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Integration of Floating Constructed Wetlands and Microbial Fuel Cells for Sustainable Wastewater Treatment and Bioelectricity Generation

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Abstract

Floating wetlands have emerged as a sustainable alternative for improving water quality, and although some studies have investigated their performance, there is still much to be understood regarding their integration with energy-generating technologies. This study evaluated a combined system of floating wetlands and microbial fuel cells (MFCs) for treating real wastewater and generating bioelectricity. Experiments were conducted in batch mode to simulate application in natural water bodies, using real wastewater collected on different dates. As a result of the natural variability of the influent, initial chemical oxygen demand (COD) concentrations of 405 and 289 mg/L were observed. Performance was assessed in terms of organic matter and nitrogen removal, as well as voltage generation. COD removal efficiencies reached 50% and 69% for the higher and lower organic loads, respectively, indicating improved treatment at reduced concentrations. Maximum removals of 56% for ammoniacal nitrogen (NH_3-N) and 40% for total nitrogen (TN) were achieved, reflecting moderate nutrient removal capacity. Voltage generation was sustained for approximately 21 days, confirming stable bioelectrochemical activity, and power output was found to depend on the organic load serving as substrate for electrogenic microorganisms. Overall, the system represents a viable approach for wastewater treatment with the added benefit of energy recovery, although its performance is influenced by influent characteristics and operation conditions.

Keywords: floating wetlands; microbial fuel cells; water bodies; contaminated; wastewater; bioelectricity

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1. Introduction

The growth of the global population has led to an increase in pollutant discharges from industrial, domestic, and agricultural sources into surface waters [1,2]. Although conventional water and wastewater treatment methods do exist, they often involve high installation and maintenance costs, significant energy consumption, and require specialized supervision [3,4]. The increasing pressure on the recovery and maintenance of water

resources has driven the development of sustainable technologies for wastewater treatment and the restoration of natural water bodies [5,6]. In this context, constructed wetlands (CWs) are engineered systems designed for the treatment of contaminated water that utilize processes occurring in natural environments, employing plants growing on a solid support such as gravel, sand, or soil [7].

A recent variation of CWs is floating wetlands (FWs), which have gained attention due to the absence of solid supporting media. This reduces construction costs, facilitates continuous and direct contact between plant roots and contaminated water, and enables easy implementation and in situ operation without the need for complex infrastructure. [8–10]. Floating wetlands consist of vegetated platforms that support the growth of aquatic macrophytes, whose roots develop within the water column. These systems promote physical, chemical, and biological processes such as sedimentation, adsorption, bioaccumulation, and microbial degradation. Several studies have demonstrated high removal efficiencies in different water matrices, reporting reductions of up to 85–95% for BOD_5, 70–90% for total nitrogen, and 60–80% for phosphorus, using plant species such as *Eichhornia crassipes* and *Phragmites australis* [11]. More recently, Wang et al. [12] evaluated floating wetlands in eutrophic water bodies and reported removal efficiencies of up to 88% for ammonium (NH_4^+) and 75% for total phosphorus using *Typha latifolia* and *Iris pseudacorus*. These findings underscore the role of plant species in treatment performance, as different macrophytes can significantly influence nutrient removal. Accordingly, a wide variety of species has been employed in wetland systems, including *Zantedeschia aethiopica*, *Cyperus papyrus*, *Strelitzia reginae*, and *Juncus* spp., the latter being particularly common due to its adaptability and treatment performance [13,14].

In parallel to wetland-based treatment systems, microbial fuel cells (MFCs) have emerged as a promising technology that enables simultaneous wastewater treatment and energy recovery. These systems harness the metabolic activity of electroactive microorganisms to oxidize organic matter and transfer electrons to an anode, thereby generating electrical current [15–17]. Genera such as *Geobacter sulfurreducens*, *Shewanella oneidensis*, *Pseudomonas aeruginosa*, *Rhodopseudomonas palustris*, and *Acidithiobacillus ferrooxidans* have been widely reported for their ability to form dense, highly conductive biofilms, playing a key role in electron transfer and pollutant degradation [18–21]. In terms of performance, MFCs have demonstrated COD removal efficiencies ranging from 70–95% and power densities between 0.5 and 2.5 W/m^2, depending on reactor configuration and organic substrate characteristics [22–24]. Although MFCs can generate electrical energy directly from wastewater, the power densities reported in the literature remain relatively low, typically ranging from tens to hundreds of mW/m^2 depending on the reactor configuration and operating conditions [25]. These values are generally insufficient to meet the energy demands of conventional electrical equipment or wastewater treatment facilities. Therefore, MFC technology is currently considered primarily as a wastewater treatment alternative rather than as a standalone energy production system. In this context, the electricity generated during operation may help partially offset the energy requirements associated with wastewater treatment, contributing to the overall sustainability of the process [26].

