Applied Science and Engineering Progress, Vol. 20, No. 3, 2027, 8315

Research Article

Comparative Life Cycle Assessment of Bioelectrochemical and Integrated Microbial Fuel Cell Technologies for Sustainable Wastewater Treatment and Resource Recovery

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Received: 12 June 2026; Revised: 30 July 2026; Accepted: 11 August 2026; Published online: 14 September 2026

Abstract
Bioelectrochemical systems (BES) provide dual functionality for wastewater treatment and resource recovery, with integrated configurations offering enhanced potential within the water-energy nexus. This study evaluated the environmental performance and hotspots of various BES and integrated microbial fuel cell (MFC) systems using a multidimensional life-cycle assessment framework. Eight configurations were assessed using the ReCiPe 2016 characterization method and the Ecoinvent database in SimaPro 10.3.0.1. The membrane distillation (MD)-integrated MFC (MD + MFC) emerged as the most sustainable system, leveraging the displacement of the energy-intensive industrial desalination process and the recovery of value-added tap water to achieve a balanced, robust environmental profile. While the microbial electrolysis cell (MEC) offers unparalleled carbon-reduction potential through hydrogen recovery, its operational reliance on fossil-fuel-based electricity creates a critical trade-off with air quality, necessitating the integration of renewable energy to offset its grid dependence. Construction accounts for up to 90% of environmental burdens across most systems, including the standalone MFC and the microalgae-MFC (MA + MFC). The massive physical scale of constructed wetland (CW) + MFCs has entailed significant mineral investment and logistical demands, despite CWs being inherently natural systems. The low-impact microbial desalination cell (MDC), plant-MFC (PMFC), and vermiculture-based MFC (VBMFC) are ideal candidates for decentralized, self-sustaining applications due to their negligible footprints and low toxicological risks. Future studies should explore bio-derived alternatives and circular supply chains to mitigate global warming and resource scarcity. This study further provides stakeholders with evidence-based solutions to identify optimal BES and integrated MFC configurations to advance wastewater treatment and resource valorization.

Keywords: Bioelectricity generation, Environmental impact, Integrated bioelectrochemical system, Life cycle assessment, Microbial fuel cells, Resource recovery, Wastewater treatment

1 Introduction

Untreated wastewater poses serious environmental risks, including water pollution, eutrophication [1], pathogen contamination [2], and threats to human health [3] and aquatic ecosystems [4]. Failure to effectively treat wastewater allows its organic matter to enter the surrounding environment through the emission of greenhouse gases (GHGs), such as carbon dioxide and methane, which contribute to global warming [5]. However, traditional industrial wastewater treatment technologies are highly energy-intensive, often accelerating fossil fuel consumption and climate change, and exacerbating the global energy crisis [6]. This led to growing interest in more efficient, less energy-intensive wastewater treatment methods.

A bioelectrochemical system (BES) is an emerging technology with promising dual functionality for treating wastewater and recovering resources (e.g., electricity, desalinated water, hydrogen, biodiesel) via microbial activity [7]. BESs have significant potential to contribute to the circular economy and carbon neutrality by treating solid waste and toxic aromatic hydrocarbons in *in situ* bioprocess scenarios [8]. These systems harness microbial or enzymatic metabolism within an electrochemical framework to enhance electron transfer [9] as observed in numerous technologies with versatile configurations.

The advent of BES research is driven by its strengths, namely its ability to generate energy and provide a sustainable approach to mitigating the massive global energy demands of wastewater treatment [10]. Among BES variants, microbial fuel cells (MFCs) represent the most extensively studied configuration, followed by microbial electrolysis cells (MECs) and microbial desalination cells (MDCs) [6]. Its popularity stems from its economic and environmentally friendly mechanisms, including relatively low energy consumption [10], the absence of secondary pollutants [11], high energy conversion efficiency, and low sludge production [12]. Standalone MFCs can produce electricity in the range of 2-260 kWh/ton of product from wastewater treated and are thus more suitable for digester effluents as final polishing [13].

Despite the advantages of BES, several studies have identified techno-economic and environmental hurdles to its development. For MEC, the need for additional external voltage to overcome the thermodynamic limitations of hydrogen production imposes several constraints on its operations [11], such that proper control of external voltage and operating conditions is advised to reduce methane emissions, energy inputs, and hydrogen consumption [6]. While generally more economically viable and profitable than most conventional methods [14], MFCs incur high installation costs due to the high material intensity (i.e., proton-exchange membranes, cathodes, electrodes) of their components [15], limited overall nitrogen and phosphorus removal, and limited buffering capacity and substrate conductivity [11]. Integrating MFCs with other technologies is known to improve their environmental performance by generating co-products with additional environmental benefits [6]. Such integrated systems include microalgae (MA) fermentation [16], constructed wetlands (CW) [17], plants [16], vermiculture [17], and membrane distillation (MD) [6].

To ensure a fair comparative analysis and address inconsistent findings regarding the environmental profiles of these BESs and integrated MFC systems, numerous life cycle assessments (LCA) have been employed [7]. LCA is a standardized, quantitative decision-making tool for assessing the environmental sustainability of products or waste treatment systems [18]. Chin *et al.,* [6] reported that the double-chamber air-cathode MEC, membrane distillation-integrated MFC (MD + MFC), standalone MFC, and MDC are among the most favorable systems for offsetting environmental loads due to the generation of value-added by-products. However, standalone MFCs significantly affect resource use due to their resource-intensive construction.

MD + MFC outweighed the total environmental burdens associated with global warming, particulate matter formation, human carcinogenic toxicity, and fossil resource scarcity, owing to the high environmental benefits of tap water production for domestic use. This addresses both water shortages and energy scarcity by reducing fossil-fuel-based electricity consumption, which energy-intensive industrial desalination processes use [6]. Meanwhile, CWs are integrated into the standalone MFC as a low-impact, multifunctional alternative for cost-sensitive wastewater treatment [7], offering a middle ground between its standalone counterparts [15] in terms of environmental and operational benefits at moderate cost [13].

Between algae-based MFC and CW + MFCs, the latter yields superior results despite periodic fluctuations associated with light and dark cycles [6]. Meanwhile, microalgal MFCs offer superior biomass production with reduced environmental impacts [19], making them important for wastewater management and renewable energy generation [13]. However, energy generation can only offset the electricity consumption for operation (0.019-667.8 kg CO_2-eq per year) in minor amounts [6].

