Evaluation of Energy Recovery from Constructed Wetlands-Microbial Fuel Cell Systems.

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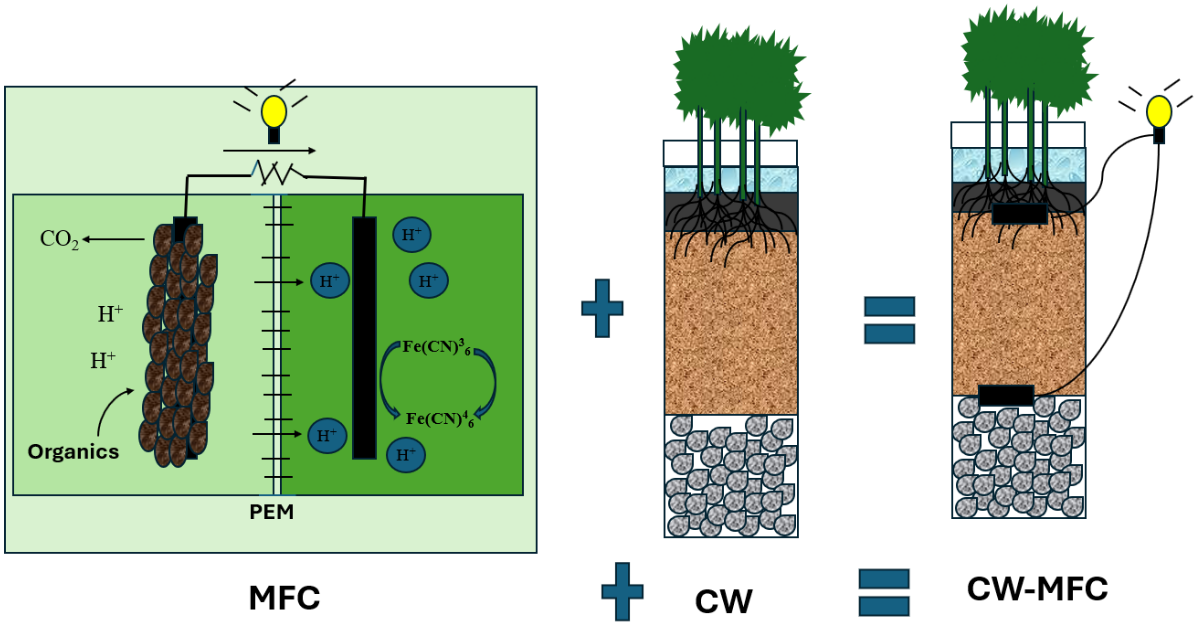
Keywords: Energy Recovery, Sustainability, Sustainable Drainage Systems (SUDs), Agricultural Wastewater, Constructed Wetlands, Green Energy, Microbial Fuel Cell, Water Reuse.

Abstract

Constructed wetlands integrated with microbial fuel cells (CW-MFCs) represent an innovative approach to wastewater treatment, combining ecological water purification with sustainable energy recovery. This study evaluates the performance and efficiency of CW-MFC systems in terms of energy generation, considering the ph of the wastewater and varying environmental temperatures, and the effects of CW-MFC size on power generation. This study also evaluates the CW-MFCs' efficiency under different operating conditions. For example, the planting of bamboo in two of the pilot-scale experimental rigs. The CW-MFC system degrades organic pollutants in agricultural wastewater and generates electricity by leveraging the metabolic activity of electrochemically active microorganisms. Key performance indicators, including power density, chemical oxygen demand (COD) removal, and nutrient recovery, were analysed across electrode materials, substrate types, and operational configurations. Four pilot-scale CW-MFCs were designed with gravel, sharp sand and garden soil with electrodes embedded at aerobic and anaerobic sections of the CW-MFC to pick up and transmit electrons. Fargesia Black Pearl bamboo was planted on two of the rigs to create variables, and the other two were left without plants as a control measure. The bamboo is added to the variables to see the effects of the bamboo root exudates on the electric generation capability of the CW-MFC. Voltage was measured hourly from 16:00:00 on 11/01/2025 to 15:00:00 on 02/03/2025. A total of 1,200 entries were recorded for each rig and analysed with the graphs below.