Recent research has demonstrated that MFCs can be effectively integrated with wetland-based systems, combining biological treatment with bioelectrochemical processes to enhance overall wastewater treatment performance. In particular, constructed wetlands coupled with MFCs have shown promising results, with COD removal efficiencies of up to 92% and power densities of 1.8 W/m^2 [27,28] while also achieving TN removal of up to 78% and voltage generation of 103 mV in hybrid systems treating synthetic wastewater [29]. These results have been linked to the role of macrophytes, as the incorporation of species such as *Phragmites australis* enhances electron transfer, improves system stability, and en-

ables organic matter removal efficiencies above 90% [30]. More recently, the integration of MFCs with floating wetlands (FW–MFC) has been explored as an alternative configuration. These systems have been evaluated in eutrophic lagoons, achieving removal efficiencies of up to 78% for TN, 59% for total phosphorus, and 88% for COD, along with output voltages of 0.4 V [31]. Similarly, FW–MFC systems applied to university campus wastewater using mixed ornamental plant species have reported COD and TN reductions of 71.4% and 8.4%, respectively, with peak voltage and maximum power density values reaching 225 mV and 0.93 mW/m^2, respectively [7]. In addition to conventional wastewater applications, FW–MFC systems have also been evaluated for more complex effluents. Plant species such as *Chrysopogon zizanioides* and *Typha angustifolia* have been tested for the treatment of textile effluents, achieving removal efficiencies of 82% for color, 75% for COD and BOD, 67% for total dissolved solids (TDS) and 70% for total suspended solids (TSS), while generating a power density of 0.077 W/m^2 at a current density of 0.385 A/m^2 [32]. Beyond pollutant removal and energy generation, these systems may also provide additional environmental benefits, including the reduction in greenhouse gas emissions and improvements in urban landscape quality [33].

The integration of MFCs with wetland systems has been widely explored; however, most studies have focused on traditional constructed wetlands with solid support media and have been conducted at the laboratory scale. While these configurations have demonstrated promising pollutant removal efficiencies and energy generation, their applicability under real environmental conditions remains relatively unexplored. In contrast, the integration FW–MFC systems has received comparatively less attention, particularly under pilot-scale and in situ conditions for the treatment of natural water bodies. Addressing this gap is essential to assess the feasibility, stability, and overall performance of these systems in practical applications. In this context, this study proposes the development and evaluation of a FW–MFC system for the in situ treatment of contaminated water bodies using real wastewater, aiming to provide a more realistic assessment of its potential for sustainable wastewater treatment and energy recovery.

2. Results and Discussion

2.1. COD Removal

The artificial FW-MFC with Juncus spp. demonstrated a progressive and effective removal of COD throughout the testing period. According to the data presented in Figure 1a, during the first experiment, the COD concentration decreased from 405 mg/L to 204 mg/L, corresponding to a removal efficiency of approximately 50% (Figure 1b). In the second run, a more significant reduction was achieved, dropping from 289 mg/L to 90 mg/L, resulting in a removal efficiency of 69%. These results are in close agreement with those previously reported using a similar arrangement of FW-MFC for the remediation of eutrophic water, which reports a COD removal of 88% [31]. The different initial COD concentrations observed in Experiment 1 and Experiment 2 were associated with the use of real wastewater collected from the same source on different dates. Since no preconditioning or adjustment of the wastewater was performed prior to the experiments, variations in the initial pollutant concentrations reflected the natural variability of the influent.