While integrated MFC systems are often compared with industrial wastewater treatment processes, studies comparing the environmental performance of different BESs and integrated MFC systems remain scarce [20]. In this study, a comprehensive LCA is conducted to compare and investigate the impacts and environmental hotspots of various BESs and integrated MFC systems under the same functional unit. The analysis also identifies environmental hotspots across the systems and accounts for the value-added by-products generated during wastewater treatment. In-depth analysis of the environmental profiles of these systems would provide stakeholders with quantifiable insights and evidence-based solutions to leverage the potential of BESs and integrated MFC systems to achieve the water-energy nexus through microbial-based wastewater treatment and resource recovery.

2 Materials and Methods

The LCA methodology is employed as a standardized decision-making tool in quantifying and analyzing the environmental performance of BES, adhering to the four stages of the ISO 14040:2006 framework: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) life cycle interpretation [18].

2.1 *Goal and scope definition*

This study aims to evaluate and compare the environmental impacts of various BES and integrated MFC configurations to identify critical environmental hotspots and significant credits arising from value-added by-products. In addition to BES, this analysis incorporates integrated MFC systems, given their growing prominence in coupling MFCs with complementary technologies to enhance resource recovery and overall performance [21]. The eight systems under evaluation include:

1. Microbial fuel cell (MFC)
2. Microbial electrolysis cell (MEC)
3. Microbial desalination cell (MDC)
4. Microalgae (MA) + MFC
5. Membrane distillation (MD) + MFC
6. Plant-Microbial fuel cell (PMFC)
7. Constructed Wetland (CW) + MFC
8. Vermiculture-based MFC (VBMFC)

The standalone MFC has a single-chamber air-cathode configuration with bioelectricity generation. MEC is known for biohydrogen production and has a double-chamber air-cathode configuration. MDC is tubular, producing bioelectricity and desalinated water. Both MFC and MDC have a similar wastewater treatment mechanism [6].

The integrated CW + MFC, MA + MFC, and MD + MFC are designed with double-chamber configurations and can all generate electricity. MA + MFC integrates microbial anaerobic oxidation at the anode with algal photosynthesis occurring at the cathode to further produce biolipid, which can be used as biodiesel [22]. MD + MFC employs a thermal membrane-based water purification system that simultaneously treats wastewater and generates electricity [6]. CW complements the dual-chamber configuration of MFCs by providing a natural vertical redox gradient. This enables CW + MFC to harvest bioelectricity directly into a natural, plant-based wetland bed [14]. PMFC is based on a 110-day rice growth cycle in a 10 × 3 m chamber using irrigation pumping [23] while earthworms (i.e., *Eudrilus eugeniae*) act as a biocatalyst to degrade complex biodegradable wastes and produce electricity in a VBMFC [17].

The schematic diagram demonstrating the general system boundary for each system is shown in Figure 1. System boundaries encompass construction and operation phases. These include materials, energy inputs and outputs, and value-added products (e.g., energy or recovered resources) eligible for potential environmental credits.

The functional unit (FU) is defined as the treatment of 1 m^3 of wastewater over a 10-year operational lifespan. Normalizing values to the FU is important for maintaining consistency across reference systems and ensuring comprehensive assessments, thereby enabling more accurate,

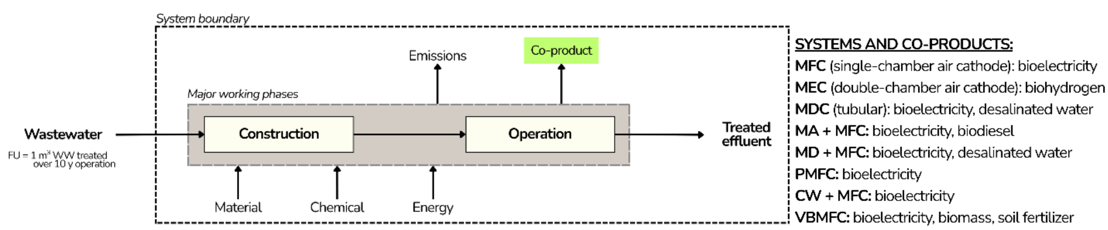

Figure 1: Generalized system boundary for the BES and integrated MFC systems.

holistic evaluations of environmental impacts in wastewater treatment and bioelectrochemical systems [24]. End-of-life (EoL) phases are excluded, as prior analyses indicate negligible contributions relative to construction and operation [25]. For all treatment options, construction materials and electricity consumption are included as input data, while the output data include direct GHG emissions, co-products, and effluent. Scenarios only reflect laboratory- or pilot-scale setups. Thus, the need for large-scale maintenance over a relatively short period is omitted. Inoculum cultivation is beyond the scope, as it involves cultivation farms.

2.2 *Life cycle inventory*

Tables 1 - 3 summarize the foreground data for input and output flows (i.e., energy consumption, direct GHG emissions, effluent, amount of construction material, and by-products generation) compiled and derived from peer-reviewed experimental journals or literature sources for each treatment option. The background data (e.g., material production inventories) were sourced from the Ecoinvent v3.8 database in SimaPro 10.3.0.1 [26]. Industry standards and other conversion factors (i.e., lower heating value) were accounted for to ensure that values are

Table 1: Life cycle inventory sheet for BES based on FU (1 m^3 of treated wastewater over 10y).

Treatment option	Stage	Material	Quantity
Microbial Fuel Cell (MFC) [7]	Construction	Acrylic reactor (PMMA)	2.7 kg
		Graphite plate electrodes	0.0737 kg
		Resistance box	0.8 kg
		Titanium wire	0.0277 kg
		Membrane	2.01 kg
		Silicone tubes	0.132 kg
		Graphite felt (3×200×300 mm)	0.027 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption	1.9726 kWh
		Energy produced	0.0624 kWh
		COD	0.0417 kg
		TN	0.0317 kg
		NO_3	0.001337 kg
		TP	0.001967 kg
		CH_4	5.2055 kg
		CO_2	3.0137 kg
		Polypropylene container	0.0970 kg
Microbial Electrolysis Cell (MEC) [6]	Construction	Polycarbonate (anode chamber)	0.436 kg
		Graphite felt	0.00396 kg
		Polycarbonate (cathode chamber)	0.436 kg
		Carbon paper (cathode)	0.00107 kg
		Nickel	0.0000498 kg
		J-cloth (separator)	0.000622 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption	14.40 kWh
		COD	0.0238 kg
		Hydrogen gas (vehicle fuel)	3.25 kg
Microbial Desalination Cell (MDC) [6]	Construction	Carbon brush (anode)	0.00348 kg
		Carbon cloth (cathode)	0.00469 kg
		Activated carbon	0.00099 kg
		Anionic exchange membrane	0.00701 kg
		Cationic exchange membrane	0.00728 kg
		Polyvinyl chloride	0.0264 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption	2.40 kWh
		COD	0.005 kg
		Electricity produced	0.19 kWh
		Tap water	200 kg

normalized to the FU. Transportation and electricity consumption parameters are also incorporated into the assessment during the construction phase to ensure that environmental impacts associated with logistics and energy inputs are accounted for in a more comprehensive LCA.