On average, the control rigs generated a minimum of 0.7 Volts and a maximum of 0.88 Volts, which is a 25% increase, while the variable rigs generated a minimum of 0.33 Volts and a maximum of 0.9 Volts, which is a 177.4% increase. The variables started off with low voltage generation and gained about a 177.4% increase within the period of the experiment. This shows that the bamboo plant has an influence on the amount of current generated by CW-MFC.

This evaluation highlights the potential of CW-MFCs as a sustainable solution for renewable energy production that can be utilised to power low-energy-consuming gadgets in farms. Even with the results from the experiment, some of the challenges for real-life applications in agriculture would be low energy efficiency and scalability. Therefore, future research should focus on enhancing design for real-life applications, scaling up rigs for practical applications *in agriculture, and integrating CW-MFCs with other renewable technologies. This study underscores the feasibility of CW-MFCs in advancing the nexus of clean water and energy sustainability for agriculture while addressing global environmental.*



INTRODUCTION

Background

With global concerns about water and food shortages coupled with an increase in environmental pollution, innovative solutions are desperately needed to clean agricultural wastewater and possibly, turn it into a resource recovery opportunity. The traditional practice of treating wastewater only for pollution management should be replaced by a paradigm shift wherein wastewater is considered a potential source of recovery of valuable resources, such as energy. This paradigm shift emphasises the significance of biosystem engineering and state-of-the-art wastewater treatment methods in achieving sustainable water resource recovery.

The increasing world population is accompanied by an increase in urbanisation, climate change, and economic uncertainty. It will not be out of place to assume that the amount of wastewater generation globally will also increase as the world population increases. Wastewater, as we know, contains a lot of energy and nutrients, and it will be a great resource loss if an innovative method that can recover these resources during treatment is not widely adopted. It has been predicted that by 2050, almost 6 billion people across more than 50 countries and regions will live in water poverty (Burek et al., 2016). This also makes finding innovative sustainable solutions to reduce the gap between water supply and demand one of the most pressing issues that needs to be resolved this century.

One concept that might be the answer to solving the future water problem in a sustainable manner is the use of engineered biosystems for wastewater treatment. The biosystems harness the combined strengths of chemical, biological, and physical processes to optimise resource recovery while mitigating adverse environmental impacts. If the biosystems are optimised, it is possible to have a circular system where no external energy will be needed for wastewater treatment and on the other hand, create a paradigm where wastewater is viewed not as a waste but as a resource that may assist various industries, including agriculture, energy, and industry.

RATIONALE

Agricultural wastewater is sometimes overlooked because some believe it is less harmful than stormwater runoff in urban areas. There is a notion that urban stormwater runoffs are the major contributor to water quality degradation (Davis and Birch, 2009) due to industrial activities and pollutants like polyaromatic hydrocarbons from highways and microplastic tyre wear, which finds their way into water bodies and groundwater, but when one considers the pollutant makeup of agricultural wastewater, it can be argued that agricultural runoffs contributes more to water quality degradation than urban area stormwater runoff. Agricultural runoff contains a significant source of diverse pollutants, including sediments, nutrients, pathogens, veterinary medicines, pesticides, metals and sometimes, runoffs from paved roads (stormwater). Modern agricultural practices depend extensively on agrochemicals such as pesticides, herbicides, and hormones to achieve higher yields within shorter timeframes (Willis and McDowell, 1982). Pollutants, including nitrogen, phosphorus, organic matter, heavy metals, and polycyclic aromatic hydrocarbons, are also present in agricultural wastewater (Malaviya and Singh, 2012; Liu et al., 2019). These pollutants are often concentrated during the washing of livestock, washing their environment, washing farm produce, and during the initial stages of rainfall (known as the "First-flush event") (Lee et al., 2002; Avila et al., 2013). Traditional agricultural wastewater management practices (the so-called "grey infrastructures") are frequently insufficient and can lead to inundation, soil damage, pollution, and straining wastewater treatment facilities to their maximum capacity. Sustainable drainage systems (SuDS) such as the CW-MFC offer a cutting-edge method for managing agricultural wastewater.

This project aims to increase sustainable energy recovery from agricultural wastewater by investigating the relationship between biosystem engineering and developments in wastewater treatment. Through carefully examining prior research, experimental studies, technology development, and socioeconomic assessments, this study aims to uncover novel approaches that combine environmental protection with economic prosperity. This concept aligns with the broader goal for a sustainable and fair future and the Sustainable Development Goals (SDGS), which include ensuring that everyone has access to clean drinking water.

