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Original Research Article

Application of a Vertically Layered Microbial Fuel Cell (MFC) System in an Evapotranspiration Reactor for COD and BOD Treatment in Leachate Using Sente Plants (Alocasia macrorrhiza)

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Abstract

Leachate is liquid waste with high organic content, including COD and BOD. This study applied a system combining Giant Taro plants (Alocasia macrorrhiza) and Microbial Fuel Cells (MFC) to treat leachate while producing electricity. The reactor was operated with continuous flow of 10 liters/day for 15 days, with COD, BOD, and electricity measured periodically. COD was analyzed using closed reflux spectrophotometry, BOD with a DO meter, and electricity with a multimeter. Results showed COD removal efficiency reached 62.1% on day 3, decreased to 44% and 17.2% on days 6 and 9, then increased to 35.67% on day 12. BOD removal followed a similar trend, with 88.7% on day 3, declining to 84.8% and 78.7%, then rising to 83.3% on day 12. Maximum electricity generation was 1.65 W on day 14. Performance was influenced by plant roots, microbial activity, and reactor conditions.

Keywords: Alocasia macrorrhiza, BOD removal, COD removal; evapotranspiration reactor; leachate treatment; Microbial fuel cell;

1. Introduction

Leachate generated from municipal solid waste landfills is widely recognized as one of the most complex and problematic forms of wastewater due to its highly variable composition and elevated pollutant concentrations (Kjeldsen et al., 2002; Renou et al., 2008). This liquid, which results from the percolation of rainwater and the natural decomposition of waste materials, typically contains a wide range of contaminants, including organic pollutants, nutrients such as nitrogen and phosphorus, and various toxic or refractory compounds (Christensen et al., 2001; Foo & Hameed, 2009). When leachate is discharged into the environment without undergoing adequate treatment, it can cause serious and long-lasting contamination of soil, surface water, and groundwater resources (Kulikowska & Klimiuk, 2008). Among its many constituents, organic matter plays a particularly significant role in contributing to environmental degradation. The presence of organic material is commonly quantified through parameters such as chemical oxygen demand (COD) and biochemical oxygen demand (BOD), both of which serve as indicators of the potential for oxygen depletion in receiving water bodies (Metcalf & Eddy, 2014). Elevated COD and BOD values are directly associated with the deterioration of water quality, as they stimulate microbial activity that rapidly consumes dissolved oxygen, leading to hypoxic or anoxic conditions harmful to aquatic ecosystems (Spellman, 2013).

To address the risks associated with landfill leachate, a number of conventional treatment methods have been developed and widely implemented. Biological processes, including both aerobic and anaerobic systems, are among the most frequently used due to their ability to effectively degrade biodegradable organic pollutants (Tchobanoglous et al., 2014). In aerobic treatment, microorganisms utilize oxygen to break down organic matter, while anaerobic systems rely on the absence of oxygen and specialized microbial communities to achieve degradation. In addition to biological processes, chemical coagulation techniques have been applied to remove suspended solids and certain dissolved pollutants, while advanced oxidation processes (AOPs) target recalcitrant organic compounds through the generation of highly reactive radical species (Deng & Englehardt, 2006; Wang et al., 2017). Despite their proven effectiveness, these treatment methods are not without limitations. Many require substantial energy inputs, continuous chemical dosing, or highly skilled operators to ensure consistent performance (Renou et al., 2008). Consequently, the operational costs can be prohibitively high, particularly when scaled up to handle the large and variable volumes of leachate typically produced by municipal landfills (Foo & Hameed, 2009). Furthermore, the maintenance demands of these systems can be intensive, requiring regular monitoring, replacement of equipment or media, and strict process control (Kulikowska & Klimiuk, 2008).

For low-resource settings or municipalities with limited financial and technical capacity, these challenges pose significant barriers to the sustainable management of landfill leachate. As a result, while conventional approaches remain important benchmarks in the field of wastewater engineering, there is an urgent need to explore more adaptable, cost-effective, and low-maintenance treatment strategies that can provide long-term environmental protection without placing excessive burdens on local communities. Recent studies have explored microbial fuel cell (MFC) technology as an alternative, which utilizes the metabolic activity of electrogenic microorganisms to degrade organic matter while generating electricity (Logan et al., 2006; Pant et al., 2010). This bioelectrochemical approach provides a dual benefit since it not only reduces the pollutant load of leachate but also produces renewable energy in the form of electrical output, thereby offering an environmentally sustainable solution compared to conventional methods (Logan & Rabaey, 2012). In recent years, efforts to enhance the performance of MFCs have led to the integration of these systems into evapotranspiration (ET) reactors. ET reactors are planted systems that combine phytoremediation and soil filtration, where plants contribute to pollutant uptake, oxygen release through root systems, and enhanced microbial interactions in the rhizosphere. The integration of MFCs into such reactors offers the potential for simultaneous pollutant removal and renewable energy recovery, creating a treatment system that harnesses biological, electrochemical, and ecological processes within a single framework (Zhang et al., 2016).

