovery potential, and scale-up experiences. Particular emphasis is placed on identifying technical and operational limitations, evaluating implementation readiness, and outlining future research directions aimed at improving long-term stability, economic viability, and practical deployment. By synthesizing scientific contributions published between 2010 and 2026, this review aims to support the advancement of CW-MFC systems as viable and sustainable solutions for wastewater treatment and resource recovery.

2 Methodology

2.1 Databases sources

Prior to the literature search, the keyword combinations were defined and structured into four thematic groups, as detailed in Table 2. The first group included terms related to MFCs technology, the second focused on concepts associated with CWs systems, the third covered terms describing the implementation scale, and the fourth refers to the energy recovery related terms. Boolean logic was applied for the search: "AND" for complementary terms and "OR" for synonyms. The search was conducted in May 2026 and restricted to publications from 2010 to 2026. All retrieved records were exported as plain text(.bib) files to enable subsequent bibliometric analysis.

The literature review was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, which provides an internationally recognized standard for transparent reporting of literature identification, screening, eligibility assessment, and inclusion (Parums, 2021). Figure 2 presents the PRISMA flow diagram summarizing the selection process. A total of 92 documents were retrieved from Scopus (46 documents) and Web of Science (46 documents). After removing 26 duplicates and excluding four documents due to access restrictions, 62 records underwent a full-text evaluation. Of these, seven were excluded due to insufficient relevance to the research field or limited content.

2.2 Bibliometric tools

The bibliometric analysis was carried out using the pyBibX library in Python (version 3.11.12), a tool developed for detailed bibliometric and scientometric assessment of raw data files (Pereira et al., 2025). The use of bibliometric analysis allows researchers to reveal the structure of their respective fields and identify dominant themes, as well as identify where there is a knowledge gap and, therefore, an opportunity to address it (Visser et al., 2021).

The co-occurrence data were created from the bibliographic database and imported into VOS viewer (version 1.6.20), a mapping tool developed by the Centre for Science and Technology Studies (CWTS) at Leiden University (Van Eck and Waltman, 2010). A total of 193 keywords were identified and organized into groups according to their frequency of co-

TABLE 1 **Overview of selected review papers on CW-MFC systems.**

Main target	Scope	Key contribution	Reviews
Greenhouse gas emissions and extracellular electron transfer	Greenhouse gas mitigation and extracellular electron transfer mechanisms	Focus on emission control and electron transfer	Zhang et al. (2023)
Pollutant treatment and green energy production	Plant–microbe interactions and optimization strategies	Focus on biological and operational optimization	Rusyn and Gómora-Hernández (2024)
Technological evolution of CW-MFC	Bibliometric and patent analysis	Focus on research trends and technology maturity	Miwornunyuie et al. (2025b)
Pollution and carbon emission reduction	Pollutant removal and carbon neutrality	Focus on environmental sustainability	Wu et al. (2025)
Power generation versus treatment efficiency	Critical reassessment of CW-MFC performance	Focus on treatment–energy trade-offs	Wu et al. (2026)
System architecture and implementation readiness	Design, intensification, scaling, microbial ecology, performance and deployment	Integrated systems-level assessment from laboratory to full-scale applications	Present review

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TABLE 2 Structured keyword groups used for literature search, including terms related to microbial fuel cells (MFC) technology, constructed wetland (CW) systems, implementation scale, and energy recovery.

	Technology used	System used	Scale	Energy
Keywords	Microbial fuel cell	Constructed wetland	Full-scale	Electric energy
	MFC	CW	Full scale	Bioelectricity
	Fuel cell	Treatment wetland	Real-scale	Bioenergy
	Electroactive bacteria	Engineered wetland	Real scale	Energy
	Bioelectrochemical systems		Pilot-scale	Renewable energy
	Plant-Microbial Fuel Cells		Pilot scale	Energy generation
	CW-MFC		Lab-scale	Energy production
			Lab scale	Energy harvesting

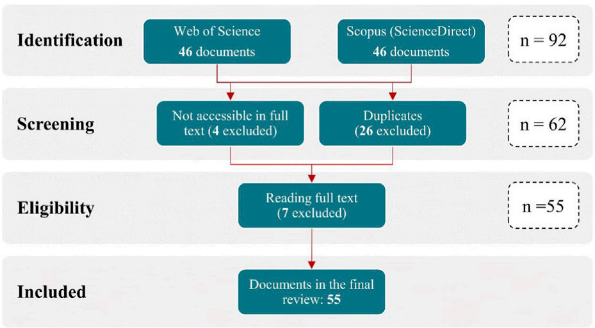

FIGURE 2
PRISMA flow diagram illustrating the study selection process, including identification, screening, eligibility assessment, and final inclusion of records from Scopus and Web of Science.

occurrence within the same documents. A minimum occurrence threshold of four was applied, resulting in at least 22 co-occurrence links. In the maps, nodes represent keywords, and their size indicates their frequency of occurrence. Connecting lines illustrate co-occurrence relationships, i.e., how often terms appear together in documents. Closely related groups of terms are denoted by different colors, reflecting different thematic subtopics within the field of research.

2.3 Systematic literature review

For this systematic literature review, the extracted data were qualitatively synthesized to identify patterns, recurring methodologies, and existing knowledge gaps. Particular attention was given to integration approaches and design configurations, microbial community dynamics and system performance, and key performance metrics related to energy generation. In addition, the review examined the economic and technical challenges associated with implementation, upscaling potential, and broader sustainability implications, especially the capacity of CW-MFC systems to enhance resource and energy recovery. This thematic structure enabled a coherent comparison of design approaches, performance indicators, and functional outcomes across the selected studies, as well as an informed discussion on intensification strategies that serve as a basis for future upscaling efforts.

3 Results and discussion

3.1 Data analysis and visualization

Figure 3 shows the number of documents related to the search terms analyzed from the databases. As shown in Figure 3a, research articles represented the predominant document type, accounting for 80% of the total publications, followed by review articles (20%). The classification by subject area, as shown in Figure 3b, indicates that environmental sciences were the main field, with 24 documents, followed by environmental engineering (14), chemical engineering (10), and water resources (8). Other subject areas, including green and sustainable science and technology, energy and fuels, and biotechnology and applied microbiology, were also represented to a lesser extent, accounting for approximately 4%–7% of the total publications. It should be noted that journals indexed in the database can be assigned to multiple subject categories; therefore, the cumulative number of publications across all subject areas may exceed the total number of documents.

Figure 4 shows the temporal evolution of publications identified over the last 16 years. Scientific output in this field remained limited until 2015, suggesting that research activity was initially exploratory and fragmented. From 2018 onwards, there has been a notable and sustained increase in the number of publications, reflecting a growing scientific interest and greater recognition of the relevance of the topic within environmental and energy-related research. The highest number of publications was recorded in 2023, with nine documents published, indicating a peak in research activity, while the average number of documents per year is 3.8. This trend is reinforced by the cumulative publication curve, which shows a steady upward trajectory, highlighting the progressive consolidation and expansion of the field over time.

Figure 5 shows the number of published documents per country. The results indicate that scientific output is concentrated in a limited number of countries, with China leading in terms of number of publications (14), followed by India (11) and Spain (8). A second group of countries, including England, Australia, Bangladesh, Ireland, and the USA, contributed three publications each, while the remaining countries contributed fewer documents. Overall, the findings indicate an uneven global distribution of research activity, largely driven by a small group of leading countries, without clear regional dominance, and complemented by emerging contributions from other parts of the world.

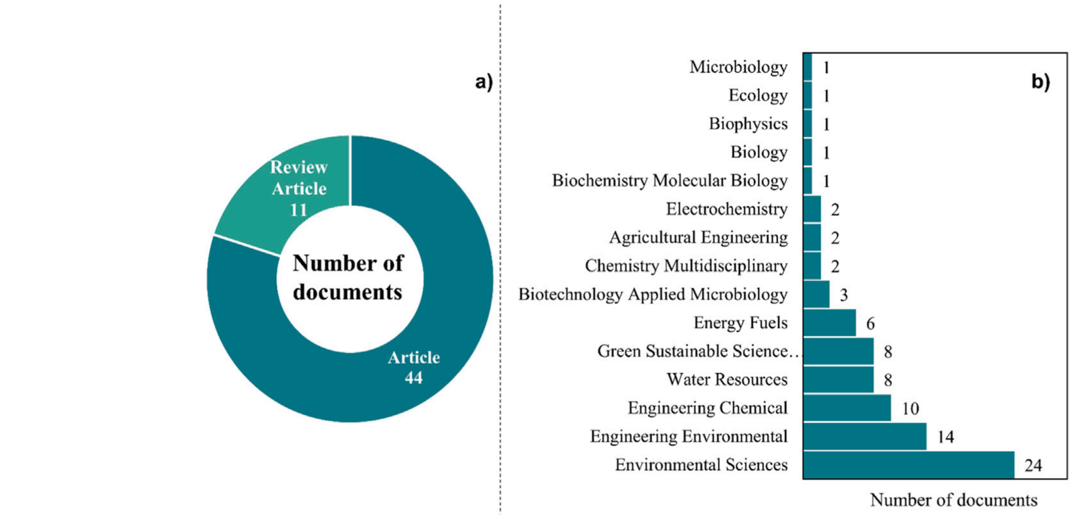

FIGURE 3
Distribution of retrieved documents by **(a)** document type and **(b)** subject area, highlighting the predominance of research articles and the main contributing research fields.