RESEARCH AIM

This research aims to build and test a green infrastructure system, such as Constructed Wetlands – Microbial Fuel Cell (CW-MFC), using recycled material and bamboo for the treatment of agricultural wastewater while simultaneously producing bio-energy that can be stored and used when needed.

RESEARCH OBJECTIVES

1. Critical Analysis of Current State: Review and critically evaluate the state of the art in resource recovery techniques, biosystem engineering principles, and agricultural wastewater treatment technology. Examining the benefits, drawbacks, and weaknesses of current resource utilisation and wastewater treatment methods can help achieve this goal.
2. Development of Sustainable water resource recovery, biosystems engineering, wastewater treatment and energy recovery.
3. Contribution to Academic Literature: By sharing research findings through peer-reviewed publications, conference presentations, and involvement in pertinent academic professional forums. Also, sharing knowledge, perceptions, and advances with the international research community is the goal of this mission.

RESEARCH QUESTIONS

1. How can the CW-MFC be designed to optimise its ability to treat agricultural wastewater efficiently?
2. How can the CW-MFC design be optimised to maximise energy recovery?

RESEARCH SIGNIFICANCES

The combination of CW and MFC has become a promising hybrid technology due to its high compatibility in generating electricity and removing pollutants from wastewater. The research focuses on integrating CW and MFC Cells using recycled aggregates as substrates to reduce the quantity of unwanted aggregates that go to landfills. It will evaluate bioelectricity generated from CW-MFC, which can be stored for later use by farmers to power pumps, UV lights for water treatment, etc.

This study will also bridge a serious research gap in CW-MFC for agricultural wastewater treatment and resource recovery, considering the fact that very little has been done in the last decade. Figure 1 shows research advancements within the last 10 years in different design, operational, and functional aspects and modelling CW-MFC on the Web of Science. The keywords used were Constructed Wetlands, Microbial Fuel Cell, Constructed Wetlands for wastewater treatment, Constructed Wetlands for agricultural treatment, Constructed Wetland-Microbial Fuel Cell, Constructed Wetlands-Microbial Fuel Cell for wastewater treatment, Constructed Wetlands-Microbial Fuel Cell for agricultural wastewater treatment, Energy recovery from wastewater using CW-MFC, and Energy recovery from agricultural wastewater using CW-MFC.

