



Dual-Chamber microbial fuel cell for Azo-Dye degradation and electricity generation in Textile wastewater treatment

Julius Nnamdi Ndiva^a, Simeon Okechukwu Eze^b, Somtochukwu Godfrey Nnabuife^c,
Boyu Kuang^{d,*}, Zeeshan A. Rana^e

^a Department of Chemical Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Anambra State, Nigeria

^b Department of Chemical and Petroleum Engineering, University of Lagos, Nigeria

^c School of Water, Energy, and Environment, Cranfield University, Cranfield, MK43 0AL Bedfordshire, United Kingdom

^d School of Aerospace, Transport, and Manufacturing, Cranfield University, Cranfield, MK43 0AL Bedfordshire, United Kingdom

^e Department of Mechanical Engineering, Prince Mohammad Bin Fahd University, Al-Khobar, Saudi Arabia

ARTICLE INFO

Keywords:

Bioelectrochemical systems
UV-Vis spectroscopy
Carbon-based electrodes
Wastewater bioremediation
Nafion 117 membrane
Sustainable energy recovery

ABSTRACT

Textile wastewater, particularly azo dyes, poses significant environmental challenges due to its poor biodegradability and toxicity. This study explores a dual-chamber microbial fuel cell (MFC) for simultaneous wastewater treatment and electricity generation. The MFC consists of an anaerobic anode chamber and an aerobic cathode chamber, separated by a proton exchange membrane (PEM). Electroactive microorganisms in the anode chamber metabolize organic substrates, including azo dye contaminants, breaking them down into simpler by-products. Electrons released during this process flow through an external circuit to generate current, while protons migrate across the PEM to the cathode chamber for oxygen reduction. Electrochemically active microbes were isolated from azo-dye-contaminated soil, and their degradation abilities validated through assays. Optimized carbon-based electrodes and a Nafion 117 PEM were used to enhance conductivity and microbial activity. UV-Vis spectroscopy tracked dye degradation, with the absorbance peak of reactive yellow dye at 410 nm decreasing from 2.9 to 0.4, indicating effective azo-bond cleavage. The MFC achieved peak voltage and current outputs of 0.20 mV and 0.16 mA, respectively, demonstrating its dual functionality. Adding NaCl as a supporting electrolyte further improved ionic conductivity and performance. This study demonstrates MFC technology as a sustainable solution for industrial wastewater challenges, integrating microbial degradation with bioelectricity generation. Future work should address scalability, operational stability, and advanced electrode designs to enhance its practical applications.

Introduction

The scarcity of clean water resources and sustainable energy have become two significant challenges modern worldwide society faces (Kim et al., 2024; Wang and Azam, 2024). With population growth and ongoing industrialisation, the conflict between wastewater treatment demands and the energy consumption required for the corresponding processes has become increasingly pronounced (Duan et al., 2024). This issue harms ecosystems and significantly hinders the achievement of global sustainable development goals (Mehmood et al., 2023; Singh et al., 2023). Among the various sources of industrial effluent, dye wastewater, particularly that containing azo-dyes, is of particular

concern. These pollutants are characterised by their complex chemical structures and poor biodegradability, resulting in high ecological toxicity (Gude, 2016; Yaqoob et al., 2021). If inadequately treated, the discharge of dye wastewater can lead to eutrophication, the accumulation of toxic compounds in aquatic ecosystems, and subsequent threats to human health and biodiversity (Gadore et al., 2024; Kifle et al., 2023).

On top of this context, microbial fuel cells (MFCs) have garnered substantial attention because of their dual potential for wastewater treatment and energy recovery. MFCs are bioelectrochemical systems in which bacteria oxidise organic matter and transfer electrons through electron transport chains to electrode surfaces, generating electricity (Ye et al., 2024). This process utilises microbial metabolic activity and

* Corresponding author.

E-mail addresses: julleytex15@gmail.com (J.N. Ndiva), Simonsokey20@gmail.com (S.O. Eze), godfreynnabuife@yahoo.co.uk (S.G. Nnabuife), neil.kuang@cranfield.ac.uk (B. Kuang), zrana@pmu.edu.sa (Z.A. Rana).

<https://doi.org/10.1016/j.wmb.2025.100195>

Available online 26 March 2025

2949-7507/© 2025 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

leverages bioelectrochemical mechanisms to create a renewable energy source while reducing organic waste. This technology harnesses microbial metabolic activity to degrade organic pollutants into harmless molecules while simultaneously generating electricity (Bajracharya et al., 2015; Zhou et al., 2024). Electricity generation in MFCs relies on the natural cellular respiration processes of exoelectrogenic bacteria, such as *Geobacter sulfurreducens* and *Shewanella putrefaciens*. These bacteria are electro-chemically active and can transfer electrons to anode surfaces, utilising conductive pili and soluble electron shuttles to facilitate electron transfer outside their cells. The setup typically involves an anaerobic anode chamber where microbial oxidation occurs and an aerobic cathode chamber for electron acceptance.

Compared to traditional wastewater treatment methods, MFCs have the advantage of significantly reducing energy consumption and can produce valuable by-products, for example, electrical energy or chemical resources (Wang et al., 2022; Ahmed and Kim, 2024). MFCs have demonstrated the capacity to treat a wide range of pollutants, including heavy metals and organic compounds, through microbial reduction and oxidation processes. Adsorption processes, such as those involving manganese dioxide, have been shown to remove heavy metals from wastewater effectively (Kanungo et al., 2004). Specific microbes, known as electrons, directly accept or transfer electrons to electrodes, enhancing pollutant removal (Wu et al., 2020). For example, *Geobacter* species have been extensively studied for their ability to reduce heavy metals such as chromium and uranium via electrode-based electron transfer mechanisms. Therefore, MFCs are increasingly regarded as a promising solution to the interconnected problems of environmental pollution and energy shortages.