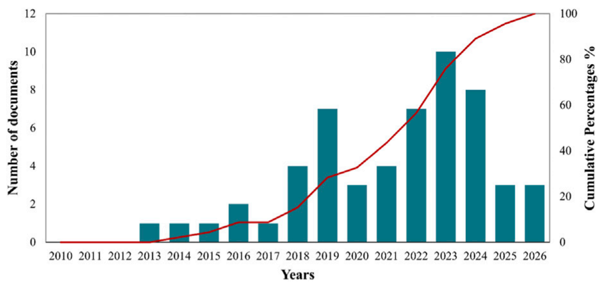

FIGURE 4
Temporal distribution of publications from 2010 to 2026, showing annual output and cumulative percentage, highlighting the increasing research trend over time.

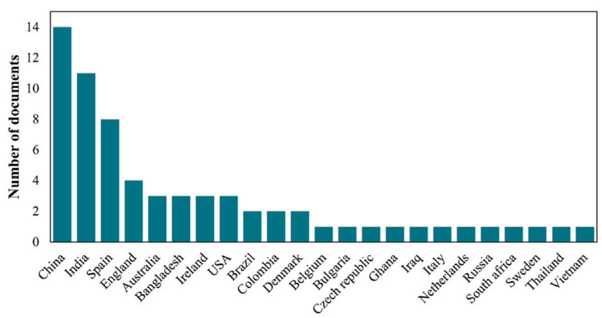

FIGURE 5
Distribution of publications by country, highlighting the leading contributors and the uneven global research output.

Figure 6 presents a co-occurrence network of keywords related to CW-MFC systems (Figure 6a). The network is divided into three main groups, listing the keywords associated with each thematic group. By selecting the keyword, it was possible to more easily visualize the terms that were directly related. Together, the three groups illustrate the conceptual structure of the research field, revealing a strong integration between wastewater treatment and energy generation. CWs act as multifunctional treatment platforms, while MFCs represent the technological engine for bioelectricity production, with an increasing emphasis on performance and scalability. The blue group highlights the strongest keyword associations focusing on "microbial fuel cells" as a key technological driver, closely linked to "wastewater treatment processes", "nutrient removal", and "bioelectricity generation" (Figure 6b). The green cluster highlights "constructed wetlands" as a central element linking wastewater treatment processes, "electricity generation", and system performance, emphasizing their multifunctional role (Figure 6c). It also highlights the related "pilot-scale" implementation. The orange cluster related to "performance" groups keywords associated with system evaluation and operational efficiency, including "removal," "sludge", and "electricity production" (Figure 6d). This group reflects a strong focus on assessing system functionality, optimizing operating conditions, and balancing treatment efficiency and energy generation in CW systems and MFCs.

3.2 CW-MFC integration strategies and design architectures

3.2.1 CW-MFC design

Table 3 summarizes the main characteristics of CW-MFC studies, including system scale, CW configuration, electrode

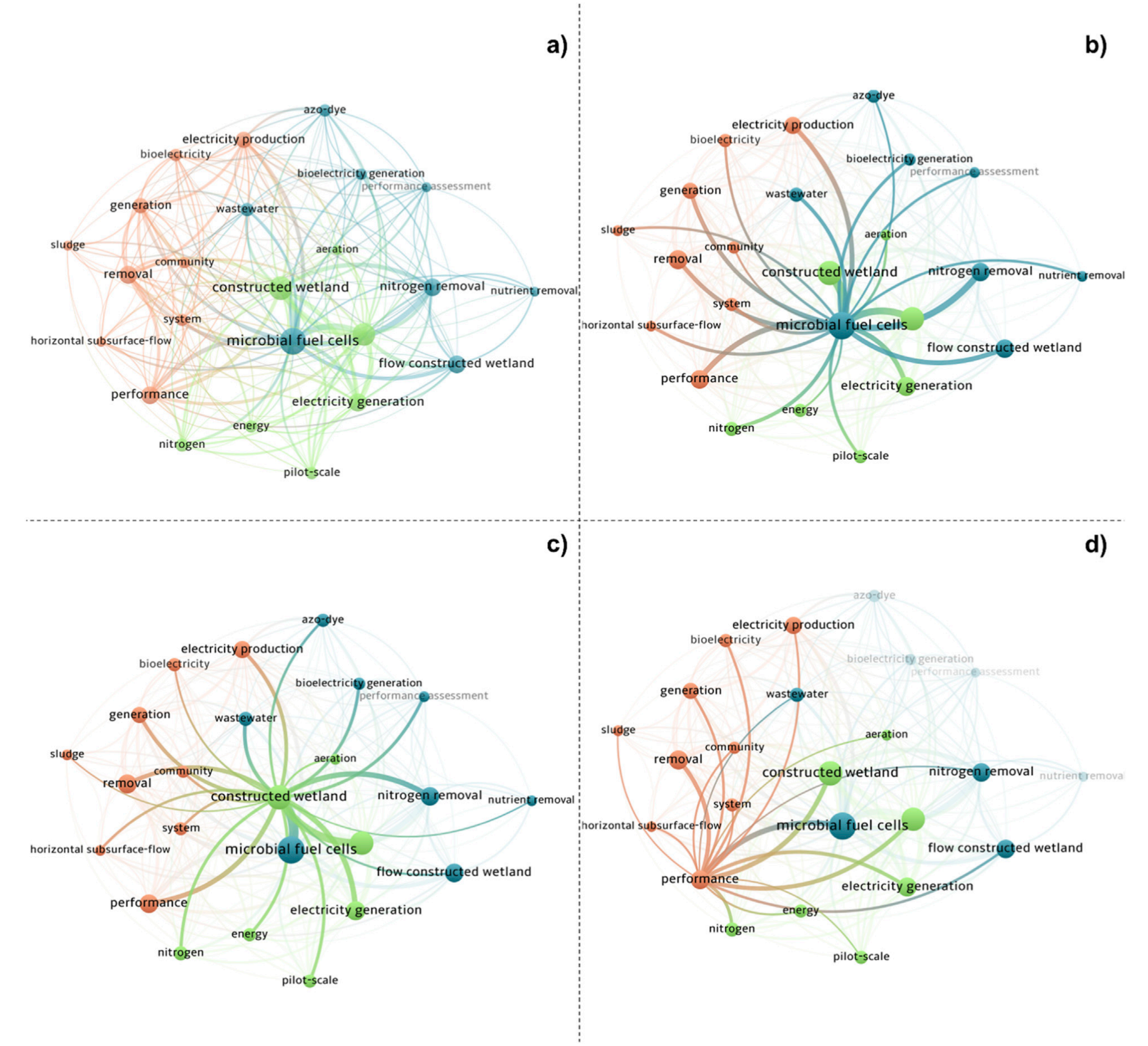

FIGURE 6
Keyword co-occurrence network of constructed wetland–microbial fuel cell (CW-MFC) research showing **(a)** overall network structure and thematic clustering, and detailed views of the main clusters: **(b)** microbial fuel cells–focused cluster, **(c)** constructed wetlands–focused cluster, and **(d)** performance-related cluster.

materials and dimensions, external resistance, inoculation strategies, and geographical distribution. External resistance and inoculation conditions were not consistently reported across studies and are indicated as not specified where applicable. Across the literature, laboratory-scale systems, which enable optimized understanding of CW-MFC, and pilot-scale systems, which provide valuable design insights under more realistic operating conditions, such as fluctuating real wastewater characteristics, environmental variations, and long-term system stability, are the most investigated.

Considering the geographical distribution of CW-MFC studies, environmental and climatic conditions strongly influence system configuration and operational strategies. Studies conducted in tropical and subtropical regions, such as Brazil, India, Bangladesh and Thailand, has primarily focused on system performance under climatic conditions that enhance microbial activity and support pollutant removal (Treesubsuntorn and Thiravetyan, 2021; Colares et al., 2022; Selvaraj and Velvizhi, 2023). In contrast, studies from temperate regions, including Europe, Australia, and China, have emphasized design adaptations to optimize redox gradients, electrochemical interactions, and microbial efficiency under more variable environmental conditions (Corbella and Puigagut, 2018; Ebrahimi et al., 2023; Zhu et al., 2026). Recent studies published between 2024 and 2026 have expanded the geographic representation of the literature to include countries such as Ethiopia, Pakistan, and Luxembourg, among others (Angassa et al., 2024; Kosar et al., 2025; Mittal et al., 2026). They

TABLE 3 **Summary of the main characteristics of the studies included in the constructed wetland–microbial fuel cell (CW–MFC) literature review.**