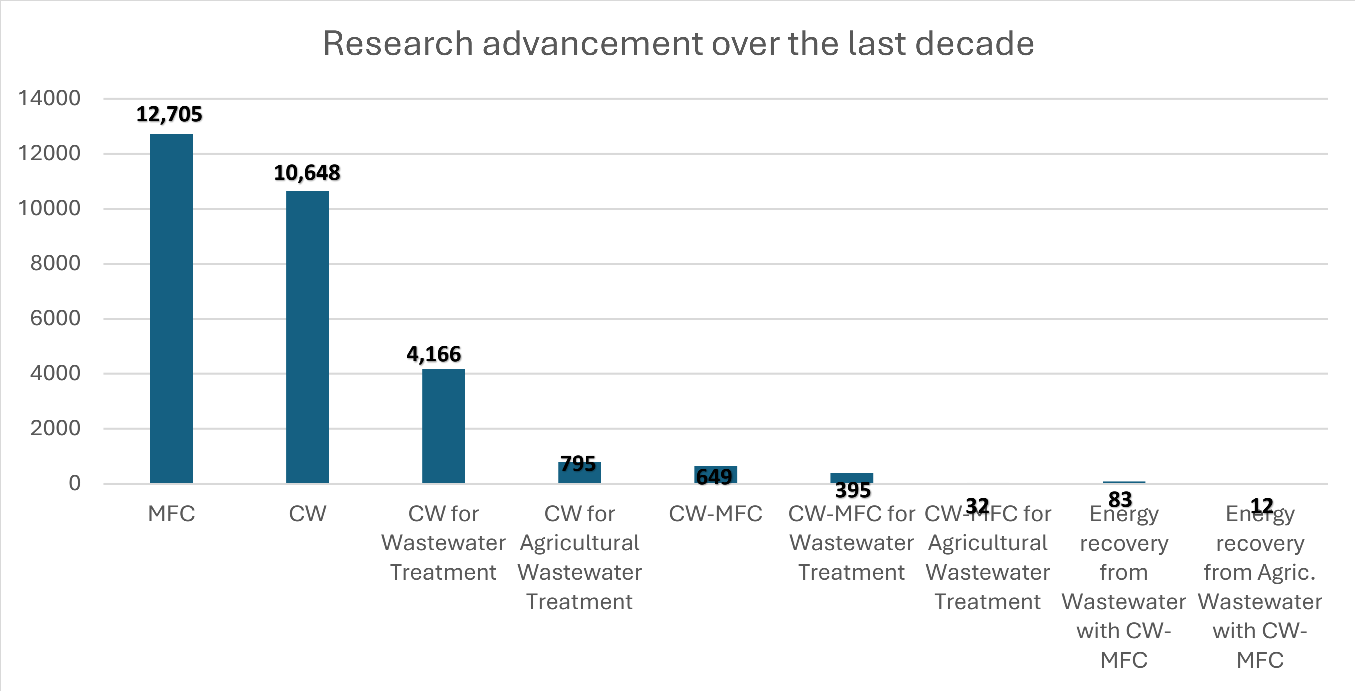


Figure 1: Research advancement over the last decade

LITERATURE REVIEW AND OTHER SPECIFIC WORK DIRECTLY RELATED TO THE RESEARCH

The CWs 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 advantages of CWs include low operational and maintenance costs compared to conventional wastewater treatment systems (Dotro et al., 2017), provision of habitat for wildlife, enhancing biodiversity, and contribution to the aesthetic value of the landscape (Vymazal, 2011). And the MFCs are bio-electrochemical devices that generate electricity by converting the chemical energy contained 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, generating electricity (Logan, 2009). The MFCs are classified sometimes as Sediment Microbial Fuel Cells (SMFCs), Soil Microbial Fuel Cells (S-MFCs) and Plant Microbial Fuel Cells (P-MFCs). In SMFCs, bacteria in the sediment metabolise organic matter, releasing protons and electrons. These electrons move from the anode to the cathode via an external electrical circuit, while the protons migrate to the cathode chamber, completing the current loop via the external circuit. The open-circuit redox has a potential of approximately 0.7–0.8 V established between the sediment and the overlying water (Allen & Bennetto 1993). For SMFC, the anode is placed in sediments where microorganisms metabolise organic materials to generate electrons. The electrons generated move through the outside circuit to the cathode placed in the water overlay region. The movement of these electrons produces an electrical current (Wang & Lim, 2020; Zhang & Liu, 2017). The reactions if glucose is used as the electron donor at the anode and oxygen as the oxidant are as follows:

Oxidation at the anode:

$$C_6H_{12}O_6 + 6H_2O \longrightarrow 6CO_2 + 24e^- + 24H^+ \quad (1)$$

Reduction at the cathode:

$$6O_2 + 24e^- + 24H^+ \longrightarrow 12H_2O \quad (2)$$

Overall reaction:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 12H_2O \quad (3)$$ (Simeon et al., 2022)

The glucose in the MFC is oxidised by the bacteria present, and electrons (e^-) are released in the process. The released electrons are moved to the anode via direct contact, mediators, or microbial nanowires. Electrons flow through an external circuit to the cathode, while protons pass through a proton exchange membrane into the cathode chamber; then, at the cathode, oxygen accepts the electrons and then combines with protons to form water through a reduction reaction (Simeon et al., 2022). In S-MFCs, electricity generation results from the metabolic activity of microorganisms that attach to the anode, metabolising nutrients in the soil. As organic matter is broken down, electrons are released and transported through the external circuit to the cathode, which reacts with electron acceptors. The available nutrients in the soil determine the duration and efficiency of electricity generation (Wolińska et al., 2014; Uria-Molto et al., 2022). And in P-MFCs, the rhizodeposites secreted by plant roots form a sustained source of energy (Nitisoravut & Regmi, 2017). The microbes metabolise these rhizodeposits, releasing electrons that travel from the anode to the cathode and, as a result, generate electricity. P-MFCs utilise the exact energy-harvesting mechanism as S-MFCs, relying on rhizodeposits—organic compounds secreted by plant roots—as the energy source. The key distinction between the two systems is that plants in P-MFCs continuously produce rhizodeposits, whereas S-MFCs depend on the finite nutrients initially present in the soil (Nitisoravut & Regmi, 2017). In S-MFCs, energy and electricity are byproducts of microbial metabolism by various microorganisms that colonise the anode of the fuel cells (Wolińska et al., 2014; Uria-Molto et al., 2022).

