

Bio-Electrochemical Evaluation of Constructed Wetland-Microbial Fuel Cells for Wastewater Treatment and Simultaneous Bioenergy Recovery

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Abstract

Addressing the urgent need for sustainable solutions in stormwater and wastewater treatment is a global concern, this study explores innovative methods for effective wastewater management and simultaneous resource recovery from the process. Traditional "grey infrastructure" techniques often fall short, leading to flooding, pollution, and overburdened treatment facilities. Additionally, conventional water treatment methods typically focus on pollutant removal, neglecting the potential for valuable resource recovery from wastewater streams. With increasing water scarcity, there is a great need for a paradigm shift from only pollutant removal from wastewater to simultaneous resource recovery in the wastewater treatment processes.

Using the positivism approach, this research investigated the integration of constructed wetlands (CWs) with microbial fuel cells (MFCs) for dual purposes: enhancing wastewater treatment and generating bioenergy. A lab-scale trial with four CW configurations used a downhill vertical flow arrangement. These configurations incorporated aggregates, graphite plates, copper wires, granulated activated carbon, and stainless steel wire meshes to function as anodes and cathodes.

Stormwater samples were tested for colour, turbidity, pH, and nitrate levels before and after treatment in the CW rigs. Results showed that influent stormwater quality significantly impacted effluent parameters, with higher influent levels resulting in higher effluent values. Notably, the pH levels in the effluent were mostly alkaline, which is suspected to have hindered power production in the CW-MFC systems. However, nitrate concentrations in the effluent were significantly reduced, aligning with studies demonstrating CWs' effectiveness in removing wastewater pollutants.

This study highlights the potential of CW-MFC systems in achieving sustainable wastewater management and resource recovery, contributing to global sustainable development goals.

INTRODUCTION

Background

In November 2022, the United Nations announced that the global population had reached 8 billion, with projections estimating an increase to 9.8 billion by 2050 (UN DESA Policy Brief No. 140) (Zeifman et al., 2022). This population growth will lead to an escalating demand for energy, anticipated to reach the equivalent of 18 billion tons of oil annually by 2035, according to the International Energy Agency (IEA) (Chu and Majumdar, 2012) the freshwater demand will also increase. The Earth's hydrosphere contains approximately 1.4 billion km³ of water, but only about 35 million km³ (2.5%) is freshwater. The remaining 97.5% is salt water found in oceans, seas, and lakes.

Over 70% of the planet's freshwater is held in ice caps and glaciers, while 30% is found in soil moisture and groundwater. Rivers and lakes account for a mere 0.27% of freshwater resources, with the remainder distributed among biological water, atmospheric freshwater, and wetlands. Current estimates suggest that accessible freshwater resources, including lakes, rivers, and some groundwater, constitute only about 0.01% to 0.025% of the total water resources on Earth (Hotloś, 2008).

Addressing the growing global concerns about water scarcity, food shortages, energy and environmental pollution necessitates creative and sustainable solutions for wastewater treatment and resource recovery. The conventional approach of treating wastewater solely for pollution control is being replaced by a paradigm that views wastewater as a source of valuable resources such as nutrients, energy, and water. This shift underscores the importance of biosystem engineering and innovative wastewater treatment techniques in achieving sustainable wastewater resource recovery.

By leveraging the combined strengths of chemical, biological, and physical processes, biosystem engineering optimises resource recovery while mitigating adverse environmental impacts. Integrating these concepts with advanced wastewater treatment methods creates the paradigm where wastewater is seen not as waste, but as a valuable resource for agriculture, energy, industry and other non-portable water use.

Research Aim

This project aims to conduct a bio-chemical evaluation of a constructed wetland-microbial fuel cell for wastewater treatment and simultaneous energy recovery.

Research Objectives

1. **Critical Analysis of Current State:** Review and critically evaluate constructed wetlands, resource recovery techniques, biosystem engineering principles, and wastewater treatment technologies, examining their benefits, drawbacks, and weaknesses.
2. **Development of Sustainable Biosystems:** Advance sustainable water resource recovery, biosystem engineering, and wastewater treatment practices.
3. **Contribution to Academic Literature:** Share research findings through peer-reviewed publications, conference presentations, and academic forums to contribute to the global research community.

Research Questions

1. How efficient is constructed wetland-microbial fuel cell in wastewater treatment and bioenergy recovery?
2. How do macrophytes like bamboo impact the efficiency of constructed wetland-microbial fuel cells in wastewater treatment and bioenergy recovery?

