Evaluating the Effect of Constructed Wetland and Microbial Fuel Cell (CW-MFC) in Wastewater Treatment with Floating and Emergent Plant-Based Systems

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Abstract. Constructed Wetlands and Microbial Fuel Cells represent two promising low-energy technologies for domestic wastewater treatment. Their integration has the potential to enhance both pollutant removal and bioelectricity generation through combined microbial, plant-based, and electrochemical processes. This study evaluated the performance of an integrated CWMFC system operated with two plant configurations, namely the emergent species Equisetum hyemale and the floating species Pistia stratiotes. Five reactor configurations were examined: CW MFC with aeration and bacterial augmentation (CWMFC AB), CW MFC with bacterial augmentation (CWMFC B), CW MFC without augmentation (CWMFC), MFC only system, and CW only system. Each reactor with a volume of 9 liters was operated in batch mode for 18 d using domestic greywater, with monitoring conducted every three days. The CWMFC AB configuration consistently produced the greatest reductions in BOD, COD, and TAN. Emergent plant systems demonstrated stronger TAN removal than floating plant systems. Bioelectricity generation reached a maximum of 794.7 milliwatts per square meter in the emergent CWMFC AB reactor, whereas floating systems produced up to 196.5 milliwatts per square meter. These results indicate that the combined CW MFC approach supported by aeration and Lactobacillus plantarum augmentation, offers an effective strategy for decentralized wastewater treatment and energy recovery.
Keyword: Constructed wetland; Microbial fuel cell; Emergent plants; Floating plants; Domestic wastewater; Bioelectricity generation

1 Introduction

Domestic wastewater in coastal cities, such as Surabaya in Indonesia, contains a complex mixture of pollutants originating from household activities. Typical contaminant groups include organic matter, nutrients, detergents, suspended solids, and microbial loads, which collectively elevate key parameters such as Chemical Oxygen Demand, Biochemical Oxygen Demand, Total Ammonia Nitrogen, and fluctuations in pH [1]. When discharged without adequate treatment, these pollutants accelerate eutrophication, degrade aquatic ecosystems, and pose risks to coastal environments that are already vulnerable to tidal influences and limited freshwater exchanges. The increasing population density in suburban and peri-urban districts further exacerbates these challenges, creating a pressing need for decentralized, low-energy, and adaptive treatment systems suitable for domestic wastewater management in coastal urban settings [2].

Constructed Wetlands have emerged as an attractive alternative because they operate using natural treatment mechanisms involving plants, microbial biofilms, and supporting media. CWs can reduce organic matter, stabilize pH, and transform ammonia through plant-assisted nitrification and microbial pathways. Their advantages include low operational costs, minimal energy demand, and high resilience to variable influent quality. However, CWs can be

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limited by slow degradation rates, low oxygen transfer, and inconsistent performance when treating wastewater with elevated organic or nutrient loads, which are common in domestic greywater.

Microbial Fuel Cells represent another innovative low-energy treatment option, in which electroactive bacteria oxidize organic matter and generate an electric current as electrons move through an external circuit. MFCs have demonstrated the ability to reduce COD and BOD while simultaneously producing renewable electricity. Despite this potential, standalone MFC systems often suffer from limited power output, sensitivity to environmental conditions, and unstable, long-term operation. Consequently, their application in the treatment of real domestic wastewater remains constrained.

The integration of Constructed Wetlands (CWs) with Microbial Fuel Cells (MFCs) has garnered significant attention as a strategy to leverage the complementary strengths of both technologies. As suggested by several studies, the combined CW-MFC system can enhance pollutant degradation by coupling plant-mediated oxygenation with electrochemical microbial processes, potentially improving Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Ammonia Nitrogen (TAN), and pH stabilization simultaneously [3]. Consequently, CW-MFC modules with vegetation demonstrated higher treatment efficiency than unplanted wetland modules, with average COD, NH4 +, and TP removal efficiencies ranging from around 80-90% [4] [5]. However, it remains unclear whether these systems consistently enhance each other or whether operational interactions may restrict performance. The presence of plant roots may alter electrode aeration, biofilm development, and electron transfer patterns, whereas the electrochemical environment in the MFC may influence rhizosphere microbial communities. These uncertainties underline the need for a systematic evaluation of integrated system dynamics under real wastewater conditions.

Furthermore, while emergent and floating plants are frequently utilized in constructed wetland (CW) applications, their specific impact on the performance of integrated CW microbial fuel cells (MFCs) has not been thoroughly examined. Research suggests that various types of vegetation demonstrate differing effectiveness in the removal of contaminants from wastewater, with the emergent plant Typha angustifolia exhibiting superior removal capabilities compared to three other emergent plant species [2]. Emergent plants with solid root structures may provide better oxygen diffusion, whereas floating plants offer larger surface area coverage but limited rhizosphere depth. In addition, the role of bacterial augmentation in enhancing CW processes, MFC activity, or both components collectively remains inadequately explored. Determining whether augmentation enhances treatment efficiency or primarily benefits only one subsystem is crucial for optimizing the design of the combined CW MFC reactor.