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 (Li et al., 2014). Additionally, developing cost-effective and durable electrode materials is crucial for improving the efficiency and longevity of CW-MFC systems (Logan 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 (Xu et al., 2024).

RESEARCH FINDINGS AND DISCUSSION

Integrating CW with MFC 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 electricity generation. The research approach involved setting up vertical flow CW integrated with MFC using strategically placed electrodes to enhance microbial activity and pollutant degradation (Vymazal, 2011; Logan et al., 2006). Agricultural wastewater samples were collected and analysed for key parameters such as pH, electrical conductivity, salinity, TDS, and temperature. The wastewater is systematically pumped into the system at multiple time intervals to assess treatment performance and bioelectricity generation (Davis et al., 2009; Liu et al., 2019). Data on water quality improvements and electrical output will be statistically analysed to determine the most efficient CW-MFC configurations, aiming to optimise energy recovery (Zhang et al., 2014).

Experimental Design

Four (4) CW-MFC experimental rigs were set up with the same substrate configuration. Fargesia Black Pearl bamboo was planted on two of the rigs to create variables, and the other two were left without plants as a control measure. The bamboo is added to the variables to see the effects of the bamboo root exudates on the electric generation capability of the CW-MFC.

Configuration:

- **Type:** Vertical flow constructed wetlands.
- **Dimensions:** Acrylic square-shaped reactors, 250mm x 200mm x 1,000mm.
- **Substrate:** Layers of recycled granite, sharp sand mixed with granite, sharp sand and garden soil.
- **Vegetation:** Fargesia Black Pearl bamboo.
- **Arrangement:** Four CW configurations:
  - **Control Rig 1:** CW-MFC
  - **Control Rig 2:** CW-MFC
  - **Variable Rig 1:** CW-MFC + Fargesia Black Pearl bamboo
  - **Variable Rig 2:** CW-MFC + Fargesia Black Pearl bamboo

- **Anode:** Positioned in the anaerobic zone (bottom layer) of the CW.
- **Cathode:** Positioned in the aerobic zone (top layer) of the CW.
- **Connection:** Electrodes connected externally via copper wires to measure electrical output.

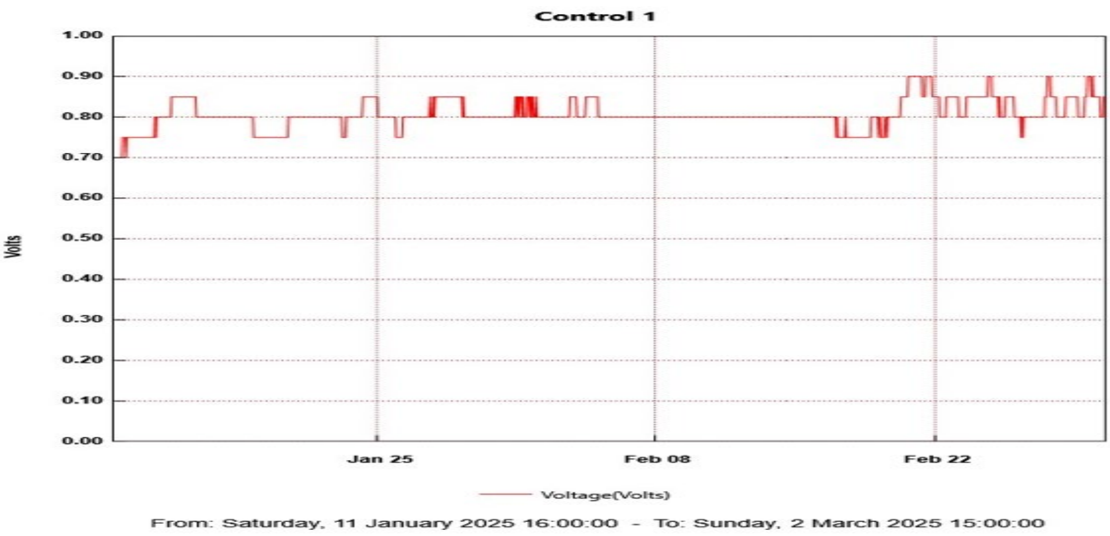
Wastewater Sample Collection and Characterisation

