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Exploring the Life Cycle Environmental Performance of Different Microbial Fuel Cell Configurations

Min Yee Chin[a], Zhen Xin Phuang[a], Marlia Mohd Hanafiah[b,c], Zhen Zhang[d], Kok Sin Woon[a,*]

[a] School of Energy and Chemical Engineering, Xiamen University Malaysia, Jalan Sunsuria, Bandar Sunsuria, 43900 Sepang, Selangor Darul Ehsan, Malaysia.
[b] Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Selangor, Malaysia.
[c] Centre for Tropical Climate Change System, Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Selangor, Malaysia.
[d] College of Natural Resources and Environment, Joint Institute for Environmental Research & Education, South China Agricultural University, Guangzhou, 510642, China.
koksin.woon@xmu.edu.my

Drastic global population and economic growth have escalated energy and water crises across the world. The overconsumption of energy and water resources without proper planning has entailed adverse environmental impacts. The emergence of microbial fuel cell (MFC) as a bio-electrochemical system (BES) for wastewater treatment and electricity generation shows potential as a prospective solution for the crises. To date, there is no study focused on the environmental impact comparison of different MFC configurations from a life cycle perspective. In this study, the environmental performance of five common MFC configurations (MFC 1: air-cathode MFC; MFC 2: H-type MFC; MFC 3: U-type MFC; MFC 4: flat MFC; and MFC 5: modularized MFC) from the construction stage to the operational stage are being investigated and compared via life cycle assessment methodology. MFC 1, MFC 3, and MFC 4 are single chamber reactors, while MFC 2 and MFC 5 are double chamber reactors. Data collected for this study are mainly sourced from peer-reviewed journal articles and evaluated using the ReCiPe 2016 impact assessment method in SimaPro 9.0 software. The results reveal that the MFC 4 induces the highest overall environmental burdens due to the high hydraulic retention time for wastewater treatment. The other options share significantly low and similar overall environmental burdens. It is also found that the energy consumption from MFC options accounts for 60-90 % of environmental loads in wastewater treatment. The COD level of the treated effluent in all options meets the discharge standard, but the nitrogen and phosphorus content level have to be further reduced to minimise the eutrophication risk to the aquatic ecosystems. This study provides data-driven insights to the renewable energy policymakers and wastewater treatment stakeholders on the environmental potential of different MFC configurations in relieving energy and water crises.

1. Introduction

The rapid growth of global energy demand due to the rise of the world's population and industrialisation is an alarming worldwide concern. BP Statistical Review of World Energy (2020) disclosed that the global primary energy consumption had risen 1.3 % in 2019, with the energy consumption share mainly from oil (33 %), coal (27 %), and natural gas (24 %). The high dependence on fossil fuels (84 %) will lead to fossil depletion soon. The world is actively driving renewables to replace fossil fuels to overcome environmental problems.

The increase in water demand is another severe global issue. The annual global water demand is about 4,600 km^3 for all uses, with an approximate annual increment rate of 1 % and tends to grow significantly over the next two decades in households, industry, and agriculture sectors (United Nations World Water Assessment Programme, 2020). Around 67 % of the world population is expected under water "stress" conditions (500 - 1,000 m^3/y/capita of water scarcity value) by 2025. A consistent clean water supply is necessary for essential human activities and ecosystem health to achieve Sustainable Development Goal 6.

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Microbial fuel cell (MFC) is a technology that associates the benefits of wastewater treatment and electricity generation. It converts the chemical energy to electrical energy from the electrochemical bacterial metabolic activities carried out in the substrate (i.e., wastewater) (Sawasdee and Pisutpaisal, 2018). Figure 1 shows the schematic diagrams and working principle of various MFCs. A typical MFC comprises a set of anode and cathode immersed in a substrate and separated with a membrane, which both are connected with an external circuit to form a complete loop for electrons to flow through. MFC has gained attention in experimental studies (0.03-250 L) and pilot-scale studies (250 - 1,200 L) starting from the past decades. Recent studies focus primarily on the upscaling of MFC to commercial applications by enhancing electricity production efficiency.