The reactor has a capacity of 2.7 kg or a volume of 0.005 m^3 with a hydraulic retention time of 24 hours. In 10 years, each treatment option is assumed to treat 18.25 m^3 of wastewater. Wherever applicable, a 90% removal rate (e.g., BOD, COD) and 10% emission (i.e., methane) are assumed. The electrode area is set at 0.18 m^2.

The general equations governing the calculation of material and energy consumption for the construction and operation phases are expressed in Equations (1) – (3) below, where W_m is the material i weight in kg; n_i is the total amount of material i; V_i is the volume of material i in m^3; ρ_i is the density of the material i in kg/m^3; $E_{c/g}$ is the amount of electricity

Table 2: Life cycle inventory sheet for integrated MFCs based on FU (1 m^3 of treated wastewater over 10y) Part 1.

Treatment option	Stage	Material	Quantity
Microalgae—Microbial Fuel Cell (MA + MFC) [6]	Construction	Acrylic reactor (PMMA, anode chamber)	0.45 kg
		Carbon fiber cloth (anode)	0.0103 kg
		Acrylic reactor (PMMA, cathode chamber)	0.45 kg
		Carbon fiber cloth (cathode)	0.0103 kg
		Cationic exchange membrane	0.417 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption	0.23 kWh
		Energy produced	0.03 kWh
		COD	0.18 kg
		Lipid (biodiesel)	0.3052 kg
Membrane Distillation — Microbial Fuel Cell (MD + MFC) [6]	Construction	Glass (anode chamber)	2.33 kg
		Carbon mesh (anode)	0.00142 kg
		Glass (cathode chamber)	2.33 kg
		Carbon mesh (cathode)	0.00142 kg
		Polytetrafluoroethylene	0.00263 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption	0.21 kWh
		COD	0.027 kg
		Electricity produced	1.99×10^{-5} kWh
		Tap water	17000 kg
Plant—Microbial Fuel Cell (PMFC) [23]	Construction	Earthen pot (ceramic)	20 kg
		Activated biochar (anode) 900 cm^2 × 3 mm thick	0.27 kg
		Activated biochar (cathode) 900 cm^2 × 3 mm thick	0.27 kg
		Wiring (current collector)	0.05 kg
		Electric circuit (1.8 kΩ)	0.00025 kg
		Circuit support (0.09 kg breadboard)	
		Plastic body	0.00419 kg
		Metal contacts	0.00074 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption (irrigation pump)	2.7375 kWh
		Soil	20 kg
		Rice plants	0.0548 kg
		CH_4 reduction (-27.1%)	7.32×10^{-4} kg
		Electricity produced	0.4629 kWh
		Inorganic fertilizer (per ha scaled to 30 m^2)	
		Nitrogen	0.01315 kg
		Phosphorus	4.11×10^{-3} kg
		Potassium	5.75×10^{-3} kg

Table 3: Life cycle inventory sheet for integrated MFCs based on FU (1 m^3 of treated wastewater over 10y): Part 2.

Treatment option	Stage	Material	Quantity
Constructed Wetland—Microbial Fuel Cell (CW + MFC) [7]	Construction	Graphite plate electrodes	1.8 kg
		Resistance box	0.8 kg
		Titanium wire	0.0277 kg
		Silicone tubes	0.132 kg
		Gravel	4.54 kg
		Activated carbon	4.54 kg
		Zeolite	4.54 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption (pumps)	1.9726 kWh
		Energy produced	0.0192 kWh
		COD	0.0259 kg
		TN	7×10^{-4} kg
		NO_3	1.06×10^{-3} kg
		TP	7.9×10^{-4} kg
		CH_4	3.9452 kg
		CO_2	1.3151 kg
Vermiculture-based — Microbial Fuel Cell (VBMFC) [17]	Construction	Rectangular glass container (12 × 6 × 7 in = 504 in^3)	18.42 kg
		Cationic exchange membrane	0.417 kg
		Duct tape border (7 × 6 in perimeter)	5.3×10^{-3} kg
		Resistance box	0.8 kg
		Current collectors (graphite rods, copper wires)	0.025 kg
		Bedding material (for moisture and aeration)	0.035 kg
		Drilling appliance	0.018 kWh
		Transportation	0.0637 tkm
	Operation	Electricity consumption	0.21 kWh
		COD	0.012 kg
		Watering (maintenance)	0.0822 kg
		Compost (additional bedding)	0.054 kg
		Substrate (worm feed)	146 kg
		Electricity produced	4.8×10^{-3} kWh
		Biomass (80 adult *Eudrilus eugeniae*)	5×10^{-3} kg (dry wt.)
		Soil fertilizer	9.65×10^{-4} kg

generated or consumed in kWh; $P_{a/v}$ is the area or volume power density of the system in W/m^2 or W/m^3; t is the operational time in h; F is the amount of conventional fuel to be replaced in MJ; r is the biofuel production rate in kg/h, and HHV is the heating value of the produced biofuel in MJ/kg [6].

$$W_{mi} = n_i \times V_i \times \rho_i \quad (1)$$

$$E_{c/g} = P_{a/v} \times x_{a/v} \times t \quad (2)$$

$$F = r \times t \times HHV \quad (3)$$

The environmental loads from the collected and calculated inventory data are normalized to the FU and classified according to their related impact categories. The inventory data included construction materials, electricity consumption for operations, chemical use, and emissions to air and water to better evaluate the comparative impacts of the different BES and integrated MFC systems. For the local data parameters, the electricity mix from the Philippines was used since the research was conducted in said country. Transportation distances are based on the inventory data from Miwornunyuie *et al.,* [7].

2.3 *Life cycle impact assessment*

Environmental benefits are assessed using various environmental impact indicators, based on the ReCiPe 2016 midpoint characterization method in SimaPro 10.3.0.1, providing a standardized framework for assessing the environmental performance of the BESs and integrated MFC systems [6]. The midpoint method quantifies emissions or extractions from the life-cycle inventory of the treatment system by characterizing them into various impact categories using a common reference substance [26]. For example, kg CO_2-eq is used as a basis for global warming, while kg 1,4-DCB is used as a basis for human carcinogenicity. The following midpoint impact categories are considered: global warming (GW), fine particulate matter formation (FPMF), terrestrial acidification (TA), freshwater eutrophication (FE), marine ecotoxicity (ME), human carcinogenic toxicity (HCT), mineral resource scarcity (MRS), and fossil resource scarcity (FRS). These impact categories are considered the primary affected impacts (i.e., over 75% of the endpoint category) and are often studied by related studies [6].

