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Original Research Article

Effect of Floating Plants on Constructed Wetland Microbial Fuel Cell Treating Domestic Wastewater

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Abstract

Sustainable domestic wastewater treatment is urgently needed amid water scarcity and rising energy demands. The Constructed Wetland–Microbial Fuel Cell (CW-MFC) system integrates phytoremediation and bioelectricity production by electroactive microorganisms, yet previous studies rarely compared the synergistic effects of different plant species within this system, limiting its optimization. This study evaluated CW-MFC performance using three plant configurations (*Pistia stratiotes, Eichhornia crassipes*, and their combination) integrated with *Lactobacillus plantarum* at two concentrations (2×10^8 CFU/mL and 5×10^8 CFU/mL). The reactors were operated for 18 days under identical hydraulic conditions to assess BOD, COD, ammonia, and TSS removal efficiencies and power density generation. Results showed that Eichhornia crassipes achieved the highest pollutant removal efficiencies with COD reduction up to 82%, while the system with 2×10^8 CFU/mL bacterial concentration produced the highest power density of approximately 1032 mW/m^2. Interestingly, lower bacterial concentrations yielded higher power outputs, possibly due to reduced microbial competition for electron transfer sites, enhancing electroactive bacteria performance. In conclusion, integrating Eichhornia crassipes with L. plantarum at 2×10^8 CFU/mL optimizes both pollutant removal and bioelectricity production, confirming CW-MFC as an environmentally friendly technology with potential for sustainable wastewater treatment and renewable energy generation.

Keywords: Bioelectricity production; constructed wetland–microbial fuel cell; phytoremediation

1. Introduction

Water pollution caused by domestic wastewater remains a major environmental challenge worldwide, particularly in densely populated urban areas of developing countries. Domestic wastewater contains high concentrations of organic matter, suspended solids, ammonia, and nutrients, which, if discharged without treatment, deteriorate water quality and damage aquatic ecosystems (Luo et al., 2019). Globally, around 80% of wastewater is released into the environment without adequate treatment (UNESCO, 2017). In Indonesia, approximately 75% of domestic wastewater is discharged untreated into rivers and other water bodies, significantly contributing to surface water pollution and public health risks (BAPPENAS, 2021). These conditions highlight the urgent need for effective and sustainable domestic wastewater treatment technologies.

The Constructed Wetland–Microbial Fuel Cell (CW-MFC) system has emerged as an innovative green technology combining phytoremediation with bioelectricity generation by electroactive microorganisms (Wang et al., 2016). In conventional wastewater treatment, constructed wetlands effectively reduce organic matter, nutrients, and suspended solids through plant uptake, sedimentation, and microbial degradation. However, their potential for resource recovery remains underutilized. Integrating constructed wetlands with MFC systems not only enhances treatment efficiency but also enables renewable electricity generation (Li et al., 2022). In CW-MFC systems, wetland plants facilitate pollutant removal via root uptake and microbial activity in the rhizosphere, while electroactive bacteria oxidize organic pollutants and transfer electrons to the cathode to produce electricity. Recent studies have reported that CW-MFC systems can achieve COD removal efficiencies of 70–85% and power densities ranging from 100 to 1500 mW/m^2, depending on reactor design and operational parameters (Yan et al., 2022). These findings demonstrate that CW-MFC offers dual benefits for environmental remediation and renewable energy generation, making it a promising technology to address sustainable wastewater treatment challenges, especially in developing countries.

Floating macrophytes such as *Eichhornia crassipes* (water hyacinth) and *Pistia stratiotes* (water lettuce) are widely used in phytoremediation due to their rapid growth, high nutrient uptake capacity, and adaptability to polluted waters (Putri et al., 2023). Eichhornia crassipes, in particular, has been proven effective in reducing BOD, COD, ammonia, and TSS in various wastewater treatment studies (Siswoyo et al., 2020). However, its integration with MFC systems still requires evaluation to optimize pollutant removal efficiency and electricity production. Additionally, the introduction of electroactive bacteria such as *Lactobacillus plantarum* commonly known as a probiotic and fermentation agent—has been reported to enhance organic matter degradation and support electricity generation in MFC systems by facilitating electron transfer processes (Zhang et al., 2023). Moreover, electrode materials play a crucial role in CW-MFC performance, with graphite electrodes widely used due to their high conductivity, stability, and biocompatibility (Logan et al., 2006).

Most previous studies have focused on evaluating a single plant species or specific bacterial strain within CW-MFC systems, resulting in limited understanding of synergistic interactions between multiple plant species and bacteria under identical operational conditions. Such comparative assessments are essential to optimize system performance for both pollutant removal and energy generation. Furthermore, while many studies have utilized electroactive bacteria such as Shewanella or Geobacter, the potential of *Lactobacillus plantarum* widely available and generally recognized as safe (GRAS) remains underexplored despite its reported bioelectrochemical activity.

Therefore, this study aims to address these knowledge gaps by evaluating the performance of CW-MFC systems integrating three plant configurations (*Eichhornia crassipes, Pistia stratiotes*, and their combination) with *L. plantarum* at two different concentrations (2×10^8 CFU/mL and 5×10^8 CFU/mL), operated with graphite electrodes to simultaneously reduce domestic wastewater pollutants and generate bioelectricity over an 18-day period. The findings of this study are expected to provide insights into optimizing plant–microbe combinations in CW-MFC systems, thereby enhancing their feasibility as sustainable wastewater treatment technologies with renewable energy co-benefits, particularly in resource-limited settings.

2. Methods

This study employed an experimental quantitative research design to evaluate the performance of Constructed Wetland–Microbial Fuel Cell (CW-MFC) systems. The experiments were conducted at the Environmental Engineering Laboratory, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia, from January to March 2025.