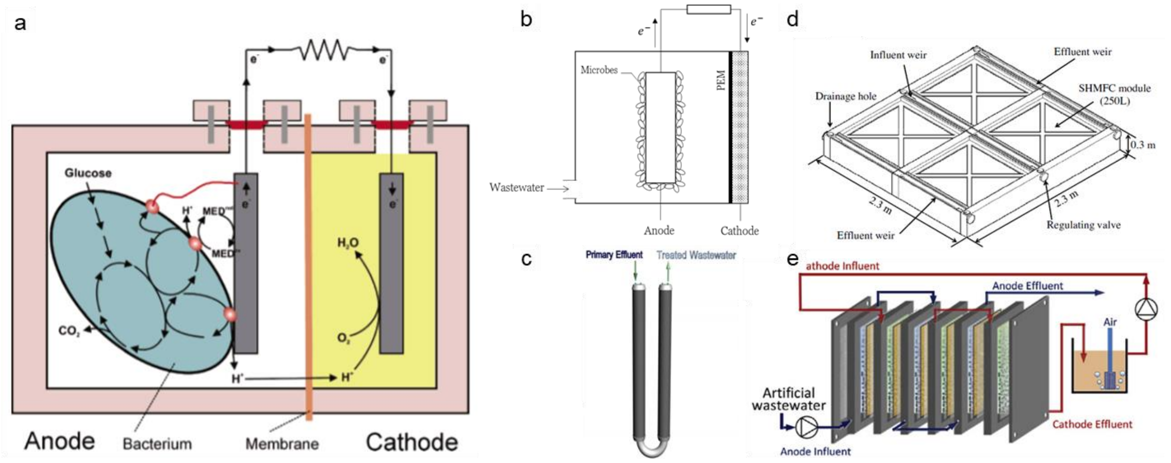

Figure 1: Schematic diagram and working principle of (a) typical MFC (H-type) (Logan et al., 2006), (b) air-cathode MFC, (c) U-type MFC (Zhang et al., 2013), (d) flat MFC (Feng et al., 2014), (e) modularized MFC (Liang et al., 2018)

Various configurations, such as H-type MFC, air-cathode MFC, and U-type MFC, have been explored to determine the best fit MFC implemented in different places and improve the technical performance of MFC. Corbella et al. (2017) conducted a study to compare the environmental performance of constructed wetland coupled with different anode materials of MFC. Comparison studies of MFC with other bio-electrochemical systems (BESs) and benchmarking with existing wastewater treatment plants (WWTPs) were carried out to investigate the best eco-friendly treatment system. A pilot-scale MFC and microbial electrolysis cell (MEC) were compared by Foley et al. (2010) with a high-rate anaerobic wastewater treatment plant. Environmental impacts of different BES, namely MFC, MEC, and microbial desalination cell, were investigated by Zhang et al. (2019a). Another study assessed the environmental performance of osmotic-MFC and benchmarked it with different conventional WWTPs and BESs (Zhang et al., 2019b). Yet, none of the existing life cycle assessment (LCA) studies compares the environmental impact of MFC in various configurations. This comparison study is essential as the electricity generation and wastewater treatment performance of the MFC is commonly affected by design and operating parameters as evidenced by Aboelela et al. (2020). Investigating the environmental impacts caused by different configurations allows us to design an environmentally friendly MFC with effective treatment performance. This study evaluates the life cycle environmental impacts of various MFC configurations and identifies the environmental hotspots of the studied MFC.

2. Methodology

To quantify the environmental burdens and evaluate the potential impacts systematically, LCA is a feasible option as it is internationally standardised (Woon and Lo, 2014). This study is conducted based on the LCA framework following the ISO 14040 under four phases: (1) goal and scope definition, (2) life cycle inventory analysis, (3) life cycle impact assessment, and (4) life cycle interpretation. The detailed contexts for each phase are presented in the following sections.

2.1 Goal and scope definition

The goal of this LCA study is to compare the environmental impact incurred by the significant hotspots of MFC in various configuration options, i.e., MFC 1: air-cathode MFC; MFC 2: H-type MFC; MFC 3: U-shape MFC; MFC 4: flat MFC; and MFC 5: modularized MFC. The functional unit (FU) of this study is 1 L of wastewater treated. The lifespan of MFC is assumed to be 10 y of operation as validated by the pilot-scale study in Foley et al. (2010). The system boundary is illustrated in Figure 2. This study includes only the construction and operational stages of MFC. The end-of-life stage is omitted as it does not cause significant impacts as compared to the construction and operational stages (Foley et al., 2010).