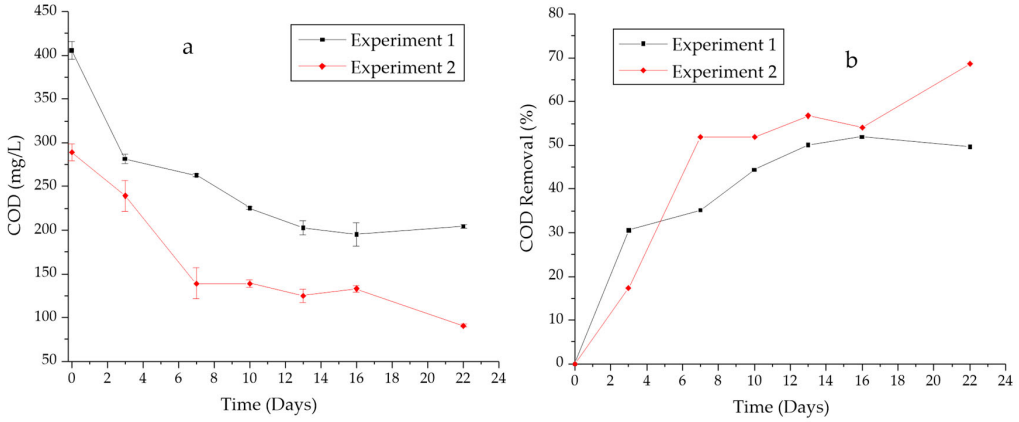


Figure 1. Organic matter removal: (**a**) residual COD and (**b**) COD removal in the wastewater in contact with the floating wetland. First (black) and second (red) experiments.

2.2. Ammoniacal Nitrogen (NH_3–N) Removal

As shown in Figure 2a, NH_3–N exhibited a clear decreasing trend throughout the evaluation period in both experiments. These results indicate that the system effectively promotes nitrogen transformation processes, achieving significant reductions over time under real wastewater conditions. In the first experiment, NH_3–N concentrations decreased from approximately 135 mg/L to 75 mg/L, corresponding to a removal efficiency of 45% over a 21-day period (Figure 2b). In the second experiment, higher removal efficiencies were observed, with NH_3–N concentrations decreasing from approximately 90 to 40 mg/L, reaching removal values of about 55%; however, this increase in efficiency is apparent and is related to the lower NH_3–N content in the wastewater.

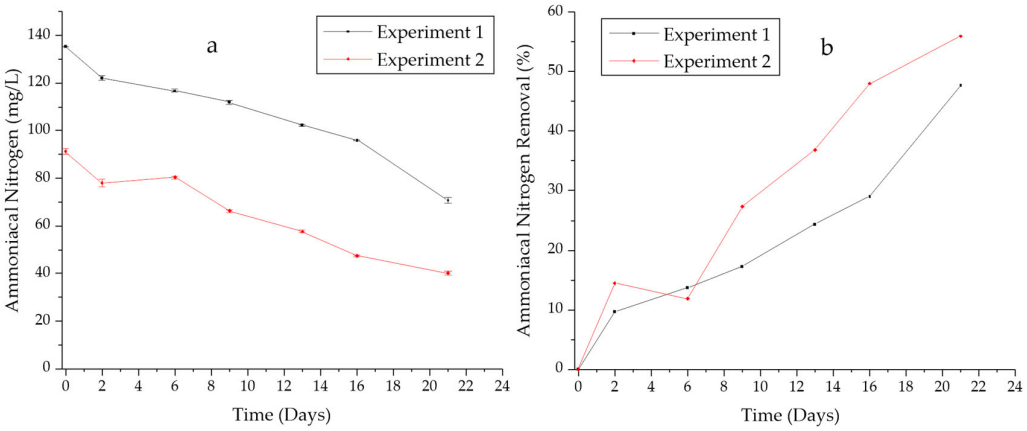


Figure 2. Ammoniacal nitrogen removal: (**a**) residual NH_3–N and (**b**) NH_3–N removal in the wastewater in contact with the floating wetland. First (black) and second (red) experiments.

2.3. Total Nitrogen (TN) Removal

According to the experimental data presented in Figure 3a, the remaining TN concentration shows a gradual decrease in TN in the treated wastewater throughout the experimental period. In the first experimental run, TN decreased from 125 to 104 mg/L, while in the second test, a more pronounced reduction was observed, from 115 to 75 mg/L. As shown in Figure 3b, which presents the corresponding removal efficiencies, TN removal was moderate in the first run, with an efficiency of approximately 25%, whereas in the second run, a higher removal efficiency of around 40% was achieved. These values are lower than the 78.8% reported for a FW–MFC system [31]; however, in that study, TN concentration was approximately 3.5 mg/L, nearly 30 times lower than that of the wastewater used in this work.

