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Proposed constructed wetland-microbial fuel cell system for decentralized wastewater treatment and energy generation

Propuesta de sistema de humedales construidos acoplados con celdas de combustible microbianas para tratamiento descentralizado de aguas residuales y generación de energía

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Abstract
This study presents the conceptual design and theoretical simulation of a constructed wetland system coupled with microbial fuel cells (CW-MFC) for decentralized wastewater treatment in non-residential settings. Four configurations were evaluated by combining two filtering substrates (quartz sand and activated carbon) and the inclusion or exclusion of an Imhoff tank as a pretreatment stage, considering a system designed for a population of 50 people under the climatic conditions of Yucatán, Mexico. Using a simulation model based on data reported in the literature, chemical oxygen demand (COD) removal and bioelectricity generation were estimated. The results indicated that configurations employing activated carbon achieved higher COD removal efficiencies and improved energy performance. Although the incorporation of an Imhoff tank reduced the influent organic load, it also limited the potential for energy generation. Overall, this study provides a technical and methodological basis for the preliminary design and integrated evaluation of CW-MFC systems in decentralized scenarios.
Keywords: Constructed wetland, microbial fuel cell, bioelectricity, wastewater treatment.

Resumen
Este estudio presenta el diseño conceptual y la simulación teórica de un sistema de humedales construidos acoplados con celdas de combustible microbianas (CW-MFC) para el tratamiento descentralizado de aguas residuales en contextos no residenciales. Se evaluaron cuatro configuraciones que combinan dos sustratos de filtración (arena de cuarzo y carbón activado) y la inclusión o exclusión de un tanque Imhoff como etapa de pretratamiento, considerando un sistema dimensionado para una población de 50 personas bajo las condiciones climáticas de Yucatán, México. Mediante un modelo de simulación basado en datos reportados en la literatura, se estimaron la remoción de demanda química de oxígeno (DQO) y la generación de bioelectricidad. Los resultados indicaron que las configuraciones que emplean carbón activado alcanzaron mayores eficiencias de remoción de DQO y un mejor desempeño energético. Aunque la incorporación de un tanque Imhoff redujo la carga orgánica del afluente, también limitó el potencial de generación de energía. En conjunto, el estudio proporciona una base técnica y metodológica para el diseño preliminar y la evaluación integrada de sistemas CW-MFC en escenarios descentralizados.
Palabras clave: humedales construidos, celdas de combustible microbiana, bioelectricidad, tratamiento de agua residual.

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1 Introduction

Rural and peri-urban communities face limited access to conventional sanitation technologies, which has driven the search for decentralized, sustainable, and low-cost solutions for wastewater treatment. In this context, constructed wetlands (CWs) are artificial systems inspired by natural wetlands, designed for wastewater treatment through the control of specific physicochemical conditions (Ren *et al*., 2021).

The integration of these systems with microbial fuel cells (MFCs) has led to an innovative hybrid technology known as CW-MFC, which, in addition to removing contaminants from wastewater, enables the generation of bioelectricity through microbial metabolism (Liu *et al*., 2022). MFCs are known to generate renewable energy through bioelectrochemical processes (Dorazco-Delgado *et al*., 2021; Zamri et al., 2023). More broadly, renewable energy diversification has gained relevance as a strategy to address energy demand sustainably (Álvarez-Ley *et al*., 2025a). It is worth noting that biological processes are used for the decomposition of various organic pollutants (Medrano-Hurtado *et al*., 2022).

Reported studies have projected the application of CW-MFC systems as a viable alternative for electricity generation due to the vast spatial extent of wetland ecosystems, which cover between 8 and 10 million square kilometers worldwide (Wetser *et al*., 2015).

Depending on the type of CW, the literature reports several architectural configurations for integrated MFCs, including up-flow, downflow, horizontal flow, combined flow, hybrid systems, and stacked structures (Mittal *et al*., 2023). Among these, vertical-flow systems stand out due to their operational advantages, as they enhance hydraulic retention, improve contact between wastewater, the substrate, and plant roots, and promote greater oxygenation of the medium.

In vertically configured CW-MFC systems, particularly those operating under downflow conditions, the influent enters from the upper section and moves through the filtering medium, facilitating the formation of well-defined redox gradients, with a predominantly anaerobic lower anodic zone and an upper cathodic zone with greater oxygen availability. This redox stratification is further reinforced by oxygen diffusion from the atmosphere and oxygen release in the rhizosphere, which promotes the functional separation between oxidation and reduction reactions. As a result, electron transfer between electrodes is optimized, interference among competing biological processes is reduced, and the overall efficiency of the electrochemical system is enhanced (Ebrahimi *et al*., 2021).

Likewise, according to Q. Wang *et al*. (2020), vertical-flow CWs exhibit a greater accumulation of total suspended solids in the upper layer of the filtering medium, whereas in horizontal-flow systems, solid particles are distributed along a horizontal gradient, with higher concentrations near the inlet and a progressive decrease toward the outlet.

In light of the above, the present article presents a conceptual design proposal for a wastewater treatment train based on constructed wetlands coupled with microbial fuel cells (CW-MFC), integrating preliminary screening and flow equalization, followed either by an Imhoff tank as a primary treatment stage and a CW-MFC system as a secondary treatment stage (Design A), or by direct feeding of the equalization tank effluent to the CW–MFC system as the main treatment stage (Design B), in a downflow vertical configuration hydraulically connected in series with a horizontal-flow stage.

The system is conceived as a replicable alternative for non-residential buildings, such as schools or offices, with a baseline design for a population of 50 people under climatic conditions representative of Yucatán, Mexico. Despite the advances reported to date, the number of studies that integrate, within a single analytical framework, both the preliminary sizing of the treatment train and the combined estimation of treatment performance and bioelectrical potential remains limited, while also explicitly comparing substrate and pretreatment configurations.

The proposed design includes a comparative evaluation of the components of the wastewater treatment train, the incorporation of an energy recovery scheme through battery storage, and the simulation of system performance in terms of electrical energy generation and chemical oxygen demand (COD) removal, based on values reported in the specialized literature. In particular, four configurations are evaluated, combining two filtering substrates (quartz sand and activated carbon) and the inclusion or exclusion of an Imhoff tank, in order to identify trade-offs between regulatory compliance and energy recovery.