This study evaluated these knowledge gaps by assessing organic matter removal, ammonia transformation, pH regulation, and electricity production in an integrated CW MFC system operated with emergent and floating plant-based configurations. The experimental approach compared individual and combined systems to determine whether integration yields a synergistic effect or introduces operational constraints under real domestic wastewater conditions.

2 Materials and Methods

This study was conducted at the Environmental Engineering Laboratory of Institut Teknologi Sepuluh Nopember (ITS), Surabaya, in October 2024. The methodological framework was designed to evaluate the treatment efficiency and electricity generation of combined constructed wetland and Microbial Fuel Cell systems under controlled laboratory conditions. The procedures encompassed domestic wastewater characterization, plant propagation and acclimatization, bacterial culture preparation, and the construction and operation of CW MFC reactors. Each component of the methodology was structured to ensure consistent operating conditions and enable systematic comparisons across reactor configurations, including both individual and integrated systems.

2.1 Domestic Wastewater Characterisation

Domestic greywater was collected from a residential complex in Sedati District, Sidoarjo, East Java. Sampling followed the Indonesian National Standard SNI 8990-2021 regarding methods for sampling wastewater for physical and chemical analysis. Initial characterization showed that the wastewater exceeded the quality standards set by the Regulation of the Minister of Environment and Forestry (Permen LHK) No. 68 of 2016. The key parameters measured were pH, Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and Total Ammonia Nitrogen (TAN). The wastewater exhibited high organic loads and alkaline conditions, with COD and BOD values far above the permissible limits, indicating the presence of both biodegradable and recalcitrant pollutants. Ammonia concentrations also exceeded regulatory thresholds, suggesting a high risk of eutrophication if it is discharged without treatment. These characteristics underscore the need for effective biological and electrochemical treatment approaches.

Table 1. Domestic Wastewater Concentration.

Parameters	Unit	Domestic Wastewater Concentration	Maximum Concentration	Description
BOD_5	mg/L	912	30	Non Compliant
COD	mg/L	4.096	100	Non Compliant
TSS	mg/L	50,55	30	Non Compliant
Ammonia	mg/L	36	10	Non Compliant
pH	-	9,62	6-7	Non Compliant

2.2 Plant Propagation and Acclimatization

Prior to their use in the reactors, the selected plant species were propagated and acclimatized to controlled laboratory conditions. *Pistia stratiotes* (floating plant) and *Equisetum hyemale* (emergent plant) were chosen based on their robustness, pollutant uptake capacity, and aesthetic potential for future landscape-integrated CW-MFC applications. Propagation involved encouraging vegetative growth until sufficient healthy shoots were obtained for the experiment. Acclimatization was conducted in clean water for one week, during which the plant condition was monitored based on leaf turgidity, stem structure, color, and absence of necrotic symptoms. A range-finding test using wastewater concentrations of 10%, 25%, 50%, 75%, and 100% was conducted to evaluate plant tolerance. Both species exhibited optimal performance at a wastewater concentration of 25 %, which was selected as the influent concentration for reactor operation.

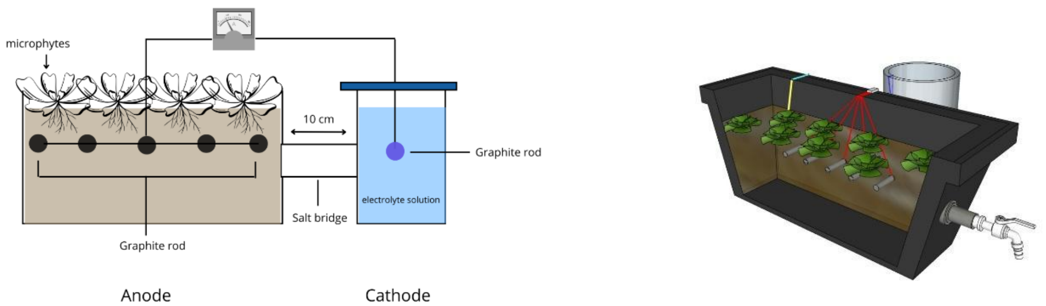

Fig. 1. Reactor Design; (left) Schematic Configuration of CW-MFC Reactor; 3D configurations of CW-MFC Reactors

2.3 Bacterial Culture

Lactobacillus plantarum was used as the bacterial augmentation agent. Cultivation began by inoculating sterile MRS broth with bacterial colonies and incubating under anaerobic conditions at 37°C for 18–24 h. The culture was then scaled up by transferring the starter into a larger volume of MRS broth and incubating further until the concentration reached approximately 1×108 CFU/mL, as verified through optical density measurements and a standard calibration curve. This inoculum was added to the designated reactors to evaluate its influence on pollutant removal and power generation.

2.4 Reactor Configuration

The CW MFC system consisted of laboratory-scale batch reactors, as shown in fig. 1. to evaluate the combined and individual performance of the CW and MFC components. Each reactor measured 50 cm × 24 cm × 20 cm with a working volume of 9 L for floating systems and 7.5 L for emergent systems, the latter supplemented with a 2.5 L gravel substrate layer. The substrate comprised two gravel layers: a 4 cm layer with a particle size of 1–2 cm and a 3 cm layer with a particle size of 3–5 cm. Gravel was used to support biofilm development and root–microbe interaction.