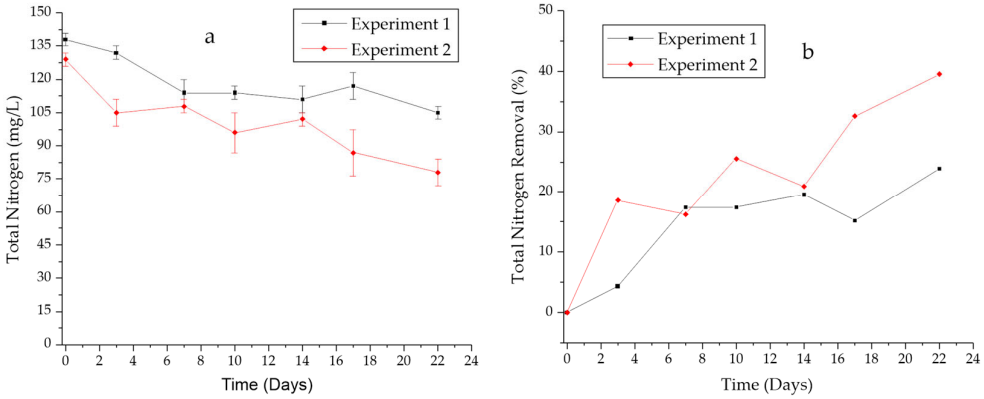


Figure 3. Total nitrogen removal: (**a**) residual TN and (**b**) TN removal in the wastewater in contact with the floating wetland. First (black) and second (red) experiments.

As shown in Figures 2 and 3, NH_3–N removal (45–55%) was higher than TN removal (25–40%) in both experimental runs. These results indicate that NH_3–N removal was greater than the overall reduction in TN. Since only NH_3–N and TN concentrations were monitored during this study, additional measurements of nitrite and nitrate would be useful to better understand nitrogen transformations within the FW-MFC system [34]. Nevertheless, the difference between NH_3–N and TN removal suggests that part of the ammonium may have been transformed into other nitrogen species through nitrification. The reduction in TN also suggests that denitrification and nitrogen assimilation processes may have contributed to nitrogen removal. Part of the nitrogen may have been taken up by plants during growth, while another fraction could have been incorporated into microbial biomass associated with biofilms developed on plant roots and MFC electrodes.

Although the number of studies available for integrated FW-MFC systems remains limited, the nitrogen removal efficiencies obtained in this work are within the range reported in previous investigations, which have documented NH_3–N and TN removals of approximately 2.7–66.7% and 1.5–78.8%, respectively [7,31].

2.4. Electrical Parameters

Voltage

In both experimental runs, a voltage close to 0.5 V was achieved during the initial days of operation, indicating that the MFCs were electrochemically active. This value is representative and within the range typically reported for properly functioning microbial fuel cells [15]. Since the 12 MFC units were connected in parallel, the measured voltage is expected to be similar to that of an individual MFC, whereas the electrical current reflects the combined contribution of all connected cells. Therefore, the observed voltage of approximately 0.5 V is consistent with the expected performance of the electrical configuration used in this study (Figure 4a). As the contact time between the cell–plant system and the wastewater increased, a clear decline in voltage was observed, suggesting substrate limitation due to the progressive depletion of organic contaminants, as reflected by the concurrent decrease in COD. A comparison of the voltage generated in the first and second experiments, with initial COD concentrations of 405 and 204 mg/L, respectively, shows that from day 3 to day 11, higher voltage values were obtained at a higher COD concentration, highlighting the influence of organic load on the system performance. However, in the subsequent days, this difference was no longer significant, and by the end of the experimental period (approximately 18–21 days), the voltage in both cases decreased to values below 0.1 V. In general, the obtained voltage values are higher than those reported

by Wu et al., who observed values between 0.125 and 0.4 V during 24 days of operation in FW–MFC systems [31].