Traditional wastewater treatment methods have many challenges in addressing the increasing effluent, which often relies on energy-intensive physical, chemical, or biological processes, for example, activated sludge systems and chemical oxidation, with energy requirements ranging from 950 to 2850 kJ per cubic metre of water treated (Li et al., 2023; Kim et al., 2024; Gadore et al., 2024). Moreover, the traditional methods are often inefficient in handling complex pollutants, including azo-dyes. They usually require additional chemical inputs or energy, raising operational costs and causing secondary pollution (Singh et al., 2023; Bajracharya et al., 2015). Meanwhile, global energy production still relies heavily on fossil fuels, including oil, natural gas, and coal (Wang and Azam, 2024). These resources are finite, whereas their extraction, transportation, and usage lead to significant amounts of greenhouse gases, exacerbating climate change (Mehmood et al., 2023; Osman et al., 2023). According to portions by the International Energy Agency (IEA), global energy demand is expected to rise to 18 billion tonnes of oil equivalent by 2035, a 50 % increase from the current level of 12 billion tonnes (Ye et al., 2024; Wang and Azam, 2024). The non-renewable nature of fossil fuel reserves underscores the urgent need for alternative, clean, and renewable energy sources.

Thus, developing integrated technologies that can simultaneously utilise wastewater as a resource and recover energy is essential. Addressing these challenges requires tackling multiple technical bottlenecks, including enhancing energy efficiency during pollutant removal and increasing the recovery of chemical energy embedded in wastewater. MFCs, as an emerging bioelectrochemical system, have demonstrated outstanding potential in degrading organic pollutants while recovering electrical energy. The degradation of organic and inorganic pollutants in wastewater using MFCs is achieved through the action of electroactive microbes, often referred to as exoelectrogens. These microbes facilitate the breakdown of pollutants in the anode chamber, releasing electrons that travel through an external circuit to the cathode chamber, where protons react with oxygen to form water. Advanced mechanisms such as long-range electron transfer via conductive pili have been identified as critical for improving the efficiency of electron transport and enhancing power generation. However, there are still significant challenges, including low energy output, difficulties in scaling up, and long-term operational instability (Gude,

2016; Rathinavel et al., 2024). The current focus of researchers and industry lies in exploring high-efficiency and sustainable wastewater treatment and energy recovery solutions, particularly for the practical application of MFCs in handling complex industrial wastewater.

Current research indicates that MFCs can degrade complex organic pollutants in wastewater through microbial metabolism while converting the chemical energy stored in the pollutants into electricity. This dual functionality offers a promising solution for addressing environmental pollution and energy recovery challenges (Bajracharya et al., 2015; Umar et al., 2020). Under controlled laboratory conditions, studies have demonstrated that optimising microbial communities and electrode materials significantly enhances the degradation efficiency of recalcitrant pollutants, including azo-dyes and promotes electrochemical reactions (Yaqoob et al., 2021; Zhou et al., 2024). Moreover, improvements in the conductivity and biocompatibility of specific electrode materials have further validated the feasibility of MFCs at the laboratory scale (Umar et al., 2020; Rathinavel et al., 2024).

However, most of these related studies remain confined to small-scale laboratory settings and lack validation in real-world industrial wastewater scenarios (Gude, 2016; Singh et al., 2023). For instance, industrial effluents containing azo-dyes are known for their high chemical stability and poor biodegradability, presenting significant challenges in wastewater treatment. While existing chemical and physical treatment methods can partially degrade such pollutants, they are often associated with high energy consumption and potential secondary pollution (Rathinavel et al., 2024; Zhou et al., 2024). By contrast, MFCs, with their unique bioelectrochemical mechanisms, can achieve efficient pollutant degradation and simultaneous energy recovery, which can significantly reduce treatment costs and environmental impact. Nonetheless, challenges, including low energy output, long-term operational stability, and the ability to handle complex pollutants, remain critical obstacles to transitioning MFC technology from laboratory research to industrial-scale applications (Singh et al., 2023; Zhou et al., 2024).

Further research is required in several critical areas to enable the large-scale application of MFCs in industrial wastewater treatment. First, an in-depth exploration of the relationship between microbial electron transfer mechanisms and electrode optimisation is essential to improving energy output efficiency (Yaqoob et al., 2021; Zhou et al., 2024). Second, enhancing the degradation efficiency and stability of MFC systems under conditions involving complex pollutants is crucial. Last, designing MFC systems that are better suited to the operational conditions of real-world industrial environments can lay the foundation for their broader industrial adoption. Integrated systems, such as microbial fuel cells combined with constructed wetlands, highlight innovative approaches to enhance wastewater treatment efficiency (Saeed et al., 2022).