Country	Scale	CW configuration	Electrode material		Electrode size	External resistance (Ω)	Inoculation/ Microbial seeding	References
			Anode	Cathode				
Spain	Lab	HSSF	Graphite	Graphite	Rectangular 0.70 m × 0.15 m and 0.03 m	120	Biological sludge	Villasenor et al. (2013)
China	Pilot	HSSF	Graphite	Graphite	Rectangular Anode: 28 cm × 10 cm × 0.5 cm; Cathode: 25 cm × 10 cm × 0.5 cm	1,000	N/S	Wu et al. (2015)
Spain	Pilot	HSSF/VSSF	Graphite	Graphite	Rectangular 0.70 m × 0.15 m and 0.03 m	120	Biological sludge	Camacho et al. (2014)
Spain	Pilot	HSSF	Graphite	Graphite	Rectangular 0.70 m × 0.15 m and 0.03 m	120	N/S	Camacho et al. (2017)
UK	Lab	Self-stratifying	Carbon fiber	Sintered activated carbon	Rectangular 45 × 100 x 3 mm	500, 300 and 1,000	Inoculated with 50% (v/v) effluent from a matured urine-fed MFC and 50% fresh human urine	Walter et al. (2018)
Spain	Lab	HSSF	Graphite rods	Graphite felt	Rods Anode 1 × 0.5 cm; Cathode 4 pieces, 1.12 cm thick	50, 220, 402, 604 and 1,000	Domestic wastewater for 1 year	Corbella and Puigagut (2018)
South Africa	Lab	Hybrid CW	Granular activated carbon	Platinum-coated carbon	Anode: 1.7–3 mm; Cathode: paper (70 × 70 mm	1,000	Wild-type *Escherichia coli* inoculum mixed with synthetic greywater	Bolton and Randall (2019)
China	Pilot	Vertical flow	Stainless steel	Carbon felt with stainless steel	Cathode 300 mm square; Anode rectangular 30 x 14 cm	12,600	Cathode: Aerobic activated sludge; Anode: anaerobic sludge	Tang et al. (2019)
Denmark	Mesocosm	EABB-CW	calcined petroleum coke	calcined petroleum coke	50 cm; diameter 16 cm	N/S	Primary settled pig manure	Ramirez-Vargas et al. (2019)
India	Pilot	HSSF	Graphite gravel	Graphite gravel	Anode and cathode: 2.0 cm thick, diameter 5.0–8.0 cm	1,200	5.0 L of digested biogas slurry (mixed with tap water at a 1: 1 ratio)	Srivastava et al. (2020)
Thailand	Lab	HSSF	Hydrate carbon fiber	Hydrate carbon fiber	Rectangular 15 × 4 cm and 1 mm thickness	10 to 200,000	2% (v/v) *B. thuringiensis* (CP010577.1) grown in a nutrient broth	Treesubsuntorn and Thiravetyan (2021)
India	Pilot	HSSF	Stainless steel	Stainless steel	Surface area of 0.0126 $m^{2.}$	500 (10–10,000 for polarization)	Enriched electroactive bacterial community DC5	Patel et al. (2021)

(*Continued*)

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TABLE 3 Continued

Country	Scale	CW configuration	Electrode material		Electrode size	External resistance (Ω)	Inoculation/ Microbial seeding	References
			Anode	Cathode				
Spain	Pilot	HSSF	Stainless steel mesh	Carbon felt mat	Rectangular anodes; cathode of 0.03 m^2	220 Ω	None	Fernandez-Gatell et al. (2022)
Brazil	Pilot	Hybrid CW	Graphite sticks	Graphite stick	40 Graphite sticks 2.0 × 0.5 cm each	150 to 235,000	None	Colares et al. (2022)
Denmark/ Spain	Full	METland	Electroconductive coke	Electroconductive coke	60 cm high and 0.12 cm in diameter	1.5	N/S	Penacoba-Antona et al. (2022)
China	Pilot	Algal-CW	Carbon cloth	Carbon cloth	50 g/m^2, thickness 0.07 mm, diameter 530 mm	1,000	Granular sludge on anode surface; mixed microalgae on cathode	Wang et al. (2022a)
China	Full	Hybrid CW	Carbon cloth + GAC	Carbon cloth + GAC	N/S	N/S	VSS granular sludge in the substrate, microalgal electroactive biofilm at the top GAC layer	Wang et al. (2022b)
Australia	Lab	Vertical flow	GAC-layered stainless steel	GAC-layered stainless steel	Anode 170 × 170 mm; cathode 190 × 190 mm plates	1,000	Concentrated anaerobic sludge from a municipal WWTP	Ebrahimi et al. (2023)
Netherlands	Pilot	Tubular CW	Carbon felt	Carbon felt	Thickness 5 mm, size: 100 × 10 cm	330	Electrochemically active bacteria	de Jager et al. (2023)
Bangladesh	Pilot	Floating CW	Metallic aluminum-based anode	Metallic aluminum-based cathode	Rectangular 0.88 m × 0.22 m	10,000; 12,600	N/S	Saeed et al. (2023b)
India	Pilot	Hybrid CW	Graphite felt	Graphite felt	Rectangular 9 cm × 6 cm	480; 1,000	Anaerobic activated sludge from WWTP	Kumar et al. (2023)
Bangladesh	Pilot	VSSF	Graphite and steel	Graphite and steel	N/S	820	CW waterlogged for 13 weeks for microbial growth	Saeed, (2024)
India	Pilot	Vertical flow	Aluminum mesh	Stainless steel grade 316	Circular anode and cathode of diameter 13 cm each	N/S	N/S	Gogoi et al. (2024)
Brazil	Pilot	Tidal CW	Copper rod	Graphite carbon sheet	N/S	10,000	5L of UASB sludge from sewage treatment plant	Souza et al. (2024)
Spain	Pilot	HSSF	Anthracite GAC	Anthracite GAC	10 cm thick anode and cathode	50	Anaerobic sludge and sodium acetate	Bosch-Jimenez et al. (2024)

(Continued)

TABLE 3 Continued

Country	Scale	CW configuration	Electrode material		Electrode size	External resistance (Ω)	Inoculation/ Microbial seeding	References
			Anode	Cathode				
India	Lab	HSSF	Graphite rod	Graphite rod	Graphite rods, 30.48 cm length, 12 mm diameter	1,000	Indigenous microbial community	Kumar et al. (2025)
USA	Lab	HSSF	Graphite plate	Graphite plate	450 cm2 anode area, 230 cm2 cathode area	N/S	Standard inoculum (not specific)	Miwornunyuie et al. (2025a)
China	Pilot		Stainless-steel-mesh-wrapped carbon felt	Stainless-steel-mesh-wrapped carbon felt	N/S	2000	Native microbial community in greywater	Zhu et al. (2026)

N/S: not specified; GAC: granular activated carbon; PANI: polyaniline; UASB: upflow anaerobic sludge blanket; VSS: suspended volatile solids; EABB: Electroactive Biofilm-Based; HSSF: horizontal subsurface flow; VSSF: vertical subsurface flow.

incorporate contributions from regions that were previously underrepresented and highlight advances in conductive substrates, the treatment of diffuse agricultural pollution, and CW-MFC systems at the mesocosm scale. In general, climatic factors influence the variety of reactor designs, the choice of substrate, and the intensification strategies employed in the design, with the aim of improving the performance and long-term viability of CW-MFC systems.

Other representative pilot scale implementations that are critical for upscaling include horizontal subsurface flow CW-MFC (Camacho et al., 2017; Srivastava et al., 2020), vertical subsurface flow (VSSF) CW-MFC (Gogoi et al., 2024; Tang et al., 2019), a tubular plant-MFC operated outdoor for more than 26 months (de Jager et al., 2023), and a bioreactor system coupled with MFCs that achieved N removal and energy recovery (Li et al., 2024). The literature indicates that CW–MFC systems have evolved into a variety of physical configurations. Among these, hybrid subsurface flow designs, particularly HSSF and VSSF systems, are increasingly preferred. This is mainly due to their ability to maintain stable redox stratification, limit oxygen intrusion into the anode region, and support consistent microbial biofilm development. These subsurface CW-MFC designs are usually self-stratifying and membrane-less and have the anode and cathode in a single liquid column benefiting from the natural redox conditions developed within the single chamber. They are simple in construction and low cost. Many studies have experimentally demonstrated their usage for the treatment of urine (greywater) (Corbella and Puigagut, 2018; Walter et al., 2018), with some exploring the hybrid configuration like microalgal photobioreactor (Gogoi et al., 2024), algae-bacterial MFCs in CWs (Wang et al., 2022a), reactive bed filter (Colares et al., 2022), bioretention system (Li et al., 2024), and biological sand filter (BSF) (Bolton and Randall, 2019), to treat various wastewaters and generate electricity. Vertical flow and upflow subsurface CW-MFC designs have been explored to enhance oxygen transfer for cathodic processes, reduce clogging within the system, and support nitrification processed (Saeed, 2024).

The multi-stage CW-MFC configuration utilizes the spatial separation of redox conditions across treatment compartments to remove pollutants and treat high-strength agricultural/industrial nitrogen-rich wastewaters, usually through sequential nitrification-denitrification processes (Fernandez-Gatell et al., 2022; Patel et al., 2021). Other innovative and practical implementations that avoid the use of traditional anode-cathode electrodes in MFCs include electroactive biofilm-based CWs and Microbial Electrochemically Assisted Treatment Wetlands (METland) operating in short-circuit mode with electroconductive beds (Penacoba-Antona et al., 2022; Ramirez-Vargas et al., 2019). This emerging electrode-less CW-MFC systems employ conductive materials as extended electrodes providing a large surface area for electron sinks and enabling operation through an engineered bed in short-circuit mode.

3.2.2 Integration of MFCs in CWs systems

The physical integration of MFCs within the CWs systems is a critical factor, as it directly influences internal resistance, redox stratification, electrode performance, pollutant removal efficiency and electrical output, and therefore plays a key role in process intensification strategies. A classical standalone self-stratifying MFC described earlier (Walter et al., 2018), could serve as a benchmark for comparing CW-MFC systems. Aside from classical integration and hybrids, multi-electrode arrays (stacked, series, parallel, multi-level) are also integration designs that exploit the whole redox gradient to increase electrode areas for reduced internal resistance, better electron-harvesting capacity, and higher power density of the CW-MFC. Other integrations include the hybrid CW-MFC with additional treatment and/or resource-recovery units but with complex designs to provide for higher energy recovery and pollutant removal. To boost cathode performance, some CW-MFC are aerated to enhance cathodic oxygen availability. They provide higher power density, however, with attendant increase in energy cost (Fan et al., 2016; Saeed et al., 2023a).