2.4 *Life cycle interpretation*

Environmental contributions from key processes and emissions are evaluated across all parts of the BESs and integrated MFC systems. The impacts across all phases are summed to represent the net environmental performance, enabling evaluation of each system's overall burden or benefits. These further reveal hotspots and inform the comparative environmental viability of microbial-based technologies.

To further evaluate the stability of the baseline LCA results, a literature-based sensitivity analysis was conducted in lieu of arbitrary parameter perturbation. Key parameters include variation with construction, electricity consumption, chemical consumption, and direct emissions [27]. These were benchmarked against published literature quantifying the sensitivity analyses of BESs. This empirical cross-validation enables robust assessment of system variations and stability across different grid and industrial conditions.

3 Results and Discussion

This section provides a comprehensive discussion of environmental hotspot analysis and comparison study of the BESs (MFC, MEC, and MDC) and the integrated MFC systems (MA + MFC, MD + MFC, PMFC, CW + MFC, and VBMFC) whose environmental profiles are studied against eight (8) impact categories across a multi-dimensional LCA framework.

3.1 *Impact assessment and environmental hotspot analysis of bioelectrochemical systems*

The environmental impacts for the three BESs, namely the single-chamber air-cathode MFC, double-chamber air-cathode MEC, and tubular MDC, under the eight selected midpoint impact categories, are demonstrated in Figure 2. Table 4 further shows the net impact values for each treatment option classified by midpoint category. The positive values represent environmental burdens, while the negative values indicate avoided impacts, assessed on a functional-unit basis throughout the BES lifecycle.

The standalone MFC had the highest environmental impact on global warming (GW), accounting for up to 90% of the overall environmental burdens, with a net impact of 211.92 kg CO_2-eq. [7] Its construction phase surfaced as the most significant contributor across all categories, except in GW and FE, where operation dominates.

Its high environmental burdens in MRS (0.2370 kg Cu-eq) and ME (0.2356 kg 1,4-DCB) are attributed to the associated mining and chemical processing to develop the specialized electrodes and metal-based catalysts. In addition, polymethyl methacrylate (PMMA), the primary component of the acrylic reactor, is produced through an energy-intensive process. Its use in the assembly could also have had a significant impact on the FRS category (2.247 kg oil eq).

The standalone MFC also utilizes graphite plate electrodes and graphite felt in its assembly, which imposes additional environmental burdens as the extraction of carbon-based electrodes produces NO_x. and volatile organic compounds (VOCs) [7]. The potential toxicity of its components poses health risks, which can be correlated with its high impacts on the HCT (0.1536 kg 1,4-DCB) and FPMF (0.0307 kg Cu-eq) categories.

In hindsight, the rampant reliance of BESs on fossil fuels for their operations results in undesired particulate emissions and acidification hotspots that endanger local air quality and natural habitats. This implies that for global warming concerns, the direct emissions and the background impacts of the

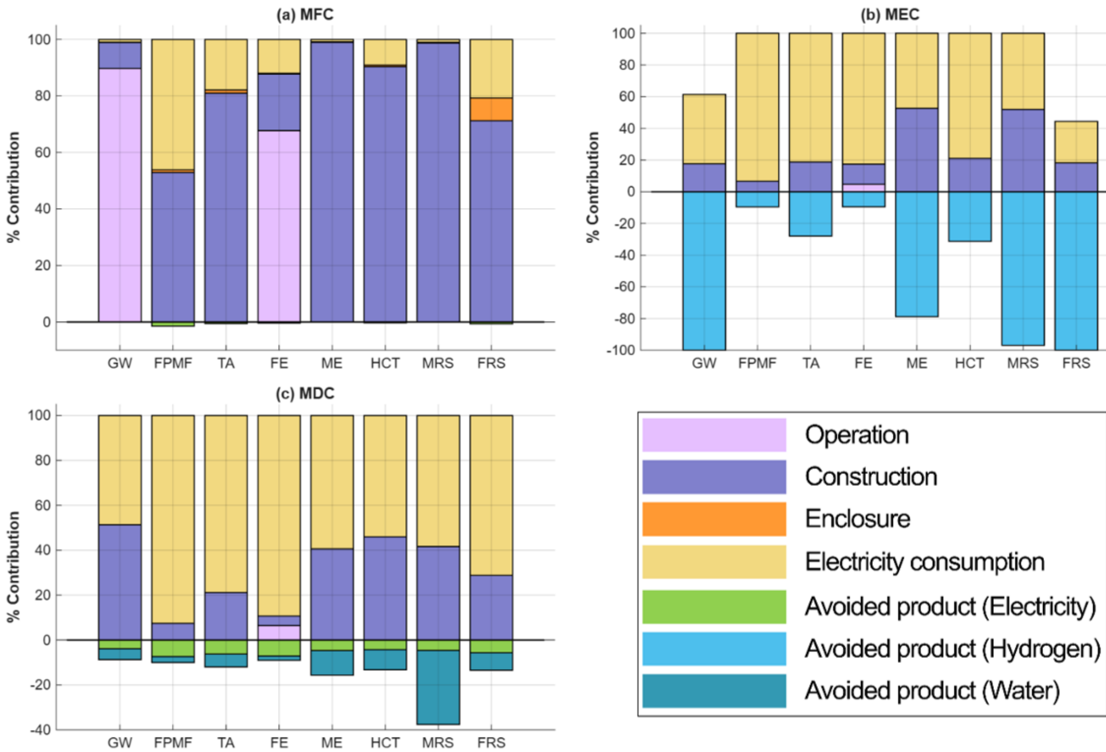

Figure 2: Environmental impacts of BES, based on FU (1 m^3 of treated wastewater over 10 y of operation).

Table 4: Net impact values of BES per impact category.

Impact category	Unit	MFC	MEC	MDC
Global warming	kg CO_2eq	211.92	-12.90	4.584
Fine particulate matter formation	kg PM2.5 eq	0.0307	0.1019	0.0170
Terrestrial acidification	kg SO_2 eq	0.0535	0.0626	0.0131
Freshwater eutrophication	kg P eq	0.0033	0.0032	0.0005
Marine ecotoxicity	kg 1,4-DCB	0.2356	0.0065	0.0034
Human carcinogenic toxicity	kg 1,4-DCB	0.1536	0.0892	0.0274
Mineral resource scarcity	kg Cu eq	0.2370	0.0011	0.0031
Fossil resource scarcity	kg oil eq	2.247	-7.268	0.6936

treatment of 1-m^3 of wastewater in ten (10) years are relatively more significant than the environmental costs from construction. In fact, sensitivity analyses confirm that electricity consumption significantly contributes to GHG emissions [27], leading to high uncertainty regarding the environmental feasibility of BESs.