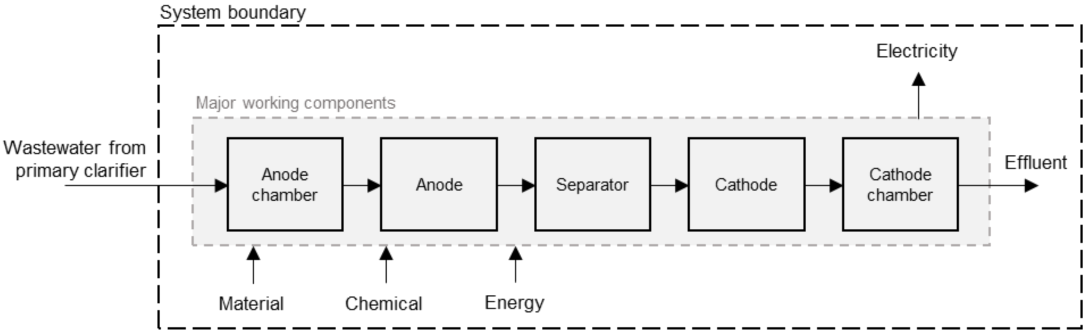

Figure 2: System boundary for this LCA study

2.2 Life cycle inventory analysis (LCI)

The life cycle inventory data after converted by the FU are summarised in Table 1. They are mainly collected and calculated from peer-reviewed journal articles. The collected chemical oxygen demand (COD) data of the sewage wastewater from primary clarifier is constrained within 250-500 mg COD/L. The data span from the input to the output for the primary processes within the system boundary. These include material and chemical utilisation, power consumption and generation, and effluent emission.

Table 1: Inventory data for the studied options, referred to FU (1 L of wastewater treated over 10 y operation).

Parameter	Unit	Option[3]				
		MFC 1[2a]	MFC 2[2b]	MFC 3[2c]	MFC 4[2d]	MFC 5[2e]
Configuration		Air-cathode (SC)	H-type (DC)	U-type (SC)	Flat (SC)	Modularized (DC)
Treatment capacity	L/y	10.22	183.96	3185.4	15,330	1,314,000
HRT[1]	h	24	16.56	11	144	2
Effluent COD	mg/L	112.5	43.5	90.3	70	50
Anode chamber		PMMA	PMMA	N/A	PMMA	PVC
	g/FU	3.98×10^{-3}	3.34×10^{-2}	N/A	7.44×10^{-1}	3.92×10^{-2}
Anode		Carbon paper	Graphite felt	Carbon brush	Carbon brush	Coal GAC
	g/FU	5.89×10^{-4}	1.63×10^{-3}	2.89×10^{-3}	5.96×10^{-3}	1.43×10^{-2}
Cathode chamber		N/A	PMMA	N/A	SS mesh	PVC
	g/FU	N/A	3.34×10^{-2}	N/A	3.94×10^{-2}	3.92×10^{-2}
Cathode		Carbon cloth	Carbon brush	Carbon cloth	Carbon mesh	Coal GAC
	g/FU	7.9×10^{-4}	6.83×10^{-4}	2.27×10^{-3}	2.58×10^{-3}	1.43×10^{-2}
		Platinum	N/A	AC powder	Platinum	N/A
	g/FU	3.42×10^{-5}	N/A	9.86×10^{-4}	3.26×10^{-5}	N/A
Separator		PEM	CEM	CEM	Polypropylene	CEM
	g/FU	2.47×10^{-3}	7.2×10^{-3}	2.61×10^{-2}	3.52×10^{-2}	5.8×10^{-3}
Artificial Catholyte	L/FU	N/A	N/A	N/A	N/A	4
Electricity consumption	kWh/FU	2.4×10^{-3}	3.34×10^{-3}	1.1×10^{-3}	1.43×10^{-2}	6.67×10^{-4}
Biomass formation	mg/FU	11	31.32	15.15	21.06	20
Electricity generation	kWh/FU	1.68×10^{-5}	1.71×10^{-5}	2.55×10^{-5}	6.52×10^{-5}	1.78×10^{-5}

[1] HRT: Hydraulic retention time, SC: Single chamber, DC: Double chamber, PMMA: Polymethyl methacrylate, PEM: Proton exchange membrane, AC: Activated carbon, CEM: Cation exchange membrane, SS: Stainless steel, PVC: Polyvinyl chloride, Coal GAC: Coal granular activated carbon, N/A: data are not applicable in the literature