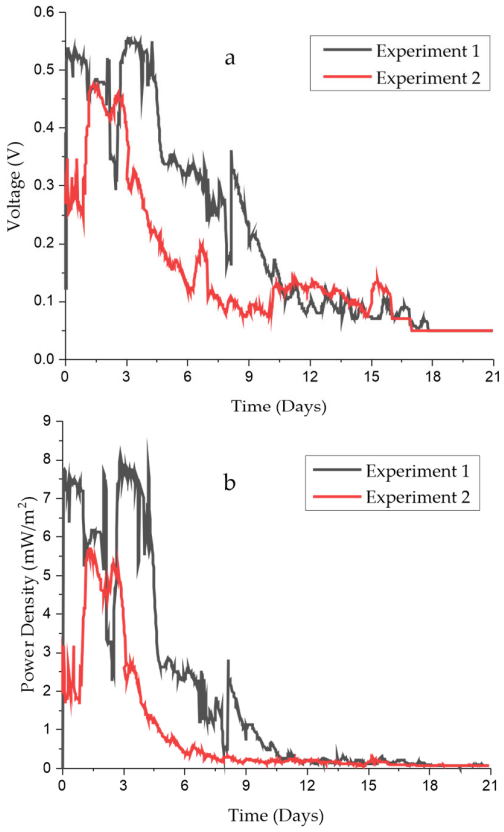


Figure 4. Continuous measurement of electric parameters: (**a**) Voltage, (**b**) Power. First (black) and second (red) experiments.

Current

In terms of current generation (Figure S1), the MFC system in both experiments produced peak currents in the range of 12–15 mA/m^2, which were sustained for several days before a gradual decrease. This decline can be attributed to reduced microbial activity within the cells, resulting from the decrease in COD of the treated wastewater. By the end of the 21-day experimental period, the current dropped to values on the order of 1 mA/m^2.

Power generation

The power generated by the MFC system reached maximum values of approximately 8 mW/m^2 in the first experimental run and 5.5 mW/m^2 in the second (Figure 4b). This difference is consistent with the higher initial COD in the first run (405 mg/L) when compared to the second one (289 mg/L), indicating that a higher organic load promotes greater power generation. Accordingly, during the first 10 days of operation, the power output was consistently higher in the first case, coinciding with the greater availability of organic substrates. As the process progressed, a gradual decline in power output was observed, driven by the depletion of organic matter, as evidenced by the decrease in COD. Consequently, power values approached zero by day 18 in both cases. These results highlight the key role of the initial COD concentration in determining the electrical performance of the system, as higher organic loads enhance power generation.

Polarization and Power Curves

The polarization curves show that, in the first experimental run with higher organic loading (405 mg/L COD), open-circuit voltage (OCV) values on the order of 600 mV were

achieved (Figure 5a), with the curves obtained during the first five days exhibiting very similar profiles. From day 15 onward, a marked decrease in OCV was observed, reaching values of 250 mV and 100 mV. Regarding the power curves, the first experimental run exhibited values near 40 mW/m^2 during the initial days, followed by a sharp decline in 15 days, which can be attributed to the decrease in COD in the wastewater sample (Figure 5b). By the end of the experiment, the detected power was practically negligible.

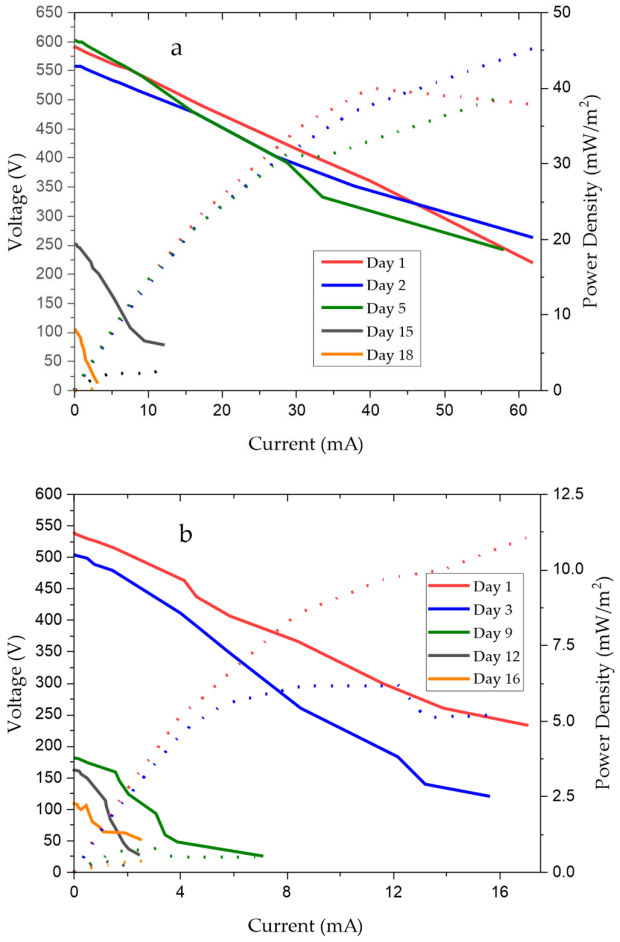


Figure 5. Polarization curves: (**a**) First experiment (405 mg/L of COD), (**b**) Second experiment (204 mg/L of COD). Polarization (solid lines) and power (dashed lines) curves.