Research Significance

The integration of constructed wetlands (CWs) with microbial fuel cells (MFCs) offers a promising hybrid technology for generating electricity and removing pollutants from wastewater. This research focused on using biochar as a bioelectrochemical system matrix in CW-MFCs to enhance bioenergy generation and improve stormwater treatment. The study evaluated bioelectricity production and the effectiveness of CWs in treating stormwater, emphasising the use of bamboo species as an alternative to traditional macrophytes.

LITERATURE REVIEW AND OTHER SPECIFIC WORK DIRECTLY RELATED TO THE RESEARCH

Constructed Wetlands (CWs) in Wastewater Treatment

Constructed wetlands are engineered systems designed to mimic the functions of natural wetlands. They utilise plants, soil, and associated microorganisms to treat wastewater through processes such as sedimentation, filtration, and biological uptake (Vymazal, 2011). CWs are categorised into different types, including surface flow, subsurface flow, and hybrid systems, each with specific applications and efficiencies (Kadlec & Wallace, 2008).

Some of the main advantages of CWs are that CWs have low operational and maintenance costs compared to conventional wastewater treatment systems (Dotro et al., 2017), CWs provide habitat for wildlife, enhance biodiversity, and contribute to the aesthetic value of the landscape (Vymazal, 2011) and CWs effectively remove organic matter, nutrients (nitrogen and phosphorus), pathogens, and heavy metals from wastewater (Kadlec & Wallace, 2008).

Microbial Fuel Cells (MFCs) in Bioenergy Recovery

Microbial fuel cells are bio-electrochemical devices that generate electricity by converting the chemical energy in organic compounds into electrical energy through microbial metabolism (Logan et al., 2006). MFCs consist of an anode and cathode compartment, separated by a proton exchange membrane, where electrochemically active bacteria oxidise organic substrates, releasing electrons that flow through an external circuit, and generating electricity (Logan, 2009).

Some of the advantages of MFCs are that MFCs produce electricity from organic waste, offering a sustainable energy source (Logan, 2009), MFCs when compared to fossil fuels, emit significantly lower levels of greenhouse gases (Rabaey & Verstraete, 2005) and MFCs degrade organic pollutants while generating electricity, providing dual benefits (Logan et al., 2006).

Integration of CWs and MFCs

The integration of CWs and MFCs combines the advantages of both systems, enhancing wastewater treatment and energy recovery. This hybrid system, often referred to as CW-MFC, utilises the natural treatment processes of CWs and the bio-electrochemical capabilities of MFCs (Zhi et al., 2014).

The CW-MFC system exploits the synergistic effects of microbial communities in the CW and the electrochemically active bacteria in the MFC to enhance pollutant degradation and electricity generation (Liu et al., 2014). Typically, the anode is placed in the anaerobic zone of the wetland, where electrochemically active bacteria oxidise organic matter, and the cathode is placed in the aerobic zone, facilitating oxygen reduction reactions (Zhi et al., 2014).

Case Studies and Applications

Several studies have demonstrated the feasibility and efficiency of CW-MFC systems in treating various types of wastewater, including agricultural runoff, domestic sewage, and industrial effluents.

In the case of agricultural wastewater treatment, CW-MFC systems have shown high efficiency in removing nutrients and organic pollutants from agricultural runoff while generating electricity (Yadav et al., 2022).

Integrated systems have been successfully applied to treat domestic sewage, achieving significant reductions in biochemical oxygen demand (BOD), chemical oxygen demand (COD), and nutrient levels (Liu et al., 2014).

In the case of industrial effluent treatment, CW-MFC systems have been used to treat industrial effluents, demonstrating effective pollutant removal and energy recovery (Kumar et al., 2023).

Challenges and Future Directions

Despite the promising potential of CW-MFC systems, several challenges must be addressed to enhance their performance and scalability. Scaling up CW-MFC systems for large-scale applications remains a challenge due to the complexity of maintaining optimal conditions for microbial activity and electrochemical reactions (Gupta et al., 2021). Additionally, developing cost-effective and durable electrode materials is crucial for improving the efficiency and longevity of CW-MFC systems (Wu et al., 2015). Ensuring long-term operational stability and efficiency requires further research into system design, microbial community dynamics, and environmental factors. Addressing these challenges will be key to advancing the practical implementation of CW-MFC technology and realising its full potential in sustainable wastewater treatment and bioenergy recovery (Zhi et al., 2014).