The CW-MFC system was designed in a dual-chamber configuration consisting of a main reactor (anode chamber) and an external cathode chamber connected by a 5% KCl salt bridge to facilitate ion exchange. The main reactor measured 50 cm in length, 24 cm in width, and 20 cm in height, while the cathode chamber was cylindrical with a diameter of 20 cm and height of 10 cm. Graphite electrodes were installed at the bottom of the main reactor as the anode, and the cathode electrode was submerged in the cathode chamber. This reactor design allowed effective plant growth and provided sufficient space for electrochemical processes. The schematic design and dimensions are presented in Figure 1.

Three plant configurations were applied: *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), and their combination, arranged according to the treatment variations (Figures 2–4). Each CW-MFC reactor was inoculated with *Lactobacillus plantarum* at two different concentrations: 2×10^8 CFU/mL and 5×10^8 CFU/mL.

The system was operated in batch mode for 18 days. The independent variables were plant configuration and bacterial concentration, while the dependent variables were pollutant removal efficiencies (COD, BOD_5, ammonia, and TSS) and power density.

Water quality parameters were analyzed every three days using Standard Methods (APHA, 2017) to evaluate removal efficiencies. COD was measured using the dichromate reflux method, BOD_5 via 5-day incubation, TSS by gravimetric analysis, and ammonia using Nessler reagent spectrophotometry. Removal efficiency for each parameter was calculated using the formula (1):

$$\text{Removal efficiency (\%)} = \frac{Co - Ct}{Co} \quad (1)$$

Where,

C_o = Initial concentration of the measured parameter (mg/L)

C_t = Concentration of the parameter at time t (mg/L)

Power density measurements were carried out daily at 09:00 AM (daytime) and 07:00 PM (nighttime) using a digital multimeter (DT830B) connected to the electrodes. Power density was calculated based on the measured voltage (V) and current (I) using the formula (2):

$$P\left(\frac{mW}{m2}\right) = \frac{I\ (mA) \times V\ (Volt)}{A\ (m2)} \quad (2)$$

Where,

P = power (W)

V = measured voltage (V)

I = current (A).

Power density (W/m^2) was then calculated by dividing the power by the projected surface area of the anode electrode (A) and the results were multiplied by 1000 to convert to mW/m^2.

Data obtained were analyzed descriptively and statistically using Microsoft Excel 2019 for graphing and preliminary analysis, and IBM SPSS Statistics 26 for One-Way ANOVA and Tukey post-hoc tests to determine significant differences ($p < 0.05$) among treatments.

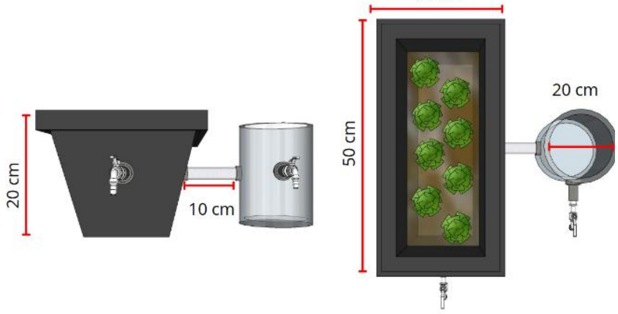


Figure 1. Schematic design and dimensions of the CW-MFC reactor system

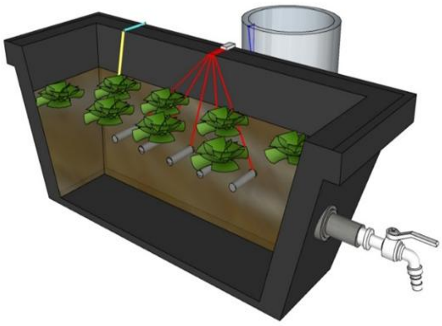


Figure 2. Reactor configuration with treatment of *Pistia stratiotes*

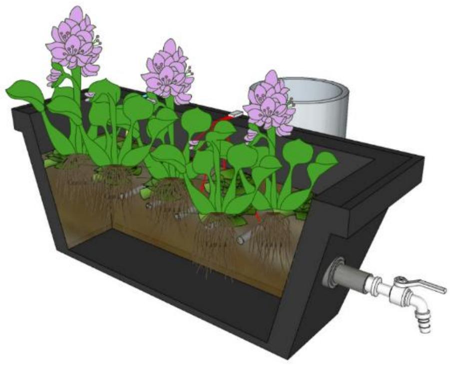


Figure 3. Reactor configuration with the *Eichhornia crassipes*

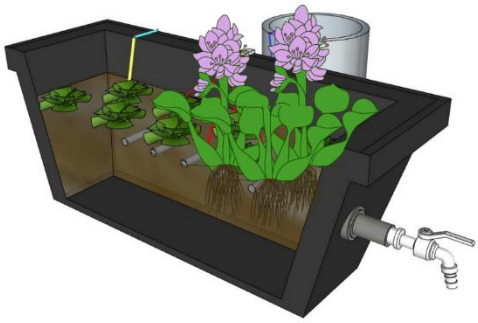


Figure 4. Reactor configuration with the combination of *Pistia stratiotes* and *Eichhornia crassipes*

3. Result and Discussion

3.1. Influent Wastewater Characteristics

The initial characterization of the domestic wastewater used in this study is presented in Table 1. The wastewater exhibited high pollutant loads, with a COD of 4870 mg/L, BOD_5 of 354 mg/L, TSS of 1218 mg/L, ammonia of 113 mg/L, and total nitrogen of 117 mg/L. These values greatly exceed the wastewater discharge standards in Indonesia, indicating the need for effective treatment before disposal. Prior to the CW-MFC experiments, an acclimatization test was conducted to evaluate the tolerance and survival of *Eichhornia crassipes* and *Pistia stratiotes* at various wastewater concentrations. The results showed that both plant species could survive optimally at wastewater dilutions up to 25%, which was subsequently selected as the operational concentration for all treatment and electricity generation experiments in this study.