In the second experimental run (Figure 5b), performed with a slightly lower COD concentration (204 mg/L), the OCV values ranged between 500 and 540 mV, and high voltage values in the polarization curves were maintained during the first 3 days. Subsequently, both voltage and current decreased significantly, which may be attributed to reduced microbial activity associated with the decline in COD within the system. Regarding power generation, a maximum power density of approximately 11.5 mW/m^2 was obtained, which gradually decreased over time. These results highlight the influence of the initial COD concentration, with higher values enabling sustained increases in voltage, current, and power output that decrease with treatment time.

2.5. Comparison with Previous Studies

Table 1 presents a comparison between the FW-MFC system evaluated in this study and previously reported integrated FW-MFC systems. In general, the treatment efficiencies and electrical output obtained in the present work were comparable to those reported in the literature. The system achieved 69% COD removal, 55% NH_3-N removal, and 40% TN

removal, together with a maximum voltage of 480 mV and a power density of 5.5 mW/m^2. These results confirm that the proposed FW-MFC configuration can simultaneously contribute to wastewater treatment and bioelectricity generation when operated with real urban wastewater.

Table 1. Comparison of wastewater treatment performance and electrical output of integrated FW–MFC systems reported in the literature and the present study.

Type of Wastewater and Volume System	Initial COD (mg/L)	COD Removal Efficiency (%)	Initial NH_3-N (mg/L)	NH_3-N Removal Efficiency (%)	Initial TN (mg/L)	TN Removal Efficiency (%)	Voltage (mV)	Power Density (mW/m^2)	Reference
University campus urban wastewater 700 L	178.8	25	69.0	2.7	7.89	1.5	225	0.93	Colares et al., 2021 [7]
Synthetic wastewater 37 L	90.2	88.2	11.7	66.7	11.9	78.8	400	0.38	Wu et al., 2022 [31].
Municipal wastewater 500 L	67	82	11.6	88	32	80	53	2.3	Saeed et al., 2023 [35]
Urban wastewater 300 L	289	69	90	55	115	40	480	5.5	Results obtained in this research
	405	50	135	45	125	25	530	8	

2.6. Implications for Scale-Up and Practical Implementation

Although the results obtained in this study demonstrate the potential of FW-MFC systems for wastewater treatment and bioelectricity generation, several aspects should be considered before their implementation under real field conditions. One advantage of this approach is that MFC can be incorporated into existing FW systems with relatively minor modifications, reducing the need for additional treatment units and minimizing infrastructure requirements. During both experimental runs, the system maintained pollutant removal and bioelectricity generation while treating real wastewater, suggesting stable operation under the evaluated conditions. However, the wastewater used in this study was collected directly from the discharge point and used without dilution, representing relatively high pollutant concentrations. Future studies could evaluate less contaminated conditions and continuous or periodic feeding strategies to better simulate natural aquatic environments. In addition, long-term performance, maintenance requirements, electrode durability, and economic feasibility should be evaluated to determine the practicality of large-scale implementation.

3. Materials and Methods

3.1. Design of an Artificial Floating Wetland Using Microbial Fuel Cells

The use of a wastewater treatment system based on FW-MFC has emerged as a promising alternative for wastewater treatment. This approach integrates nutrient removal from wastewater through plant root uptake with the degradation of organic pollutants by the biomass that develops both around the plant roots and on the anode surface of the FW-MFC [33]. To simulate this process, an artificial FW was designed and constructed, consisting of a rectangular metallic container measuring 0.8 m in width, 1.4 m in length, and 0.5 m in depth, which housed 300 L of urban wastewater for treatment purposes. The flotation system for the wetland employed polyvinyl chloride (PVC) tubes with a diameter of 2 inches. Two expanded polystyrene (EPS) plates were placed on top of the tubes, each containing six perforations for the installation of the MFCs, resulting in a total of 12 MFC units in the system. The MFCs were connected in parallel using stainless steel wire and linked to a remote monitoring system for continuous measurement of voltage, current, and power output. Additionally, the EPS plates featured four holes for the accommodation of

Juncus spp. within plastic pots (made of polypropylene) of 0.03 m^2 each, supported with gravel. The Juncus spp. specimens were obtained from mature natural wetlands that were in contact with wastewater discharge permanently and were positioned in pots inserted in the flotation system (See Figure 6a,b).