Previous works on MFCs for wastewater and leachate treatment have demonstrated promising COD and BOD removal efficiencies, showing that the technology is capable of addressing one of the most critical challenges in landfill leachate management (Min et al., 2005; Li et al., 2014). However, most existing designs are configured as horizontal or single-layer systems, which limit contact between microorganisms, substrate, and electrodes (Logan et al., 2006). These limitations reduce the effective surface area available for microbial colonization, restrict substrate distribution within the reactor, and consequently lower both pollutant removal efficiency and electricity generation (Santoro et al., 2017). The reduced interaction among these components highlights the need for improved reactor configurations that can provide greater electrode contact, optimized substrate flow, and more favorable conditions for microbial metabolism.

This study investigates the application of a vertically layered MFC system integrated into an ET reactor planted with Sente (*Alocasia macrorrhiza*) for leachate treatment. The choice of Sente is based on its capacity to thrive in wastewater environments, its significant evapotranspiration ability, and its potential to support the microbial community in the root zone (Vymazal, 2011). The novelty of this approach lies in the multi-layered vertical arrangement, which is expected to increase the surface area for microbial activity, improve organic matter removal efficiency, and enhance electricity generation compared to conventional horizontal systems (Santoro et al., 2017). By stacking multiple layers vertically, the system can maximize the interaction between leachate, microbial communities, and electrode surfaces, while ensuring a more even distribution of substrates throughout the reactor. The objective of this research is to evaluate the performance of the integrated system in reducing COD and BOD concentrations in leachate, as well as to assess its electricity production potential as an added benefit. Beyond these immediate goals, the study also seeks to demonstrate the feasibility of combining bioelectrochemical and phytoremediation-based processes in a low-cost, low-maintenance configuration that is suitable for application in resource-limited settings. Through this approach, the study contributes to the growing body of knowledge on innovative leachate treatment technologies, while also exploring pathways for achieving both environmental protection and renewable energy recovery within a single treatment system (Pant et al., 2010; Logan & Rabaey, 2012).

2. Methods

This research was conducted to evaluate the efficiency of COD and BOD removal in leachate using a Microbial Fuel Cell (MFC) system integrated with *Alocasia macrorrhiza* (Giant Taro) and to determine the electricity generation potential from the process. The experimental work was carried out at the Environmental Engineering Laboratory, Diponegoro University, with leachate samples collected from the Jatibarang Landfill, Semarang.

Figure 1. Location Map of The Study Area in Jatibarang Landfill, Semarang

The main materials used in this study were leachate obtained from Jatibarang landfill, Giant Taro plants (Alocasia macrorrhiza), sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), and distilled water (aquadest). Each of these materials was carefully selected due to its specific and essential role in both preparing the experimental setup and carrying out the analytical procedures required for performance evaluation. The leachate served as the primary substrate, providing the organic matter to be treated and simultaneously functioning as the source of pollutants targeted for removal. The Giant Taro plants were integrated into the system because of their known capacity for phytoremediation, particularly their ability to absorb contaminants and promote evapotranspiration. Sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH) were employed as reagents for pH adjustment during the experimental process to maintain optimal conditions for both biological activity and electrochemical reactions. Distilled water (aquadest) was used in various steps of reactor preparation and cleaning, ensuring that no external contaminants interfered with the results.