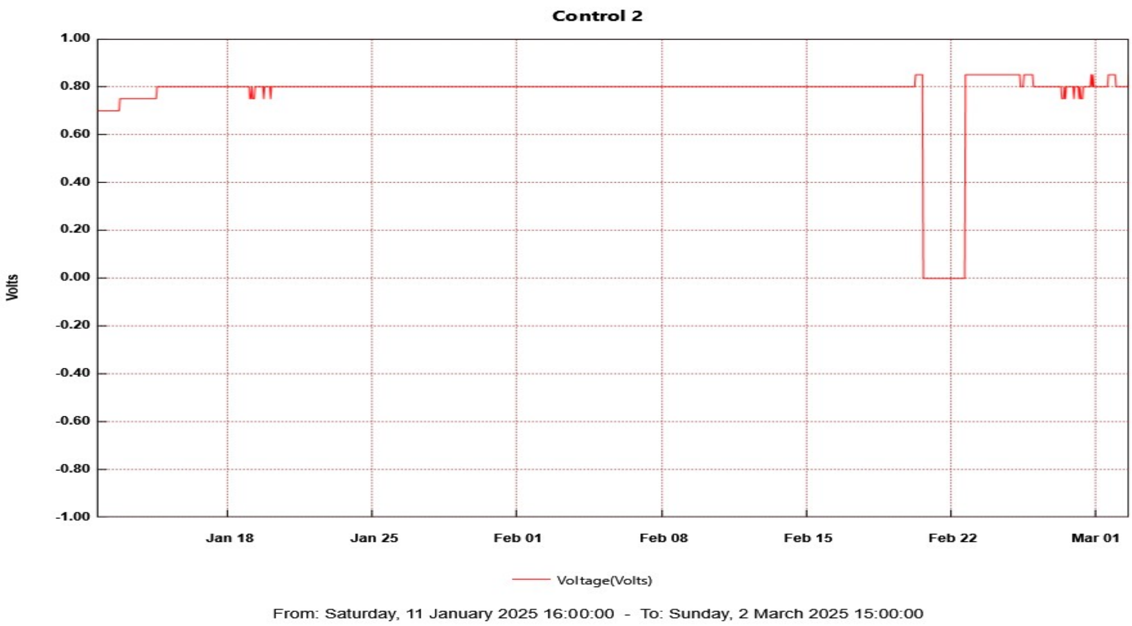
Sample Collection

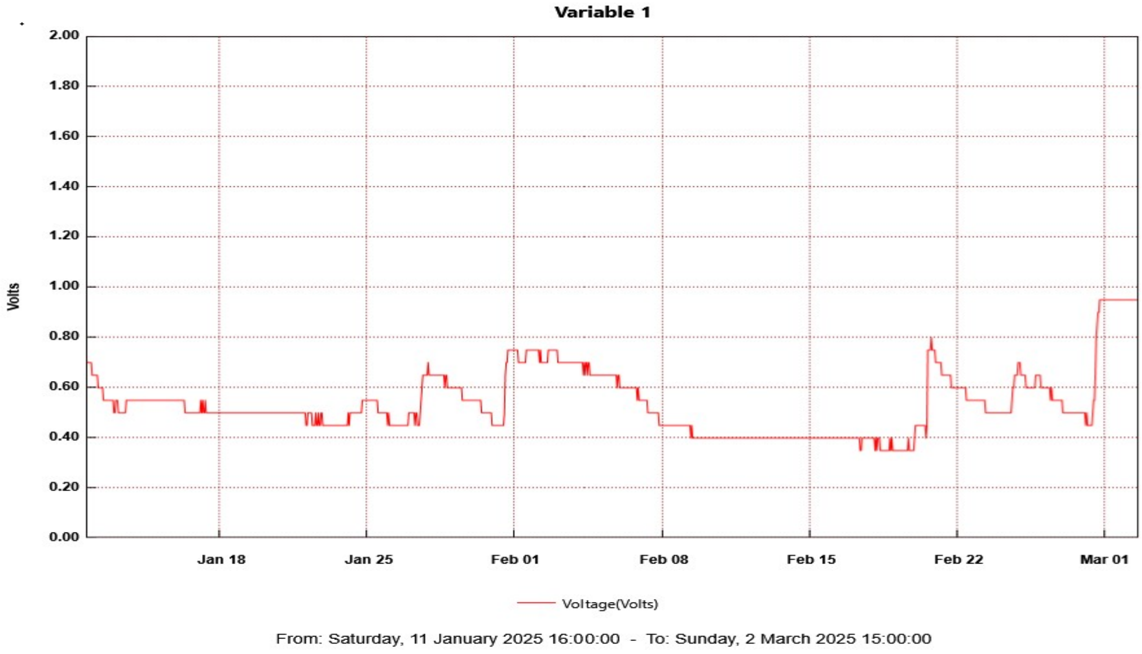
This study is focused on the management and treatment of agricultural wastewater. Agricultural wastewater used for the experiment was obtained from a farm located 17 miles from the Royal Agricultural University, Cirencester, UK. The wastewater was stored in a 200l container and pumped into the rigs automatically and uniformly. A Voltage Data Logger programmed to take hourly readings was connected to the electrodes.