Table 1. Characteristics of the influent domestic wastewater

Parameter	Unit	Cons. (mg/L)	Max. Permissible Cons. (mg/L)	Description
COD	mg/L	4870	100	Exceeded standard

Parameter	Unit	Cons. (mg/L)	Max. Permissible Cons. (mg/L)	Description
BOD_5	mg/L	354	30	Exceeded standard
TSS	mg/L	1218	30	Exceeded standard
Ammoniac	mg/L	113	36	Exceeded standard

3.2. Pollutant Removal Performance

3.2.1. Chemical Oxygen Demand

Chemical Oxygen Demand (COD) is a key indicator of organic pollution in wastewater, representing the amount of oxygen required to chemically oxidize organic and inorganic matter. High COD levels, such as those found in domestic wastewater, can significantly deteriorate water quality and pose ecological risks if discharged without treatment (Metcalf & Eddy, 2014). In this study, the initial COD concentration of the domestic wastewater sample was 1217 mg/L, which far exceeds the Indonesian discharge standard of 100 mg/L. Experiments were conducted to evaluate the COD removal performance using CW-MFC systems with different plant configurations (*Eichhornia crassipes*, *Pistia stratiotes*, and their combination) integrated with *Lactobacillus plantarum* at two bacterial concentrations (2×10^8 CFU/mL and 5×10^8 CFU/mL) and graphite electrodes, compared to the control reactor. The COD reduction trends observed in this study are presented in Figure 5.

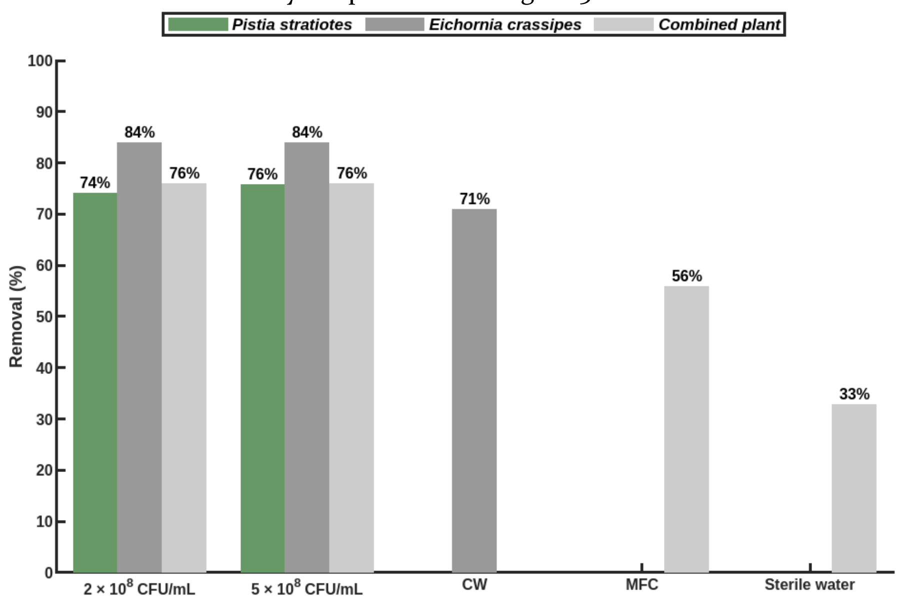


Figure 5. COD removal efficiency in each treatment

The highest COD removal efficiency, reaching approximately 84%, was recorded in the treatment with Eichhornia crassipes combined with *Lactobacillus plantarum* (2×10^8 CFU/mL) and graphite electrodes. This result is consistent with Siswoyo et al. (2020), who reported an 84.4% COD reduction using Eichhornia crassipes in constructed wetlands for domestic wastewater treatment. The treatment with *Pistia stratiotes* showed slightly lower COD removal efficiency (74–76%), in line with Fonkou et al. (2002), who reported COD reductions of 60–70% using *Pistia stratiotes* for domestic wastewater phytoremediation. Meanwhile, the combination of both plants resulted in intermediate COD removal, indicating interspecies competition that may reduce the phytoremediation capacity of each plant.

The CW control reactor containing only plants without electrodes or bacterial inoculation achieved approximately 71% COD reduction, demonstrating the natural phytoremediation capability of floating macrophytes in reducing organic pollutants. In comparison, the MFC control reactor (electrode + bacteria without plants) showed a higher COD removal of around 56%, highlighting the significant role of electroactive bacteria and electrochemical processes in organic matter oxidation. Overall, these results indicate that the integration of *Eichhornia crassipes* with electroactive bacteria and graphite electrodes in the CW-MFC system enhances COD removal efficiency. This is supported by Wang et al. (2016), who emphasized the synergistic roles of plant uptake and microbial oxidation in hybrid bioelectrochemical wastewater treatment systems.

COD removal in the CW-MFC system occurs through complex mechanisms involving interactions among plants, microbes, and electrodes. *Eichhornia crassipes* and *Pistia stratiotes* play important roles in phytoremediation due to their ability to absorb dissolved organic compounds through their root systems and enhance oxygenation in the rhizosphere via photosynthetic activity, thereby supporting the degradation of organic compounds by aerobic microorganisms (Putri et al., 2023; Siswoyo et al., 2020).

The presence of *Lactobacillus plantarum* as an electroactive bacterium further enhances degradation processes by oxidizing complex organic compounds into simpler substances, producing electrons and protons through microbial respiration (Zhang et al., 2023). The generated electrons are then transferred to the anode electrode and flow through the external circuit to the cathode electrode, generating electrical energy in the MFC system (Logan et al., 2006; Wang et al., 2016).