The main equipment utilized throughout the experimental work included an Electric Furnace (Thermofisher), which was specifically applied during the preparation of electrodes, particularly for carbon activation and conditioning. A digital pH meter (Hanna Instruments) was used to monitor the acidity or alkalinity of the leachate and effluent, providing continuous data on environmental conditions inside the reactor. For the evaluation of organic pollutant levels, a COD reactor (Hach, DRB200) was employed to digest samples, followed by analysis using a UV-Vis spectrophotometer (Shimadzu UV-1800) to measure COD concentrations accurately. These instruments were central to ensuring that the results obtained reflected the true extent of pollutant reduction and treatment efficiency. At the heart of the experimental setup was a self-designed Microbial Fuel Cell (MFC) reactor unit, which served as the core innovation of this study. This reactor was constructed with a vertically layered configuration, integrating the biological process of evapotranspiration from the Giant Taro plants with the electrochemical conversion of organic matter into electricity. The combination of phytoremediation and bioelectrochemical technology was aimed at achieving both environmental treatment and renewable energy generation. Electrodes made of activated carbon plates were arranged in a parallel circuit configuration. This design choice was made to ensure that the electrical output remained stable, even in the event that one of the electrodes became disconnected, thus enhancing the overall reliability of the system.

During the operation of the reactor, leachate was continuously supplied to the system at controlled rates. Effluent samples were then collected at scheduled intervals for further analysis, particularly focusing on COD and BOD as indicators of pollutant removal efficiency. Electricity production from the MFC system was recorded daily using a multimeter, allowing for monitoring of energy output trends over time in response to changes in leachate characteristics and plant performance. In addition to these specialized instruments, supporting laboratory tools, such as glassware, pipettes, and other standard equipment, were also employed throughout the experimental procedures. However, as these items are considered common laboratory materials, they are not described in detail. The complete design of the main reactor system, including the vertical layering, electrode arrangement, and integration with Giant Taro plants, is illustrated in Figure 2. This schematic representation provides a clearer understanding of how the experimental components were combined to form a functional system capable of both leachate treatment and electricity generation.

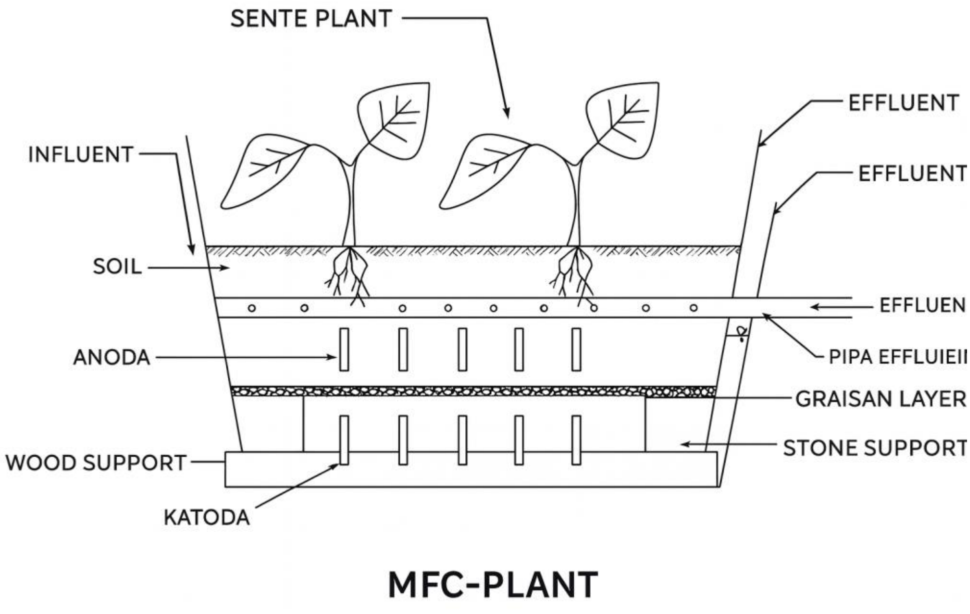

Figure 2. Experimental Setup of the Microbial Fuel Cell System integrated with Giant Taro Plant (*Alocasia macrorrhiza*) in Leachate Treatment

3. Result and Discussion

The initial characterization of leachate was conducted to determine the baseline concentrations of COD, BOD, pH, temperature, and salinity. The leachate samples were obtained from Jatibarang Landfill, Semarang City. COD was analyzed using the spectrophotometric method, BOD was measured electrochemically with a DO meter, while pH, temperature, and salinity were recorded using digital instruments. The results were then compared with the applicable standards based on the Regional Regulation of Central Java Province No. 5 of 2012 concerning Wastewater Quality Standards (Appendix IX, Group I). The results are presented in Table 1.