The proposal is grounded in a specialized and up-to-date bibliographic review, through which structural configurations, functional materials, and plant species compatible with tropical conditions and the operational requirements of decentralized systems were identified. The aim of this article is to establish a technical basis for the development of a functional and adaptable system that contributes to local wastewater treatment and sustainable energy recovery, with potential for demonstrative, educational, and research applications, and that serves as a starting point for experimental validation and performance optimization in future studies.

2 Methodology

The present proposal was based on a literature review focused on the conceptual design of a hybrid CW-MFC system, consisting of a downflow vertical-flow constructed wetland hydraulically connected in series with a horizontal-flow constructed wetland. The system was dimensioned for a baseline population of 50 people, considering a daily wastewater generation of 25 L per person (Rivas Hernández, 2022) concentrated over a 12 h operational period. Under these conditions, a total daily volume of 1,250 L was estimated, with a flow rate of 104.16 L h^{-1} during the hours of operation. The incorporation of treatment systems connected in series for wastewater treatment has been previously reported in the literature as an effective strategy to improve overall system performance (Ren *et al.*, 2021; Rivas Hernández, 2022).

The bibliographic search was conducted in specialized scientific databases (ScienceDirect, Scopus, SpringerLink, MDPI, Web of Science, and Google Scholar), prioritizing peer-reviewed articles published in English or Spanish. Trends, design configurations, functional materials, and plant species employed in CW-MFC systems were analyzed, with particular emphasis on studies conducted under tropical conditions, such as those present in Yucatán, Mexico.

Based on the information collected, the technical and environmental components of the proposed system were defined, the stages of the wastewater treatment train were dimensioned, and an energy recovery scheme was incorporated. For the storage of the generated energy, the use of a lithium iron phosphate ($LiFePO_4$) battery was considered. In addition, as part of the treatment train definition process, a comparative evaluation was carried out, including an analysis of system performance using quartz sand versus activated carbon as filtering substrates, as well as an assessment of the effect of incorporating an Imhoff tank as a pretreatment stage.

Finally, a theoretical simulation of system performance was developed using a model implemented in Python, with the aim of estimating chemical oxygen demand (COD) removal and electrical energy generation based on standard redox potentials. The simulation considered microbial activity associated with the oxidation and reduction processes occurring in the anodic and cathodic regions of the CW-MFC system. System performance was analyzed over a total period of 34 h, considering glucose oxidation at the anode and oxygen reduction at the cathode as the model reaction, in accordance with the global reaction reported in the literature (Álvarez-Ley *et al.*, 2025b).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + electricity + biomass$$

This simplification allowed a direct relationship to be established between chemical oxygen demand (COD) removal and electron transfer, considering that the complete oxidation of one mole of glucose generates 24 moles of electrons. The literature reports that, when converting glucose concentration to COD equivalents, this corresponds to 1.067 g of COD per gram of glucosa (Hitit & Hallenbeck, 2021).

Given that the present proposal focused on non-residential buildings, such as offices and schools, an influent COD value of 288 mg L^{-1} was adopted for the primary treatment system, in accordance with the values reported by Phan *et al.* (2024), for wastewater generated in office buildings. Under these conditions, the simulation of the CW-MFC system was carried out using first-order removal kinetics, with a kinetic constant (k) of 0.87 day^{-1}. This value was selected based on the experimental study by Li *et al.* (2013), in which a CW-MFC system planted with Canna indica operated with a hydraulic retention time (HRT) of 3 days.

Coulombic efficiency (CE) in CW-MFC systems is influenced by the organic load of the treated wastewater. Peñacoba-Antona *et al.* (2022) reported that, under low organic loading conditions (2.0-16.4 g COD $m^{-2}\cdot day^{-1}$), CE reached values of up to 53%, whereas under high organic loads (41.9-45.6 g COD $m^{-2}\cdot day^{-1}$), it decreased significantly, to values ranging between 0.8% and 2.5%.

Similarly,, González *et al.* (2021) observed CE values below 1% in a CW-MFC system operating with a COD concentration close to 540 mg L^{-1}. In the present simulation, considering a moderate organic load corresponding to COD concentrations of 288 mg L^{-1} and 144 mg L^{-1}, the latter resulting from the incorporation of an Imhoff tank as a pretreatment stage, CE values of 3.0% were adopted for the vertical-flow CW-MFC stage and 4.5% for the horizontal-flow CW-MFC stage. These values were selected within the ranges reported in the literature for systems operating under similar conditions.

Since experimental voltage measurements were not available, theoretical maximum value of 1.1 V per redox reaction was adopted as a reference, corresponding to the upper limit of the electrochemical potential associated with the oxidation and reduction reactions considered. Under this assumption, a maximum voltage of 11 V per cell was established by considering ten redox pairs connected in series. It should be noted that each cell was treated as an electrically independent unit, given that the electrochemical processes occur over different time intervals and not simultaneously.

To estimate the electrical power generated under closed-circuit conditions, a fixed external resistance

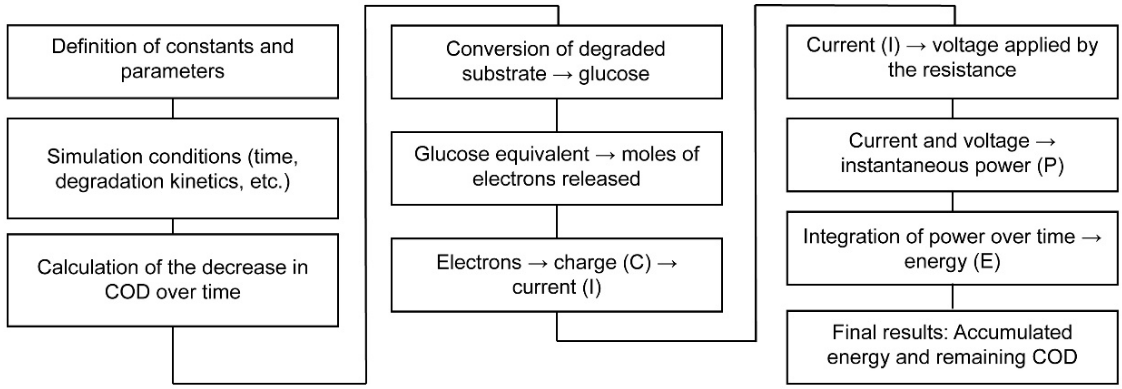

Figure 1. Flowchart of the CW-MFC system simulation program.

of 1 Ω was employed, which allowed the calculation of current and energy production as a function of organic load removal and system hydraulic retention time. The results obtained from the simulation of COD removal were compared with those established in the applicable regulations, in order to assess the feasibility of the proposed system as an alternative for wastewater treatment.