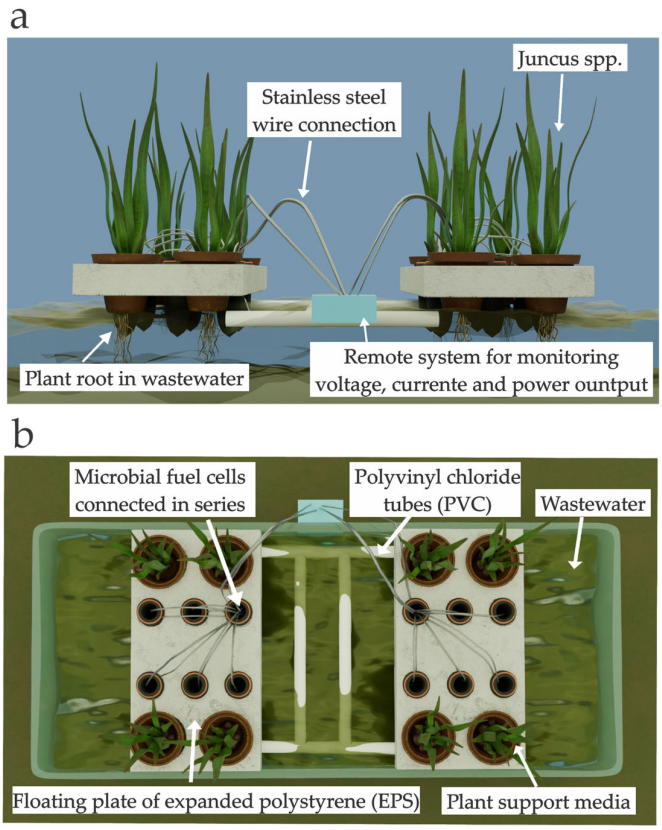


Figure 6. (**a**) Aerial view of the FW–MFC system schematic; (**b**) vertical section of the FW–MFC system. The illustration was developed using Autodesk Maya 2026.3, Adobe Substance 3D Painter 11.0.3, and Blender 4.1.

The MFCs used in this study were configured as dual-chamber systems separated by a ceramic membrane, a configuration previously reported for wastewater treatment and bioelectricity generation [36]. MFCs were fabricated using ceramics in a semi-cylindrical shape, with average dimensions of 9.2 cm in diameter, 12 cm in height, and 0.5 cm in width. Each MFC was equipped with an anode made of a carbon felt piece measuring 32 cm in length, 11 cm in width, and 6 mm in thickness, which was wrapped around the ceramic and secured with a plastic strap. A second carbon felt piece, 21 cm long and 11 cm wide, served as the cathode, wrapped around the inner surface of the ceramic cylinder and filled with activated plant-derived carbon. To promote biofilm development, a preliminary run was carried out using the same system, which was exposed to real wastewater for 25 days. The system was operated in batch mode as an initial approach to evaluate the behavior of the integrated FW-MFC system. Unlike conventional constructed wetlands, which are generally used for wastewater treatment under continuous flow conditions, the FW-MFC configuration proposed in this work is mainly intended for the remediation of water bodies such as lakes, lagoons, ponds, and small reservoirs. In these environments, water may remain in the system for relatively long periods, making batch studies useful for evaluating pollutant removal and bioelectricity generation before moving toward field applications. The pilot FW-MFC system was operated outdoors between May and July under natural

environmental conditions. To prevent dilution of the wastewater, the system was covered to avoid direct rainfall from entering the tank.

3.2. Origin of Wastewater

The wastewater used in this study was collected from the sanitary drainage system of CIDETEQ (Center for Research and Technological Development in Electrochemistry, Querétaro, Mexico). The wastewater consisted primarily of sanitary wastewater generated by staff and visitors, together with minor contributions from laboratory activities. The wastewater was collected prior to treatment and used without pre-treatment in all experimental runs.