This study aims to investigate the degradation efficiency and electricity generation performance of Microbial Fuel Cells (MFCs) in treating industrial wastewater containing azo-dyes. Microbial strains with high electrochemical activity were isolated from contaminated soil and characterised to optimise their catalytic efficiency. A dual-chamber MFC was constructed using carbon-based electrodes and a Nafion 117 proton exchange membrane to enhance system performance. The experimental process included monitoring dye degradation using UV-Vis spectroscopy and recording electrochemical outputs such as voltage and current. Additionally, the study evaluated the effects of operating conditions, including dye concentration and electrode materials, on system efficiency and stability. This research provides experimental evidence and insights for advancing sustainable wastewater treatment and energy recovery technologies.

The technical contributions of this study can be summarised as follows: (i) A novel MFC-based method for the degradation of azo-dye wastewater and simultaneous energy recovery was proposed and validated for its feasibility and effectiveness. (ii) The study systematically analysed the electrochemical mechanisms underlying microbial

degradation of azo-dyes, providing data and theoretical foundations for optimising MFC performance.

(iii) This study explored the practical application potential of MFCs in treating complex industrial wastewater, offering insights for scaling up this technology for industrial use.

The structure of the paper is as follows: Section 2 details the experimental methodology, including microbial screening and MFCs system setup. Section 3 presents the experimental results and analysis, focusing on dye degradation efficiency and electricity generation. The main conclusions and directions for future research are discussed in Section 4.

Method

The methodology of this study is divided into three main parts: microorganism isolation and identification, MFC construction, and experimental measurements. Antimicrobial factors significantly determine microbial activity during isolation and characterisation (Yang et al., 2023). Firstly, microorganisms with high electrochemical activity were isolated and cultivated from contaminated soil samples. To verify their pollutant degradation capabilities, these strains were screened and identified for suitability in degrading azo-dyes through rigorous biochemical tests, including staining and enzymatic activity analyses. Then, a dual-chamber MFC was constructed, incorporating carbon-based electrodes and a Nafion 117 proton exchange membrane to optimise system performance. Carbon-based electrodes, widely utilised for their high conductivity and microbial affinity, play a crucial role in wastewater treatment systems (Jatoi et al., 2024). The anode chamber contained dye wastewater and bacterial cultures, operating under anaerobic conditions, while the cathode chamber was filled with an electron acceptor solution and aerated to facilitate redox reactions. Finally, experimental measurements included using ultraviolet-visible (UV-Vis) spectroscopy to monitor the degradation efficiency of azo-dyes and digital multimeters to record voltage and current outputs from the MFC. The study also evaluated the impact of various operating parameters, including dye concentration, electrode material, and operational duration, on the performance and stability of the system. Fig. 1 illustrates the workflow of the study.

Microorganism isolation and identification

Synthetic dye wastewater preparation

Reactive yellow azo-dye was employed as a representative pollutant to simulate industrial wastewater contamination. In the beginning, 1 g

(g) of the azo dye was dissolved in 1 L (L) of distilled water to prepare synthetic dye wastewater with a concentration of 1000 ppm (1 g/L). Then, 4.5 kg (kg) of loamy soil were collected from a farmland site at a depth of 30 cm (cm) below the surface to ensure uniformity and representativeness. The soil sample was thoroughly mixed with 1L of the synthetic dye wastewater to create contaminated soil, which served as the source for isolating and cultivating target microorganisms.

To separate microorganisms from the contaminated soil, 1 g of soil was dissolved in 99 ml (ml) of distilled water to produce an initial dilution. Serial dilutions were performed by transferring 1 ml of each diluted sample into 99 ml of distilled water, ultimately creating a dilution series up to 10^{-9} . Dilution samples at 10^{-5} , 10^{-7} , and 10^{-9} were inoculated onto three different culture media: Nutrient Agar, MACCONKEY Agar, and Sabouraud Dextrose Agar. The inoculated media were incubated at 25°C for 24 h to promote the growth of bacteria and fungi.

The compositions of the three culture media were as follows:

- Nutrient Agar: 28 g/L, comprising peptone, sodium chloride, beef extract, yeast extract, and agar, adjusted to a pH of 7.4 at 25 °C.
- MacCONKEY Agar: 52 g/L, containing peptone, lactose, bile salts, sodium chloride, agar, and neutral red, adjusted to a pH of 7.4.
- Sabouraud Dextrose Agar: 65 g/L, consisting of dextrose, agar, and mycological peptone, adjusted to a pH of 5.6 at 25°C.

Construction of microbial fuel cells (MFCs)

After incubation, target microbial strains were isolated from the colonies grown on the three culture media. The selected strains were transferred to a mineral salt medium using the streaking method to obtain pure cultures for subsequent experiments. The composition of the mineral salt medium included NH_4NO_3 (1 g/L), K_2HPO_4 (1 g/L), FeSO_4 (1 g/L), MnSO_4 (1 g/L), CaCl_2 (0.1 g/L), and yeast extract (1 g/L). The medium was dissolved in 1 L of sterile water and sterilised by autoclaving at 121°C for 15 min. The isolated strains were then identified through Gram staining, catalase tests, and oxidase tests to determine their classification and electrochemical activity. Ultimately, high-efficiency bacterial strains capable of degrading azo-dyes were obtained, providing high-quality biocatalysts for the construction of microbial fuel cells.