Graphite electrodes (15 cm length) and a 10 cm salt bridge containing 1 M KCl in agar were used as the electrochemical components. The electrodes were pretreated with 1 M HCl, followed by 1 M NaOH, to remove contaminants. The anode and cathode chambers were separated by a PVC pipe housing the salt bridge, and NaCl served as an electrolyte. The voltage and current outputs were monitored using a digital multimeter.

Five reactor configurations were used for each plant type (floating and emergent), resulting in ten reactors.

1. CWMFC AB: Integrated CW MFC with aeration and bacterial augmentation
2. CWMFC B: Integrated CW MFC with bacterial augmentation but no aeration
3. CWMFC: Integrated CW MFC without aeration and without bacterial augmentation
4. MFC: MFC-only system (control 1)
5. CW: CW-only system (control 2)

The reactors were operated in batch mode for 18 d, with sampling conducted every three days (Days 0, 3, 6, 9, 12, 15, and 18). Environmental conditions were maintained in an indoor greenhouse with a stable temperature, natural light exposure, and no rainfall.

All wastewater quality analyses in this study were conducted using nationally recognized Indonesian standards, referring to the Standar Nasional Indonesia (SNI) for physical and chemical testing. These methods were applied consistently across all sampling intervals to ensure the accuracy and comparability of the data. The measured parameters and their corresponding analytical standards are as follows:

The pH of the wastewater was measured according to SNI 06-6989.11-2004 using a calibrated digital pH meter equipped with a glass electrode. The Biochemical Oxygen Demand (BOD_5) test followed SNI 6989.72:2009, with samples incubated at 20°C for five days before measuring the dissolved oxygen (DO). Chemical Oxygen Demand (COD) analysis was performed following SNI 6989.73:2009, using the closed reflux dichromate method with spectrophotometric detection. The concentration of Total Ammonia Nitrogen (TAN) was determined based on SNI 6989.30:2005. Electrical performance, including voltage and current generation in the MFC components, were recorded twice daily using a digital multimeter, and power density (mW/m^2) was calculated using the formula,

$$P=V^2/(R\times A) \quad (1)$$

where V is the measured voltage, R is the external resistance, and A is the projected anode surface area.

3 Result and Discussion

3.1 pH Dynamics Across Reactor Configurations

The initial pH of the domestic wastewater was highly alkaline at 9.62, which exceeded the optimal range for most biological treatment processes. Across all reactors, the pH declined progressively during the eighteen day operation period, reflecting biological acidification associated with organic degradation and nitrogen transformation processes [4]. However, the rate and magnitude of this decline differed substantially between the reactor configurations and plant types.

In the emergent plant systems, the pH decreased rapidly during the first nine days, reaching values between 6.77 and 7.92 by day 12. The lowest pH was observed in CWMFC B, which dropped from 9.62 to 6.41 on day 18. This substantial reduction reflects the strong oxygen transport capacity of *Equisetum hyemale* as an emergent plant that promotes nitrifying bacterial activity through root zone aeration. Enhanced nitrification leads to proton generation and subsequent pH reduction, explaining the steeper decline compared to that in floating systems. The CWMFC AB reactor also showed a stabilized pH close to neutrality (6.78) by day 18, indicating that aeration combined with microbial augmentation supported balanced microbial metabolism and mitigated excessive alkalinity.

The MFC reactor exhibited the highest pH fluctuation, consistent with earlier studies showing that MFC performance is strongly dependent on electron acceptor availability at the cathode, which can vary significantly in plant-free systems [6]. In the absence of plant-mediated oxygenation, cathodic reactions may proceed less consistently, and electroactive biofilms develop more slowly, contributing to less stable internal biochemical conditions. In contrast, the integrated CW-MFC systems benefited from plant-supported oxygen transfer and enhanced microbial activity, which promoted more stable pH trajectories.