Table 1. The Initial Characterization of Leachate

No.	Parameters	Units	Initial Leachate Characteristics	Quality Standard	Description
1.	COD	mg / L	3.183,3	100	Unfulfilled
2.	BOD	mg / L	2.130	50	Unfulfilled
3.	pH	-	8,9	6-9	Fulfilled
4.	Temperature	oC	31,9	38	Fulfilled
5.	Salinity	Ppt	8,28		

3.1 COD Removal Efficiency

The research findings showed that the highest COD removal efficiency reached 62.1% on the 3rd day, then decreased to 44% on the 6th day and 17.2% on the 9th day, before increasing again to 35.67% on the 12th day. This fluctuation indicates that the microbial and plant systems did not operate in a constant steady state but were influenced by microbial adaptation and the physiological condition of *Alocasia* macrorrhiza. The detailed COD removal efficiency for both the Sente Plant's Reactor and the Control Reactor is presented in Table 2. For a clearer visualization of the COD removal efficiency variation, the results in Table 2 are plotted in Figure 2. Similar dynamic behavior has been widely reported in biological leachate treatment systems, particularly those involving MFCs (Abbas et al., 2009; Logan et al., 2006).

Table 2. COD Removal Efficiency

Days	Sente Plant's Reactor	Control Reactor
0 (inlet)	0%	0%
3	62,10%	40,77%
6	44%	18,16%
9	17,20%	31,53%
12	35,67%	15,61%
15	23,25%	16,24%

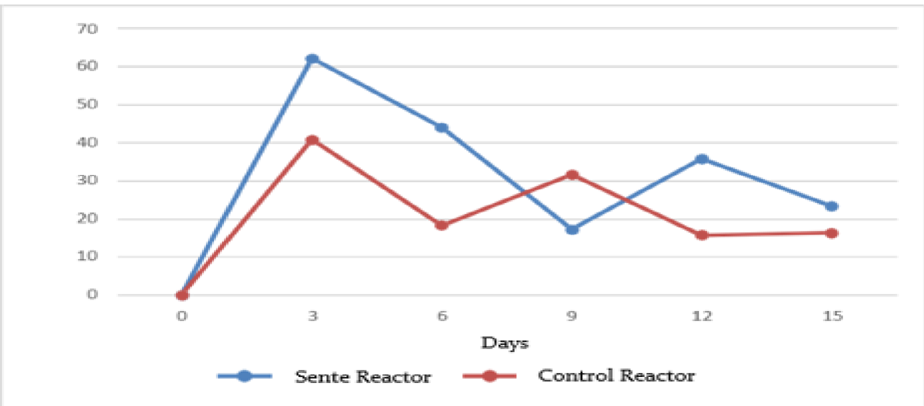

Figure 2. COD Removal Efficiency

The high COD removal observed during the initial operational phase can be attributed to the abundance of readily biodegradable organic compounds in the fresh leachate, such as volatile fatty acids, simple carbohydrates, and proteins. These compounds are rapidly metabolized by electroactive microorganisms colonizing the anode surface and the rhizosphere of *Alocasia macrorrhiza*, resulting in enhanced organic matter degradation and electron release (Logan and Rabaey, 2012; Santoro et al., 2017). The presence of plant roots further stimulates microbial activity through the release of root exudates and the creation of a favorable microenvironment, which has been reported to improve organic pollutant removal in plant-assisted treatment systems (Vymazal, 2011).

As the treatment progressed, the composition of the remaining leachate changed significantly. The easily degradable organics were gradually depleted, leaving behind more complex and recalcitrant compounds such as humic and fulvic acids. These macromolecular substances are highly resistant to biodegradation due to their complex aromatic structures and high molecular weights. As a result, the degradation process slowed down, and the overall removal efficiency showed a declining trend, particularly evident up until the 9th day of observation. This decline reflects a common limitation in biological treatment processes, where the shift from simple to complex organics poses a greater challenge for microbial communities. Interestingly, following this period of reduced efficiency, a subsequent increase in removal performance was observed. This recovery trend can be explained by microbial adaptation over time. Microorganisms in the reactor began to acclimate to the presence of the more complex organic compounds, gradually developing metabolic pathways capable of breaking them down. In parallel, the formation of stable and mature biofilms on the electrode surfaces enhanced the microbial community structure, providing a more favorable environment for sustained degradation activity. The biofilms not only improved substrate utilization efficiency but also stabilized electron transfer processes, resulting in more consistent treatment performance as well as electricity generation.