[2] Liu and Logan (2004)[a], Ye et al. (2019)[b], Zhang et al. (2013)[c], Feng et al. (2014)[d], Liang et al. (2018)[e]

Most of the articles did not indicate the amount of electricity consumed during the operating process (i.e., only pumping process); the required energy is assumed to be 0.1 kW/m^3 reactor. This value is extracted from on-site data, which is supported by Foley et al. (2010). It is assumed that 15 % of removed COD is consumed for biomass formation. The electricity generation mix adopted in this study is based on Malaysia's profile (43.4 % coal, 39.1 % gas, 15.6 % hydro, 1.3 % diesel, 0.6 % others), while the inventory data for other materials production are sourced from Ecoinvent v3 in SimaPro 9.0 software (SimaPro 9, 2019).

2.3 Life cycle impact assessment (LCIA)

The life cycle models for the studied options are constructed using SimaPro 9.0 software, and ReCiPe 2016 characterization method is used to evaluate the environmental impacts incurred by the studied options. Midpoint impact categories classify the source of emissions and resources, while the endpoint damage categories are the reflection points of the impact categories, showing the potential outcomes. ReCiPe 2016 method is selected as it has relatively low result uncertainty among the complex impact categories and able to conclude them into only three endpoint results. This study focuses on the heavily affected midpoint impact categories related to MFC's functionality (i.e., wastewater treatment and electricity generation). The selected midpoints and their related endpoints are shown in Figure 3.

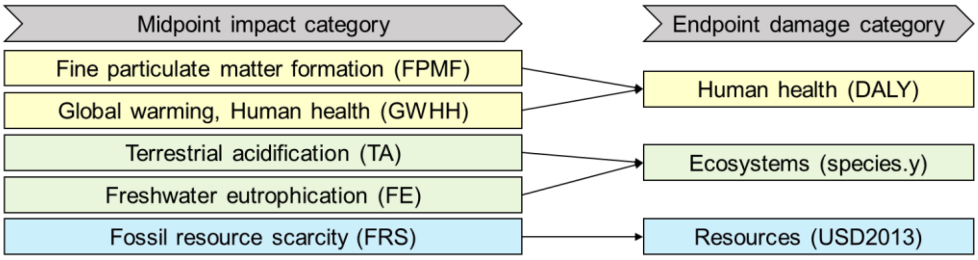

Figure 3: Relations between the selected midpoint impact categories and the endpoint damage categories

3. Results and discussion

3.1 Life cycle interpretation

Table 2 shows that the environmental loads under the construction stage (i.e., anode chamber, anode, cathode chamber, cathode, and separator) of most MFC options are 60 - 90 % lower compared to the operational stage, except for MFC 5 due to the utilisation of coal GAC as the electrode. The overall environmental loads of the MFC options other than MFC 4 (flat MFC) are significantly and similarly low (not more than 40 %) compared to that of MFC 4 based on the assessed impact categories. The overwhelmingly high environmental burdens of MFC 4 are due to its relatively low treatment capacity caused by high hydraulic retention time (HRT) for wastewater treatment. The HRT for MFC 4 is approximately 10 times longer than the other options. Albeit of high HRT, the power generation performance of MFC 4 does not correspond. Studies proved that longer HRT could improve power density, but the power density decreases when the HRT is too long, e.g., 6.32 d (Asensio et al., 2018). High HRT does not guarantee the benefits of MFC (i.e., generate electricity and treat wastewater), but instead incurs higher environmental burdens. HRT should be well-adjusted to meet wastewater discharge standards at the lowest possible environmental loads. FPMF and GWHH, TA, and FRS in human health, ecosystems, and resources, are dominated by electricity consumption, with more than 60 % environmental impact induced by each option, except for MFC 5. The electricity used in MFC treatment is solely consumed for pumping and circulation of wastewater. The phenomenon of high environmental loads is mainly attributed to the extensive mining and burning of natural gas, hard coal, and crude oil to produce electricity, which emits primarily $PM_{2.5}$, sulphur dioxide, and greenhouse gases (i.e., carbon dioxide and methane) to the air. The environmental burdens caused by electricity consumption could be reduced by replacing the on-site electricity usage with the electricity generated by MFC. The electricity generation from the studied options can only counter 0.5 - 2.7 % of their electricity consumption while treating wastewater. Among these options, the electricity generated from MFC 4 has the lowest competency to offset its consumption, with approximately 0.5 %, while MFC 5 performs the best (2.7 %). Most MFC treated raw wastewater thus far obtained less than 20 W/m^3 power density (Yu et al., 2021), which is insufficient to fully offset the conventional electricity usage (i.e., 100 W/m^3).