From the various CW-MFC configurations assessed, there is a clear evolution from simple monolithic embedded designs towards hybrid, multi-stage, and bioelectrochemical wetland systems where improved performances are primarily achieved when the redox gradients are optimally engineered rather than when using a single architectural design.

3.3 Electrode design: materials, positioning, and connectivity

3.3.1 Electrode positioning and redox separation

Electrode positioning and electrical connectivity are critical design considerations which have direct effects on internal resistance, oxygen gradients, electron flow and electricity production in the CW-MFC systems. Various electrode configurations have been explored, including cathodes partially exposed to air to enhance oxygen availability (Wu et al., 2015), placement of the anode a few centimeters above the substrate bottom to optimize substrate utilization and biofilm development (Selvaraj and Velvizhi, 2023; Treesubsuntorn and Thiravetyan, 2021), and the use of different electrical connections such as external resistors (Colares et al., 2022) or short-circuit operation modes (Penacoba-Antona et al., 2022). Additional strategies include multi-electrode assemblies, conductive wiring materials such as copper, and electrode composed of graphite-based materials (Saeed, 2024).

The positioning of electrodes plays a decisive role in establishing effective redox separation between anodic and cathodic zones, which is essential for stable MFCs operation (Tang et al., 2019). Proper anode placement in strictly anaerobic regions promotes the activity of electroactive microorganisms and enhances organic matter oxidation, thereby improving both pollutant removal and electron generation. Conversely, positioning the cathode in oxygen-rich zones facilitates efficient oxygen reduction reactions, which improves current generation. Inadequate separation between these zones can lead to oxygen diffusion into the anode, reducing Coulombic efficiency and limiting power output. Furthermore, shorter distances between electrodes can reduce internal resistance and enhance electron transfer, but may also compromise redox stratification if not properly controlled. Therefore, optimizing electrode placement involves balancing redox separation, oxygen availability, and electrical connectivity to maximize both wastewater treatment performance and energy recovery in CW–MFC systems.

3.3.2 Electrode materials

The electrode materials are an important part of the CW-MFC system. Across the papers, they can be broadly divided into carbon-based materials, metal-based materials, distributed electroconductive biofilter materials, and mixed/composite materials. Several pilot-scale studies have employed carbon-based materials such as carbon felt (Wu et al., 2015), carbon cloth (Wang et al., 2022a) graphite plates or sheets (Yang et al., 2022), graphite rods (Srivastava et al., 2020), granular graphite, granular activated carbon (GAC), and activated carbon-based cathodes (Colares et al., 2022; Ebrahimi et al., 2023). Recent work has also provided a direct comparison of commonly used conductive media in CW-MFC systems. Comparing graphite granules, GAC, and calcined petroleum coke under the same operational condition (Rao et al., 2026) demonstrated significant differences in treatment efficiency, power generation, internal resistance, and microbial community composition. These findings highlight that the selection of conductive substrate can substantially influence both electrochemical performance and wastewater treatment efficiency.

The choice of electrode material has a direct and significant impact on both electricity generation and wastewater treatment performance in CW–MFC systems. Carbon-based materials are widely preferred due to their high electrical conductivity, chemical stability, large specific surface area, and strong biocompatibility, which facilitate microbial attachment and the formation of electroactive biofilms, ultimately enhancing electron transfer and current generation (Colares et al., 2022; Ebrahimi et al., 2023). In contrast, metal-based electrodes generally offer higher intrinsic conductivity but are often limited by corrosion, cost, and potential toxicity, which can negatively affect long-term system stability and microbial activity. Distributed electroconductive media, such as granular activated carbon and conductive substrates, further improve performance by increasing the effective surface area for biofilm growth and enabling more uniform electron transfer pathways throughout the system (Srivastava et al., 2020; Wang et al., 2022a). However, excessive packing or poor material selection may lead to mass transfer limitations or clogging, thereby reducing treatment efficiency. Therefore, the optimal selection of electrode material involves balancing conductivity, durability, surface characteristics, and compatibility with microbial communities to maximize both energy recovery and pollutant removal in CW-MFC systems.

3.3.3 Electrical connectivity, internal resistance, and durability of the electrodes

Carbon-based electrodes are usually low cost and have good electrical conductivity. They are also biocompatible and they offer high surface area for easy microbial adhesion. Although metal-based electrode are excellent current collectors (Corbella and Puigagut, 2018), they are less used as they are prone to corrosion. Aside from stainless steel, other metals used for electrode materials include aluminum (Gogoi et al., 2024), titanium (de Jager et al., 2023), and copper (Saeed et al., 2023b). While titanium is good for long term

CW-MFC and good corrosion-resistant electrode material, copper is basically used as connecting wire rather than as electrode because of corrosion. The cheaper, higher porosity activated carbon-based electrodes are becoming preferred cathode material as they are seen to outperform the carbon felt and graphite-based electrodes and boost oxygen reduction reaction (ORR). In cathode optimization, innovative binders for activated carbon cathodes like polytetrafluoroethylene (PTFE), polyvinyl-alcohol (PVA), PlastiDip are reported to influence hydrophobicity, oxygen transfer and the durability of the electrode material (Walter et al., 2018). These serve as part of the intensification strategies in CW-MFC system designs. When considered collectively, these studies suggest that individual electrode materials or their precise placement play a lesser role on CW-MFC performance than the extent to which material selection, spatial positioning, and electrical connectivity jointly ensure effective redox separation and reduce internal resistance in the CW-MFC system.

3.4 System size, hydraulic configuration, and scaling behavior in CW−MFC systems

The physical dimensions, scale and the hydraulic conditions of the system are primary concerns for scaling up the CW-MFC system. Table 4 highlights clear trends across CW-MFC scales. Smaller systems (bench and lab scale) typically operate under controlled conditions with shorter Hydraulic Retention Time (HRT) and higher power densities, mainly for optimization and mechanistic studies. As scale increases, systems shift to continuous flow with longer HRT, while power density decreases and treatment becomes the primary objective. The classification shown in Table 4 was established using reactor size, HRT, operational characteristics, and intended application as reported across the reviewed studies. The references listed for each category are provided as representative examples of the corresponding scale.

The HRT is a key operational parameter in system performance. It is usually an understudied operational parameter despite being critical to the treatment and electricity generation efficiency. HRT vary widely across studies under review, ranging from a few hours to several weeks. This wide range reflects the diversity of system designs and, more importantly, the differing operational objectives of CW-MFC systems, whether they are primarily energy-focused or treatment-focused.

While the very short HRT systems of hour-ranges are seen to be typical of lab MFCs and some vertical flow systems with treatment efficiency as priority rather than electrical output (Saeed, 2024), the moderate HRT systems of few days, like 2 or 3 days, form the bulk of the HRT reported (Camacho et al., 2014; 2017; Ebrahimi et al., 2023). The moderate HRT balance treatment and energy recovery. The nutrient removing long HRT systems range between 4 and 8 days and create stable biofilms with lower variability in the energy recovered. Some CW-MFC systems, however, operate at relatively high HRT, such as 25 days (Bhagat et al., 2022; Saeed et al., 2023b) and are characterized by more pronounced anaerobic conditions, high treatment performance but lower power output.

In most of the studies, HRT was not varied to allow for performance comparison. The only four studies that compared various HRT reported higher chemical oxygen demand (COD), nitrogen (N), and phosphorus (P) removal and improved bioelectricity generation with longer HRT (Kumar et al., 2023; Saeed, 2024; Saeed et al., 2023b; Wu et al., 2015). The flow pattern, as noted in the studies, affects the availability of organics and the stability of the biofilm. More than 50% of the studies use continuous flow implemented using peristaltic pumps to maintain stable redox conditions and nitrification/denitrification processes. Other studies use batch/pulse flow (Walter et al., 2018) or tidal (Souza et al., 2024) flow for enhanced aeration, and to control the electroactive bacteria feeding model for optimized energy recovery. However, the aeration comes with the additional pumping cost. Another flow pattern is the vertical up flow where the wastewater is pushed from the anodic bottom up to the cathodic part of the CW-MFC system. This aligns well with the redox setup that ensures more stable electrochemical efficiency. The batch/pulse flow is common in the lab scale CW-MFC system. The pilot scale systems mostly have continuous flow. When the size, HRT, and flow pattern of CW-MFC systems are evaluated collectively, they consistently explain the observed decline in power density with increasing scale. This trend emphasizes the combined effects of hydraulic variability, redox instability, and increased internal resistance in larger CW-MFC systems.