For each stage, the developed code calculates COD removal using first-order kinetics, which describe the decrease in COD concentration as a function of hydraulic retention time. This behavior is represented by the following equation:

$$COD(t) = CODin * e^{-kt} \tag{1}$$

Where COD(t) represents the chemical oxygen demand concentration as a function of time, COD_{in} is the initial concentration, k corresponds to the removal rate constant (day^{-1}), and t is the hydraulic retention time, expressed in days. From the removed COD, the amount of electrons generated at the anode and, consequently, the transferred electrical charge were estimated by applying the principles of coulombic efficiency (CE) and Faraday's law. Subsequently, the generated electrical energy was calculated by considering a fixed external resistance of 1 Ω, through the numerical integration of the power dissipated over time, as described by the following equation:

$$E = \int_0^t P(t)dt = \int_0^t V(t) \cdot I(t)dt \tag{2}$$

Here, E represents the generated electrical energy (Wh), calculated as the integral of the instantaneous power P(t) over time. Power is obtained as the product of the voltage V(t) and the current I(t) generated at each time instant t (seconds).

For the implementation of the calculations, a Python-based program was developed that integrates the stages of parameter definition, simulation of COD removal, estimation of electron transfer, and calculation of the generated electrical energy (Figure 1). It should be noted that the value of the external resistance was adopted as a theoretical reference, as it allows a direct relationship to be established between the electrical variables obtained in the simulation through Ohm's law, thereby facilitating the estimation of current, power, and energy.

3 Results and discussion

3.1 Bibliometric analysis

In CW-MFC systems, wastewater treatment and electricity generation occur simultaneously through the interaction among plants, rhizodeposits, and microorganisms. Vegetation stimulates bacterial activity, while microorganisms present in the rhizosphere degrade organic compounds and root exudates, playing an essential role in water purification processes and electron transfer (Paucar & Sato, 2022).

Figure 2 shows the annual evolution in the number of scientific publications related to CW-MFC technology, obtained from the Web of Science (WoS) database through a "Topic" search using the exact term "constructed wetland microbial fuel cell". The results clearly evidence a growing trend in scientific production over the last decade, reflecting the sustained interest of the scientific community in the development and application of this technology for wastewater treatment and energy generation.

Figure 3 presents the keyword co-occurrence mapping based on data obtained from the Dimensions database and processed using the VOSviewer software. This visualization made it possible to identify the main thematic lines addressed in the CW-MFC field, as well as to explore the relationships among key concepts.

Figure 2. Annual evolution of the number of publications indexed in WoS related to CW-MFC technology.

Among the most prominent terms are denitrification, total nitrogen, treatment technology, anode, power density, and emission, reflecting a shared interest in nutrient removal, energy generation efficiency, and environmental impact mitigation. Overall, this representation was instrumental in identifying the most relevant elements, materials, and approaches considered in the design of the proposed system.

3.2 *CW-MFC systems design proposal*

A typical CW-MFC system consists of anodic and cathodic regions separated by media such as soil, sand, gravel, fibrous materials, or ion exchange membranes (Paucar & Sato, 2022). However, due to the large volume characteristic of these systems, several studies have indicated that the use of ion exchange membranes is not viable in this context (Gupta *et al.*, 2023). Likewise, it has been reported that the difference in power generation between systems that incorporate a separator and those that do not may be relatively small (Jacobs *et al.*,2024). For this reason, the present proposal omits the inclusion of a material explicitly intended to function as a separator.

It has been demonstrated that CW-MFC systems can significantly improve their performance compared to individual CW or MFC systems. Paucar & Sato (2022) compared a CW-MFC system with a conventional CW, observing that the integrated configuration increased wastewater treatment efficiency in terms of COD removal by 27-49% and also improved NH_4^+-N removal efficiency by 22%. Similarly, Yang *et al.* (2022) evaluated a CW-MFC system for domestic wastewater treatment and bioelectricity generation, reporting improvements in the removal of COD, NH_4^+, NO_3^-, and total phosphorus compared to a conventional wetland, as well as a voltage of 388 ± 12 mV and a power density of 107.54 mW m^{-3} under optimal conditions.