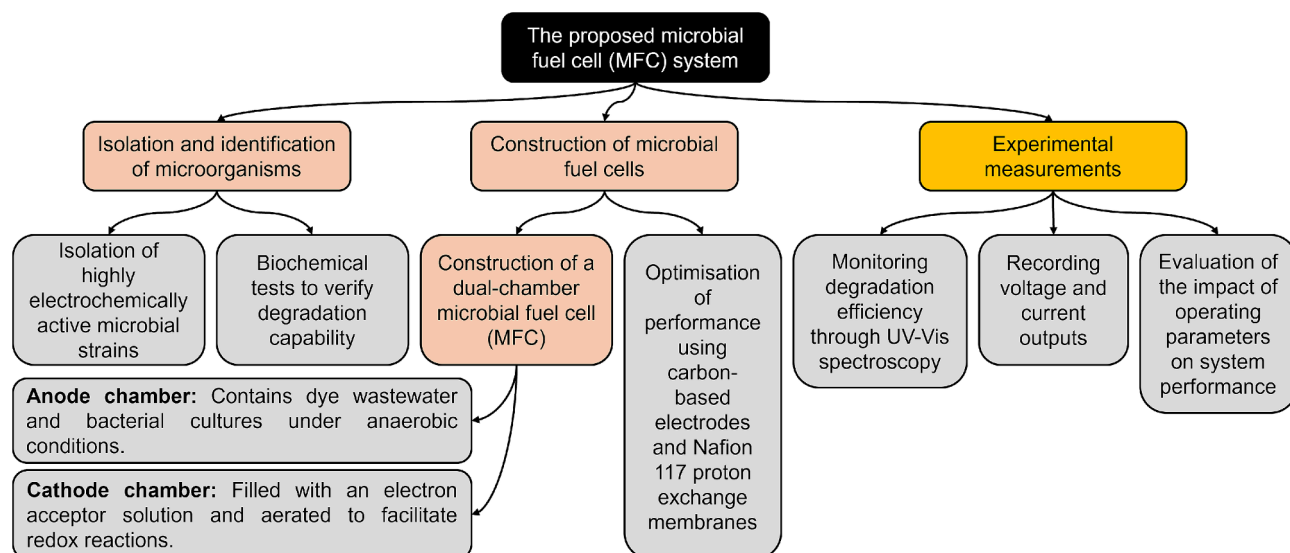


Fig. 1. Overview of the Proposed Microbial Fuel Cell (MFC) System Development and Evaluation Process.

Construction of microbial fuel cells (MFCs)

The microbial fuel cells (MFCs) system was constructed using a dual-chamber design consisting of an anode chamber and a cathode chamber. The anode chamber housed the microbial culture medium, while the cathode chamber contained the electron acceptor solution. The bacterial strains utilised in the anode chamber were those isolated and identified in Section 2.1 for their high electrochemical activity. These strains demonstrated strong azo-dye degradation capabilities and efficient electron transfer properties, serving as the core biocatalysts for pollutant treatment and energy recovery within the MFC system. The construction of the MFC focused on optimising electrode materials, assembling a robust cell structure, and enhancing both conductivity and proton transfer efficiency.

Electrode preparation

The experiment utilised three types of carbon-based electrode materials: graphite plates, carbon felt, and carbon paper, each with a surface area of 16 cm^2 . To enhance the effective surface area, holes with a diameter of 0.1 cm were drilled into each electrode. To ensure optimal conductivity and biocompatibility, the electrode materials underwent a pre-treatment process comprising the following steps:

- Immersion in a 0.5 M (molarity) sulphuric acid (H_2SO_4) solution for 20 min to remove any metallic contaminants.
- Subsequent soaking in deionised water for 24 h further cleansed the electrodes and enhanced their conductive properties.

This pre-treatment was designed to improve the conductivity of the electrode materials and their compatibility with microbial electron transfer, thereby laying the groundwork for optimising the performance of the MFC system.

MFC Assembly

The MFC system utilised a dual-chamber design, with the anode and cathode chambers separated by a Nafion 117 proton exchange membrane. The membrane, measuring 25 cm^2 , underwent a pre-treatment process to enhance its porosity and proton conductivity. This involved sequential boiling in 30 % hydrogen peroxide (H_2O_2), deionised water, 0.5 M sulphuric acid (H_2SO_4), and deionised water, each for one hour. The anode chamber contained 50 mL of bacterial culture and 25 mL of synthetic dye wastewater at a concentration of 50 mg/L , operating under sealed anaerobic conditions. The cathode chamber was filled with 75 mL of 0.1 M potassium permanganate solution as the electron acceptor and was aerated to maintain aerobic conditions. To improve solution conductivity, 5 mL of 0.1 M sodium chloride (NaCl) was added to both the anolyte and catholyte solutions. All openings were sealed with epoxy resin to prevent solution mixing and leakage, ensuring the stable operation of the MFC system.

External circuit

The anode and cathode were connected using copper wires measuring 0.4 m in length and 1.5 mm in diameter, completing the external circuit setup. To enhance contact performance, the connection points between the electrodes and the copper wires were sealed with epoxy resin. After allowing the system to stabilise for 24 h, testing commenced, during which the open circuit voltage (OCV) was recorded. Voltage and current output were measured using a digital multimeter under three parallel resistance conditions: $330\ \Omega$, $100\ \Omega$, and $52\ \Omega$. These measurements were repeated every 12 h, with the experiment running continuously for 25 days to evaluate the long-term stability of the system.