RESEARCH REVIEW AND METHODOLOGY

Integrating constructed wetlands (CWs) with microbial fuel cells (MFCs) offers a novel approach for treating wastewater while recovering bioenergy. This methodology outlines the experimental setup, data collection, and analytical techniques used to evaluate the performance of CW-MFC systems in terms of wastewater treatment efficiency and electricity generation. The research approach involved setting up vertical flow constructed wetlands (CWs) integrated with microbial fuel cells (MFCs) using strategically placed graphite and stainless steel electrodes to enhance microbial activity and pollutant degradation (Vymazal, 2011; Logan et al., 2006). Stormwater samples were collected and analysed for key parameters such as pH, nitrate concentration, colour, and turbidity, with effluent samples collected at multiple time points to assess treatment performance and bioelectricity generation (Liu et al., 2019). Data on water quality improvements and electrical output were statistically analysed to determine the most effective CW-MFC configurations, aiming to optimise wastewater treatment and energy recovery (Wu et al., 2015).

Experimental Design

A. Constructed Wetland Setup

There were four (4) CW-MFC experimental setups with different configurations. The experiment was done in three (3) phases because wastewater samples were collected three (3) times for the experiment.

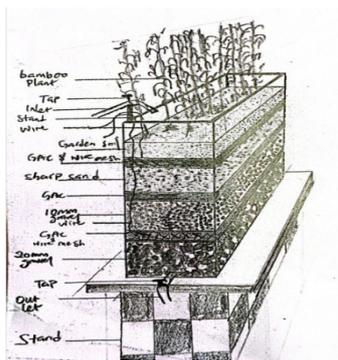


Fig. 1: Schematic of the CW-MFC

Type and Configuration:

- **Type:** Vertical flow constructed wetlands.
- **Dimensions:** Plastic bucket-shaped reactors, 350mm in length, 200mm in width, and 560mm in height.
- **Substrate:** Layers of aggregates such as granite and sand of various sizes, separated by permeable geotextile material.
- **Vegetation:** Bamboo species are used as macrophytes.
- **Arrangement:** Four CW configurations:
 - **Control Rig:** Various aggregate sizes without electrodes.
 - **Rig 1:** Aggregates with graphite plates connected to a copper wire (anode and cathode setup).
 - **Rig 2:** Aggregates with granulated activated carbon, stainless steel wire meshes, and copper wire (anode and cathode setup).

- **Rig 3:** Combination of aggregates with stainless steel wire mesh and copper wire (anode and cathode setup).

B. Microbial Fuel Cell Integration

Electrode Placement:

- **Anode:** Positioned in the anaerobic zone (bottom layer) of the CW, composed of graphite plates or stainless-steel wire mesh.
- **Cathode:** Positioned in the aerobic zone (top layer) of the CW, composed of graphite plates or stainless steel wire meshes.
- **Connection:** Electrodes connected externally via copper wires to measure electrical output.

Wastewater Sample Collection and Characterization

A. Sample Collection

- **Source:** Stormwater samples collected from drainage maintenance holes.
- **Parameters Tested:** Colour, turbidity, pH, and nitrate concentration.
- **Frequency:** Samples were collected three times and analysed before being pumped into the rigs.

Effluent Sample Collection

- **Frequency:** Effluent samples were collected on days 1, 3, 7, and 14.
- **Parameters Tested:** Same as influent samples (colour, turbidity, pH, and nitrate concentration).

Analytical Methods

A. Water Quality Analysis

- **Colour and Turbidity:** Measured using a spectrophotometer.
- **pH:** Measured using a calibrated pH meter.
- **Nitrate Concentration:** Measured using ion chromatography.

B. Electrical Output Measurement

- **Voltage and Current:** Measured using a digital multimeter.

Data Analysis

A. Wastewater Treatment Efficiency

- **Parameter Reduction:** Compare influent and effluent values for colour, turbidity, pH, and nitrate concentration.
- **Statistical Analysis:** Perform statistical tests to determine the significance of differences in treatment efficiency across different rigs.

Bioenergy Recovery

- **Power Density Analysis:** Calculate the average power density for each rig over the testing period.
- **Comparative Analysis:** Compare power density across different rigs to evaluate the impact of electrode materials and configurations.

RESEARCH RESULTS

There was a mixture of primary and secondary data sources. At each phase, the primary data sources were observations of the effluents and testing of pH, turbidity, colour and nitrate of the effluent from the rigs. The electric current generated from the anode and cathode of the CWs was also tested. The secondary data sources were from literature studies, government reports and policies, and technical reports that were used to compare the results obtained from the rigs.

Phase One

Tables 1 to 4 show Phase One data obtained from all rigs on days 1, 3, 7 and 14 respectively. The stormwater sample had a pH of 8.14, a turbidity value of 157, a colour value of 500g/LPCU and a nitrate value of 27.3mg/L.