Unlike the other impact categories, FE under ecosystems is mainly induced by the effluent. Effluent possesses 68 %, 60 %, 84 %, 31 %, and 86 % of the total environmental loads of MFC 1, MFC 2, MFC 3, MFC 4, and MFC 5, in FE. The high environmental impact is due to the emission of phosphorus and nitrogen in the effluent. Although the COD effluent for most of the options has met the sewage discharge standards (i.e., 200 mg/L), the limiting nutrients in the effluent are not on par. Reason being that the enhancement of electricity generation is commonly given more emphasis than that of wastewater treatment in most options. To leverage the dual functionality of MFC, MFC should be placed as the secondary treatment system in the conventional WWTP for energy-saving and further water sanitation improvement purposes.

Table 2: Results of selected impact categories related to studied options referred to the FU (1 L of wastewater treated over 10 y operation). The positive value indicates the environmental burdens incurred by the option, while the negative value indicates the environmental benefits contributed.

Option	Compartment	Impact category[a] (Unit)				
		FPMF (DALY/FU)	GWHH (DALY/FU)	TA (species.y/FU)	FE (species.y/FU)	FRS (USD2013/FU)
MFC 1	Anode Chamber	5.42×10^{-11}	6.70×10^{-11}	5.87×10^{-14}	1.85×10^{-15}	8.77×10^{-06}
	Anode	1.83×10^{-12}	3.18×10^{-12}	2.01×10^{-15}	1.88×10^{-18}	5.51×10^{-07}
	Separator	2.74×10^{-11}	2.68×10^{-10}	2.02×10^{-14}	5.99×10^{-15}	1.82×10^{-06}
	Cathode	2.46×10^{-12}	4.27×10^{-12}	2.69×10^{-15}	2.52×10^{-18}	7.40×10^{-07}
	Electricity Consumption	5.63×10^{-09}	3.32×10^{-09}	2.49×10^{-12}	9.79×10^{-13}	2.14×10^{-04}
	Effluent	0	0	0	2.68×10^{-12}	0
	Electricity Generation	-3.84×10^{-11}	-2.32×10^{-11}	-1.74×10^{-14}	-6.86×10^{-15}	-1.50×10^{-06}
	Total	5.54×10^{-09}	3.64×10^{-09}	2.55×10^{-12}	3.66×10^{-12}	2.25×10^{-04}
MFC 2	Anode Chamber	4.55×10^{-10}	5.63×10^{-10}	4.92×10^{-13}	1.55×10^{-14}	7.36×10^{-05}
	Anode	5.07×10^{-12}	8.81×10^{-12}	5.55×10^{-15}	5.19×10^{-18}	1.53×10^{-06}
	Separator	2.23×10^{-11}	2.36×10^{-11}	1.93×10^{-14}	3.44×10^{-15}	4.00×10^{-06}
	Cathode	2.13×10^{-12}	3.69×10^{-12}	2.33×10^{-15}	2.17×10^{-18}	6.40×10^{-07}
	Cathode Chamber	4.55×10^{-10}	5.63×10^{-10}	4.92×10^{-13}	1.55×10^{-14}	7.36×10^{-05}
	Electricity Consumption	7.64×10^{-09}	4.62×10^{-09}	3.46×10^{-12}	1.36×10^{-12}	2.98×10^{-04}
	Effluent	0	0	0	2.68×10^{-12}	0
	Electricity Generation	-3.91×10^{-11}	-2.36×10^{-11}	-1.77×10^{-14}	-6.98×10^{-15}	-1.53×10^{-06}
	Total	8.54×10^{-09}	5.76×10^{-09}	4.46×10^{-12}	4.07×10^{-12}	4.50×10^{-04}
MFC 3	Anode	8.99×10^{-12}	1.56×10^{-11}	9.84×10^{-15}	9.20×10^{-18}	2.71×10^{-06}
	Separator	8.31×10^{-11}	8.79×10^{-11}	7.16×10^{-14}	1.28×10^{-14}	1.49×10^{-05}
	Cathode	2.18×10^{-11}	2.34×10^{-11}	2.05×10^{-14}	3.44×10^{-15}	2.55×10^{-06}
	Electricity Consumption	2.52×10^{-09}	1.52×10^{-09}	1.14×10^{-12}	4.49×10^{-13}	9.82×10^{-05}
	Effluent	0	0	0	3.00×10^{-12}	0