Bioenergy Recovery

Voltage was measured hourly from 16:00:00 on 11/01/2025 to 15:00:00 on 02/03/2025. A total of 1,200 entries were recorded for each rig and analysed with the graphs below. Graphs 1,2,3, and 4 show the amount of voltage generated by each rig from 11/01/2025 to 02/03/2025, while Table 1 shows the summary.







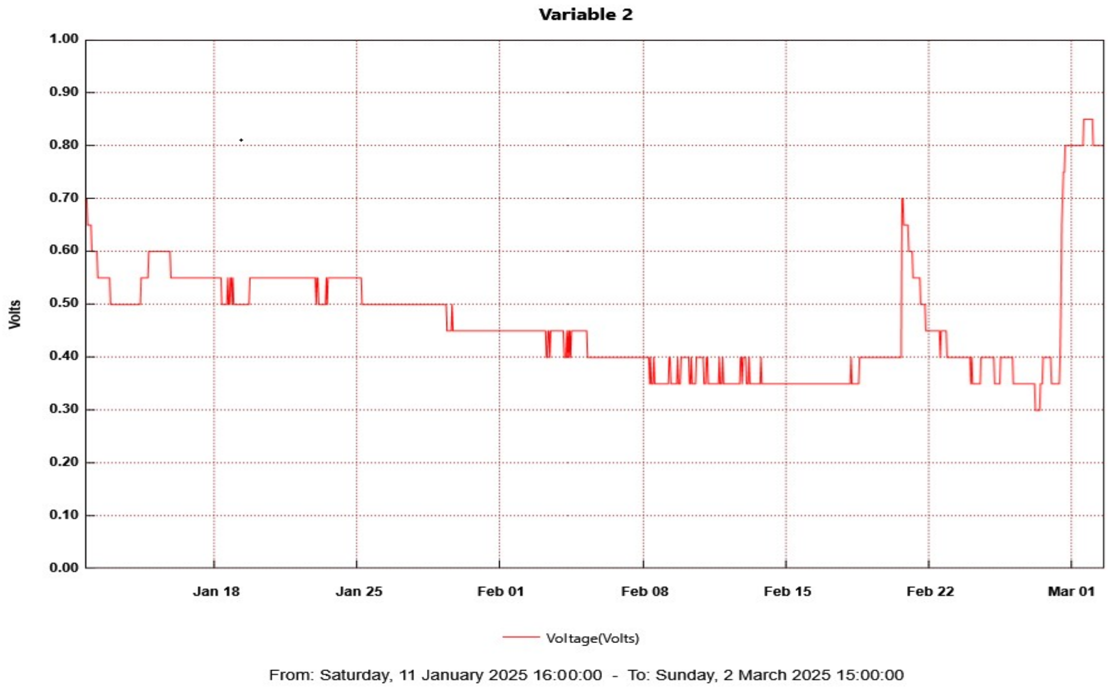
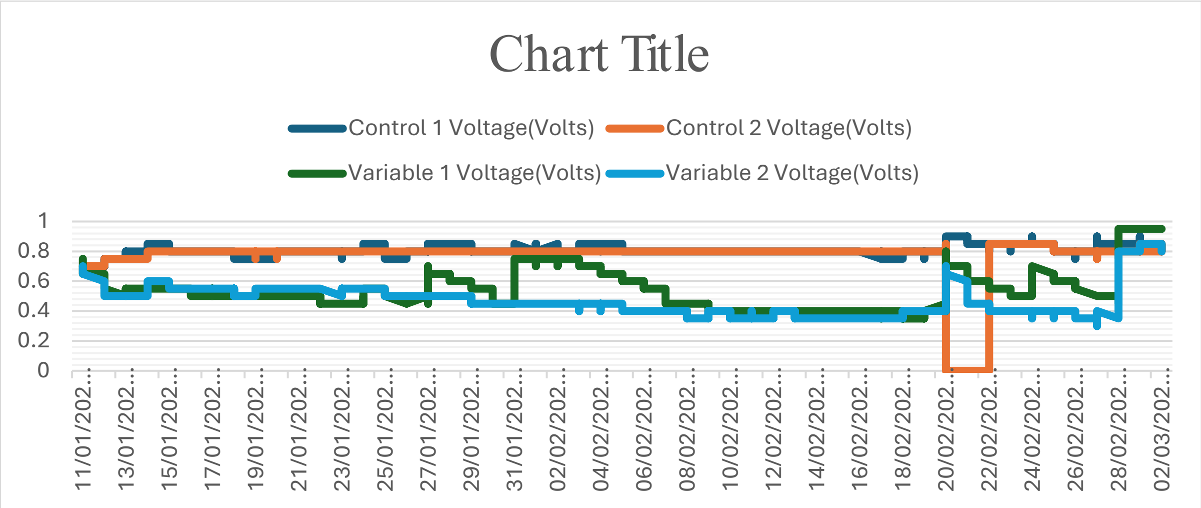