3.5 Substrates and media engineering in CW−MFC systems

The substrate used in a CW-MFC system is very important. It serves as the receiving medium for the wastewater, and it directly affects hydraulic conductivity, porosity, flow, redox stratification, biofilm growth, nutrient adsorption, electrode performance, and more importantly intensification strategies in CW-MFC systems (Colares et al., 2022; Ramirez-Vargas et al., 2019; Tang et al., 2019). The substrates used in CW-MFC are mostly globally available conventional mineral substrates like gravel or fine sand; which are for good hydraulic properties and natural microbial colonization (Camacho et al., 2014; Srivastava et al., 2020; Wu et al., 2014), industry-made media like Lightweight Expanded Clay Aggregate (LECA) substrate (Calheiros et al., 2015), industrial by-products like jhama brick (Saeed, 2024), and dewatered alum sludge (Tang et al., 2019). Others include innovative electroconductive substrates, such as calcined petroleum coke with low sulfur and nitrogen content (Ramirez-Vargas et al., 2019) and reactive adsorptive substrates like zeolite, granular activated carbon, and mixture of pyrite, biochar, and sand (Li et al., 2024).

It is worth noting that substrates could be multi-layered thereby engineering redox zoning and electrochemical interfaces profiles. Among the types of substrates, the gravel-based substrates are the most used, the electroconductive substrates are innovative, the waste-derived industrial by-product materials ensure sustainability/circular economy while the reactive substrates are for process intensification. From the studies, the selection of substrate appears as a multifunctional design variable that affects hydraulics, redox stratification, microbial colonization, and electron transfer, thus being a key parameter for process optimization and long-term sustainability of CW-MFC systems.

TABLE 4 **Classification of constructed wetland–microbial fuel cell (CW–MFC) systems by scale, including size ranges, typical hydraulic retention time (HRT), power density trends, operational characteristics, and representative studies.**

MFC category	Size range	Typical HRT	Power density	Flow regime	Primary objective	References
Bench-top	<1 L	Hours – <1 day	up to ~500 mW/m^3	Batch/ controlled	Mechanistic understanding, electrode/material testing	Walter et al. (2018), Corbella and Puigagut (2018); Treesubsuntorn and Thiravetyan, (2021)
Lab-scale	1–50 L	1–3 days	7.5 mW/m^2	Batch/semi-continuous	Optimization of design parameters (substrate, spacing, plants)	Ebrahimi et al. (2023), Kosar et al. (2025), Dai et al. (2026); Mittal et al. (2026)
Pilot-scale	50–500 L	2–8 days	~10–100 mW/m^3	Continuous	Performance validation under realistic conditions	Srivastava et al. (2020), Fernandez-Gatell et al. (2022); de Jager et al. (2023)
Mesocosm	500–5000 L	5–25 days	<200 mW/m^3	Continuous	Field simulation and system integration	Ramírez-Vargas et al. (2019), Selvaraj and Velvizhi (2023), Souza et al. (2024), Junca-Gomez et al. (2026)
Full-scale	Field systems (>5000 L)	not reported	<20 mW/m^2	Continuous	Wastewater treatment (primary objective)	Penacoba-Antona et al. (2022), (Wang et al., 2022b), Li et al. (2024)

3.6 Influent types and organic load

Table 5 presents the different influent types and corresponding treatment efficiencies reported for CW–MFC systems. Across all studies, the influent types are diverse and form one of the main backbones of the studies with their compositions reflecting pollutant loads, organic matter availability, microbial community development, and consequently determining the achievable power density. The influent types are also one of the main considerations of the treatment objectives and suitability for real-world implementations with real domestic wastewater dominating (Table 5).

Real domestic/municipal wastewater such as, real urban wastewater, domestic sewage, and polluted pond water, are the most common in the studies. They are characterized by low–medium strength and variable composition, with influent COD values typically ranging from about 230 to 800 mg/L (Camacho et al., 2014; Camacho et al., 2017; Colares et al., 2022), and are most suited for practical deployment and system scaling (Camacho et al., 2014; Camacho et al., 2017; Corbella and Puigagut, 2018). In contrast, synthetic domestic wastewater, including synthetic handwashing wastewater, simulated stormwater, synthetic septic tank effluent, and lab-prepared municipal wastewater, is widely used to provide stable and controllable influent COD and nutrients, with reported COD values ranging from 150 to over 1,000 mg/L (Patel et al., 2021; Srivastava et al., 2020; Tang et al., 2019), making it most suited for experimental studies and controlled investigations. Beyond these, agricultural and industrial wastewaters such as piggery wastewater, fishpond aquaculture wastewater, and real textile dye wastewater are also explored. These are characterized by high pollutant strength, solids, high N/P ratio, and high conductivity, with influent COD values reaching up to 2,300 mg/L for aquaculture wastewater and 3,800 mg/L for piggery wastewater (Gogoi et al., 2024; Wang et al., 2022b; Yang et al., 2022), all contributing to higher energy recovery. A study (Walter et al., 2018), however, reported using human urine (blackwater), which has high conductivity and high nutrient load and is seen as an excellent electrolyte in the MFC.

Influent characteristics reflect the strength of the incoming wastewater and are directly related to treatment efficiency, redox conditions, and power recovery in MFCs. Although some studies did not report influent characteristics, possibly due to inconsistent reporting standards in CW literature, the available data allow influent characteristics to be broadly categorized based on influent COD as follows:

High strength wastewater of COD above 1,000 mg/L with strong potential for electricity generation, as is the case of wastewater from piggery with a COD concentration of 3,621 mg O_2/L (Gogoi et al., 2024) and 2,313.4 mg O_2/L in Wang et al. (2022b).

Medium strength domestic/municipal wastewater with values ranging from 200 to 900 mg O_2/L COD, which corresponds to the typical range supporting stable microbial growth in CW-MFC systems. In their studies (Bhagat et al., 2022) reported influent values of COD 667–886 mg O_2/L.

Low strength wastewater with low electric conductivity and COD concentration below 200 mgO_2/L. Pond water and aquaculture wastewater are examples noted by Wang et al. (2022a) and Yang et al. (2022).

Other categories include highly conductive influents (e.g., human urine, blackwater and domestic wastewater, with electric conductivities of 28,000 µS/cm, 5,854 µS/cm and 1,600 µS/cm, respectively), nutrient rich influents (various industrial/ agricultural wastewaters) and toxic containing influents like

TABLE 5 Summary of influent types and corresponding treatment performance of constructed wetland–microbial fuel cell (CW–MFC) systems, including operational conditions and removal efficiencies for key pollutants.

Wastewater type	Flow regime	Flow rate (L/d)	HRT (days)	Influent COD (mg/L)	COD removal (%)	TN removal (%)	NH_4^+-N removal (%)	TP removal (%)	References
Synthetic	Continuous	30	3.2	250 - 1,100	80 - 95	N/S	N/S	N/S	Villasenor et al. (2013)
Synthetic	Continuous	9.6	5	228	91.2	98	99	96	Wu et al. (2015)
Domestic	Continuous	30	3.2	230	65	N/S	N/S	N/S	Camacho et al. (2014)
Domestic	Continuous	35	2.75	300	~100	N/S	N/S	N/S	Camacho et al. (2017)
Domestic	Batch	-	7	625	78 - 82	N/S	66	20	Corbella and Puigagut (2018)
Greywater	Continuous	23	2.3	400-800	80-99	63	N/S	75	Bolton and Randall (2019)
Synthetic	Continuous	20	2	500	91.7	N/S	97,3	N/S	Tang et al. (2019)
Synthetic	Continuous	9.85	6.6	150-520	98	N/S	N/S	N/S	Srivastava et al. (2020)
Synthetic	Batch	-	4	1,058	62-74	N/S	N/S	N/S	Patel et al. (2021)
Industrial	Continuous	26.1	3.9	20-24	72-86	N/S	04 - 21	N/S	Fernandez-Gatell et al. (2022)
Urban	Continuous	50	7	800	65	68	93	86	Colares et al. (2022)
Urban	Batch/Pulse	-	-	50-910	80-90	20 -70	22	50	Penacoba-Antona et al. (2022)
Urban	Intermittent/ Pulse	-	01-02	60	75	77	71	85	Wang et al. (2022b)
Aquaculture	Continuous	2000	1	2,300	98	95	98	91	Wang et al. (2022a)
Agriculture	Continuous	-	3	130	66 -75	N/S	N/S	N/S	Yang et al. (2022)
Septic	Continuous	2.88	2.12	400	98	44 - 62	100	N/S	Ebrahimi et al. (2023)
Municipal	Continuous	44.6	24	320	72 - 94	58 -75	62-86	82 - 97	Saeed et al. (2023b)
Synthetic	Batch/ Continuous	-	96	1,150	97	N/S	N/S	N/S	Kumar et al. (2023)
Municipal	Continuous	24.0	1.12	1,480	70 - 97	36 - 84	30 - 97	67- 98	Saeed, (2024)
Piggery	Continuous	5	1.28	3,800	90	40	65	95	Gogoi et al. (2024)
Domestic	Tidal	-	0.21	450	80 - 83	N/S	N/S	N/S	Souza et al. (2024)

N/S: not specified; COD: chemical oxygen demand; TP: total phosphorus; TN: total nitrogen; NH_4^+-N: ammonium nitrogen; HRT: hydraulic retention time.

textile dyes (Patel et al., 2021), heavy metals (Saeed et al., 2023a) and phenolic compounds.

Together, these evidences suggest that CW-MFC systems are suitable to medium and high strength wastewaters that contain organic compounds that sustain electroactive biofilms. On the other hand, low strength influents primarily benefit from improved treatment rather than energy recovery.

3.7 Microbial community structure, inoculation strategies, and functional implications

Microbial communities in CW-MFC systems are typically established through bioaugmentation or natural development within the system. These communities drive biofilm development, which in turn governs electrochemical performance, pollutant removal, microbial ecology, and importantly the overall system stability.