Experimental measurements

This study systematically evaluated the performance of MFCs,

focusing on their efficiency in degrading azo-dye wastewater and generating electricity. The OCV was recorded using a digital multimeter, and voltage and current outputs were measured under three parallel resistance conditions: $330\ \Omega$, $100\ \Omega$, and $52\ \Omega$. These measurements were taken every 12 h over a continuous 25-day period to assess the electrochemical performance and long-term operational stability of the system. Besides, the degradation efficiency of the azo-dye solution was monitored using UV-Vis spectroscopy by tracking changes in absorbance. This allowed for the quantification of degradation rates and the development of dynamic concentration curves to analyse the kinetics of microbial pollutant degradation. The integration of bioelectrochemical systems demonstrates significant potential in energy recovery and pollutant transformation, as shown in related microbial electrosynthesis studies (Le et al., 2024).

The study also explored the effects of various operational parameters on system performance to identify optimisation strategies for improving degradation efficiency and power output. In terms of dye concentration, different initial concentrations were tested to determine their impact on pollutant degradation rates and electrochemical performance. The conductivity and microbial attachment properties of graphite plates, carbon felt, and carbon paper were compared for electrode material selection. Regarding operational duration, the stability of the MFC system was monitored across different time intervals to investigate its potential impact on degradation capacity and power generation. These investigations provided important insights into the limitations of MFC performance and potential optimisation strategies.

The analysis of experimental results revealed the synergistic mechanisms between pollutant degradation and energy recovery in MFCs while also evaluating their stability and adaptability under varying conditions. Notably, a strong correlation was identified between degradation efficiency and electrochemical output, offering valuable theoretical and experimental support for enhancing the applicability of MFCs in industrial wastewater treatment. These findings provide robust data to assess the potential of MFCs and guide further design improvements.

Results and discussion

Isolation and identification of microbial species

Microbial Fuel Cells (MFCs) utilize electroactive microbes to generate electricity from organic substrates. Isolation involves cultivating microbes from environments like wastewater and sludge under MFC-like conditions. Screening identifies electrogenic species via electrochemical tests and substrate utilization assays. Identification uses molecular techniques, such as 16S rRNA sequencing, to characterize microbes, advancing MFC efficiency for renewable energy and wastewater treatment applications.

The experiment aimed to isolate, identify, and characterise microbial strains capable of degrading reactive yellow dye and generating electricity. This aligns with (Yaqoob et al., 2021) (Yaqoob et al., 2021). The microbial strains that seemed to thrive in azo-dye-contaminated soil were subjected to biochemical tests: oxidase, catalase, and gram staining. Seventeen (17) microbial strains with different morphological and cultural characteristics were identified and assigned the numbers MO 1 to MO 6 and CR 1 to CR 11. A total of 17 microbial strains with distinct morphological and cultural characteristics were isolated and characterised (Table 1). These included bacteria (for example, *Bacillus Megatrium* and *Lactobacillus delbrueckii*) and fungi (for example, *Aspergillus flavus* and *Aspergillus Miger*). The % of similarities of the bacteria and fungi strains isolated from azo dye-contaminated soil were gotten using molecular sequencing methods (e.g., 16S rRNA for bacteria or ITS regions for fungi).

Table 1

Bacterial and fungal isolates identified from azo-dye-contaminated soil and their % similarities.

Isolate Code	Isolate Name	Type	(%)Similarity
CR1	<i>Bacillus Megatrium</i>	Bacteria	98 %
CR2	<i>Lactobacillus delbrueckii</i>	Bacteria	96 %
CR3	<i>Bacillus sphaericus</i>	Bacteria	97 %
CR4	<i>Pseudomonas</i> sp.	Bacteria	95 %
CR5	<i>Bacillus lentus</i>	Bacteria	99 %
CR6	<i>Erwinia</i> sp.	Bacteria	96 %
CR7	<i>Bacillus pumilus</i>	Bacteria	97 %
CR8	<i>Aspergillus flavus</i>	Fungi	98 %
CR9	<i>Aspergillus Miger</i>	Fungi	97 %
CR10	<i>Rhizopus stonolifer</i>	Fungi	97 %
CR11	<i>Fusarium</i> sp.	Fungi	95 %
MO1	<i>Kurthia species</i>	Bacteria	96 %
MO2	<i>Bacillus</i> sp.	Bacteria	98 %
MO3	<i>Serratia</i> spp.	Bacteria	96 %
MO4	<i>Bacillus pumilus</i>	Bacteria	97 %
MO5	<i>Aspergillus Fumigatus</i>	Fungi	96 %
MO6	<i>Fusarium</i> sp.	Fungi	95 %

Ultraviolet–Visible studies

In order to investigate the dye degradation and decolourisation as well as visualise the changes in the absorption spectra and the peaks and valleys corresponding to the chromophores contained in the reactive yellow dye compound, a full wavelength scan utilising an ultraviolet–visible spectrophotometer is crucial. Due to their capacity to absorb light, chromophore groups and conjugate bonds can be found using the ultraviolet–visible studies approach. The spectrophotometer used is called the Shimadzu uv-3600 manual.

Fig. 2 illustrates the UV–Vis absorption spectra of reactive yellow dye, with a significant reduction in the absorbance peak at 410 nm from 2.9 to 0.4 after 7 days of microbial oxidation counting for the overall Azo dye removal efficiency of 86.20 %. A new peak at 325.5 nm with an absorbance of 1.1 indicates the fragmentation of the dye's molecular structure, resulting in simpler, smaller molecules. The result obtained from the UV Vis absorption spectra graph shows that the absorbance peak of the reactive yellow dye at 410 nm decreased from 2.9 to 0.4 after 7 days of microbial oxidation, indicating the degradation of azo bonds ($-N=N-$) and chromophore groups. This bathochromic shift, characterised by a new absorption peak at 325.5 nm with an intensity of 1.1, suggests the fragmentation of the dye into smaller, simpler molecules.