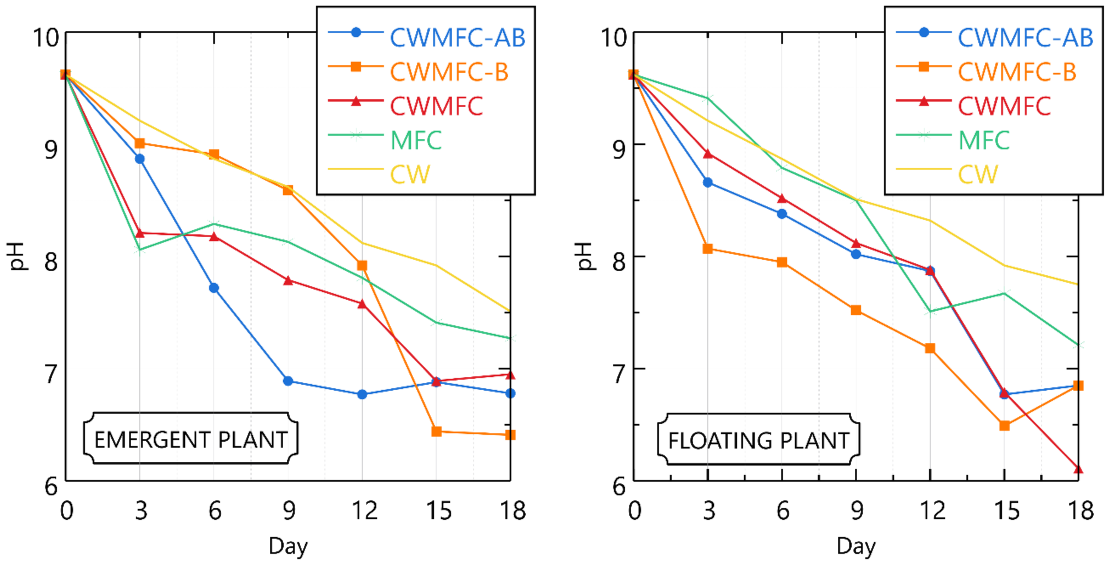

Fig. 2. pH dynamics over time for (left) emergent plants and (right) floating plants.

3.2 Biochemical Oxygen Demand Removal

BOD concentrations declined steadily in all reactor configurations during the 18 days of operation, although the extent of reduction varied across the treatment systems and plant types. In the emergent plant units, the integrated CW-MFC configurations achieved the highest levels of organic pollutant removal. The CWMFC AB system reduced BOD from 228 mg/L to 20 mg/L by day 18, representing approximately 91% removal. This superior performance is associated with the combined influence of aeration, bacterial augmentation, and the development of electroactive biofilms, which together strengthen both aerobic and anaerobic degradation pathways, as previously reported in related studies [7]. The CWMFC B reactor followed with a final concentration of 24 mg/L, while the non-augmented CWMFC system exhibited slower degradation, ending at 116 mg/L. The individual MFC and CW reactors showed comparatively limited reductions, reaching 112 mg/L and 100 mg/L, respectively, further indicating that neither technology alone was able to achieve substantial BOD removal under the tested conditions.

In the floating plant systems, all reactors also showed declining BOD trends, although the overall performance was lower than that observed in the emergent systems. The CWMFC AB configuration again produced the most pronounced decrease, reaching a final BOD concentration of 28 mg/L. This result was followed by CWMFC B at 40 mg/L and the non-augmented CWMFC system at 112 mg/L, respectively. The floating MFC and CW controls remained above 100 mg/L at the end of the experiment, confirming their limited efficiency in the absence of system integration. The slower rates observed in floating systems may be linked to the lack of gravel media, which restricts biofilm formation, and the relatively low radial oxygen release from *Pistia stratiotes* roots. These limitations reduce the availability of aerobic microhabitats and weaken the early establishment of effective microbial communities.

Emergent plant systems consistently outperformed floating systems in all reactor variants. This improved performance is likely supported by the extensive rhizosphere of *Equisetum hyemale*, which promotes greater oxygen transfer, provides larger microbial attachment surfaces, and facilitates diverse pollutant degradation pathways. Floating plants produce a shallower and less oxygenated root zone, which reduces the intensity of plant–microbe interactions and slows organic matter degradation. Despite these constraints, the floating CWMFC AB configuration achieved substantial improvement compared to the floating control systems, demonstrating that aeration and bacterial augmentation can compensate for the physiological limitations associated with floating vegetation.

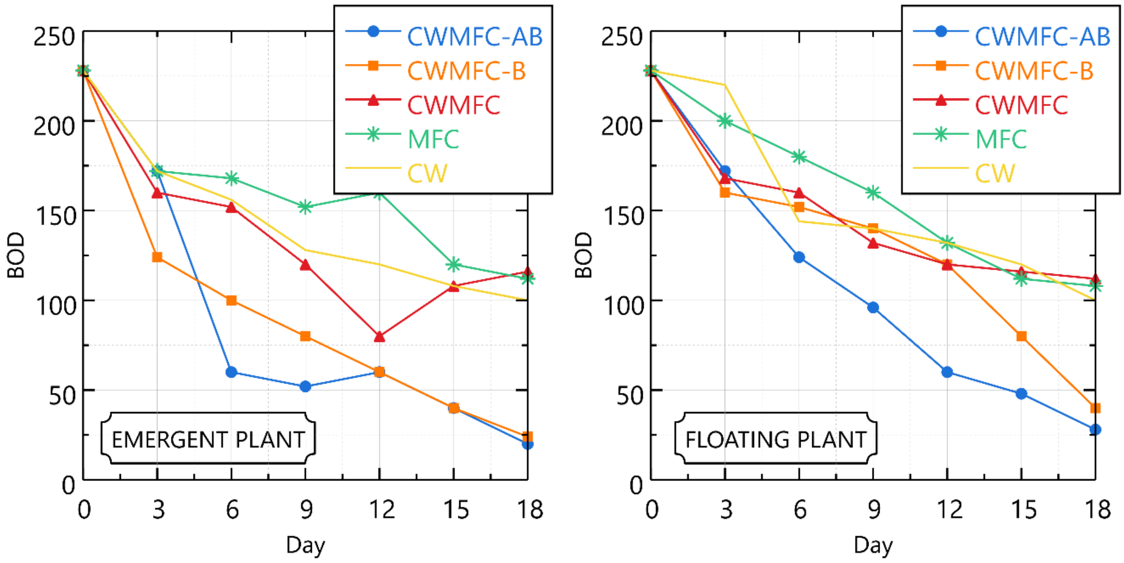

Fig. 3. BOD removal over time for (left) Emergent Plant and (right) Floating Plant.