Among the three BESs analyzed, the standalone MFC is the least environmentally friendly due to its intensive material requirements. In fact, about 90% of its overall GW burden is due to high operational electricity consumption. Therefore, efforts to reduce GW potential should focus on optimizing energy use during the operational phase [7] to leverage their inherent energy-saving design [9] and to avoid producing secondary pollutants [12].

The same trend is observed for MEC and MDC, where electricity consumption is a critical trade-off. The highly dynamic environmental profile of MEC stems from biohydrogen production, which offsets the need for industrial treatment via steam methane reforming. The displacement of this industrial process avoids substantial toxic releases and mining requirements, yielding significant environmental credits in ME (-0.024 kg 1,4-DCB) and MRS (-0.035 kg Cu-eq). However, MEC still had a notable impact on FPMF (0.1019 kg PM2.5-eq) and TA (0.0626 kg SO_2-eq) due to potential SO_2 and NO_x emissions during operations.

Its vulnerability, therefore, lies in its heavy reliance on fossil-fuel-based power and high energy requirement to produce high-value hydrogen gas. Thus, its sustainability is closely linked to how efficiently biohydrogen production can offset its energy use through substantial environmental credits in GW (-12.90 kg CO_2-eq) and FRS (-7.268 kg oil-eq). Nonetheless, MEC has a more efficient resource-to-output ratio, with fewer hazardous materials and a more efficient distribution across its FU, unlike a standalone MFC.

MDC has generally low environmental impacts across all eight categories. However, the impact remains positive, with its construction and operation phases contributing 22.7% and 58.7% of the total GW burdens, respectively, across the entire life cycle [28]. This is attributed to the material composition (e.g., polytetrafluoroethylene PTFE binder and ion-exchange membrane) and electricity consumed for water pumping. Sensitivity analysis is usually conducted to investigate how environmental impact varies with increasing power density. For instance, Zhang *et al.,* [25] reported that the increase in power density in MDC affects its desalination capacity, suggesting its direct proportionality with the quadratic of the water flow rate. To boost its environmental benefits and make it a net-negative technology, it must be integrated with other sustainable technologies to advance its wastewater treatment and resource recovery potential.

Despite promising performance for energy generation and resource recovery, the findings reveal that the environmental profile of BESs remains heavily affected by their physical infrastructure and manufacturing footprint. While MEC emerges as a leading system for climate mitigation through hydrogen production, its environmental profile reveals a significant shift in environmental burdens toward local air quality concerns. Hence, to make it ultimately sustainable across all categories, research should pivot on coupling with renewable energy sources, such as intermittent solar or wind energy, to eliminate their huge impacts on GW and FPMF. Sensitivity analysis indicates significant reductions in GHG emissions and energy demand by 37.4% and 22.1%, respectively, if systems switch to renewable energy sources [29].

Finding alternative low-cost materials is also necessary. Walter *et al.,* [30] replaced expensive proton exchange membranes with inexpensive separators and employed membrane-less configurations. Similar studies have also replaced Nafion with ceramic-based membranes [31] and platinum-based cathodes with non-precious catalysts without compromising efficiency, yet curbing costs and embedded emissions [22].

Recycled materials (e.g., carbon from waste tires) can also be extracted for use in assembling BESs. Petroleum-based membranes and mineral catalysts could also be replaced with bio-derived materials, such as biochar, to reduce toxicity. LCA studies on biochar signify its role in GW mitigation (1.34-2.94 t CO_2-eq/ton), carbon sequestration (4.98×10^8 t CO_2-eq/year), crop yield increase (17-53%), fertilizer use reduction (up to 25%), enhanced soil fertility, and high pollutant removal efficiency (70-99.6%) [32].

This further necessitates the application of green chemistry to improve the material composition of BES [20] and to offset undesirable environmental footprints beyond their biological power outputs [33]. Future studies should pivot on redirecting the switch toward carbon-neutral, locally sourced, and recycled components to help curb associated emissions [7].

3.2 *Impact assessment and environmental hotspot analysis of MFC and its integrated systems*

The performance of integrated MFC systems is compared with that of standalone MFCs (Figure 3) to determine whether integration results in synergistic effects that enhance wastewater treatment and resource recovery.

MD + MFC offers the most balanced and robust environmental profile among standalone MFCs and their integrated systems. This integrated configuration emerged as the best system, achieving net-positive performance and significant environmental credits across all midpoint impact categories. Despite requiring a complex assembly to integrate the membrane distillation unit into the MFC, it effectively offsets the initial environmental debts of the standalone MFC and yields optimal resource recovery.

MD + MFC has an overall impact of -0.2198 kg 1,4-DCB for HCT and -0.1224 kg Cu-eq for MRS, indicating the most substantial health benefit from displacing the energy-intensive industrial desalination process. It also avoids particulate matter formation, resulting in a net impact of -0.0305 kg PM2.5-eq and providing significant environmental credits that effectively offset the environmental debt associated with its footprint.