Additionally, the use of graphite electrodes increases COD removal efficiency because they serve as stable external electron acceptors, enabling electroactive bacteria to release electrons from organic degradation processes optimally (Logan et al., 2006). *Eichhornia crassipes* demonstrated higher COD removal performance compared to *Pistia stratiotes* due to its longer and denser root system, which provides a larger surface area for microbial biofilm growth and facilitates oxygen penetration into the reactor media, accelerating organic compound degradation (Siswoyo et al., 2020; Putri et al., 2023).

Based on these findings, it can be argued that Eichhornia crassipes is the most suitable plant species for integration in CW-MFC systems treating high-COD domestic wastewater, especially when combined with electroactive bacteria and graphite electrodes to maximize removal efficiency. Moreover, the data suggest that the dominance of electrochemical degradation processes over phytoremediation alone indicates the potential scalability of CW-MFC technology for decentralized wastewater treatment in developing regions. This highlights the importance of selecting plant species with strong rhizofiltration and oxygenation capabilities alongside robust electroactive bacterial populations to achieve optimal treatment outcomes.

Overall, the synergy between plant phytoremediation, biological degradation by heterotrophic and electroactive bacteria, and bioelectrochemical oxidation by electrodes enables the CW-MFC system to achieve COD removal efficiencies exceeding 80%, in line with previous findings highlighting the crucial role of these bio-physico-chemical interactions in domestic wastewater treatment (Fonkou et al., 2002; Wang et al., 2016).

3.2.2. Biological Oxygen Demand (BOD_5)

Biological Oxygen Demand (BOD_5) indicates the amount of oxygen required by microorganisms to decompose biodegradable organic matter over a five-day period, making it an important parameter for assessing wastewater pollution levels (Metcalf & Eddy, 2014). High BOD_5 levels in effluents can deplete dissolved oxygen in receiving water bodies, damage aquatic ecosystems, and accelerate eutrophication processes (Tchobanoglous et al., 2014). In this study, the initial BOD_5 concentration of the diluted (25%) wastewater was approximately 88 mg/L, which still exceeds the Indonesian domestic wastewater discharge standard of 30 mg/L. The study was conducted over an 18-day operation period with analyses performed every three days. The results obtained are presented in Figure 6.

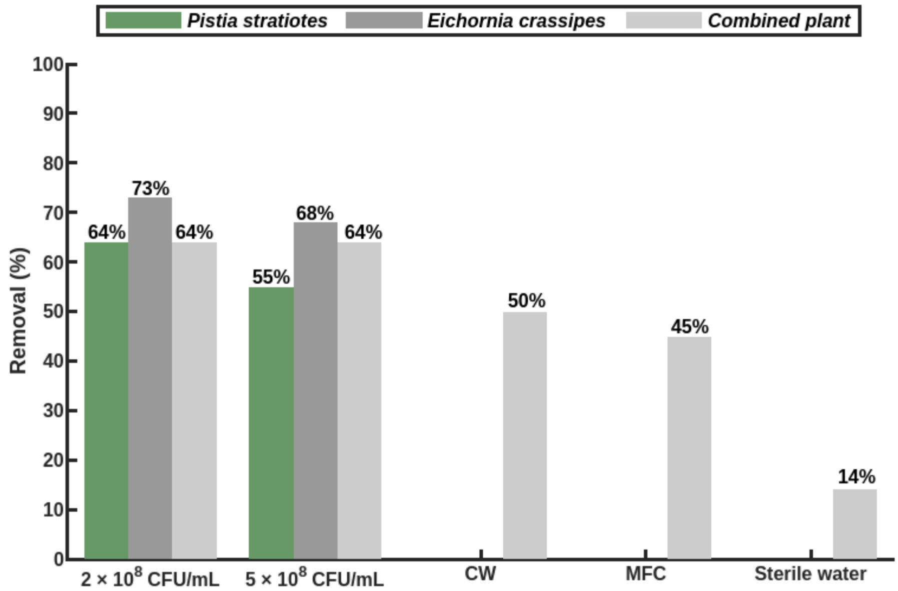


Figure 6. BOD_5 removal efficiency in each treatment

Based on the results, the treatment with *Eichhornia crassipes* combined with *Lactobacillus plantarum* at a concentration of 2 × 10^8 CFU/mL was able to reduce BOD_5 by up to 73%, reaching approximately 24 mg/L, while at 5 × 10^8 CFU/mL the efficiency slightly decreased to 68% (around 28 mg/L). *Pistia stratiotes* showed BOD_5 reductions of 63.64% at 2 × 10^8 CFU/mL (around 32 mg/L) and 64% at 5 × 10^8 CFU/mL (31.7 mg/L). The combined plant treatment resulted in lower reductions, namely 64% at 2 × 10^8 CFU/mL (31.7 mg/L) and 54.55% at 5 × 10^8 CFU/mL (40 mg/L). For comparison, the CW control reactor (plants only, without electrodes and bacteria) achieved a final BOD_5 of 44 mg/L (50% reduction), while the MFC control reactor (electrodes and bacteria without plants) showed slightly lower performance with a final BOD_5 of 48 mg/L (45% reduction). Sterile water (PDAM) only showed a 14% reduction to 75 mg/L, indicating limited natural degradation without the presence of plants, bacteria, or electrodes.

The BOD_5 removal mechanism in the CW-MFC system involves synergistic processes of phytoremediation by plants, biological degradation by bacteria, and bioelectrochemical oxidation by electrodes. *Eichhornia crassipes* has a long and dense root system, increasing the surface area contact with wastewater, allowing for the adsorption and direct uptake of dissolved organic compounds by root tissues (Putri et al., 2023). Additionally, the plant's photosynthetic activity produces oxygen that is transferred to the rhizosphere zone, supporting the growth of aerobic microorganisms to decompose organic matter into CO_2 and water (Siswoyo et al., 2020).