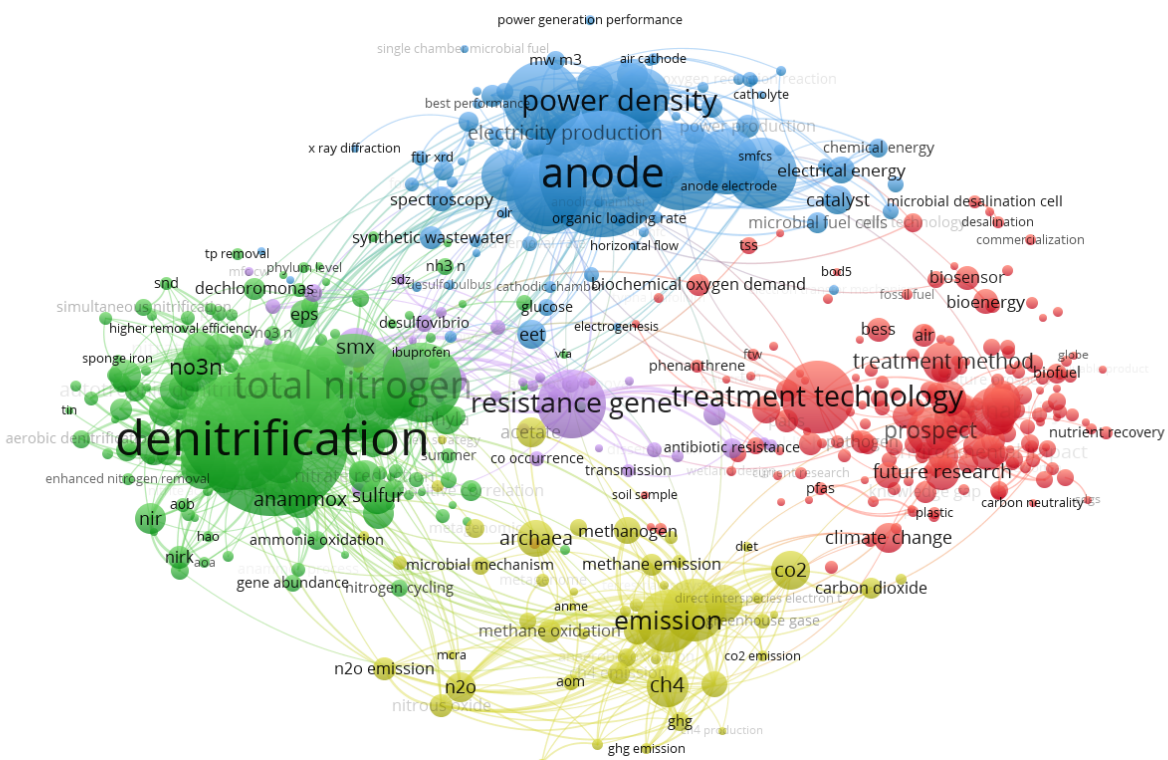

Figure 3. Mapping of keyword co-occurrence in scientific publications on CW-MFC.

According to Ancona *et al*. (2024), in several cases, systems involving plant species, such as CW-MFCs, operate as a "black box", since it is not fully clear whether contaminant degradation or removal is carried out by electroactive bacteria or by microorganisms specialized in degrading those compounds.

In this context, a hybrid CW-MFC system was proposed for the decentralized treatment of wastewater generated by a population of 50 people. The system integrates two configurations connected in series: an initial vertical-flow stage followed by a horizontal subsurface-flow stage

For the selection of the most suitable filtering substrate, quartz sand (30% porosity, adapted from the values reported by Lee *et al*. (2025)), and activated carbon (60% porosity, according to Biessikirski *et al*. (2025)) were employed as CW filtering substrates. The analysis considered the individual use of each substrate in the CW-MFC systems, without evaluating combinations of both materials. In addition, graphite rod electrodes (cathode) and carbon fiber electrodes (anode) were selected, along with the use of Canna indica as the plant species.

CW-MFC units are composed of a surface soil layer for plant establishment, an aerobic zone where cathodes are partially exposed to air, and a lower anaerobic zone that houses the anodes, over a base of washed gravel. The anaerobic zones are composed of filtering substrates.

In these units, the influent enters through a lower lateral inlet and the effluent is collected through an upper lateral outlet, generating an upward flow that promotes redox stratification. The anodes are located in the middle zone of the bed, while the cathodes are placed in the upper section, in partial contact with air, which enhances oxygen availability for the cathodic reaction.

Each CW-MFC unit incorporated ten cathodes uniformly distributed across the system surface, both in the vertical-flow and horizontal-flow configurations. These electrodes, manufactured from graphite rods, were inserted vertically into the upper layer, so that they remained in direct contact with the air, the surface soil, and the underlying quartz sand, thereby ensuring adequate oxygen availability for the cathodic reaction.

This arrangement favors electron exchange under aerobic conditions without interfering with the development of plant cover. In contrast, the anodes consisted of perforated carbon fiber sections, placed transversely within the filtering bed in the middle or lower zone of the system, in order to ensure anaerobic conditions favorable for oxidation processes.

The vertical stage is composed of five CW-MFC units, each with dimensions of 0.58 × 0.80 × 1.5 m. Depending on the characteristics of each filtering substrate, the effective volume when using quartz sand

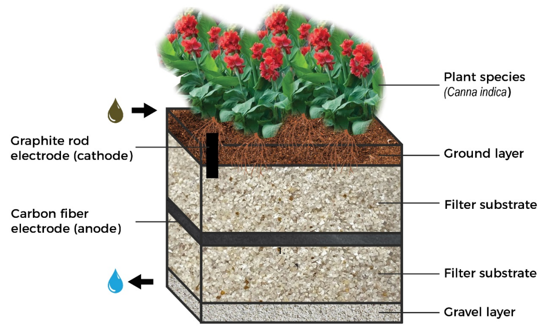

Figure 4. General composition of CW-MFC models.

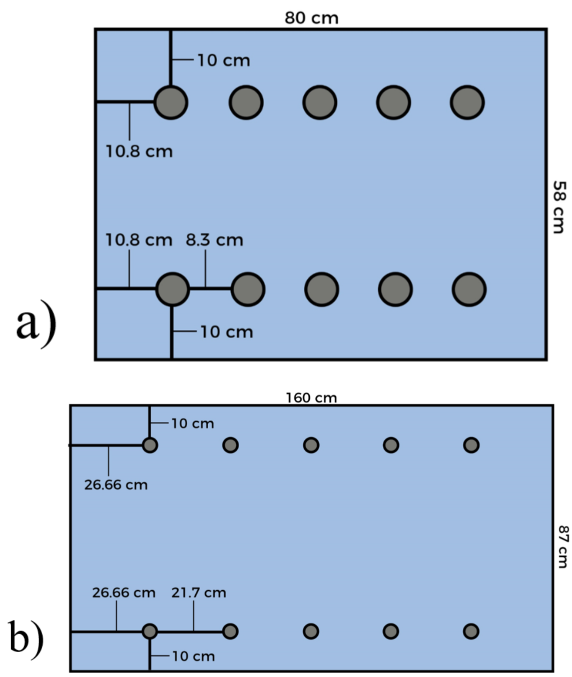

Figure 5. Electrode spacing in the system. a) Vertical flow CW-MFC. b) Horizontal flow CW-MFC.

is 0.208 m^3, with a hydraulic retention time (HRT) of 10 h, whereas when activated carbon is used, the effective volume increases to 0.417 m^3, with an HRT of 20 h.