The treatment hierarchy was consistent for both plant categories, with CWMFC AB providing the strongest removal efficiency, followed by CWMFC B, CWMFC, and finally, the single technology reactors. This performance pattern reinforces the positive interaction between constructed wetland processes and the mechanisms of microbial fuel cells. Constructed wetlands enhance oxygen diffusion and root exudate supply, whereas microbial fuel cells support electron transfer and sustained bioelectrochemical oxidation. The improved outcomes observed in the augmented and aerated reactors align with the existing literature, showing that enriched microbial communities and improved oxygen availability accelerate organic pollutant degradation and strengthen electroactive consortia [8]. The findings confirm that the integrated CW-MFC concept delivers significantly higher BOD removal than either system operating independently, and that appropriate operational enhancements can further maximize treatment performance.

3.3 Chemical Oxygen Demand Removal

COD concentrations decreased steadily in all reactor configurations across the 18-day operational period. The initial COD value of 1024 mg/L was identical for every reactor, which allowed a direct comparison of the treatment performance between the individual and integrated systems. The observed trends highlight the contributions of plant-mediated processes, microbial activity, and bioelectrochemical reactions to organic pollutant degradation in both emergent and floating plant configurations.

In the emergent plant systems, the most substantial COD reduction occurred in the CWMFC AB. The COD declined from 1024 mg/L to 89.6 mg/L on day 18, indicating an overall removal efficiency of approximately 91 percent. This outcome demonstrates the combined effect of aeration, bacterial augmentation, and MFC-mediated electron transfer in accelerating the breakdown of organic matter, which has also been reported in previous coupled CW and MFC studies. The CWMFC B reactor had a final COD concentration of 128 mg/L, confirming that bacterial enrichment notably contributed to the system performance. The non-augmented CWMFC reactor achieved a slower decline, reaching 396.8 mg/L, whereas the MFC only and CW only systems ended at 371.2 mg/L and 358.4 mg/L, respectively. These results highlight that neither wetlands nor MFCs alone are sufficient to achieve high COD removal within the tested time frame.

A similar trend was observed in the floating plant reactors. The CWMFC AB configuration again produced the highest COD reduction, with a final concentration of 89.6 mg/L. The CWMFC B reactor followed with 153.6 mg/L on day 18, reflecting the influence of bacterial augmentation on strengthening organic matter oxidation. The non-augmented CWMFC reactor remained at 409.6 mg/L, whereas the MFC only and CW only systems performed comparably, finishing at 396.8 mg/L and 384 mg/L, respectively. These findings indicate that floating systems are capable of substantial pollutant removal, although the overall rate of COD reduction is slightly lower than that achieved by emergent systems. The reduced performance may be due to the absence of a gravel layer in the floating reactors, which limits biofilm establishment and slows microbial pathway diversification, as suggested in earlier wetland studies [9].

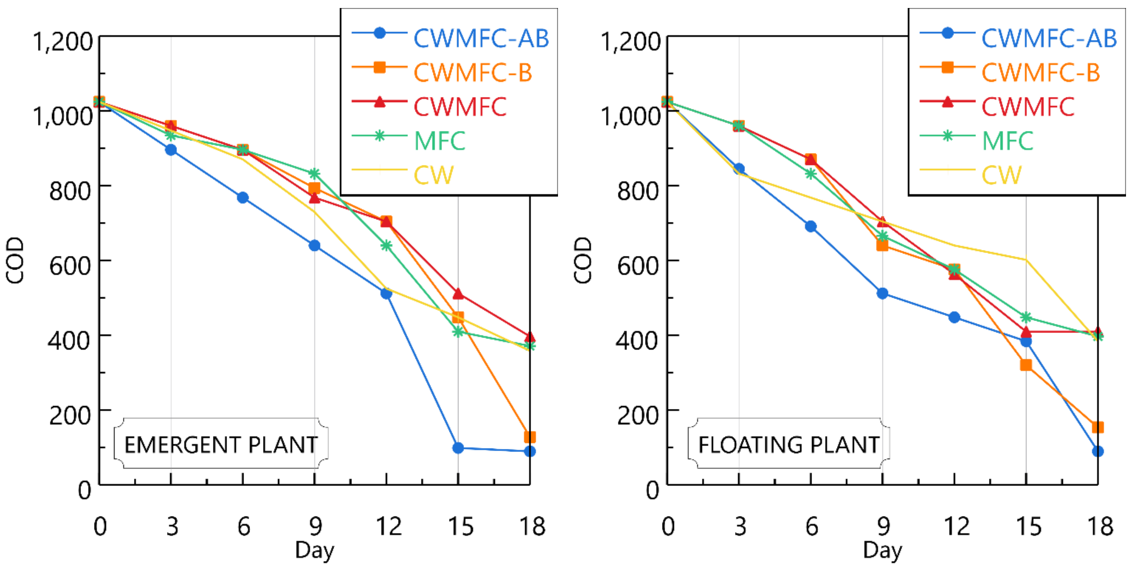

Fig. 4. COD removal over time for (left) emergent plants and (right) floating plants.