The presence of *Lactobacillus plantarum* as a heterotrophic and electroactive bacterium also enhances organic matter degradation by breaking down complex compounds into simpler substances through microbial respiration, generating electrons that are transferred to the anode electrode in the MFC system (Zhang et al., 2023). These electrons then flow through the external circuit to the cathode electrode, thus reducing BOD_5 while simultaneously generating electrical energy (Logan et al., 2006). The relatively lower BOD_5 removal efficiency observed in this CW-MFC study compared to full-scale wetlands may be attributed to the shorter hydraulic retention time, limited plant acclimatization, and high organic loading per reactor volume (Wang et al., 2016).

Based on these findings, it can be argued that integrating Eichhornia crassipes with electroactive bacteria in CW-MFC systems provides a promising approach to reduce BOD_5 levels below discharge standards, especially in decentralized treatment contexts. The data also indicate that although Pistia stratiotes performs adequately, its effectiveness remains inferior to Eichhornia crassipes due to morphological limitations such as shorter root length and lower oxygen transfer capacity. This highlights the importance of selecting plant species with high rhizofiltration capacity and root-mediated oxygenation to maximize pollutant removal, alongside optimizing bacterial concentrations to avoid substrate competition or inhibitory effects at higher inoculation levels.

3.2.3. Ammonia (NH_3–N)

Ammonia (NH_3–N) is a major pollutant in domestic wastewater that can cause eutrophication and is toxic to aquatic organisms if discharged without treatment (Tchobanoglous et al., 2014). The initial ammonia concentration after dilution (25%) was approximately 28.25 mg/L, which still exceeds the Indonesian discharge standard of 10 mg/L.This study was conducted over an 18-day operation period with ammonia parameter analyses performed every three days. The ammonia reduction results for all reactors are presented in Figure 7.

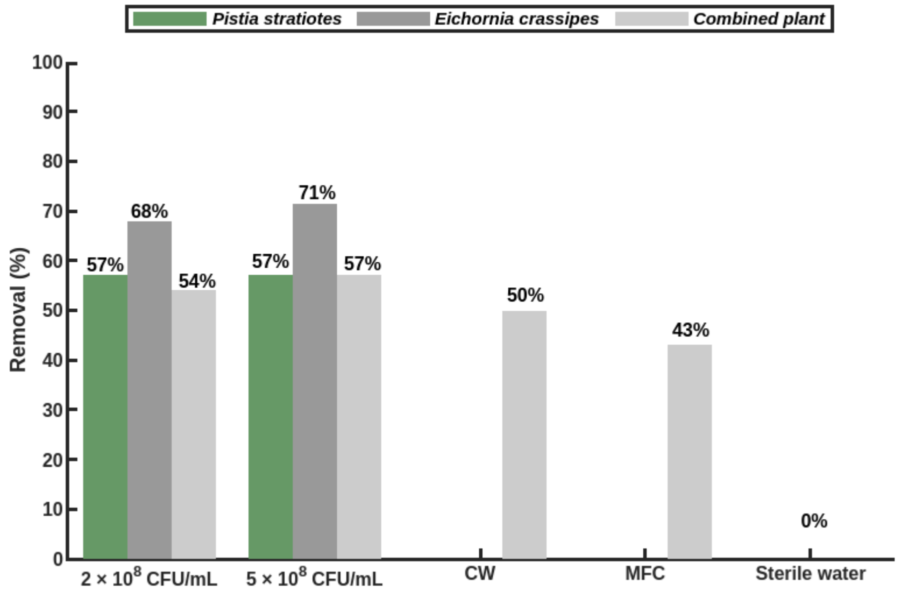


Figure 7. Ammonia removal efficiency in each treatment

Based on the results, the treatment with *Eichhornia crassipes* showed the highest ammonia removal efficiency, reaching 68% at a concentration of 2×10^8 CFU/mL (approximately 9 mg/L) and 71% at 5×10^8 CFU/mL (around 8 mg/L). This indicates the effective ammonia assimilation capability of *Eichhornia* roots as well as enhanced nitrification processes through microbial activity. *Pistia stratiotes* showed consistent removal efficiencies of 57% at both bacterial concentrations (approximately 12 mg/L), while the combined plant treatment resulted in removal efficiencies of 54% at 2×10^8 CFU/mL (13 mg/L) and 57.14% at 5×10^8 CFU/mL (12 mg/L). The CW control (plants only without bacteria or electrodes) achieved a removal efficiency of 50% (around 14 mg/L), demonstrating the phytoremediation capacity of plants even without bacterial or electrode addition. Meanwhile, the MFC control (bacteria and electrodes without plants) showed a slightly lower efficiency of 43% (around 16 mg/L), while the PDAM control (clean water) showed no ammonia reduction, as expected.

Ammonia removal in the CW-MFC system occurs through several mechanisms. *Eichhornia crassipes* and *Pistia stratiotes* can directly assimilate ammonium ions (NH_4^+) through their root systems to support plant growth and nitrogen metabolism (Zhang et al., 2014). Additionally, oxygenation of the rhizosphere zone resulting from root photosynthesis enhances aerobic conditions, supporting the activity of nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter*, which convert ammonia to nitrite (NO_2^-) and nitrate (NO_3^-) in the nitrification process (Li et al., 2022). Nitrate can then be reduced to nitrogen gas through denitrification by facultative anaerobic bacteria, effectively removing nitrogen from the aquatic system (Reddy & Delaune, 2008).