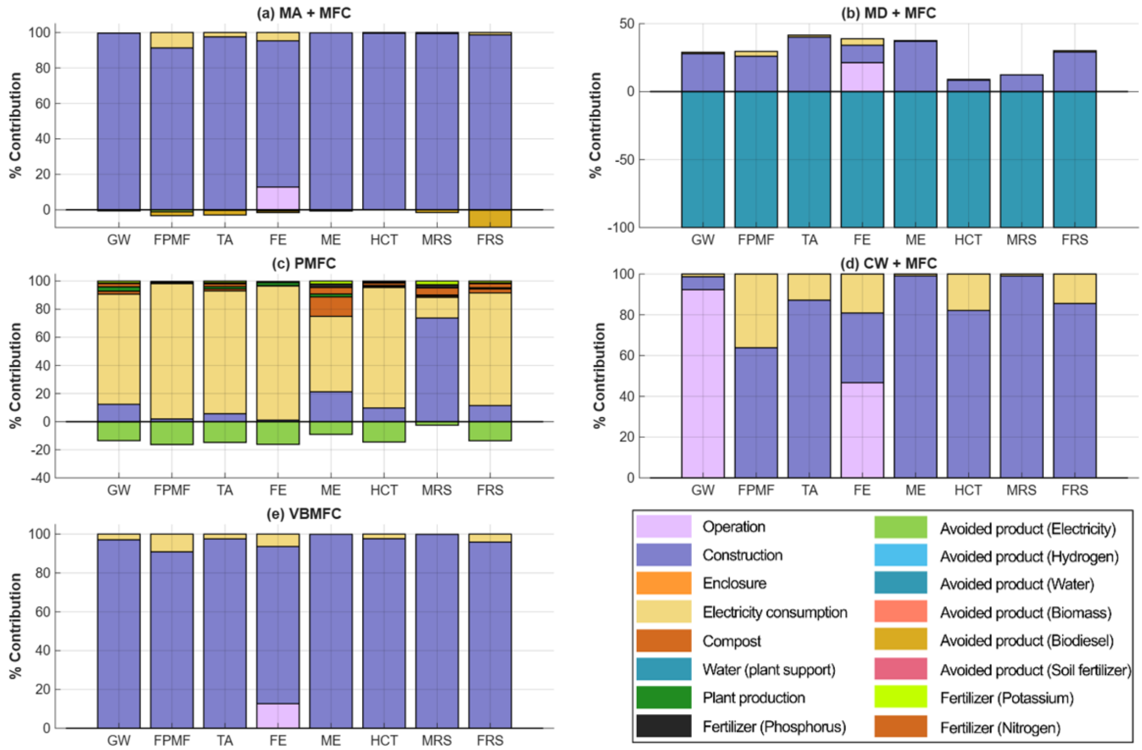

Figure 3: Environmental impacts of integrated MFCs, based on FU (1 m^3 of wastewater over 10 y operation).

Chin *et al.*, [6] confirm the effectiveness of MD + MFC in sufficiently avoiding impacts to outweigh environmental burdens under GW, FPMF, HCT, and FRS impact categories, as shown in Table 5. This novel integration addresses both water shortages and energy scarcity by providing tap water for domestic use and reducing reliance on fossil fuels for electricity. It also resulted in the least environmental impact on both human health and ecosystems. Hence, the massive credits from water recovery consistently outweigh the impacts of MD + MFC construction and operation. These findings provide primary scientific evidence that synergy is achieved when MFC systems are integrated. Hence, these results can be used by policymakers and key stakeholders to recommend policy frameworks that incentivize desalination and resource recovery, as well as carbon credits, to encourage high-performing integrated systems, such as MD + MFC.

The integrated CW + MFC system reduced emissions by 73% compared to its standalone counterpart. This is because it uses low-cost anode and cathode electrodes, resulting in lower costs, reduced complexity, and lower maintenance requirements that make it more economically viable [15]. However, this integration comes with a critical trade-off, as it is the second-highest contributor to GW (155.19 kg CO2-eq) and FPMF (0.035 kg PM2.5-eq), and has the highest impact on TA (0.075 kg SO_2-eq) among all systems.

Constructed wetlands are inherently natural systems and emit lower levels of greenhouse gases, often with a strong capacity for carbon sequestration to offset more lifecycle carbon emissions. In fact, photosynthesis in CWs offsets more than 15% of its total footprint [27]. However, the integration of MFC, whose components pose significant toxicological risks and require energy-intensive infrastructure, may have driven this increase in impact. This may also stem from the relatively large land footprint, which required large volumes of gravel and sand, as well as additional piping for the structure.

Massive quantities of specialized bulk media and metal piping, and the logistical requirements for heavy machinery and transportation fuel for the construction of the wetland infrastructure, also directed impacts on MRS (0.2595 kg Cu-eq) and FRS

Table 5: Net impact values of integrated MFC systems per impact category.

Impact category	Unit	MA+MFC	MD+MFC	PMFC	CW+MFC	VBMFC
Global warming	kg CO_2 eq	65.23	-14.72	3.074	155.19	7.289
Fine particulate matter formation	kg PM2.5 eq	0.0187	-0.0305	0.0174	0.0397	0.0167
Terrestrial acidification	kg SO_2 eq	0.0440	-0.0423	0.0131	0.0752	0.0418
Freshwater eutrophication	kg P eq	0.0010	-0.0005	0.0005	0.0021	0.0007
Marine ecotoxicity	kg 1,4-DCB	0.1322	-0.0235	0.0047	0.2190	0.2122
Human carcinogenic toxicity	kg 1,4-DCB	0.3851	-0.2198	0.0194	0.0783	0.0634
Mineral resource scarcity	kg Cu eq	0.0491	-0.1224	0.0220	0.2595	0.2250
Fossil resource scarcity	kg oil eq	3.751	-3.716	0.7019	3.236	1.216

(3.236 kg oil-eq). The upstream production of infrastructure materials and potential ammonia emissions from wetland nitrogen cycling could have also contributed to its acidification hotspots. Therefore, integration with CW induces unwanted emissions that result in elevated environmental impacts, particularly GW (155.19 kg CO_2-eq), FPMF (0.0397 kg PM2.5-eq), and TA (0.0752 kg SO_2-eq). This is because the LCA framework accounted for cradle-to-gate impacts associated with mining, processing, and transporting bulk media (i.e., sand and gravel) for wetland construction.

Scaling up CW + MFCs is more economically beneficial than standalone MFCs, as CWs are already incorporated into natural ecosystems as hosts and are therefore employed at the field level for slow wastewater treatment kinetics [15]. However, the material used for its electrode is a crucial consideration. Corbella *et al.,* [34] found that CW + gravel-based anode MFC contributed twice that of the environmental impacts of a standalone CW due to the large amount of relatively less environmentally friendly materials for MFC integration. CW + graphite-based MFC is instead suggested as the most sustainable solution to replace conventional CWs, with a potential reduction of greenhouse gas emissions by up to 20%. Thus, this study employed graphite-based electrodes. However, this system is 1.5 times more expensive than CWs.

MA + MFC can achieve its functional goal of improving nutrient removal and generating energy, but its coupling creates a toxicological hotspot. Thus, it is a stark reminder that integration will not always result in synergy to improve the environmental profile of a system. While it emerges as a smart integration with net-positive environmental impacts [19], it reveals severe trade-offs and significant toxicological and resource burdens across impact categories.

Its environmental burdens are largely determined by its construction. In fact, its construction phase dominates the HCT (0.3845 kg 1,4-DCB) and FRS (0.0496 kg Cu-eq) categories. This further indicates that adding biological complexity and petrochemical-based feedstocks could introduce a critical ecotoxicity threshold to the standalone MFC configuration, potentially leading to the release of toxic precursors during manufacturing.