3.7.1 Bioaugmentation strategies and microbial colonization in CW-MFC systems

Bioaugmentation with specialized electroactive cultures is often employed to enhance electron transfer and to improve oxygen mediation at the cathode. Commonly reported electroactive genera used in bioaugmentation strategies include *Geobacter*, *Shewanella*, *Pseudomonas*, and *Desulfuromonas*, which are known for their efficient extracellular electron transfer and biofilm forming capabilities (Ramirez-Vargas et al., 2019; Wang et al., 2022a). Bioaugmentation is typically applied during system start-up or when native microbial communities are insufficient to sustain stable electricity generation, particularly in low-strength wastewater or newly established systems. Electroactive seeding, commonly used, is an intentional introduction of active electrogenic bacteria to rapidly colonize the anode and form biofilm, improve electron transfer efficiency and stabilize the power output (Corbella and Puigagut, 2018). This approach often involves pre-enriched consortia dominated by electroactive species such as *Geobacter* and *Shewanella*, which facilitate rapid establishment of conductive biofilms and improved system start-up performance.

Generally, a pre-acclimation period is necessary to stabilize microbial consortia, improve redox gradient and achieve steady performance as demonstrated by (Saeed, 2024; Wu et al., 2015). Pre-acclimation is particularly important when transitioning from synthetic to real wastewater or when introducing new substrates, as it allows microbial communities to adapt to changing environmental and electrochemical conditions.

3.7.2 Limitations of microbial characterization and reporting

Across the reviewed studies the microbial analysis methods include high-throughput sequencing and culture-dependent techniques to characterize microbial communities in CW-MFC. Over 50% of the studies, however, did not report any microbial analysis at all and this may limit the understanding of pollutant degradation and electricity recovery pathways. The reported dominant microbial phylum is the Proteobacteria (Patel et al., 2021; Ramirez-Vargas et al., 2019; Yang et al., 2022) while other commonly identified phyla include Firmicutes and Bacteroidota. At the genus level, frequently reported electroactive microorganisms include *Geobacter*, *Shewanella*, *Pseudomonas*, *Desulfuromonas*, *Clostridium* and *Acinetobacter* (Wang et al., 2022a; Wang et al., 2022b). These genera are recognized for their ability to transfer electrons to the anode, facilitate biofilm formation and contribute to power generation with genera such as *Geobacter* and *Shewanella* being among the most widely reported electroactive microorganisms in the CW-MFC systems. The identified nitrifying/denitrifying bacteria in the studies include *Nitrospira*, *Nitrobacter*, *Azoarcus* (Wang et al., 2022b). In the work of Yang et al. (2022) higher values of Chao, ACE, Shannon, and Simpson diversity indices in the CW-MFC anodes show that electrical environment of MFC promotes rich microbial communities. Given that more than half of the reviewed studies did not report microbial analysis, microbial characterization remains inconsistent and in many cases absent. This may limit the interpretation of pollutant degradation pathways and electricity generation mechanisms in CW-MFC systems.

3.8 Wastewater treatment performance and energy recovery

3.8.1 Organic matter and nutrient removal mechanisms and efficiency

The literature consistently shows that integrated CW-MFC systems achieve higher organic matter treatment efficiencies than conventional CWs alone. However, the magnitude of improvement varies considerably among studies due to differences in reactor configuration, wastewater characteristics, hydraulic conditions, and operational parameters. To provide a clearer basis for this observation, Table 6 summarizes selected studies that directly compared CW-MFC systems with conventional CWs or their controls. Reported improvements include enhanced COD, NH_4^+-N, and total nitrogen removal with the MFC integration.

The studies summarized in Table 6 provide further evidence that integrating MFCs into CWs enhances pollutant removal performance compared to conventional CWs system. Xu et al. (2017) reported an increase in COD removal efficiency from 83.2% to 88.7% and an improvement in TN removal from 53.1% to 75.4%. Similarly, Qu et al. (2025) observed higher removal efficiencies for COD, NH_4^+-N, NO_2^--N, NO_3^--N, and TP compared with conventional CWs, while (Zhang et al., 2026) reported lower effluent COD concentrations in CW-MFC systems than in conventional CW controls (Koukoura et al., 2025). also observed superior COD and ammonium removal in CW-MFC systems relative to CW controls. These findings indicate that the incorporation of MFC components can promote more effective organic matter degradation and nutrient transformation through enhanced electron transfer processes and improved redox stratification. Nevertheless, the extent of improvement remains dependent on system design and operating conditions. The removal efficiencies are affected by flow design directions (horizontal/vertical), aeration availability (Selvaraj and Velvizhi, 2023), organics loadings (Srivastava et al., 2020), HRT, biofilter/electroconductive electrode/vegetation (Ramirez-Vargas et al., 2019; Saeed, 2024), climatic condition (winter/summer) (Wang et al., 2022b) and redox gradient. Specifically, flow design play a major role in the total nitrogen (TN), ammonium-nitrogen (NH_4^+-N) and total phosphorus (TP) removal efficiency, with values in the range between 60% and 98% for NH_4^+-N, 20% and 99% for TN, 70% and 95% for TP, although a study reported 100% NH_4^+-N removal (Ebrahimi et al., 2023) and some reported low efficiencies like 19.6% for TP where gravel was the only substrate used, there is no reactive media and the plant uptake is limited (Colares et al., 2022; Corbella and Puigagut, 2018).

The effluent quality typically assessed using key water quality parameters such as COD, TN, NH_4^+-N, NO_3^--N, NO_2^--N, and

TABLE 6 Comparative pollutant removal performance reported for constructed wetland-microbial fuel cells (CW-MFC and conventional) CW systems.

CW Comparison	COD removal (%)	Nitrogen removal (%)	Main outcome	References
Stacked CW-MFC vs. single-stage CW	88.7 vs. 83.2	TN: 75.4 vs. 53.1	Better nutrient removal	Xu et al. (2016)
Closed-circuit CW-MFC vs. CW	~5% higher than CW	NH_4^+ removal ~22% higher than CW	Enhanced treatment efficiency	Hartl et al. (2019)
CW-MFC vs. CW	7.46% increase in COD removal	NH_4^+-N: +9.08%; NO_2^--N: +3.99%; NO_3^--N: +6.73%	Better pollutant removal	Qu et al. (2025)
CW-MFC vs. standalone CW	Effluent COD reduced from 66.14 mg/L (CW) to 18.81–54.06 mg/L (CW-MFC); optimized COD removal 89.14%	Not reported	Improved COD removal	Zhang et al. (2026)
CW-MFC vs. CW-Control	CW-MFC outperformed CW-Control in COD removal under all loading conditions	Higher NH_4^+-N removal than CW-Control; NH_4^+-N removal exceeded 84%	Enhanced treatment performance	Koukoura et al. (2025)

COD: chemical oxygen demand; TN: total nitrogen; NH_4^+-N: ammonium nitrogen.

TP is inconsistently reported across the reviewed studies. Incorporating benchmarking against wastewater discharge standards (e.g., WHO, EU, USEPA) would be valuable in future studies to enable more robust evaluation of CW-MFC performance. When reported, effluent COD concentrations are generally lower than those of control or baseline systems, as demonstrated in comparative or controlled configurations such as open-versus closed-circuit operation or hybrid versus conventional CW setups (Corbella and Puigagut, 2018; Wu et al., 2015; Yang et al., 2022), confirming improved treatment performance in CW-MFC systems. The various studies have also demonstrated lower values of TN, NH_4^+-N, Nitrate (NO_3^--N), Nitrite (NO_2^--N), TP with typical values of NO_3^- < 0.1 mg/L and NO_2^- < 0.005 mg/L (Wu et al., 2015; Yang et al., 2022) and TP < 1 mg/L or even undetectable (Yang et al., 2022). Penacoba-Antona et al. (2022) reported undetectable nutrient concentration in the effluent from the electrochemically assisted VSSF. Some studies (Colares et al., 2022; Kumar et al., 2023; Saeed, 2024), are reported to have high COD concentration (higher than 150 mgO_2/L) when treating textile wastewater, piggery wastewater and sewage, which generally have high influent organic loads. These systems would require longer HRT or multi-stage system for better performance in terms of contaminants removal efficiencies.

The pollutant removal mechanisms used include biological processes for organic matter and nutrient removal (Li et al., 2024), and microbial dechlorination (Li et al., 2025), but also physicochemical processes - adsorption and precipitation (Colares et al., 2019), sedimentation (Colares et al., 2022), and volatilization (Fernandez-Gatell et al., 2022), and vegetation mediated processes - rhizofiltration and rhizodegradation as emphasized in the semi-pilot scale study on CW-MFC by (Selvaraj and Velvizhi, 2023). It is important to note that for most of the studies, no paper reported using a single mechanism for the treatment and generation of electricity. Rather many interacting processes and mechanisms are at work to achieve treatment and energy recovery.

3.8.2 Biomass production and biofilm development

Biomass production is the least reported performance indicator in CW-MFC studies despite its importance in oxygen supply, in the generation of root exudate, in the biofilm activity at the anodic region of the CW-MFC, and in carbon storage. In the limited number of studies reporting biomass productivity, this parameter was predominantly associated with biofilm accumulation, albeit quantified using different approaches. Wang et al. (2022a) described biomass productivity in terms of staged biofilm growth, while Fernandez-Gatell et al. (2022) related it to biomass expressed as COD per gram of substrate. In contrast (Sandoval-Herazo et al., 2021), quantified biomass through aboveground and belowground plant biomass production. The only study reporting biomass productivity as annual plant biomass was Souza et al. (2024), which investigated the effects of vegetation (capiacu and banana) and filling material (gravel sizes of 4.8 mm and 9.5 mm) on the CW-MFC system performance.