3.3. Measurements of Chemical and Electrical Parameters

To evaluate the treatment performance of the FW-MFC system, two experimental runs (Experiment 1 and Experiment 2) were conducted sequentially over a period of 21 days using the same experimental setup. Each experiment was performed with wastewater collected from the same source on different dates. This approach allowed the evaluation of the system during two independent operating periods using real wastewater. As an exploratory evaluation of the integrated system, the study focused on COD, NH_3-N, and TN as the primary indicators of pollutant removal. In addition, voltage, current, and power generation were monitored to assess the electrochemical behavior of the system and its potential for bioelectricity generation. Organic matter removal was evaluated through COD analyses performed using a standardized spectrophotometric method [37]. Due to the dimensions and limited availability of the pilot-scale FW-MFC system, biological replicates were not included in this study, and both experimental runs were conducted sequentially using the same experimental setup. COD, TN and NH_3–N analyses were performed in triplicate for each sampling point. The reported values correspond to the mean of the analytical replicates, and the associated standard deviations were used to construct the error bars presented in Figures 1–3. Samples collected were filtered using a 0.45 µm filter disk (Agilent Technologies, Santa Clara, CA, USA) and subsequently added to a digestion solution, where they were heated at 150 °C for 2 h (Hach digester, Hach Company, Loveland, CO, USA). Following this, absorbance was measured at 620 nm to calculate the COD concentration (Hach DR 6000 Spectrophotometer, Hach Company, Loveland, CO, USA). Monitoring of NH_3–N and TN removal was likewise conducted every three days using standardized spectrophotometric methods (from Standard Methods for the Examination of Water and Wastewater). The salicylate method was applied for NH_3–N analysis, while TN was determined using the persulfate method [38]. Continuous monitoring of current, voltage, and power generation was performed over the entire 21-day experimental period using an Arduino microcontroller.

4. Conclusions

The FW-MFC system demonstrated a strong capacity for the removal of organic contaminants present in real wastewater, as measured by COD, achieving removal efficiencies ranging from 50 to 69% for initial organic loads of 405 and 289 mg/L COD. Additionally, in terms of nitrogen removal, up to 55% of NH_3–N and 40% of TN were removed. Regarding the electrical parameters, maximum voltage, current, and power outputs were observed during the initial days, followed by a gradual decline as the treatment progressed. A similar trend was observed in the polarization and power curves, which showed higher voltage, current, and power values in the early stages, with a significant decrease over time. Finally, both the continuously monitored power output and the power curves indicate that the initial organic load and its availability throughout the treatment process play a

key role in determining the power generation of the system. Finally, the experimental results demonstrate that the coupled MFC–FW system represents a viable alternative for the in situ remediation of water bodies contaminated with wastewater, as it effectively removes both organic pollutants and nitrogen. However, future research should include reference systems, such as standalone floating wetlands and standalone microbial fuel cells, to better quantify the individual contribution of each technology and to assess the potential synergistic effects associated with their integration in FW-MFC systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/recycling11070112/s1, Figure S1: Continuous measurement of current. First (black) and second (red) experiments.

Author Contributions: Conceptualization, F.J.R.-V. and V.A.R.; methodology, E.G.H. and F.A.R.A.; formal analysis E.G.H., F.A.R.A. and V.A.R.; investigation, E.G.H., A.J.A.H., F.A.R.A. and V.A.R.; resources, V.A.R., L.A.G. and F.J.R.-V.; writing—original draft preparation, V.A.R. and E.M.P.; writing—review and editing, E.M.P., F.A.R.A., L.A.G. and V.A.R.; visualization, V.A.R.; supervision, V.A.R. and F.J.R.-V.; project administration, V.A.R. and F.J.R.-V.; funding acquisition, V.A.R., L.A.G. and F.J.R.-V. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FWs	Floating wetlands
MFCs	Microbial fuel cells
COD	Chemical oxygen demand
CWs	Constructed wetlands
BOD	Biochemical oxygen demand
FW–MFC	Floating wetland coupled to microbial fuel cells
TN	Total nitrogen
TDS	Total dissolved solids
TSS	Total suspended solids
NH_3–N	Ammoniacal nitrogen
OCV	Open-circuit voltage
PVC	Polyvinyl chloride
EPS	Expanded polystyrene

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