These findings are in agreement with the observations reported by Abbas et al. (2009), who noted that leachate treatment using MFC systems often demonstrates high efficiency in the early phases. This initial effectiveness is primarily due to the dominance of simple, readily degradable organics, which are rapidly metabolized by microorganisms. However, as the system continues to operate, a decline typically follows because of the accumulation and predominance of complex organic compounds that are inherently more difficult to degrade. The subsequent adaptation phase, accompanied by biofilm establishment, accounts for the gradual improvement in system efficiency that has also been highlighted in their study. The parallel between the current findings and those of Abbas et al. (2009) underscores the consistency of this phenomenon across different MFC-based leachate treatment studies, further validating the trends observed in this research.

3.2 BOD Removal Efficiency

The BOD removal efficiency followed a similar pattern to COD, with the highest value of 88.7% on the 3rd day, decreasing to 84.8% on the 6th day and 78.7% on the 9th day, before slightly increasing to 83.3% on the 12th day. Table 2 and Figure 3 show the efficiency of BOD removal in water treatment. This trend is reasonable since BOD is primarily associated with biodegradable organic matter, which is readily metabolized by microorganisms in the MFC system (Metcalf & Eddy, 2014). The decrease after the 6th day is attributed to the depletion of easily degradable organics and the presence of inhibitory compounds in the leachate, such as ammonia or heavy metals, which can suppress microbial activity. The subsequent improvement observed on day 12 suggests that the microbial communities adapted to the changing leachate characteristics, restoring part of their biodegradation capacity. This adaptive response is consistent with the findings of Purwono et al. (2015), who emphasized the importance of microbial acclimatization in determining BOD removal performance in MFC systems. The initial high BOD removal efficiency indicated effective microbial oxidation of biodegradable organics under favorable conditions. However, as substrate availability declined and inhibitory compounds such as ammonia and heavy metals accumulated, microbial activity was partially suppressed, leading to a reduced removal efficiency. Such inhibitory effects have been frequently reported in landfill leachate treatment studies (Kulikowska & Klimiuk, 2008; Aziz et al., 2010).

Table 2. BOD Removal Efficiency

Days	Sente Reactor	Control Reactor
0 (inlet)	0%	0%
3	88,7%	50,9%
6	84,8%	46,5%
9	78,7%	53,2%
12	83,3%	77,6%
15	79,7%	82,8%

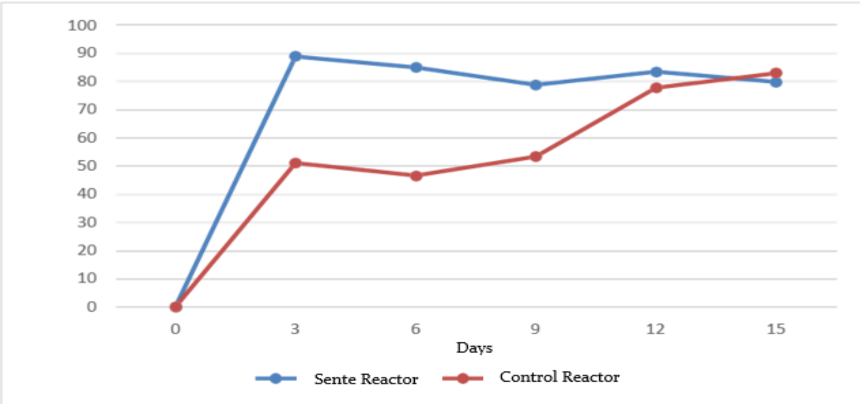

Figure 3. BOD Removal Efficiency

3.3 Electricity Production

The MFC system produced electricity with the highest power output of 1.65 W on the 14th day in the test reactor, while the control reactor reached a maximum of 1.17 W on the 11th day. This difference highlights the role of the vertically layered system and the integration of Giant Taro plants in enhancing microbial activity and improving electron transfer. The generation of electricity in both reactors is directly associated with the degradation of organic compounds by electrogenic microorganisms, which release electrons and protons during their metabolic processes. These electrons were transferred to the anode surface, moved through the external circuit, and subsequently reached the cathode, where they reacted with oxygen and protons to form water. This sequence not only demonstrates the bioelectrochemical capability of the system but also validates the effectiveness of microbial metabolism in coupling organic matter degradation with renewable energy production.