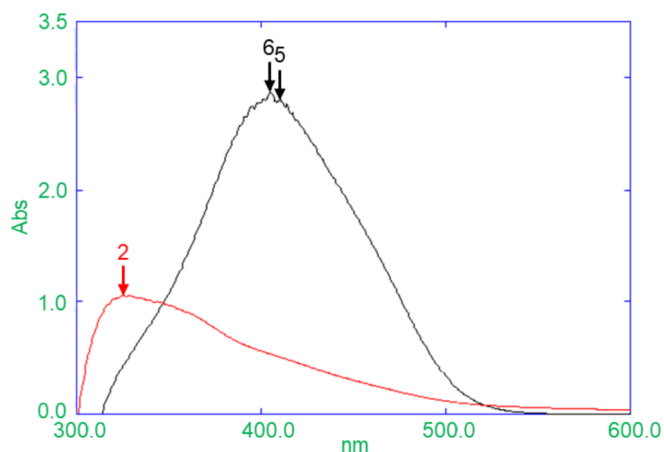


Fig. 2. illustrates the UV–Vis absorption spectra of reactive yellow dye, with a significant reduction in the absorbance peak at 410 nm from 2.9 to 0.4 after 7 days of microbial oxidation. A new peak at 325.5 nm with an absorbance of 1.1 indicates the fragmentation of the dye's molecular structure, resulting in simpler, smaller molecules. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This observation aligns with findings from Khandare *et al.* (2015) (Khandare and Govindwar, 2015).

The decrease in the intensity of the band from 2.9 to 0.4 at a wavelength of 410 and the new peak of 1.1 formed at a wavelength of 325.5 nm are suggestive that the large dye structure consisting of the azo bonds ($-N=N-$) and the multiple aromatic ring compounds present in the reactive yellow dye had fragmented into smaller and simpler molecules during the microbial oxidation in the anode chamber of the microbial fuel cell. A similar result has been reported by Khandare *et al.* (2015) (Khandare and Govindwar, 2015).

While the observed degradation mechanisms and spectral shifts align with the enzymatic processes described by Khandare *et al.* (2015) (Khandare and Govindwar, 2015), this study extends its findings by demonstrating the application of these principles in a dual-chamber microbial fuel cell. This setup enables simultaneous dye degradation and energy recovery, highlighting its potential for practical bio-electrochemical applications. Advancements in biosystem- engineering, including plant microbial fuel cells, offer promising pathways for scalable and sustainable applications of MFC technology (Nitisoravut and Regmi, 2017).

Electricity generation from microbial fuel cell

The microbial fuel cell (MFC) was designed to enhance ionic activity and conductivity using sodium chloride (NaCl) as the electrolyte (Fig. 3). NaCl facilitates the mass transfer of charged particles and boosts solution conductivity, thereby enhancing power output by increasing the ionic strength of both anolyte and catholyte solutions (Gil *et al.*, 2003). The voltage and current outputs were recorded under open circuit conditions over an 8-day period to evaluate the bioelectrochemical performance of the MFC (Fig. 4). The voltage and current outputs were initially low, measured as 0.11 mV (Fig. 5) and 0.13 mA (Fig. 6), respectively. A significant increase in both parameters was observed on the sixth day, reaching peak values of 0.20 mV and 0.16 mA. This improvement coincided with the acclimatisation of the microbial community to the carbon cloth anode.

The observed increase in voltage and current corresponds to the exponential growth phase of electrogens, where microorganisms efficiently oxidised the organic matter in the reactive yellow dye wastewater. This phenomenon is consistent with previous findings by Logan *et al.* (2007) (Logan *et al.*, 2006); which emphasise that bacterial colonisation of electrodes and enzyme production for electron transfer requires time. However, as the 8-day experimental period concluded, a decline in voltage and current was noted. This was attributed to the depletion of organic substrates and the accumulation of toxic by-products, which hindered microbial activity and promoted inter- and intra-species competition (Peleg, 2006). These findings underscore the need for strategies to maintain consistent substrate availability and mitigate by-product accumulation to ensure sustained MFC performance.

Conclusion and future works

This study successfully investigated the potential of double-chamber microbial fuel cells (MFCs) to address two critical global challenges: wastewater pollution and energy shortages. By employing a carefully constructed MFC system, high-electrochemical-activity microbial strains were isolated and utilised to degrade azo dye pollutants while generating electricity. Quantitative findings revealed that the system achieved significant dye degradation, with absorbance peaks reducing from 2.9 to 0.4 and electricity generation peaking at 0.20 mV and 0.16 mA under optimised conditions. Qualitatively, the study highlighted the synergistic relationship between microbial growth, organic pollutant degradation, and electricity output.