The performance gap between the emergent and floating plants remained relatively small for COD removal. In both configurations, the reactors that included both CW and MFC components consistently demonstrated superior removal efficiencies. The statistical analysis performed through ANOVA revealed no significant difference between the floating and emergent configurations on day 18, indicated by an F statistic of 0.029 and a p value of 0.867. This confirms that both plant types support comparable levels of COD reduction and that system performance is influenced more strongly by bacterial augmentation and MFC integration than by plant morphology alone.

The overall pattern across all treatments confirmed that the CWMFC AB configuration provided the most effective treatment performance. The synergy between plant-mediated oxygen transfer, enriched microbial populations, and electrochemical oxidation results in rapid COD degradation. The removal hierarchy observed in this study is consistent with previous investigations of integrated CW and MFC systems, where coupling these processes

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produces more efficient treatment than either technology operating independently [9]. The results of the present study confirm that the combination of biological, microbial, and electrochemical mechanisms provides a strong foundation for improving decentralized domestic wastewater treatment.

3.4 Ammonia Nitrogen Removal

Ammonia concentrations decreased across all reactors during the eighteen-day experiment, although the magnitude and rate of removal varied among the treatment configurations. The results demonstrated that systems incorporating plants, bacterial augmentation, and microbial fuel cell components consistently achieved the greatest decrease in total ammonia nitrogen, whereas reactors that lacked one or more of these elements showed slower conversion.

In the emergent plant systems, the CWMFC AB reactor achieved the lowest total ammonia nitrogen concentration by the end of the experiment, reaching 7 mg/L total ammonia nitrogen. The CWMFC B reactor produced a final concentration of 9 mg/L, reflecting the contribution of bacterial supplementation to nitrogen conversion processes. The non-augmented CWMFC reactor demonstrated a moderate decrease to 11 mg/L. The MFC only and CW only reactors showed the weakest performance, with final concentrations of 17 mg/L and 14 mg/L, respectively. These results indicate that the combined influence of plant-rooted zones, bacterial activity, and electrochemical reactions provides conditions that strongly promote ammonia transformation in emergent plant systems [10].

A similar pattern was observed in the floating plant reactors. The CWMFC AB system exhibited the fastest removal, with a final concentration of 9 mg/L. The CWMFC B reactor followed closely, reaching 10 mg/L. The non-augmented CWMFC system decreased to 17 mg/L by day 18. The MFC-only and CW-only reactors showed the slowest reductions, ending at 18 mg/L and 20 mg/L, respectively. Therefore, floating systems require the combined action of plants, bacteria, and microbial fuel cells to achieve the strongest removal, while systems lacking any single component performed noticeably less effectively than emergent plants with substrates.

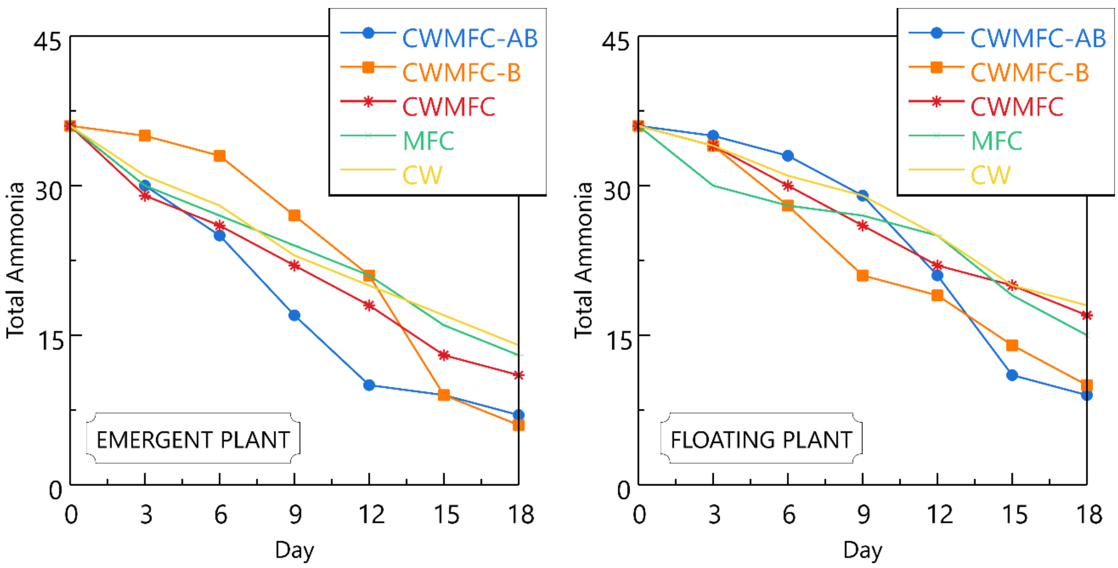

Fig. 5. TAN removal over time for (left) emergent plants and (right) floating plants.