The presence of *Lactobacillus plantarum* also plays an important role in enhancing ammonia degradation through nitrogen competition and promoting nitrification. Although not an obligate nitrifier, *L. plantarum* produces acidic environmental conditions and stimulates endogenous nitrifying communities (Li et al., 2022). Moreover, the use of graphite electrodes in the MFC system supports microbial electron transfer, allowing bioelectrochemical processes to oxidize dissolved nitrogen compounds and improve overall ammonia removal efficiency (Wang et al., 2016). These findings are consistent with Siswoyo et al. (2020), who reported ammonia removal efficiencies above 70% by *Eichhornia crassipes* in constructed wetlands. The results also show that higher *Lactobacillus plantarum* concentrations enhanced ammonia removal across all plant types, supporting microbial nitrification pathways in addition to plant uptake (Li et al., 2022).

Based on these results, it can be argued that Eichhornia crassipes is more effective than *Pistia stratiotes* in ammonia removal due to its superior root morphology and oxygen release capacity, which enhance both direct assimilation and microbial nitrification. Furthermore, the data indicate that integrating electroactive bacteria with CW-MFC systems can improve nitrogen removal through complementary pathways, suggesting that such systems have strong potential for decentralized wastewater treatment in areas with strict ammonia discharge standards. Future optimization of bacterial concentrations and electrode materials is necessary to maximize removal efficiency without compromising system stability or increasing operational costs.

3.2.4. Total Suspended Solids (TSS)

Total Suspended Solids (TSS) is an important parameter in wastewater, indicating the amount of suspended solids that can cause turbidity, reduce light penetration, and negatively impact aquatic organisms if discharged without adequate treatment (Tchobanoglous et al., 2014). In this study, the initial TSS concentration after dilution (25%) was approximately 304 mg/L, which still exceeds the Indonesian discharge standard of 30 mg/L. The study was conducted over an 18-day operation period with TSS parameter analyses performed every three days. The TSS reduction results for all reactors are presented in Figure 8.

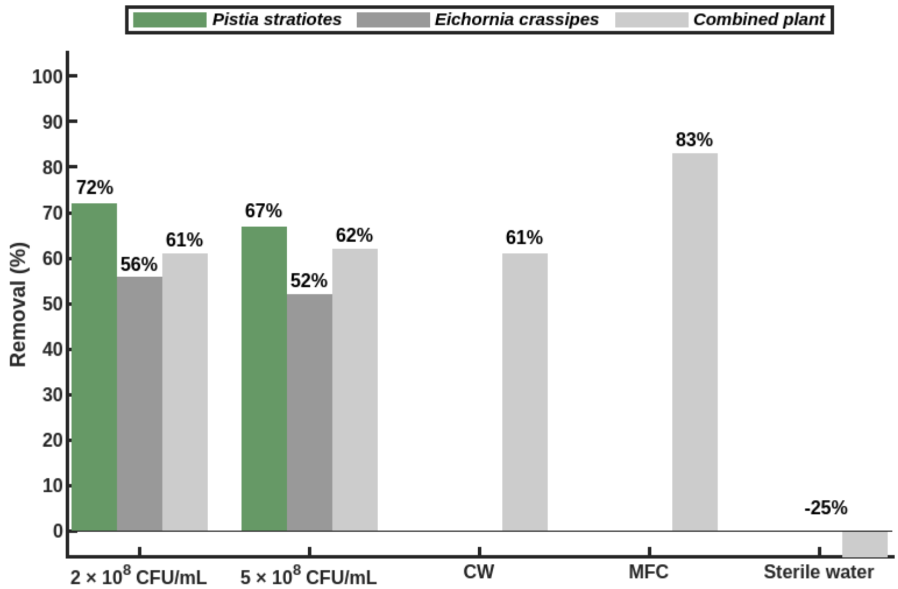


Figure 8. TSS removal efficiency in each treatment

Based on the results, the treatment with *Pistia stratiotes* showed the highest TSS removal efficiency, achieving 72% at a concentration of 2×10^8 CFU/mL (approximately 85 mg/L) and 67% at 5×10^8 CFU/mL (100 mg/L). *Eichhornia crassipes* showed removal efficiencies of 56% (133 mg/L) at 2×10^8 CFU/mL and 52% (146 mg/L) at 5×10^8 CFU/mL, while the combined plant treatment resulted in removal efficiencies of 61% (119 mg/L) and 62% (116 mg/L) at each respective concentration.

The CW control (plants without bacteria or electrodes) also showed a significant TSS reduction of 61% (118 mg/L), reflecting the natural phytoremediation capability of floating plants to trap suspended solids through their root systems. Interestingly, the MFC control (bacteria and electrodes without plants) showed the highest TSS reduction, reaching 83% (52 mg/L), possibly due to microbial flocculation and particle sedimentation stimulated by bioelectrochemical activity around the electrodes (Wang et al., 2016). Meanwhile, the sterile water control showed an increase in TSS of -25% (approximately 380 mg/L), likely due to low sedimentation in the absence of plants or microbial activity to facilitate flocculation.

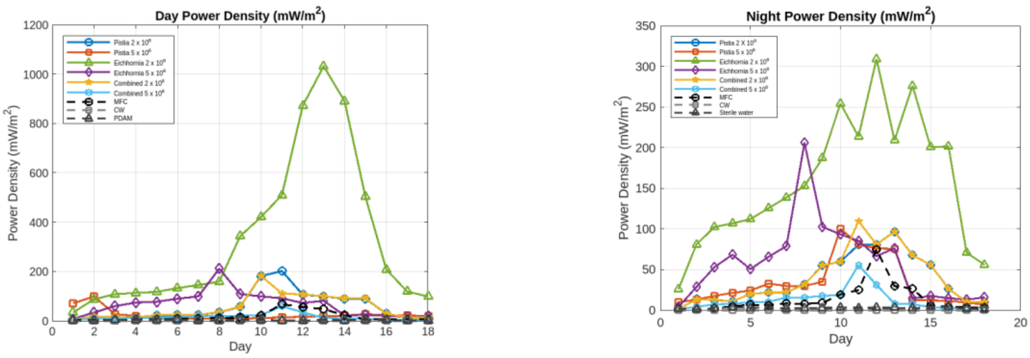
TSS reduction in the CW-MFC system occurs through several mechanisms. *Eichhornia crassipes* and *Pistia stratiotes* have dense and branched root systems that function as natural filters, trapping suspended particles and slowing water flow, allowing particles to settle (Zhang et al., 2014). Additionally, plant roots provide a large surface area for microbial biofilm growth, which contributes to the formation of large flocs through extracellular polymeric substance (EPS) secretion, enhancing suspended solid sedimentation (Reddy & Delaune, 2008).