This research makes several notable contributions. First, it demonstrated that microbial strains can simultaneously degrade bio-refractory

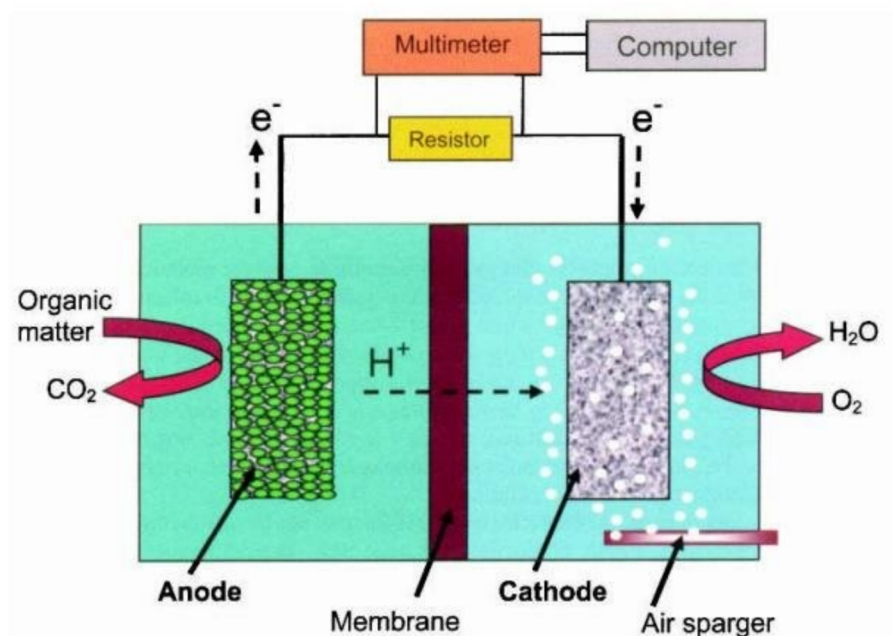


Fig. 3. Schematic set up showing MFC configuration used in the study.

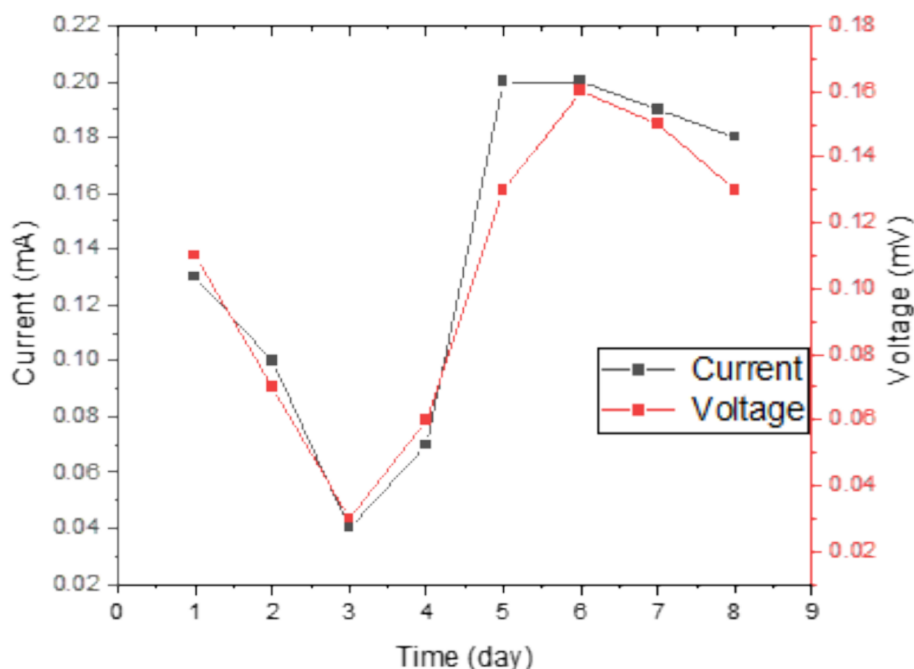


Fig. 4. Combined current and voltage output from MFC over 8 days (mA and mV).

pollutants, such as azo dyes, and generate electricity. This finding provides new insights into the capabilities of microbial communities and expands the potential applications of MFCs. The study further identified that specific operating conditions, including the presence of NaCl electrolytes, aeration in the cathode chamber, and initial dye concentration, significantly enhance both degradation and electricity generation. These optimisations pave the way for practical improvements in MFC performance. Lastly, by exploring the potential of connecting individual fuel cells in series, the study offers a pathway to scale the technology for higher power outputs.

MFC technology offers a promising solution for sustainable wastewater treatment and renewable energy generation. It can be applied in

industrial settings, municipal wastewater treatment plants, and remote areas lacking conventional energy infrastructure. Furthermore, the ability of MFCs to handle bio-refractory pollutants positions this technology as a complementary or alternative solution to existing biological treatment methods. However, this study has certain limitations. While it demonstrated the feasibility of MFCs in controlled laboratory conditions, real-world applications may face challenges such as long-term stability, scale-up difficulties, and cost-effectiveness. Future research should focus on exploring more efficient microbial strains, durable and cost-effective electrode materials, and improved system designs to enhance performance and sustainability. Additionally, understanding the effects of environmental variables, such as temperature and pH

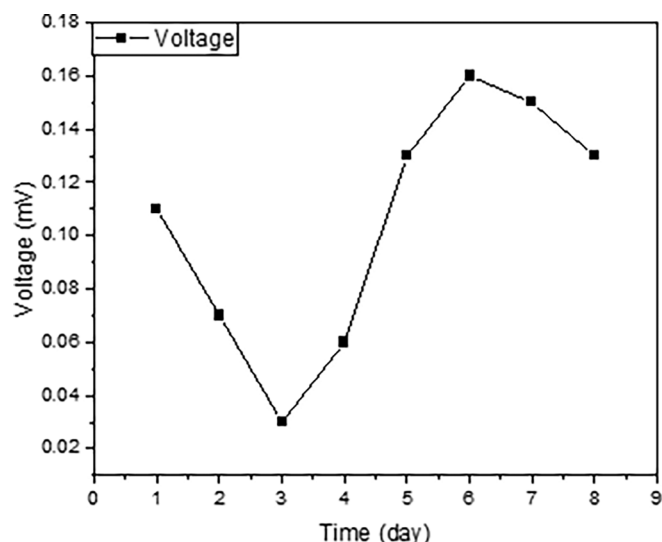


Fig. 5. Voltage output from MFCs over 8 days (mV).