A comparison between the emergent and floating subsystems revealed that the emergent plants achieved slightly greater ammonia removal. The presence of gravel substrate in the emergent reactors may have supported more stable microbial colonization and provided favorable conditions for nitrification and denitrification. Although floating plant reactors are responsive and generally effective, they depend more heavily on bacterial augmentation and microbial fuel cell integration to achieve comparable performance levels. Despite these differences, both plant-based systems generated substantially higher removal rates than the non-planted control reactors, confirming that plant physiological processes contribute meaningfully to nitrogen reduction.

Nitrogen removal observed in the integrated reactors may involve multiple biological and electrochemical pathways, including microbial nitrification and denitrification, plant-mediated uptake, and redox enhancement facilitated by microbial fuel cells. Previous studies have noted that hybrid constructed wetland and microbial fuel cell systems can accelerate nitrogen transformation by enabling interactions between aerobic and anoxic microenvironments and supporting electroactive microbial communities [10]. Overall, the reactors that incorporated plants, bacteria, and microbial fuel cell components produced the most substantial total ammonia nitrogen reductions in both the emergent and floating configurations. The control reactors displayed slower declines, confirming that each component plays an important role in the treatment process. Therefore, the results demonstrate that the integrated constructed wetland and microbial fuel cell configuration provides the most favorable conditions for effective nitrogen conversion in domestic wastewater.

3.5 Electricity Production and Electrochemical Performance

Electricity generation increased progressively in all CW MFC reactors during the eighteen-day operational period, although the magnitude of the increase varied considerably across the treatment configurations. The observed trends reflect the combined influence of plant physiology, microbial activity, and electrochemical processes occurring within the microbial fuel cell. Control reactors without one or more essential components produced negligible electricity, confirming that each removed element plays a critical role in creating electrochemical gradients and enabling current generation.

In the floating plant system, the CWMFC reactors produced very low current densities throughout the operational period. Power generation in CWMFC increased gradually from 7.03×10^{-4} mW/m^2 to 1.40×10^2 mW/m^2, while CWMFC B increased from 1.68×10^0 mW/m^2 to 1.96×10^2 mW/m^2. These values indicate limited electroactive biofilm development, which is likely related to the reduced oxygen transfer and weaker rhizosphere support provided by the floating roots. The floating CWMFC AB reactor showed a substantially higher output, reaching 1.96×10^2 mW/m^2. Electricity generation was significantly higher in the emergent plant system. The CWMFC reactor increased from 1.15×10^{-1} mW/m^2 to 4.93×10^1 mW/m^2, and the CWMFC B reactor followed a similar trend with moderate outputs, indicating that aeration or bacterial augmentation alone did not substantially enhance performance. The highest power densities were observed in the emergent CWMFC AB reactor, which reached a maximum of 7.95×10^2 mW/m^2. The elevated performance of emergent systems can be attributed to stronger oxygen release into the rhizosphere, improved structural support for biofilm growth, and better integration of electrodes with plant-mediated microenvironments that favor electron transfer [11].

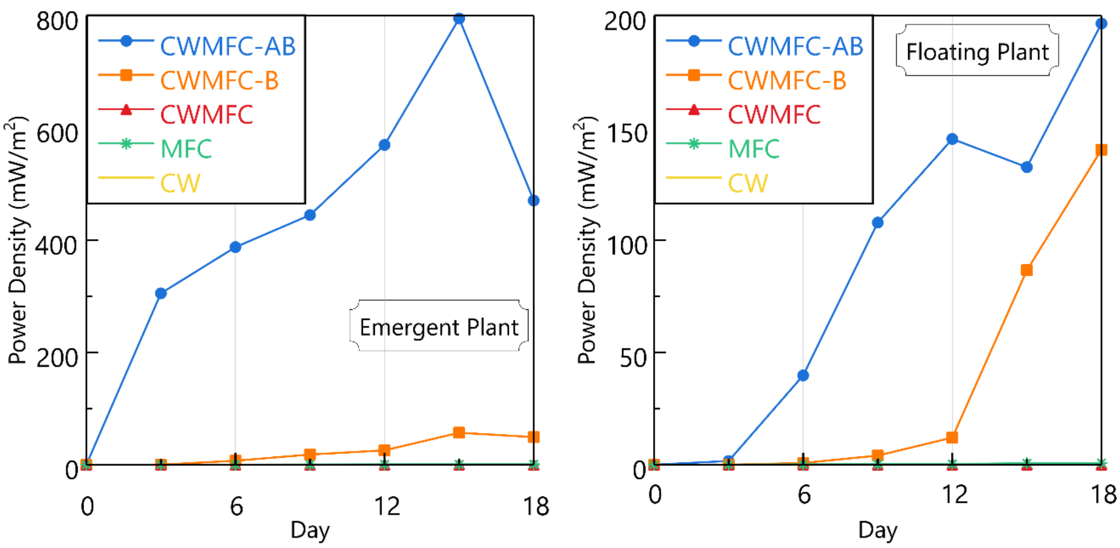

Fig. 6. Power density generation over time for (left) Emergent Plant and (right) Floating Plant.