The effluent from this stage feeds five horizontal-flow CW-MFC units, each with dimensions of 0.87 × 1.6 × 0.6 m. When quartz sand is used, the total effective volume is 0.25 m^3, with an HRT of 12 h, whereas with activated carbon the effective volume is 0.5 m^3, with an HRT of 24 h.

Based on the above, Figure 4 presents the general structure of the CW-MFC models, including the electrodes, plant species, and filtering layers. Figure 5 details the electrode spacing in the vertical-flow (Fig. 5a) and horizontal-flow (Fig. 5b) configurations.

3.2.1 *Plant species selection criteria*

The incorporation of a bioelectrical energy recovery system in constructed wetlands was first described

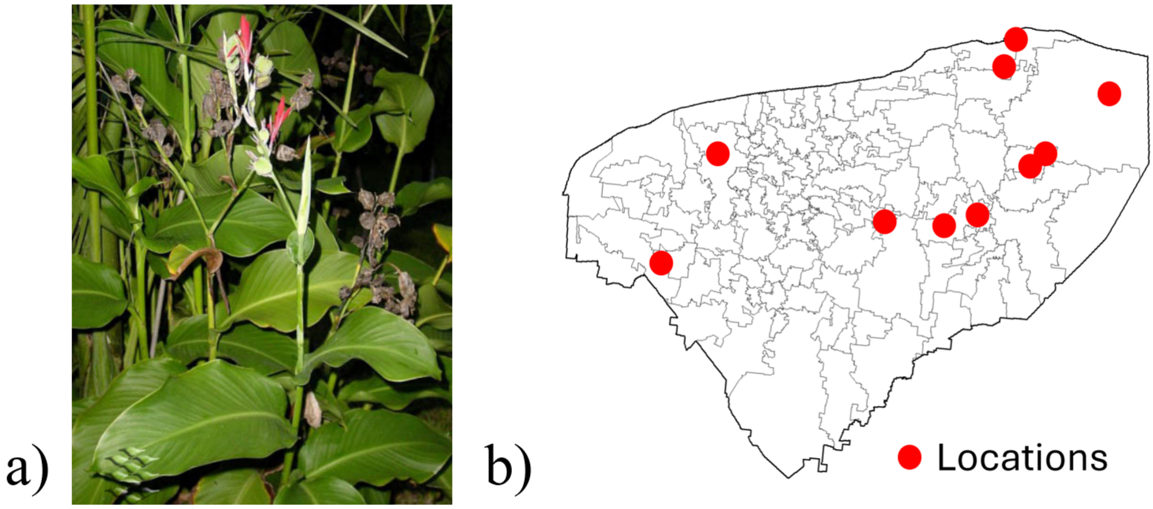

Figure 6. a) Photograph of *Canna indica* (CICY, n.d.); b) Geographic distribution of *Canna indica* in the state of Yucatán (adapted from CICY (n.d.).

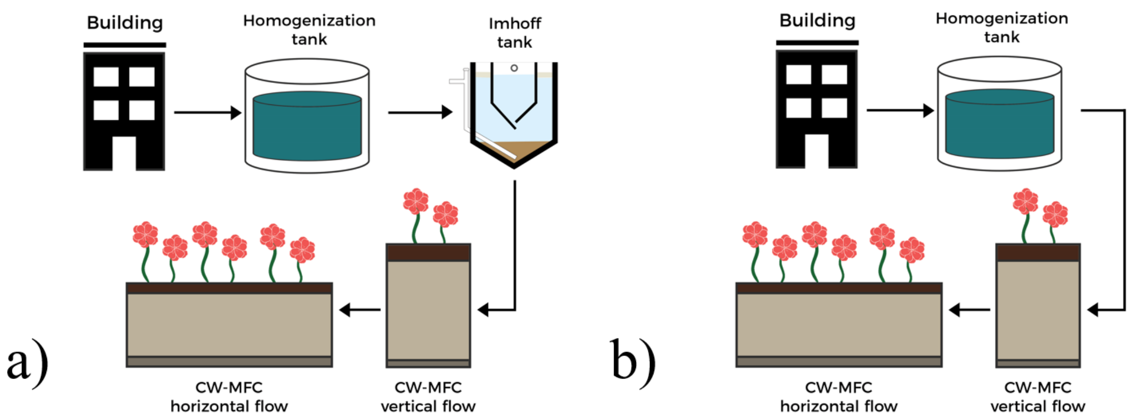

Figure 7. Design of the proposed treatment train: a) design with Imhoff tank (design A). b) design without pretreatment (design B).

in detail by Yadav *et al*. (2012), who reported a maximum power density of 15.75 mW m^{-2} using Canna indica (Fig. 6a) as the plant species. This plant has been recognized in the literature as one of the most widely used species in CW-MFC systems, demonstrating its functionality and adaptability in experimental configurations (Lu *et al*., 2015; Zhou *et al*., 2018).

In addition, Canna indica is naturally present in the state of Yucatán (Fig. 6b) and in several regions of Mexico, according to information from the Secretariat of Environment and Natural Resources (SEMARNAT, n.d.), ncluding states such as Sinaloa, Chiapas, Tabasco, Nuevo León, Tamaulipas, Oaxaca, San Luis Potosí, Veracruz, Querétaro, Tlaxcala, Hidalgo, Puebla, Morelos, Nayarit, Michoacán, Jalisco, and Colima. This wide geographic distribution reinforces its suitability as a plant species for the proposed design, as it ensures adaptation to the climatic and environmental conditions of the study area.

Likewise, Pinninti *et al*. (2022) reported an initial average root length of Canna indica of 13 cm, reaching final values of up to 47 cm. This root development promotes interaction with the substrate and the formation of active zones for biological and electrochemical exchange, thereby justifying its incorporation into CW systems.