The presence of *Lactobacillus plantarum* also supports TSS reduction by producing bioflocculation through enzymatic activity and EPS-bacteria interactions, although this bacterium mainly plays a dominant role in degrading dissolved pollutants (Li et al., 2022). These findings are consistent with Siswoyo et al. (2020), who reported TSS removal efficiencies of 78–85% by *Eichhornia crassipes* in constructed wetland systems, highlighting the important role of aquatic plants in domestic wastewater treatment. The higher TSS removal efficiency observed in the MFC control compared to the CW suggests that while plants are effective in trapping solids, bioelectrochemical systems also contribute to suspended particle sedimentation due to surface charge changes and bioflocculation induced by electroactive microbial activity (Wang et al., 2016).

Based on these findings, it can be argued that Pistia stratiotes is more effective than Eichhornia crassipes in TSS removal due to its morphological traits that enhance particle entrapment, despite Eichhornia showing superior performance in COD, BOD, and ammonia removal. Furthermore, the unexpectedly high TSS reduction in the MFC control implies that microbial flocculation and electrochemical sedimentation play crucial roles in solid removal, suggesting that integrating plants with MFC systems could further optimize TSS treatment. These results highlight the need to tailor plant selection and reactor configurations depending on the primary pollutant targeted for removal, to achieve efficient and cost-effective domestic wastewater treatment outcomes.

3.3. Bioelectricity Generation Performance

Bioelectricity generation is one of the innovative benefits of CW-MFC systems, allowing simultaneous wastewater treatment and renewable energy production. This process is driven by electroactive bacteria that oxidize organic substrates at the anode and transfer electrons through an external circuit to the cathode, generating electrical energy (Logan et al., 2006). The presence of aquatic plants further enhances system performance by supplying oxygen to the rhizosphere, supporting microbial metabolism, and facilitating electron transfer (Li et al., 2022). In this study, power density measurements were conducted during the day (09:00) and at night (19:00) over 18 days to evaluate daily variations and treatment performance. The results for daytime and nighttime power density are presented in Figure 9.



(a) (b)

Figure 9. Daytime and night time power density variation across treatments and controls

Overall, daytime power density was significantly higher than nighttime across all treatments, indicating the influence of photosynthetic activity on oxygen availability. For instance, in the treatment with *Eichhornia crassipes* and 2 × 10^8 CFU/mL of *Lactobacillus plantarum*, the maximum power density reached 1032.12 mW/m^2 during the day, while at night it only reached 309.13 mW/m^2. This difference is attributed to oxygen release from plant roots during photosynthesis, which acts as an electron acceptor and enhances microbial oxidation rates. Conversely, at night, the reduced oxygen availability limits the activity of electrogenic bacteria, resulting in lower power output.

The role of aquatic plants such as *Eichhornia crassipes* and *Pistia stratiotes* is crucial in supporting CW-MFC electricity generation efficiency. During the day, these plants perform photosynthesis, producing oxygen that is released through their root systems into the rhizosphere. This oxygen acts as the terminal electron acceptor at the cathode, increasing the oxygen reduction reaction rate, thus producing higher electric currents. Additionally, photosynthesis enhances the metabolic activity of aerobic microbes and electroactive bacteria in the root zone, supporting organic degradation and electron transfer (Wang et al., 2016; Li et al., 2022).

In contrast, at night when photosynthesis ceases, plants no longer produce oxygen and instead carry out respiration, consuming dissolved oxygen. As a result, oxygen availability in the cathode region decreases, electrogenic bacterial activity declines, and electron transfer is inhibited, producing lower power densities compared to daytime (Nguyen et al., 2021). This phenomenon aligns with the findings that the maximum power density during the day reached 1032.12 mW/m^2 in *Eichhornia crassipes* treatment with 2 × 10^8 CFU/mL bacteria, while at night it only reached 309.13 mW/m^2.

When compared by plant type, *Eichhornia crassipes* consistently produced the highest power density, followed by the combined plant treatment, and lastly *Pistia stratiotes*. This is related to *Eichhornia crassipes* having a longer and denser root system, providing a larger surface area for biofilm attachment and facilitating oxygen diffusion into the rhizosphere. The combined plant treatment showed moderate performance, indicating that although plant diversity may offer ecological benefits, interspecies competition may reduce total oxygen release and microbial colonization.

In terms of bacterial concentration, treatments with 2 × 10^8 CFU/mL showed higher power densities than those with 5 × 10^8 CFU/mL. Excessive bacterial concentrations can lead to substrate and oxygen competition among bacteria, reducing electrogenic efficiency. This finding is in accordance with Nguyen et al. (2021), who reported that high bacterial density in MFCs can reduce electricity production due to mass transfer limitations and microbial oxygen depletion.

Control treatments demonstrated the importance of integrating plants, bacteria, and electrodes to generate electricity. The MFC control (without plants) produced low but detectable power density, whereas the CW control (plants only) and sterile water control (clean water) showed very low or no power output. This confirms that bioelectricity production is mainly driven by electroactive bacterial activity, which is enhanced by plant oxygenation and electrode conductivity, as emphasized by Wang et al. (2016). Overall, these findings suggest that optimal CW-MFC performance requires the selection of high biomass plants (*Eichhornia crassipes*), appropriate bacterial concentrations, and effective electrodes to maximize electricity generation while ensuring wastewater treatment efficiency.