Electricity generation patterns in both plant systems indicated that the combined application of plants, bacterial augmentation, and aeration in the CWMFC AB configuration produced the most favorable conditions for electrogenic activity. Root exudates stimulate microbial metabolism, and oxygen released by emergent plants supports cathodic reactions that facilitate electron transfer. This interaction lowers the internal resistance and improves the bioelectrochemical conversion efficiency. Previous studies reported that integrated CW MFC systems provide an extensive surface for microbial colonization and promote the growth of electrochemically active bacteria, resulting in increased bioelectricity generation in integrated constructed wetland microbial fuel cells [12]. The electricity generated in this study was also consistent with previous CW-MFC studies that reported power densities as low as 9.4 mW/m^2 [13] and as high as 4.5-7.19x10^2 mW/m^2 [14]. Overall, the emergent plant reactors produced markedly higher power densities than the floating reactors, and the CWMFC AB configuration consistently outperformed all other configurations. However, the electricity generation results clearly show that the integration of plants, bacterial augmentation, and the microbial fuel cell system produced strong improvements in the electrochemical performance of both floating and emergent plants. Reactors that combined all three components exhibited the highest increase in power density, whereas the control reactors lacking any component produced minimal or unstable outputs.

3.6 Parameter Relation

The combined trends of pH, BOD, COD, TAN, and power density show that pollutant removal and electricity generation in CW MFC systems are interdependent processes governed by microbial activity, plant-mediated functions, and electrochemical reactions. Reactors that incorporated plants, bacterial augmentation, and MFC components consistently produced the most stable operating conditions and highest performance across all parameters. pH stability was a key factor supporting both organic degradation and electricity generation. The reactors containing plants showed more consistent pH profiles, which helped to maintain optimal microbial activity. This stability contributed to faster reductions in BOD and COD because electrogenic and heterotrophic bacteria perform more efficiently under stable pH conditions. In contrast, MFC-only reactors exhibited larger pH fluctuations, which likely reduced the establishment of electroactive biofilms and resulted in both slower organic removal and lower power densities.

The patterns of BOD and COD reduction were closely linked to the electricity generation. Reactors with rapid decreases in organic load also produced higher power densities, indicating that the oxidation of organic matter directly supplied electrons for current production [12]. This relationship was most apparent in the CWMFC AB reactors, which demonstrated the highest organic matter removal and the strongest power output. Systems lacking either plant or bacterial augmentation showed weaker removal rates and correspondingly lower power generation, confirming that efficient biodegradation supports more effective electron transfer within the MFC. TAN removal also aligns with broader system behavior. Reactors with complete configurations exhibited faster ammonia reduction, which is consistent with enhanced microbial nitrification and plant uptake. These reactors produced greater COD and BOD removal, as well as higher power densities, suggesting that the microbial communities responsible for nitrogen transformation are part of a broader set of biological processes that improve electrochemical performance [15]. In contrast, limited TAN removal in the control reactors paralleled weaker organic degradation and minimal electricity generation.

Overall, the results show that pH stability, organic matter removal, ammonia reduction, and electricity generation are interrelated. Systems that achieved strong performance for one parameter tended to perform well for all other parameters. This pattern indicates that CW MFC processes reinforce each other when plants, bacteria, and the MFC unit operate concurrently. Therefore, the integrated CWMFC AB configuration provides the most balanced biochemical and electrochemical environments, resulting in superior pollutant removal and power production compared to partial or single-component systems.

4 Conclusion

This study demonstrates that the integration of constructed wetlands with microbial fuel cells (CWMFC) significantly enhances the treatment of domestic wastewater and electricity generation compared to standalone

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constructed wetland (CW) or microbial fuel cell (MFC) systems. The CWMFC AB configuration, which combines plants, bacterial augmentation, and electrochemical processes, achieved the highest and most consistent removal efficiencies for biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total ammonia nitrogen (TAN) while maintaining a stable pH conducive to microbial and electrogenic activity. Both floating and emergent plants contributed to pollutant removal, with emergent plants yielding superior power densities, likely due to increased root surface area and improved rhizosphere conditions that foster electrogenic bacteria. The observed positive correlation between pollutant degradation rates and electrical output confirms that efficient substrate utilization by electroactive microbes simultaneously drives treatment performance and bioelectricity generation. Compared to benchmark studies, the removal efficiencies and power densities achieved here (BOD removal: 91%; COD removal: 91.25%; TAN removal:81%; power density: 7.95×10^2 mW/m^2) are comparable or superior to reported values in similar CWMFC configurations, highlighting the effectiveness of combined biological and electrochemical enhancements. These results align with broader findings in the field, reinforcing the potential of CWMFC systems as sustainable, multifunctional solutions for decentralized wastewater management and renewable energy recovery.

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