3.2.2 Substrate selection criteria

In CW-MFC systems, the substrate plays an essential role in contaminant removal. Substrates with higher surface area and porous structure can promote the adsorption of nutrients, such as nitrogen and phosphorus, as well as foster biofilm development

(Zhong *et al*., 2020). The use of granular activated carbon, ceramsite, quartz, zeolite, pyrite, and manganese minerals has been reported as filtering substrates.

Quartz sand stands out as a stable and chemically inert material; as a result of these properties, ion release into the water is limited, allowing electrical conductivity to remain practically unchanged during the treatment process(H. Wang *et al*., 2021).

In contrast, the use of activated carbon has been widely recognized for its outstanding capacity to enhance the removal of a broad range of contaminants, including organic compounds, heavy metals, nutrients, as well as pharmaceutical, industrial, and pesticide residues (Karungamye, 2024).

3.3 *Treatment train design proposal*

Figure 7 presents the conceptual designs of the proposed treatment trains, focused on the treatment of wastewater generated in decentralized contexts. The design includes one configuration with an Imhoff tank (Fig. 7a) and a second configuration without wastewater pretreatment prior to its entry into the CW-MFC systems (Fig. 7b).

Detailing the designs presented in Figure 7, both schemes consider the incorporation of a screening grid for the retention of large solids, such as paper, debris, and similar materials. This screen is located at the inlet of the homogenization tank. The main function of this tank is to equalize the variable wastewater flow, allowing its transfer to the primary treatment system in a more stable and continuous manner. For this unit, a volume of 550 L was considered, which includes a safety margin. To support this function, the homogenization tank may require mixing to reduce solids deposition and maintain a more uniform influent; however, the associated energy demand was not included in the present analysis.

Design A considers the incorporation of an anaerobic sedimentation tank of the Imhoff type, in which most of the solid material settles to form sludge (Silva, 2023). Anaerobic treatment occurs in sealed tanks, where organic residues are transformed mainly into methane and carbon dioxide (Kandelbauer *et al*., 2007). Imhoff tanks stand out due to their low investment costs and simple operation and maintenance requirements (Oakley, 2018). Likewise, according to Oakley (2018), the hydraulic retention time is 3 h, while the system volume, including a safety margin, is estimated at 350 L. The incorporation of this type of system in practical CW-MFC experiments has been reported by authors such as Corbella *et al*. (2016). This system allows a COD reduction ranging between 25% and 50% (Ferreira, 2019). For subsequent sections, a COD reduction of 50% is assumed for this unit. In this study, the Imhoff tank was considered as a conventional primary sedimentation unit operating without mechanical agitation, consistent with the usual operation of this type of reactor.

After the primary treatment stage, the wastewater is conveyed to the five vertical-flow CW-MFC units, which in Design A constitute the secondary treatment stage of the proposed train, where treatment is carried out with a hydraulic retention time (HRT) of 10 h. Once this process is completed, the flow is transferred to the horizontal-flow CW-MFC stage, which operates with an HRT dependent on the filtering substrate under evaluation. Both configurations are hydraulically connected in series, enabling sequential treatment.

In contrast, Design B considers the direct connection of the homogenization tank to the CW-MFC systems, treating these units as the main wastewater treatment stage, without a primary sedimentation unit.

3.4 *System performance simulation*

Considering the proposed system design and treatment train configurations, the nomenclature used for the comparative analysis of CW-MFC system performance was established, as presented in Table 1.

Based on the simulation, the results presented in Table 2 were estimated. It should be noted that the global value corresponds to the performance of the system composed of five parallel arrangements, each consisting of a vertical-flow CW-MFC hydraulically connected in series with a horizontal-flow CW-MFC. In contrast, the vertical CW-MFC and horizontal CW-MFC values correspond to the individual performance of each of these units within the arrangement. The percentage of COD removed does not consider the Imhoff tank, in order to exclusively evaluate the performance of the CW-MFC systems.

The results reflect differences mainly attributable to the type of filtering substrate and the inclusion of an Imhoff tank as a pretreatment stage. Configurations employing activated carbon showed higher COD removal percentages compared to those using quartz sand, which is consistent with the greater adsorption capacity and specific surface area of this material.

Table 1. Nomenclature used for the simulation of system performance.

System design	Filter substrate in CW-MFC	Nomenclature
A	Quartz Sand	AA
	Activated Carbon	AB
B	Quartz Sand	BA
	Activated Carbon	BB

Table 2. Simulation results of the proposed systems.

System	CW-MFC Global (Wh) - 5 arrangements	CW-MFC Partial (Wh) - 1 arrangement	CW-MFC Vertical (Wh)	CW-MFC Horizontal (Wh)	Final COD (mg L^{-1})	COD removed (%)
AA	0.005	0.001	0.0004	0.0006	64.87	54.95
AB	0.01	0.002	0.001	0.0008	29.22	79.71
BA	0.02	0.004	0.0016	0.002	129.73	54.95
BB	0.04	0.008	0.004	0.003	58.44	79.71

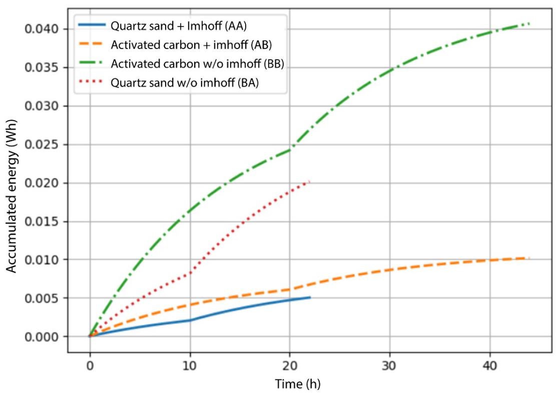

Figure 8. Cumulative production of the systems (5 parallel arrays).