3.8.3 Power and current densities

Power and current densities are among the most important performance evaluation indicators for any MFC system, as shown in Table 7. In general, studies measure these parameters, mainly in Watt or Ampere, respectively, per square meter of area of electrode or per cubic meter of volume of the reactors that contain them. (mW/m^2, mW/m^3, mA/m^2, mA/m^3). It is worth to note that strict anaerobic condition in the anode positively yield higher power (Saeed et al, 2023a) (like as high as 3,417 mW/m^3 while in an aerobic condition, the power recovered is lower (like 154 mW/m^3). Carbon-based electrodes enhance electricity recovery due to their greater surfaces for biofilm formation and stability unlike metal-based electrode materials. In general, integrating MFCs into CWs generally enhances organic and nutrient removal efficiencies, when compared to conventional CWs, however energy recovery remains secondary, variable, and increasingly constrained as system complexity and scale increase.

TABLE 7 **Summary of electrode configurations and corresponding power densities reported in constructed wetland–microbial fuel cell (CW–MFC) systems, including operational conditions and energy roles.**

Electrode design	Power density	Basis	Operation duration (days)	Energy role (primary/ secondary)	References
Anode located 12 cm above the bottom, graphite cathode 12 cm below the surface	15.6	mW/m^2	180	Secondary	Villasenor et al. (2013)
The anode was placed horizontally 4 cm above the bottom of the wetland; the cathode was placed vertically near the plants, half buried 5 cm deep in the CW and half exposed to the air	9.6	mW/m^2	15	Secondary	Wu et al. (2015)
Vertical self-stratified orientation: the anode submerged at the bottom (anaerobic) and the cathode partially submerged and partially exposed to air (aerobic)	101	mW/m^2	13	S/N	Walter et al. (2018)
The anode is placed in the anaerobic zone and the cathode in contact with atmospheric oxygen	288-346	mW/m^3	91 (365 for acclimatization)	Secondary	Corbella and Puigagut, (2018)
The anode extended to a height of 230 mm above the support layer. The cathode was positioned so that its lower end was always in contact with the wastewater	2.42 – 4.33	mW/m^3	29	Secondary	Bolton and Randall, (2019)
Multi- electrode: A cathode was placed at the water-air interface. Four anodes were placed at different depths from the cathode at 500 mm, 400 mm, 300 mm, and 200 mm	7.99	mW/m^2	>600	Secondary	Tang et al. (2019)
Anode at bottom: 2.0 cm thick graphite gravel layer (5.0–8.0 mm diameter); cathode at top: 2.0 cm thick graphite gravel layer (5.0–8.0 mm diameter); both separated by a 21.0 cm sandstone gravel bed (4.0–5.0 mm diameter).	11.67	mW/m^3	70	Secondary	Srivastava et al. (2020)
Anode placed 8 cm from bottom; cathode at 18 cm from bottom; 10 cm apart	197.94	mW/m^2	120	Secondary	Patel et al. (2021)
Multi-electrode: 10 sticks in each cathode and 30 in each anode	0.325	mW/m^2	365 (90 for acclimatization)	Secondary	Colares et al. (2022)
Anode at height of 300 mm, cathode at height of 590 mm from bottom	N/S	-	180	Secondary	Wang et al. (2022a)
Cathode at the top and anode down in the substrate with external wire and resistor connection	N/S	-	365	Secondary	Wang et al. (2022b)
The anode consisted of carbon felt (9.5 × 9.5 cm) wrapped with titanium mesh and buried in 4–6 mm gravel, while the cathode comprised a 12 cm layer of activated carbon (4–6 mm)	106	mW/m^2	87	Secondary	Yang et al. (2022)

(*Continued*)

TABLE 7 Continued

Electrode design	Power density	Basis	Operation duration (days)	Energy role (primary/secondary)	References
Cathode at 15 mm, anode at 185 mm below wastewater surface	7.5	mW/m²	290	Secondary	Ebrahimi et al. (2023)
Carbon felt anode–cathode (5 mm, 100 × 10 cm) separated by filter fabric, with titanium wire current collectors, installed at ~30 cm depth	13-18	mW/m²	170	Secondary	de Jager et al. (2023)
Multi-anode of areas 0.2 m² (0.88 m × 0.22 m), 0.17 m² (0.88 m × 0.19 m), and 0.04 m² (0.2 m × 0.2 m) with single cathode area 0.2 m² (0.88 m × 0.22 m)	0.7 – 2.3	mW/m³	210	Secondary	Saeed et al. (2023b)
Two auxiliary MFCs equipped with terracotta-based separator-electrode-assembly (SEA) integrated into the anodic zone	55.55	mW/m²	62	Secondary	Kumar et al. (2023)
Anode placed at 52 cm, cathode at 20 depths from surface	2055 - 3,204	mW/m³	168	Low-power tertiary	Saeed, (2024)
Anode at bottom, cathode at just below water level	122	mW/m³	100 (60 for acclimatization)	Secondary	Souza et al. (2024)

N/S: not specified.

3.9 Economic feasibility, system stability, and scalability

3.9.1 Capital and operational cost considerations

Because most studies prioritize treatment performance over economic evaluation, costs associated with CW-MFC, both capital expenditure (CAPEX) and operational expenditure (OPEX) are rarely reported. This omission may reflect the assumption that costs are relatively low or negligible and therefore do not guarantee detailed attention. However, inconsistent cost reporting significantly limits cross-study comparison and techno-economic assessment costs. In the few cases where costs are reported, they are usually limited to the material-related expenses, particularly those associated with electrodes (predominantly carbon-based materials), granular activated carbon (GAC), and cathode binders or fabrication materials. Only three studies provided explicit cost data, expressed in terms of material mass or area. Walter et al. (2018) reported electrode materials costs of polyvinyl-alcohol (PVA) (≈2 USD/ kg), polytetrafluoroethylene (PTFE) 60% dispersion (≈6 USD/kg), CPD (≈5–8 USD/kg), and sintered activated carbon (SAC) (0.3–3 USD/kg). Wang et al. (2022a) reported an area cost of electrode materials of 50 USD m² for carbon felt (0.5 m² used), while Wang et al. (2022b) reported the area and mass-based costs with carbon cloth priced at 31 $/m² and GAC at 0.775 USD/kg. Although reported OPEX values are generally low, CAPEX remains comparatively higher and strongly influenced by material choice, availability, and local sourcing (Bolton and Randall, 2019; Wang et al., 2022a; Wang et al., 2022b). The use of low cost, durable and locally available materials such as waste bricks in large sized CWs construction, has been highlighted as a promising strategy to improve sustainability and facilitate broader adoption across different regions.

3.9.2 Energy and cost reporting gaps

Energy consumption in the CW-MFC studies is rarely reported because the system is expected to be energy producing rather than consuming. Only two studies (Wang et al., 2022a; Wang et al., 2022b) reported actual consumption values of 0.007 kW h/m³ and 0.0045 kW h/m³ respectively and these values are specifically for low power pumping. These energy values are much lower than the conventional, and as such makes CW-MFC operation sustainable. The economic feasibility of the system has only been qualitatively reported with such expressions like "low cost", "promising approach" (Wu et al., 2015), "feasible" (Wang et al., 2022a), "practical at large scale", "energy savings", "potential", etc. rather than with concrete economic analysis data expressed through the cost-benefit analysis, the payback period, and the profitability.

Consistent with the limited reporting of energy consumption discussed earlier, only a small proportion of studies provide quantitative data on energy-related costs, such as cost per watt produced or electricity consumption associated with pumping and aeration. The cost per watt produced in the study by (Walter et al., 2018) range from \$69.42/W to \$138.82/W while the electricity tariff is \$0.11/kWh and energy operating cost of the system is $\$4.95 \times 10^{-4}/m^3$ in (Wang et al., 2022a). This high capital cost does not make CW-MFC energy recovery efficient, but rather only treatment efficient.

3.9.3 Sustainability considerations

Sustainability consideration in the review reflected in the resource circularity like utilization of waste jhama bricks as sustainable recycled material for substrate (Saeed, 2024), some reported low cost locally available electrode materials like biochar based electrode (Li et al., 2024) and cost of SAC cathodes and PVA binders for cathode in self-stratifying membrane less MFCs design in (Walter et al., 2018), low CW-MFC operating and energy consumption cost like reported by (Wang et al., 2022a). Sustainability could further be seen in long term operation like the inoculated MFC system sustainably generating electric power for longer than 160 days (Treesubsuntorn and Thiravetyan, 2021) and operation affecting greenhouse gas and carbon effect (Li et al., 2024).