	Electricity Generation	-5.83×10^{-11}	-3.53×10^{-11}	-2.64×10^{-14}	-1.04×10^{-14}	-2.28×10^{-06}
	Total	2.57×10^{-09}	1.61×10^{-09}	1.22×10^{-12}	3.46×10^{-12}	1.16×10^{-04}
MFC 4	Anode Chamber	7.34×10^{-09}	9.08×10^{-09}	7.94×10^{-12}	2.51×10^{-13}	1.19×10^{-03}
	Anode	1.85×10^{-11}	3.22×10^{-11}	2.03×10^{-14}	1.90×10^{-17}	5.58×10^{-06}
	Separator	7.50×10^{-11}	1.40×10^{-10}	7.72×10^{-14}	3.31×10^{-15}	4.56×10^{-05}
	Cathode	6.11×10^{-11}	1.02×10^{-10}	5.83×10^{-14}	4.72×10^{-17}	5.33×10^{-06}
	Electricity Consumption	3.27×10^{-08}	1.98×10^{-08}	1.48×10^{-11}	5.84×10^{-12}	1.28×10^{-03}
	Effluent	0	0	0	3.58×10^{-12}	0
	Electricity Generation	-1.49×10^{-10}	-9.01×10^{-11}	-6.76×10^{-14}	-2.66×10^{-14}	-5.82×10^{-06}
	Total	4.01×10^{-08}	2.90×10^{-08}	2.29×10^{-11}	9.64×10^{-12}	2.52×10^{-03}
MFC 5	Anode Chamber	9.01×10^{-11}	1.90×10^{-10}	9.35×10^{-14}	6.15×10^{-15}	3.40×10^{-05}
	Anode	2.14×10^{-10}	1.61×10^{-10}	1.85×10^{-13}	4.98×10^{-14}	6.22×10^{-06}
	Separator	1.85×10^{-11}	1.95×10^{-11}	1.59×10^{-14}	2.85×10^{-15}	3.30×10^{-06}
	Cathode	2.14×10^{-10}	1.61×10^{-10}	1.85×10^{-13}	4.98×10^{-14}	6.22×10^{-06}
	Catholyte	5.90×10^{-11}	3.38×10^{-11}	6.55×10^{-14}	1.42×10^{-14}	1.66×10^{-06}
	Cathode Chamber	9.01×10^{-11}	1.90×10^{-10}	9.35×10^{-14}	6.15×10^{-15}	3.40×10^{-05}
	Electricity Consumption	1.53×10^{-09}	9.22×10^{-10}	6.91×10^{-13}	2.72×10^{-13}	5.96×10^{-05}
	Effluent	0	0	0	3.22×10^{-12}	0
	Electricity Generation	-4.07×10^{-11}	-2.46×10^{-11}	-1.84×10^{-14}	-7.26×10^{-15}	-1.59×10^{-06}
	Total	2.17×10^{-09}	1.65×10^{-09}	1.31×10^{-12}	3.61×10^{-12}	1.43×10^{-04}

[a] FPMF: fine particulate matter formation; GWHH: global warming, human health; TA: terrestrial acidification; FE: freshwater eutrophication; FRS: fossil resource scarcity

4. Conclusion

The overall environmental performance of five common MFC configurations has been investigated. The operational stage (mostly from electricity consumption) of MFC induces 60 - 90 % higher environmental loads than that of the construction stage. MFC 4, the flat MFC, indicates the highest environmental burdens among the other options because of high HRT for wastewater treatment. The other options have 60 % lower burdens than MFC 4 and show quite similar overall environmental performance. FPMF, GWHH, TA, and FRS are the impact categories being significantly affected by the electricity consumption of MFC (pumping process). The effluent discharged creates 31 - 86 % of the environmental burden solely to the FE under ecosystems due to the moderately high nitrogen and phosphorus content in the treated effluent. This study provides quantitative insights to the relevant stakeholders that show interest in incorporating energy-saving and water purification technology in WTPP according to the suitability of plant design. The study can be expanded more in-depth by further investigating other BESs or comparing them with conventional or commercialised alternative WWTP.

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