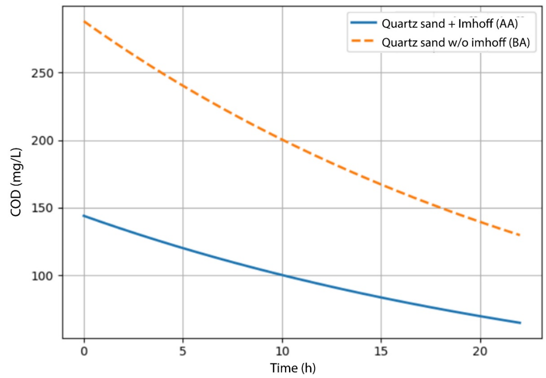

Figure 9. COD removal along a CW-MFC arrangement for systems using quartz sand.

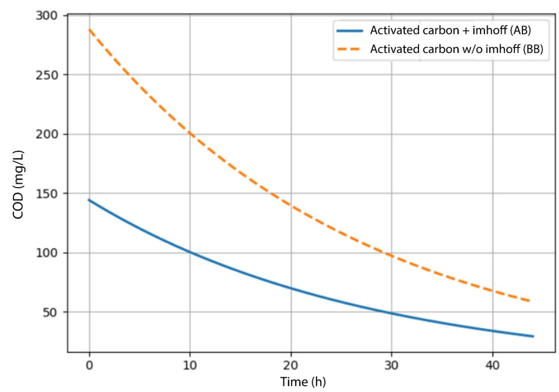

Figure 10. COD removal along a CW-MFC arrangement for systems using activated carbon.

In terms of energy generation, the obtained values ranged between 0.005 and 0.04 Wh per global system cycle. Although these values are low in absolute terms, they highlight the potential of CW-MFC systems for the bioelectrical recovery of organic matter present in wastewater, particularly when decentralized applications and their possible integration with low-power energy storage schemes are considered.

Figure 8 shows the cumulative electrical energy production of the treatment designs based on the simulation carried out considering five arrangements connected in parallel. A progressive increase in the generated energy is observed across all configurations, with differences attributable to both the type of filtering substrate and the inclusion of pretreatment through an Imhoff tank. It should be noted that the HRT values differ depending on the filtering substrate employed, which influences the rate of organic matter removal and, consequently, the energy accumulated over time. Systems employing activated carbon and operating without pretreatment (BB) exhibit the highest cumulative energy values, whereas configurations using quartz sand and an Imhoff tank show the lowest values.

Figures 9 and 10 present the COD removal profiles along a CW-MFC arrangement for the designs employing quartz sand and activated carbon, respectively. In both cases, configurations with and without an Imhoff tank are compared, allowing the effect of primary pretreatment on COD concentration over time to be analyzed.

The results show that the inclusion of an Imhoff tank leads to lower initial COD concentrations at the inlet of the CW-MFC system, whereas configurations without pretreatment exhibit a higher organic load available for electrochemical degradation. Likewise, systems employing activated carbon achieve lower final COD concentrations compared to those using quartz sand, which is associated with the greater adsorptive capacity and higher specific surface area of this material.

Based on NOM-001-SEMARNAT-2021, the system can be applied to receiving bodies such as rivers, streams, channels, drains, reservoirs, lakes, and lagoons, for which the permissible monthly average COD limit is equal to or greater than 100 mg L^{-1}. Likewise, the regulation establishes a permissible monthly average COD limit of 60 mg L^{-1} for systems intended for green area irrigation or soil infiltration, including karst soils, such as those present in Yucatán, Mexico.

In this context, based on the simulations performed, configurations AB and BB comply with the regulatory requirements, being viable for both surface water discharge and irrigation or infiltration applications. In contrast, configuration AA partially complies, as it would only be suitable for discharge into receiving bodies, whereas configuration BA does not meet the regulatory criteria and would therefore be unsuitable for practical implementation.

Although the incorporation of an Imhoff tank is not indispensable for regulatory compliance, its implementation affects the energy performance of the system. By reducing the organic load of the influent, it partially limits the amount of carbon available to electrogenic microorganisms, which results in lower electron transfer and, consequently, a reduction in the energy potential of the system.

It is important to note that the developed simulation model presents certain limitations inherent to its theoretical approach. The implemented code did not consider relevant operational variables that directly influence the actual performance of microbial fuel cells, such as temperature, pH, medium conductivity, internal system resistance, biofilm formation and maturation, among other factors.

In addition, a constant CE and a theoretical maximum voltage per redox pair, estimated based on glucose oxidation as a model compound, were assumed, resulting in an idealized scenario that does not fully reflect real dynamic operating conditions.

3.5 Energy storage proposal

For energy storage, the use of rechargeable lithium iron phosphate ($LiFePO_4$) batteries was considered. In this context, Table 3 presents the charging times required to reach full charge for a 600 mAh, 3.2 V battery based on the energy generated in each operating cycle.

Systems AA and AB, which incorporate an Imhoff tank, require longer charging times (400 and 376 days, respectively), likely as a result of the reduction in available organic matter after pretreatment, which limits energy production per cycle. In contrast, systems BA and BB, operating without an Imhoff tank, showed considerably shorter charging times (88 days), which may be attributed to the larger fraction of carbon available for microbial activity. It should be noted that the sizing was carried out assuming cyclical rather than simultaneous operation.

Table 3. Battery charging time for each system.

System	Cycle duration (h)	Energy per cycle (Wh)	Estimated charging time (days)
AA	25	0.005	400
AB	47	0.01	376
BA	22	0.02	88
BB	44	0.04	88

3.6 Comparison between simulated results and literature-reported data

In order to evaluate the consistency and applicability of the developed simulation model, a comparison was conducted between the results obtained in this study and data reported in the literature for CW-MFC systems under different configurations. This comparison is presented in Table 4 and allows for contrasting COD removal percentages and generated energy, as well as for analyzing differences associated with the assumptions adopted in the simulation.

In the cases reported by Peñacoba-Antona *et al*. (2022), the model closely reproduced the COD removal percentages, with differences of less than 3%. This behavior is attributed to the fact that these studies provide comprehensive information on operating conditions, including influent COD concentrations, hydraulic retention times, and CE ranges, parameters that fit well with the first-order kinetic scheme employed in the model. A similar agreement was observed when comparing the results with the studies by Wang *et al*. (2024) and Tamta *et al*. (2023).