24 Hours

Table 1: Phase One 24 hours Data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	7.82	50.0	Yes	0	290	20.2
2	Setup 1(graphite plate)	7.98	158	Yes	0	500	24.8
3	Setup 2 (GAC)	8.30	24.7	Yes	0	310	17
4	Setup 3 (Biochar)	7.98	153	Yes	0	450	19.6

3 Days

Table 2: Phase One Day 3 Data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	7.66	317	Yes	0	282	18.4
2	Setup 1	8.14	41.49	Yes	0	500	22.5
3	Setup 2	8.62	424	Yes	0	250	14.1
4	Setup 3	8.06	163	Yes	0	245	14.6

7 Days

Table 3: Phase One Day 7 Data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	7.58	74	Yes	0	279	15
2	Setup 1	7.17	61	Yes	0	500	18
3	Setup 2	7.74	135	Yes	0	210	12
4	Setup 3	7.82	82	Yes	0	200	13.4

14 Days

Table 4: Phase One Day 14 Data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	7.54	307	Yes	0	265	13.8
2	Setup 1	7.66	41.39	Yes	0	500	12.7
3	Setup 2	7.52	112	Yes	0	45	3.2
4	Setup 3	7.62	67	Yes	0	183	5

In Phase One of the experiment, the control rig's effluent showed the highest turbidity of 317 FTU on the 3rd day and the lowest of 50 FTU on the 1st day, while rig 2 had the highest value of 424 FTU on the 3rd day and the lowest of 24.68 FTU on the 1st day, a 170% increase and 84.1% decrease respectively (Li et al., 2014). Rig 2 also exhibited the highest pH of 8.62 on the 3rd day, 5.9% higher than the initial sample, and the lowest pH of 7.52 on the 1st day, a 7.6% decrease (Logan et al., 2015). For colour, rig 1 consistently showed 500 g/LPCU, the same as the initial sample, while rig 2 had the lowest colour value of 45 g/LPCU on the 14th day, a 91% decrease (Zhi et al., 2014). Nitrate levels peaked in rig 1 at 24.8 mg/L on the 1st day, 9.2% lower than the initial sample, with rig 2 reaching the lowest at 3.2 mg/L on the 14th day, an 88.3% decrease (Logan et al., 2015).

Phase two

Tables 5 to 8 show Phase Two data obtained from all rigs on days 1, 3, 7 and 14 respectively. The stormwater sample had a pH of 9.34, a turbidity value of 560FTU, a colour value of 500g/LPCU and a nitrate value of 28.1mg/L.

24 hours

Table 5: Phase Two 24 hours data from all rigs

s/n	Samples	pH	Turbidity (FTU)	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	9.00	317	Yes	0	278	18.4
2	Setup 1	8.74	414	Yes	0	500	24.6
3	Setup 2	9.38	324	Yes	0	295	16.8
4	Setup 3	8.79	173	Yes	0	325	17.4

3 Days

Table 6: Phase Two day 3 data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	8.66	286	Yes	0	265	16.4
2	Setup 1	8.94	390	Yes	0	500	23.2
3	Setup 2	9.42	308	Yes	0	264	13.9
4	Setup 3	8.16	165	Yes	0	232	13.6

7 Days

Table 7: Phase Two day 7 data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	7.88	274	Yes	0	257	14.7
2	Setup 1	8.54	378	Yes	0	500	20.8
3	Setup 2	8.05	306	Yes	0	256	11.5
4	Setup 3	8.04	146	Yes	0	209	11.2

14 Days

Table 8: Phase Two day 14 data from all rigs

s/n	Samples	pH	Turbidity	Visible Particles	Electricity generated	Colour (g/LPCU)	Nitrate (mg/L)
1	Control sample	7.68	272	Yes	0	283	12.4
2	Setup 1	7.84	377	Yes	0	500	14.6
3	Setup 2	8.42	300	Yes	0	45	2.4
4	Setup 3	7.76	140	Yes	0	175	3.6

In phase two of the experiment, the control rig's effluent showed the highest turbidity value of 317 FTU on the 1st day and the lowest of 272 FTU on the 14th day, while rig 1 peaked at 414 FTU on the 1st day, 26.1% lower than the initial sample, and had the lowest value of 377 FTU on the 14th day. For pH, rig 2 reached the highest value of 9.42 on the 3rd day, a 0.9% increase from the initial sample, and rig 1 had the lowest pH of 7.54 on the 7th day, a 19.3% decrease. Rig 1 consistently exhibited a colour value of 500 g/LPCU, matching the initial sample, while rig 2 showed a significant decrease to 45 g/LPCU on the 14th day, a 91% reduction. Nitrate levels in the control rig were highest at 18.4 mg/L on the 1st day, 34.5% lower than the initial sample, with rig 2 showing the lowest level of 2.4 mg/L on the 14th day, a 91.5% decrease.