The fluctuation in electricity generation observed during the experiment correlates strongly with the COD and BOD removal trends. As biodegradable substrates in the leachate became available, microorganisms were able to metabolize them efficiently, leading to higher rates of electron production and transfer. Conversely, when the concentration of simple organics decreased, electron generation slowed down, causing a decline in electricity output. This dynamic behavior confirms the close relationship between substrate availability, microbial metabolism, and power generation in MFC systems. The increasing trend of electricity observed towards the 15th day suggests that biofilm maturity played a significant role in improving electron transfer efficiency. During the early stages, microbial communities were still in the process of colonizing the electrode surfaces, resulting in relatively unstable electricity output. However, as biofilms developed and stabilized, the electron transfer pathways became more efficient and consistent, enabling higher power production. The vertically layered configuration of the reactor likely facilitated stronger microbial attachment and better substrate–electrode interaction, further contributing to the enhanced performance.

These findings are in agreement with similar observations reported by Adistia (2017), who noted that the peak power density in MFC operations was often achieved during the later phase of operation.

This phenomenon was attributed to the establishment of stable biofilm activity, which not only improved organic matter utilization but also ensured more reliable electron flow to the electrodes. In the present study, the alignment between power generation trends and COD/BOD removal further supports this explanation, emphasizing the dual benefit of pollutant removal and energy recovery. The results of electricity generation highlight the potential of integrating MFCs with phytoremediation-based systems for sustainable leachate treatment. By achieving both effective organic pollutant degradation and simultaneous energy production, the system demonstrates practical value for waste management applications, particularly in contexts where resource recovery is an added priority. The results are summarized and further illustrated in the table and graph below, which provide a clear representation of the electricity output patterns observed throughout the experiment.

Table 3. Data of Power and Power Density During Reactor Testing

Days	Sente Plant Reactor		Control Reactor	
	Power (mW)	Power Density (mW/m2)	Power (mW)	Power Density (mW/m2)
0	0	0	26,40	325,93
1	38	469,14	47	580,25
2	49,5	611,11	92,8	1.145,68
3	24,6	303,70	73,8	911,11
4	36,4	449,38	125,4	1.548,15
5	78	962,96	178,5	2.203,70
6	138	1.703,70	135,7	1.675,31
7	507,6	6.266,67	145,6	1.797,53
8	722,3	8.917,28	333,2	4.113,58
9	694,8	8.577,78	565,8	6.985,19
10	828	1.022,.22	831,6	10.266,67
11	1.103,7	13.625,93	1.171,6	14.464,20
12	1.041,3	12.855,56	576	7.111,11
13	1.354,5	16.722,22	504,6	6.229,63
14	1.646,8	20.330,86	495,6	6.118,52
15	1.518,1	18.741,98	301,5	3.722,22

Based on the Figure, electricity production in the control reactor was initially higher than in the *sente* reactor during days 0–5, indicating that the plant had not yet contributed to electricity generation. As the plant roots developed, they provided a habitat for microbes, leading to a continuous increase in electricity production after day 6 up to day 15, with the *sente* reactor showing higher performance than the control although not significantly. This trend is consistent with Kristin (2012), who reported that longer incubation periods enhance microbial adaptation and biofilm stability, thereby improving power density in microbial fuel cells. The decrease observed in the control reactor after day 11 may be attributed to limited microbial diversity compared to the plant reactor, nutrient depletion, and system losses such as electron transfer resistance and internal impedance (Sitorus, 2010; Lee, 2007; Utami et al., 2017), which collectively resulted in lower voltage output.

4. Conclusions

This study demonstrates that the integration of a Microbial Fuel Cell (MFC) system with Alocasia macrorrhiza in a vertically layered reactor configuration is an effective approach for landfill leachate treatment, while enabling simultaneous renewable energy recovery. The combined action of microbial electrochemical processes and phytoremediation resulted in substantial organic matter removal, with maximum COD and BOD reduction efficiencies of 62.1% and 88.7%, respectively. These results indicate the efficient degradation of biodegradable organic compounds, particularly during the early operational period, while sustained pollutant removal was maintained despite fluctuations associated with substrate depletion and the presence of refractory organics. In addition to treatment performance, the planted vertical MFC system achieved superior electricity generation compared to the control reactor, with a maximum power output of 1.65 W. This enhancement reflects the positive influence of vertical configuration and plant-assisted microbial activity on biofilm development and electron transfer efficiency. The observed synergistic interaction between A. macrorrhiza and electroactive microorganisms highlights the potential of plant-assisted MFC systems as low-cost, low-maintenance, and sustainable alternatives to conventional leachate treatment technologies, particularly for application in resource-limited settings.

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