By appropriately calibrating the model parameters, it was possible to approximate the removal efficiencies reported in their experiments. However, it is important to emphasize that none of the reviewed articles reported accumulated energy values in Wh, as their primary focus was on describing instantaneous voltages, power densities, or efficiency trends.

It is worth noting that total generated energy was not part of the scope of the compared studies. Therefore, Table 4 includes only the energy values estimated by the model, which serve as a reference for approximately sizing the electrical potential of each system.

Table 4. Comparison between simulated results and literature-reported data.

Case	COD removal (literature) (%)	CE (%)	Simulated COD removal (%)	Simulated energy (Wh)	Difference in removal (%)	Reference
IMDEA	80	30	82.26	0.350744	2.825	(Peñacoba-Antona *et al*., 2022)
Orby	84	2	82.79	0.078086	1.433	(Peñacoba-Antona *et al*., 2022)
CW-MFC	93.3	0.89	91.79	0.00996	1.51	(Wang *et al*., 2024)
CW-MFC graphite anode	70	0.89	69.88	0.00108	0.12	(Tamta *et al*., 2023)
CW-MFC granular activated carbon anode	95	0.89	95.02	0.00108	0.02	(Tamta *et al*., 2023)

Table 5. Comparative initial cost of the evaluated configurations.

System	Treatment train	Substrate	Estimated substrate cost (USD)	Imhoff tank cost (USD)	Total comparative initial cost (USD)
AA	Desing A	Quartz sand	334.41	2,304.00	2,638.41
AB	Desing A	Activated carbon	689.04	2,304.00	2,993.04
BA	Desing B	Quartz sand	334.41	0.00	334.41
BB	Desing B	Activated carbon	689.04	0.00	689.04

Overall, these results indicate that the model is not only capable of providing a reasonable estimation of COD removal but can also complement the experimental information available in the literature, thus constituting a useful tool for conceptual analysis and preliminary design of CW-MFC systems.

3.7 Economic analysis

In the literature, CW systems have been described as having low energy demand and relatively low operating costs in cases where land is available. Specifically, operating costs for constructed wetlands in the range of USD 0.03–0.08 per m^3 have been reported in contexts where land availability is not a limiting factor (Sampeney *et al*., 2025). In contrast, it should be noted that integrating MFCs requires the incorporation of electrical materials, such as electrodes and wiring, which may increase the capital cost if the system is not designed using low-cost components (Miwornunyuie *et al*., 2025). Likewise, unit treatment costs on the order of USD 0.033–0.054 per m^3 of treated water have been reported. In that analysis, life cycle costs accounted for approximately 80% of the total unit cost, whereas land acquisition contributed around 20% of the cost per m^3 (Chen *et al*., 2023). For the purposes of the present analysis, only the initial investment costs relevant to the comparison were considered, while maintenance costs, wetland construction, electrical connections, hydraulic connections, electrodes, and land acquisition were excluded, since the comparison focuses on the use of different substrates and the incorporation of the Imhoff tank.

For the cases considered in the present study, activated carbon has been reported as an economical alternative for application in wastewater treatment techniques and as suitable for implementation in small-scale industrial processes, standing out for its non-toxicity, since it does not introduce hazardous chemicals or residues into the treated water (Karungamye, 2024). The costs associated with activated carbon are variable; commercial prices ranging from USD 450/t (Mukherjee *et al*., 2022) to USD 1,543–2,645/t (Tsarpali *et al*., 2024) have been reported.

Regarding quartz sand, the literature has reported that the costs of constructed wetlands using sand range from USD 10–35/m^3 (Sandoval Herazo *et al*., 2023); as this material is considered low cost (T. Wang *et al*., 2023). Accordingly, for the economic analysis, the average price of industrial sand will be considered. Industrial sand is a natural silica-rich sand generally composed mostly of quartz, and its average price was reported to be USD 39/t in 2024 (U.S. Geological Survey, 2025). Likewise, to compare both treatment trains, a cost of USD 2,304 will be considered, based on commercially available public pricing (Lopez, 2023). Table 5 presents the comparative initial cost of the evaluated configurations considering only the filling of the substrate and the incorporation of the Imhoff tank.

Costs were estimated considering five vertical-flow CW-MFC units and five horizontal-flow CW-MFC units. Substrate quantities were approximated from the total geometric volume of the CW-MFC beds and the porosity assigned to each material in the manuscript. Only the cost of substrate filling and the incorporation of the Imhoff tank were considered, in accordance with the scope of this preliminary comparison.

Conclusions

The obtained results evidenced that the use of activated carbon significantly enhances chemical oxygen demand (COD) removal and the energy performance of the system compared to quartz sand, attributable to its higher adsorptive capacity and specific surface area. On the other hand, the incorporation of an Imhoff tank reduced the organic load of the influent; however, this reduction translated into a decrease in the potential for energy generation. In contrast, configurations without pretreatment exhibited shorter estimated charging times for the simulated battery.

From a regulatory standpoint, only configurations employing activated carbon complied with the limits established in NOM-001-SEMARNAT-2021 for surface water discharges and irrigation/infiltration applications, whereas systems using quartz sand presented constraints for practical implementation.

The developed simulation model demonstrated its usefulness by adequately reproducing the COD removal trends reported in the literature, supporting its validity as a conceptual tool for linking contaminant treatment with energy recovery in CW-MFC systems. Additionally, the preliminary economic analysis showed that quartz sand resulted in the lowest comparative initial costs, whereas activated carbon and the incorporation of the Imhoff tank increased the initial investment. Under the evaluated scope, configuration BB showed the most favorable balance between regulatory compliance, energy performance, and comparative initial cost.

Although the energy generated in the evaluated scenarios is low in absolute terms, this study confirms the potential of CW-MFCs as sustainable technologies for decentralized wastewater treatment, with relevant applications in demonstrative, educational, and research contexts, while highlighting the importance of considering both technical and economic criteria in system selection.

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