3.9.4 Long-term system stability and durability

The treatment and electrochemical stability within the CW-MFC system over time conveys information on stability of organic matter removal efficiency, produced voltage fluctuations, sensitivity to seasonal changes, long term electrode deterioration, responses to changes in loading rates, and operational issues (like biomass decay, salinity changes, and clogging). The operating system reaches stability when its performance remains steady. For example, the CW-MFC system studied by Ebrahimi et al. (2023) took 20 days to achieve stable bioelectricity generation and the experimental lab study carried out by (Li et al., 2024) was operated for several months until the effluent was stable. Electrode materials are noted to affect the long-term stability of the system. For instance, the PTFE and CPD cathodes demonstrated significant stability all through the experiment by (Walter et al., 2018) while the PVA-5 cathode was noticeably unstable despite producing high power. The variability of seasonal conditions have effects on treatment stability (de Jager et al., 2023). Long term operation of the system shows reduced performance due to cathode deterioration and clogging (Camacho et al., 2017), sludge accumulation and dead plant biomass (Colares et al., 2019). Tang et al. (2019) demonstrated the operation of a stable CW-MFC system for more than 600 days. However, the authors did not report specific stability parameters or identify the operational, material, or microbial factors responsible for maintaining long-term stability. Across the study, stability emerges as a critical indicator, alongside performance metrics, for evaluating the efficiency, reliability, and long-term sustainability of the CW-MFC system.

3.9.5 Pilot- and full-scale scalability pathways

As previously noted, several studies have acknowledged the treatment and energy-recovery potentials of CW-MFC, but only a few have actually demonstrated the scalability via implementing them on a pilot-scale or full-scale. Some of the real scale demonstrations include more than 2 years of operation of a hybrid CW-MFC treatment system studied by Camacho et al. (2014), the innovative full-scale METland system that has been operated under different climates, wastewater types, and hydraulic conditions to treat wastewater (Penacoba-Antona et al., 2022), and a full-scale verification swine wastewater treatment (Wang et al., 2022b). Most of these studies provide technical feasibility but their economic and operational feasibility are still not well established.

Some notable design mechanisms employed to enhance the scalability of the CW-MFC include use of common, low cost and structurally stable materials like GAC, stainless steel, PVC pipes, graphite sticks, upflow multi-anode-single-cathode pilot system (Tang et al., 2019), tidal flow CW-MFC pilot system (Souza et al., 2024) used to evaluate the vegetation and substrates sizes effect on the treatment performance and modular designs like the tubular P-MFC units to test the long-term performance of P-MFC carried out by (de Jager et al., 2023). The modular design is becoming more important in the scaling of the CW-MFC system and it is preferred over large single monolithic unit because of easier maintenance, easier hydraulic control and the redundancy it provides.

Overall, existing pilot and full-scale studies indicate that the practical feasibility of CW–MFC systems is constrained more by long-term stability, material durability, and insufficient economic reporting than by treatment performance, reinforcing their role primarily as treatment-oriented rather than energy-driven technologies.

The relatively higher prevalence of pilot scale studies reflects a growing effort to translate promising laboratory-scale results into real-world applications. However, the very limited number of full-scale, real-life studies highlights a persistent upscaling gap in the field. The CW-MFC systems come in diverse reactor shapes like columns, channels, rectangular boxes, PVC pipes, fiber tanks, High Density Polyethylene (HDPE) container, real soil trenches, and large earthen wetlands. This is an indication of non-standard architecture in the field. For upscaling the CW-MFC system, attention is directed towards using cheap, bio-compatible and readily available substrate media like graphite gravels, electroconductive coke, and calcined petroleum coke (Ramirez-Vargas et al., 2019). These approaches are primarily motivated by the need to reduce costs and enhance sustainability, both of which remain the least reported performance indicators in CW-MFC studies, while reinforcing the role of substrate selection not merely as a structural medium, but as a key long-term sustainability driver that supports hydraulics, microbial colonization, and stable redox stratification in larger systems.

It is observed that most of the small sized systems that have artificially stable redox gradients produce higher power densities, while the larger systems, although they have more realistic microbial ecology and improved hydraulics, generate lower power densities. This further supports the observation that energy recovery remains secondary and increasingly constrained as system complexity and scale increase, and further emphasizes that system-level redox control and hydraulic stability are more decisive to energy recovery outcomes than the specific choice of individual electrode materials.

Several innovative research on CW-MFC tend towards hybridization with multi-stage integrated systems designed to enhance microbial activity, redox gradient, and nutrient removal more than conventional CW systems. Such innovative hybridization across the papers involves CW-MFC with biofilters, GAC filters, osmotic membranes, floating wetlands, anaerobic digestion, and tidal flow or aeration systems.

The bioelectricity innovations in the studies are aimed at reducing cost, improving electron transfer, simplifying assembly, while supporting larger microbial populations and enabling long-term operation with minimal maintenance. Some of these innovations include self-stratifying membrane less design, the use of electroconductive support media to eliminate traditional electrodes, multi-anode-single-cathode design, reversed U-shaped cathodes, microalgal electroactive biofilm, and electrogenic bacteria augmentation. Most of these studies are gradually moving from lab-scale to real-world pilot scale validation implemented under real environmental conditions and real wastewaters. This trend reflects efforts to address the limited economic reporting and long-term stability constraints observed in CW-MFC systems.

As measures to reduce costs, most innovative designs aim to eliminate membranes, reduce costly electrode materials, simplify the structure for rural deployment, reduce external wiring, and use low-cost media materials like GAC, gravel, biochar, and jhama bricks, thereby further confirming that integrated material choice, connectivity, and redox engineering collectively outweigh the influence of any single architectural or electrode configuration.

A significant number of studies did not report any statistical analysis in the evaluation of CW-MFC performance, indicating a major weakness in the methodology employed in the CW-MFC literature, while about half of the reported analyses were simple averages with no supporting statistical tests. However, where statistical analysis is applied, ANOVA-based methods are most common, indicating some level of standardization, although inconsistencies remain in their application across studies.

Many of the works reviewed do not report inoculation, and several also omit key electrochemical parameters such as external resistance. This may be attributed to a lack of standardization and oversight in reporting experimental conditions. It could result in potential reproducibility issues and represents a key gap in the field. This lack of microbial characterization limits the interpretation of treatment performance, energy recovery, and scalability of CW-MFC systems, particularly when comparing systems treating low-strength versus medium- and high-strength wastewaters, where differences in organic loading directly influence electroactive biofilm sustainability and achievable power densities.

4 Conclusions and recommendations

The synthesis of studies between 2010 and 2026 reveals several important trends in the development of CW-MFC systems. First, pollutant removal performance appears to scale more successfully than electricity generation with many pilot-scale systems maintaining high organic and nutrient removal efficiencies despite substantial reductions in power density. Secondly, system performance is influenced more by factors such as redox stratification, electrode placement, substrate characteristics, and hydraulic operation, than by the specific CW configuration itself. Thirdly, the literature suggest that CW-MFCs are more effective as electrochemically enhanced wastewater treatment systems than as viable energy recovery technologies. Finally, while treatment performance has been extensively investigated, indicators such as long-term stability, material durability, economic feasibility, and sustainability remain insufficiently reported, limiting the assessment of the technology readiness for large scale deployment.

Although considerable effort has been devoted to scaling up CW-MFC systems, the findings of this review indicate that increases in reactor size are generally associated with declining power densities, while pollutant removal performance remains consistently effective.

Limitations exist in the electrodes and their materials, as they are costly and, in some cases, structurally unstable. An important limitation, observed also in the studies and in the scaling up of CW-MFC systems, is the sensitivity to operating environmental conditions. Sustainability, typically inferred from indicators such as material durability, use of low-cost or waste-derived materials, energy consumption, and long-term operational stability, is one of the least reported performance indicators of CW-MFC systems. As discussed in Section 3.8.1 and summarized in Table 6, comparative studies generally reported improved pollutant removal following MFCs integration into CWs systems, particularly for COD and nitrogen, although the magnitude of enhancement varied among system configurations and operating conditions. Existing pilot and full-scale studies indicate that the practical feasibility of CW-MFC systems is constrained more by long-term stability, material durability, and insufficient economic reporting than by treatment performance. This reinforces their role primarily as treatment-oriented rather than energy-driven technologies, with energy recovery remaining secondary and increasingly constrained as system complexity and scale increase.

Future research should prioritize long-term studies using real continuous-flow wastewater, rather than synthetic wastewater, in order to generate real-world data from which scalability decisions and design can be taken and sufficient microbial characterization can be established. More research is needed into sustainable and cheaper electrode alternatives, as existing electrode materials are often costly and, in some cases, structurally unstable. Sustainability should be more consistently evaluated and reported as a performance indicator in CW-MFC studies, given its current scanty evaluation and quantification, through measurable metrics such as material durability, use of low-cost or waste-derived materials, energy balance (input versus recovery), and long-term operational stability. Future studies should also adopt minimum statistical reporting standards, including the use of mean ± standard deviation, explicit reporting of sample size (n), and appropriate significance testing (e.g., ANOVA or t-tests) where comparative analyses are performed. This would improve the robustness, comparability, and reproducibility of reported CW-MFC performance data. Further work should focus on improving long-term stability, material durability, and economic reporting, as these factors constrain the practical feasibility of CW-MFC systems more than treatment performance and reinforce their role as treatment-oriented rather than energy-driven technologies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AO: Data curation, Formal Analysis, Writing – original draft, Writing – review and editing. VC: Data curation, Formal Analysis, Writing – original draft, Writing – review and editing. SA: Conceptualization, Supervision, Writing – original draft, Writing – review and editing. PR-S: Supervision, Writing – review and editing. AR: Conceptualization, Supervision, Writing – original draft, Writing – review and editing. CS: Conceptualization, Supervision, Writing – original draft, Writing – review and editing.

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