Table 1: Summary from the Volt meters

	Control 1	**Control 2**	**Average for Controls**	**Variable 1**	**Variable 2**	**Average for variables**
Max	0.9	0.85	**0.875**	0.95	0.85	**0.9**

Min	0.7	0.7	**0.7**	0.35	0.3	**0.325**
Average	0.8065	0.799262	**0.8028808**	0.538458	0.465833	**0.502146**
Stdv.	0.034947	0.0239	**0.0294231**	0.131957	0.107745	**0.119851**
% increase	28.57143	21.42857	**25**	171.4286	183.3333	**177.381**



DISCUSSION

The result shows that 1,200 readings were generated by each rig. Control 1 generated a minimum of 0.7 Volts and a maximum of 0.9 Volts which is 28.6% increase, Control 2 generated a minimum of 0.7 Volts and a maximum of 0.85 Volts which is 21.4%, Variable 1 generated a minimum of 0.35 Volts which is 171.4% and a maximum of 0.95 volts and Variable 2 generated a minimum of 0.3 Volts and a maximum of 0.85 Volts which is 183.3% increase. Of the four rigs, Variable 1 generated the maximum voltage of 0.95 volts, while Variable 2 generated the lowest voltage of 0.3 volts. On average, the control rigs generated a minimum of 0.7 Volts and a maximum of 0.88 Volts, which is a 25% increase, while the variable rigs generated a minimum of 0.33 Volts and a maximum of 0.9 Volts, which is a 177.4% increase.

CONCLUSION

The variables started off with low voltage generation and gained about a 177.4% increase within the period of the experiment. This shows that the bamboo plant has an influence on the amount of current generated by CW-MFC (Zhang et al., 2021). The CW-MFC electrical output can be optimised by connecting multiple rigs in series to form a single circuit.

Reliability and Validity

The study used standardised data collection tools (Voltage sensor with data logger) in the collection of data to guarantee reliability, and literature and results from similar studies were also used.

Research Limitation

The study was constrained by the use of convenience wastewater 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 and plants. Also, time and the unavailability of some materials and test equipment limited the study to only what was available.

Outlook

The PhD research is still ongoing to outline a comprehensive investigation into factors like the relationship between wastewater quality and energy generation. Knowledge from this research will influence major upgrades and changes in the design and configuration of the CW-MFC for the upscaling and real-life application. The anticipated outcomes of the study will also contribute to academic knowledge and provide valuable insights for policymakers. By harnessing the power of wastewater for sustainable development, the research aims to make a meaningful

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