A similar study [22] integrated MA into a biotic cathode-based MFC with *Chlorella vulgaris* as the microalgae. It was found that MA cultivation and the harvesting unit operation both returned negative environmental indices, while the MFC operation had an insignificant contribution to the environmental burden. *C. vulgaris* reduced the overall environmental burden compared to using fertilizer. However, it only reduced the burdens, not eliminated them. This further indicates that the environmental benefits of MA + MFC can be realized only if microalgae are cultivated exclusively for wastewater treatment and remediation [6].

Both PMFC and VBMFC were observed to have low environmental impacts. While their impacts are net positive, these values stayed near zero. PMFC and VBMFC have negligible impacts on GW (3.1-7.3 kg CO_2-eq), FE (0.0005-0.0007 kg P-eq), ME (0.005-0.21 kg 1,4-DCB), and FRS (0.70-1.21 kg oil-eq). These low material footprints demonstrate the efficiency of these systems compared to standalone and other integrated MFCs with greater infrastructure complexity.

The integration of plants and vermiculture into MFCs scales the eutrophication and acidification impacts in proportion to their material complexity, resulting in a relatively leaner design and energy profile. Due to the inherent photosynthetic ability of plants, PMFC also offers direct reduction of methane emissions, while VBMFC produces soil fertilizer and biomass (i.e., animal feed). While these systems do not yield large environmental credits, their low toxicological profiles and lower energy intensity make them ideal candidates for decentralized wastewater treatment and energy generation [7].

In contrast, the standalone MFC remains the leading risk across most impact categories. It demonstrated the greatest impact on eutrophication, creating a disparity in its vital role in wastewater treatment. Therefore, the benefits of nutrient removal during operations must be weighed against the phosphorus-intensive manufacturing of the system itself to optimize its performance [7].

3.3 *Overall comparison of BES and integrated MFC systems in midpoint categories*

MD + MFC is the most balanced and robust system, leading in environmental credits across all eight midpoint impact categories. It displaces the intense energy demands and chemical processing burdens of conventional desalination. Techno-economic assessments revealed that the thermal energy cost for MD operation contributes the most to the total treatment costs. Sensitivity analysis revealed that the feed total dissolved solids (TDS) level and thermal energy price contributed significant impacts on the operational costs. Thus, similar studies explored integrating the MD system with a waste heat source to reduce total wastewater treatment costs by up to 87% [35].

Cao *et al.* [36] confirmed that the novel integration of MD and MFC can contribute to the sustainable development of the water-energy nexus. Despite its promising multi-benefit integration, no large-scale studies have been reported thus far. Consequently, its scalability is constrained by substantial financial limitations stemming from investor reluctance and technical operational bottlenecks. Nonetheless, prospects for economic scalability can be addressed through key engineering advances that are set to improve performance. This includes modular stacking with low-cost electrodes and membranes without compromising high power output; power management strategies to mitigate cell reversal and related issues; and the use of alternative, low-cost yet efficient materials [21].

MEC is best suited for climate change mitigation and reducing fossil-fuel-based emissions. Its role in reducing GW and FRS is unparalleled due to hydrogen production. However, it exhibits a significant shift in burden toward FPMF, which can be addressed by integrating renewable energy as its power source for electrolysis.

The standalone MFC and high-complexity MA + MFC systems are revealed to be limited by the toxicological and resource-intensive nature of their specialized components in Figure 4. Standalone MFC had the highest contributions to GW, FE, and ME; the second-highest to HCT and MRS; and the third-highest to FPMF, TA, and FRS across all eight systems. MA + MFC has the highest impact on HCT and FRS categories. This system is a reminder that not all integrations yield synergistic effects for enhanced wastewater treatment and resource valorization.

The integration of CW into the standalone MFC configuration reduced the latter's impact on the GW category by 73%. However, it had the highest impact on TA and MRS, and notable impacts on GW, FPMF, ME, and FRS. Hence, CW + MFC serves as a valuable example that natural systems do not necessarily equate to sustainability from a full-lifecycle perspective. In this case, the physical scale of CW + MFCs involves mining, processing, and transporting bulk media (i.e., sand and gravel), creating a mineral investment that cannot repay its footprint.

VBMFC demonstrates the proportional scale of environmental impacts from structural integration, without the commensurate increase in operational benefits. VBMFC is efficient for carbon management; however, hidden environmental debts are observed in its MRS and ME profiles. Meanwhile, MDC and PMFC are low-impact treatment options that offer a decentralized, modular approach to treating wastewater while generating energy.

Material optimization is ultimately important for exploring more compact designs and for using recycled materials to reduce environmental burdens associated with the construction of BESs and integrated MFC systems. Therefore, there is a need to identify CO_2-neutral alternative materials to strengthen the vital role of MFC as a wastewater treatment technology [37].