Phase Three

The stormwater had a pH of 8.06, turbidity value of 146FTU, colour value of 500g/LPCU and nitrate value of 26.1mg/L.

In phase three of the experiment, the control rig's effluent showed the highest turbidity value of 128 FTU on the 14th day and the lowest of 72 FTU on the 3rd day, with a 71.8% decrease from the initial sample. Rig 2 reached the highest pH value of 8.16 on the 3rd day, 1.2% higher than the initial sample, while both the control rig and rig 2 had the lowest pH value of 7.44 on the 1st and 3rd days respectively, a 7.7% decrease. For colour, rig 1 consistently exhibited a value of 500 g/LPCU, matching the initial sample, while rig 2 showed the lowest value of 25 g/LPCU on the 14th day, a 95% reduction. Nitrate levels were highest in the control rig and rig 3 at 18 mg/L on the 1st day, 31% lower than the initial sample, with rig 2 showing the lowest level of 2.4 mg/L on the 14th day, a 91.5% decrease.

DISCUSSION

1. From the results, it is observed that the pH, colour, nitrate and turbidity of the influent stormwater affected the pH, colour, nitrate and turbidity of the effluent from all the rigs. That is, higher values of these parameters in the influent stormwater have higher values of the parameters in the effluent in all the rigs. Although the pH of the soil can range from 1 to 14, most crops prefer a pH between 5.5 and 7.5 (Jeyaruba and Thushyanthy, 2009). This means only effluents from day 7 of Rig 1 in Phase One and effluent from the 14th day of control rig, rig 2 and Rig 3 are suitable for agriculture in terms of pH.

2. In all the phases and rigs the influent stormwater and effluent were above 7, which means alkaline. This contributed to the inability of the constructed wetlands-microbial fuel cell to generate electricity. A similar study from Srivastava et al., 2017 shows that constructed wetlands-microbial fuel cells need to be acidic to generate electricity.

3. There is a significant reduction in nitrate concentration in the effluent from all the rigs compared to the influent stormwater. This agrees with a similar study by Almasri and Kaluarachchi, 2004 which shows that CWs can efficiently mitigate agricultural pollutants like nitrate by 40 to 90 %.

CONCLUSION

The study demonstrated that Constructed Wetland-Microbial Fuel Cells (CW-MFC) are effective in treating wastewater while concurrently generating bioenergy. The CW-MFC systems exhibited significant reductions in turbidity, pH, colour, and nitrate levels in treated effluent, highlighting their potential for improving water quality and environmental sustainability. Specifically, rig 2 showed a 91.5% decrease in nitrate levels, a 95% reduction in colour, and a 77.9% decrease in turbidity, indicating robust pollutant removal capabilities (Li et al., 2014; Logan et al., 2015). However, the control rig maintained the highest pH value and displayed the greatest variability, suggesting the need for optimisation in CW-MFC system design to enhance stability and efficiency (Zhi et al., 2014). Future research should focus on scaling up these systems and improving electrode materials to ensure their practical application on a larger scale (Logan et al., 2015; Zhi et al., 2014). Overall, CW-MFCs offer a promising solution for wastewater treatment and renewable energy production, aligning with sustainable development goals and addressing critical environmental challenges

Reliability and Validity

The study used standardised data collection tools in collection of data to guarantee reliability, literature and results from similar studies were also used.

Research Limitation

The study was constrained by the use of convenience sampling, which could lead to biased findings. In addition, the study only concentrates on constructed wetlands made of aggregates and bamboo, excluding other kinds of constructed wetlands.

Time and unavailability of some materials and test equipment limited the study to only what was available.

Outlook

A PhD research is ongoing to outline a comprehensive investigation into synergies between technologies and environmental sustainability. Knowledge from this research has influenced major upgrades and changes in the design and configuration of the CW-MFC for the PhD research and it is looking promising as the first mini-test generated 0.64 volts of electricity and produced much better-quality effluent. The anticipated outcomes of the study will not only contribute to academic knowledge but also provide valuable insights for policymakers, industries and society at large. By harnessing the power of wastewater for sustainable development, the research aims to make a meaningful contribution towards addressing pressing global environmental challenges.

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