Based on these findings, it can be argued that Eichhornia crassipes is the most effective plant for maximizing bioelectricity generation in CW-MFC systems due to its superior oxygen release capacity and root morphology that supports biofilm development. Additionally, the results indicate that using moderate bacterial concentrations optimizes electron transfer without inducing substrate competition or oxygen depletion. This highlights the potential of CW-MFC systems as a sustainable wastewater treatment technology with co-benefit of renewable energy generation, particularly for decentralized applications in rural and peri-urban areas where energy access remains limited. Future studies should explore the long-term stability of power output under variable environmental conditions to support practical scale-up of this technology.

4. Conclusions

This study demonstrates that the CW-MFC system integrating Eichhornia crassipes and *Lactobacillus plantarum* (2×10^8 CFU/mL) is effective in reducing COD by up to 82%, BOD_5 to 61 mg/L, ammonia by 71%, and TSS by 68%, while simultaneously producing a maximum power density of 1032.12 mW/m^2 during the day. Eichhornia crassipes outperformed *Pistia stratiotes* due to its dense root system, which enhances rhizosphere oxygenation and supports microbial degradation. Excessively high bacterial concentrations were found to decrease electricity production due to substrate and oxygen competition among bacteria. Moreover, daytime electricity generation was higher than nighttime due to photosynthetic activity increasing oxygen release, which acts as an electron acceptor. In conclusion, the CW-MFC system has significant potential as an environmentally friendly wastewater treatment technology capable of simultaneously generating renewable energy..

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Reference

Cañizares-Villanueva, R, O, Domínguez-Mendoza, B, E, Rivas-Ortiz, C, I, and Ibarra-Junquera, V. 2016. A kinetic model of aerobic biodegradation in constructed wetlands. Ecological Engineering 97, 330–337.

De Schamphelaire, L, et al. 2008. Microbial fuel cells generating electricity from rhizodeposits of rice plants. Environmental Science & Technology 42(8), 3053–3058.

Fonkou, T, Agendia, P, Kengne, I, Akoa, A, Nya, J, Zebaze, S, and Dongmo, J. 2002. Treatment of domestic wastewater with Pistia stratiotes in a pilot-scale constructed wetland. Water Research 36(12), 3063–3068.

Kadam, A, M, Oza, G, H, Nemade, P, D, and Sahu, A, K. 2009. Treatment of municipal wastewater using laterite-based constructed soil filter. Ecological Engineering 35(7), 1051–1061.

Langergraber, G. 2008. Simulation of the treatment performance of outdoor subsurface flow constructed wetlands in temperate climates. Science of The Total Environment 380(1–3), 210–219.

Li, X, Zhao, Q, Chen, Y, and Bai, S. 2022. The role of oxygen supply in constructed wetland microbial fuel cells: Enhanced pollutant removal and bioelectricity generation. Bioresource Technology 344, 126690.

Logan, B, E, Hamelers, B, Rozendal, R, Schröder, U, Keller, J, Freguia, S, and Rabaey, K. 2006. Microbial fuel cells: Methodology and technology. Environmental Science & Technology 40(17), 5181–5192.

Metcalf & Eddy. 2014. Wastewater engineering: Treatment and resource recovery, 5th edn. New York: McGraw-Hill Education.

Nguyen, T, T, Nguyen, H, T, and Ngo, H, H. 2021. Impacts of bacterial density on performance of microbial fuel cells treating wastewater. Microorganisms 9(7), 1413.

Putri, D, A, Yuliani, E, and Firdiana, R. 2023. Phytoremediation of textile wastewater using Eichhornia crassipes in constructed wetlands. International Journal of Chemical Engineering 2023, 6640903.

Rabaey, K, and Verstraete, W. 2005. Microbial fuel cells: Novel biotechnology for energy generation. Trends in Biotechnology 23(6), 291–298.

Roy, S, Ghosh, S, and Das, S. 2020. Bioelectricity production and wastewater treatment using Pistia stratiotes in plant microbial fuel cell. Bioresource Technology Reports 12, 100591.

Siswoyo, W, Astuti, W, and Rahmawati, F. 2020. Efisiensi Eichhornia crassipes dalam penurunan COD, BOD dan TSS limbah cair industri tapioka menggunakan sistem constructed wetland. Jurnal Teknologi Lingkungan 10(1), 20–28.

Tchobanoglous, G, Burton, F, L, and Stensel, H, D. 2014. Wastewater engineering: Treatment and reuse, 5th edn. New York: McGraw-Hill Education.

Wang, H, Park, J-D, and Ren, Z, J. 2016. Practical energy harvesting for microbial fuel cells: A review. Bioresource Technology 215, 60–70.

Wu, S, et al. 2014. Treatment of industrial effluents in constructed wetlands: Challenges, operational strategies and overall performance. Environmental Pollution 192, 245–262.

Yadav, A, K, Kumar, N, and Singh, N. 2012. Removal of heavy metals from wastewater using water hyacinth (Eichhornia crassipes). Journal of Environmental Research and Development 6(3A), 504–510.

Yadav, K, S, and Chandra, R. 2018. Phytoremediation of textile effluent using water hyacinth (Eichhornia crassipes). International Journal of Phytoremediation 20(1), 85–91.

Zhao, Y, et al. 2013. Preliminary investigation of constructed wetland incorporating microbial fuel cell: Batch and continuous flow trials. Chemical Engineering Journal 229, 364–370.

Zhou, M, Wang, H, Hassett, D, J, and Gu, T. 2013. Recent advances in microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) for wastewater treatment, bioenergy and bioproducts. Journal of Chemical Technology & Biotechnology 88(4), 508–518.