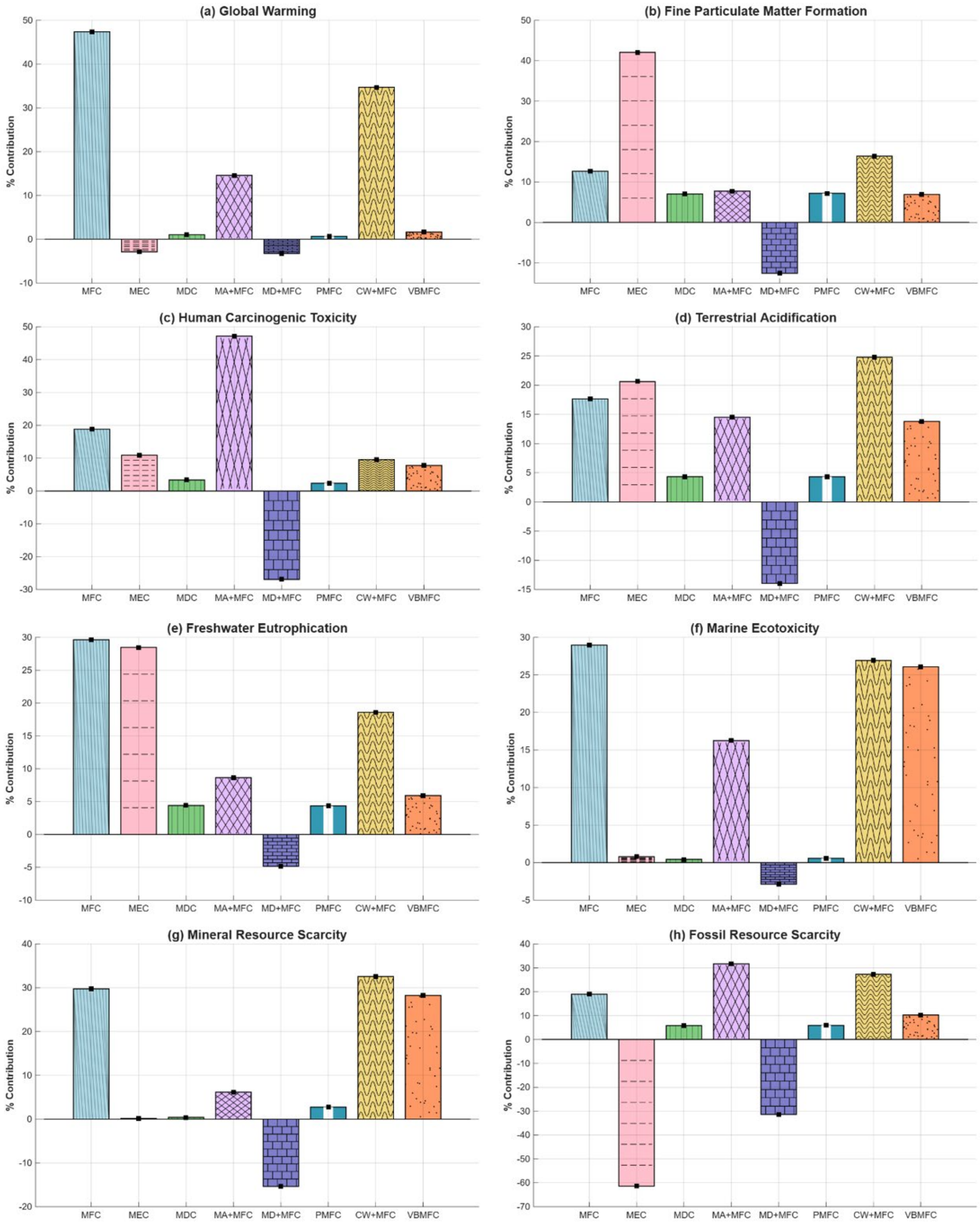

Figure 4: Comparative environmental profiles of BES and integrated MFC systems.

3.4 *Future directions*

While BESs may not replace centralized power plants, they would likely serve as critical decentralized nodes in a circular economy [20]. MFCs can be integrated with photovoltaic cells for lighting and charging applications in remote locations deprived of electricity [9]. MECs can be used as small-scale hydrogen generators to reduce the fossil-fuel dependence of the transport and chemical sectors. MDCs are poised to offer modular, net-positive water-recovery mechanisms in water-scarce regions.

PMFCs and MD + MFCs provide pathways for self-sustaining agriculture and water-treatment systems, contributing to the water-energy-food nexus through *in situ* energy generation and wastewater treatment, while ensuring crop health with minimal resource depletion. Once the environmental hotspots of MA + MFC and CW + MFC are addressed, they can be used for nutrient removal and decentralized wastewater treatment. Meanwhile, VBMFCs offer a low-impact organic waste treatment option that can improve soil fertility.

These findings reveal a direct proportionality between a system's environmental credits and the amount of product it displaces. The recovery of high-value hydrogen and water in MEC, MD+MFC, and MDC, respectively, provides the most robust pathway toward resource valorization and carbon neutrality in the bioelectrochemical sector.

This study revealed that not all natural and bio-based systems are inherently low-impact. Therefore, LCA studies should analyze systems to determine the potential integration of a circular supply chain and recycled and sustainable materials to mitigate high GW, MRS, and eutrophication impacts of the standalone MFC. The integration of intermittent renewable sources is also important for eliminating particulate matter risks to local air quality and addressing the critical trade-off in MECs.

Studies show the pivotal role of FU in understanding and interpreting associated environmental impacts within a system by balancing system comparability, environmental relevance, and scalability to real-world applications to best align with industry standards [29]. Thus, functional units should also account for variable wastewater compositions to capture the influence of influent concentration on nutrient removal and desalination during operations.

Key stakeholders and policymakers should require in-depth cradle-to-gate LCAs for green infrastructure and technology before they are employed. This should be coupled with a techno-economic analysis to assess the system's feasibility in terms of investment and operational costs relative to industrial technologies.

Policy frameworks should account for the diverse, multi-output nature of BESs to foster their deployment across communities. Policies should also incentivize desalination cells and nutrient recovery mechanisms to encourage the ecological benefits of high-performing integrated MD + MFC systems.

Given the potential of MD + MFC and MDC to serve as decentralized wastewater treatment and resource recovery systems, policymakers should structure development grants and policy support mechanisms to prioritize decentralized wastewater treatment solutions over more massive, energy-intensive centralized plants. Overall, this study provides data-driven insights to help stakeholders choose suitable BESs that meet their needs to improve water management, achieve carbon neutrality, and enhance resource recovery.

4 Conclusions

The environmental performances of the different BESs and integrated MFC systems are evaluated using the LCA framework. Among the eight configurations, MD + MFC emerged as the most balanced and robust solution, with net-negative environmental credits resulting from the displacement of the energy-intensive industrial desalination process. The production of high-value hydrogen in MEC drives its unparalleled role in climate change mitigation, but it comes with localized air-quality risks due to heavy reliance on a fossil-fuel-based electrical grid. This establishes that the capacity of BESs to achieve a net-negative environmental profile is proportional to the energy intensity of the conventional industrial process it displaced. Therefore, coupling BESs with intermittent, renewable energy sources is recommended to offset high operational electricity costs. Meanwhile, construction remains the primary driver of environmental burdens in most systems (i.e., accounting for up to 90% of impacts). This proves that the infrastructure and material components often pose sustainability bottlenecks in the performance of BES, which underscores the role of green chemistry in exploring mechanisms and substitutes to improve the material composition of these treatment options. This is crucial, as not all natural and bio-based integrations guarantee low environmental impact. This is evidenced by the integration of CWs with MFCs, which entailed significant mineral investment and transport energy demands that negated the expected ecological benefits of CWs. Low-impact MDC, PMFC, and VBMFC systems are ideal for decentralized, self-sustaining applications for agriculture, remote water monitoring, and localized wastewater treatment. Thus, policies incentivizing green technologies must include incentives for desalination and nutrient recovery to match the technical diversity of treatment options. LCA integrated with techno-economic assessments must be a mandatory prerequisite for funding and scaling decentralized wastewater treatment systems. The study outcomes are projected to provide data-driven, evidence-based solutions as a principal guide for stakeholders in selecting suitable BESs and implementing policies to advance wastewater treatment and resource valorization.

Acknowledgments

The authors would like to acknowledge the support of the Department of Science and Technology – Engineering Research and Development for Technology (DOST-ERDT) in this study.

Author Contributions

S.M.: conceptualization, investigation, methodology, research design, data analysis, writing- original draft, writing—reviewing and editing; K.R.P.: research design, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the Grammarly tool to enhance the language and readability of the manuscript.

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