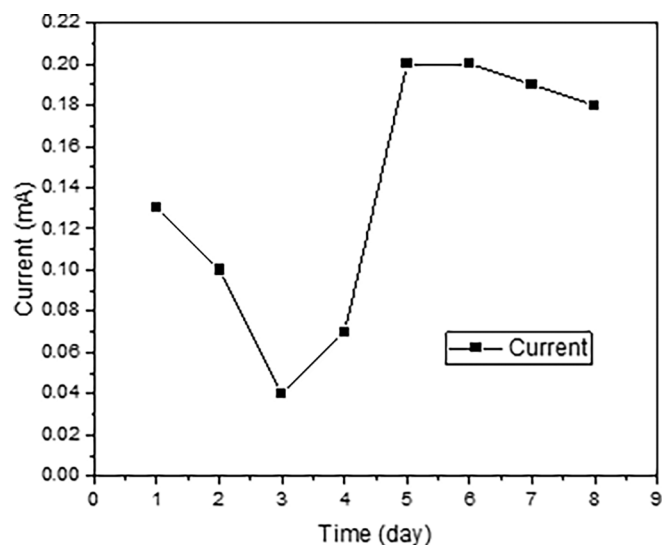


Fig. 6. Current output from MFC over 8 days (mA).

fluctuations, on MFC efficiency could further optimise its application.

Funding information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to improve language and readability with caution. After using this tool/service, the author(s) reviewed and edited the content as needed and took (s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Julius Nnamdi Ndivé: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Simeon Okechukwu Eze:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Somtochukwu Godfrey Nnabuife:**

Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration. **Boyu Kuang:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration. **Zeeshan A. Rana:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge the Department of Chemical Engineering, Chukwuemeka Odumegwu Ojukwu University and the Department of Chemical Engineering, Nnamdi Azikiwe University, Awka, all the equipment and some chemicals utilised throughout this research study.

Data availability

Data will be made available on request.

No new data were created or analysed during this study. Data sharing is not applicable to this article.

References

- Kim, H., Kim, S., Park, C., 2024. Advancements and challenges in ceramic membranes incorporating two-dimensional nanomaterials for semiconductor wastewater treatment: A critical review. *J. Water Process Eng.* 68, 106308.
- Wang, J., Azam, W., 2024. Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries. *Geosci. Front.* 15 (2), 101757.
- Duan, Y., Xi, H., Qin, Z., Guo, R., Wang, F., Yuan, Y., 2024. Water quality characteristics of municipal wastewater treatment plants and the prospect of reclaimed water utilisation in lower-middle-income and water-scarce areas: A case study of buying. *Water Cycle*.
- Mehmood, A., Hanif, M.A., AlMasoud, N., Alomar, T.S., Jilani, M.I., 2023. Removal behaviour and mechanisms of reactive dyes from aqueous streams using engineered nanocomposites of Barona marble waste. *Desalin. Water Treat.* 298, 141–154.
- Singh, B.J., Chakraborty, A., Sehgal, R., 2023. A systematic review of industrial wastewater management: Evaluating challenges and enablers. *J. Environ. Manage.* 348, 119230.
- Gude, V.G., 2016. Wastewater treatment in microbial fuel cells—an overview. *J. Clean. Prod.* 122, 287–307.
- Yaqoob, A.A., Ibrahim, M.N.M., Umar, K., Parveen, T., Ahmad, A., Lokhat, D., Setapar, S.H.M., 2021. A glimpse into the microbial fuel cells for wastewater treatment with energy generation. *Desalin. Water Treat.* 214, 379–389.
- Gadore, V., Mishra, S.R., Yadav, N., Yadav, G., Ahmaruzzaman, M., 2024. Advances in zeolite-based materials for dye removal: Current trends and future prospects. *Inorg. Chem. Commun.* 112606.
- Kifle, T., Alemayehu, E., Dereje Kitila, C., 2023. Development of microbial fuel cell for wastewater treatment and electricity generation using domestic wastes. *Environm. Health Eng. Manage. J.* 10 (3), 273–279.
- Ye, Y., Shi, H., Lu, Y., Liao, Y., Lin, S., Luo, H., 2024. Enhanced electricity generation of a 1.2-l microbial fuel cell with acclimation of applied voltage. *Water Cycle* 5, 156–166.
- Bajracharya, S., ter Heijne, A., Benetton, X.D., Vanbroekhoven, K., Buisman, C.J., Strik, D.P., Pant, D., 2015. Carbon dioxide reduction by mixed and pure cultures in microbial electrosynthesis using an assembly of graphite felt and stainless steel as a cathode. *Bioresour. Technol.* 195, 14–24.
- Zhou, Y., Zheng, S., Qin, W., 2024. Electrochemical biochemical oxygen demand biosensors and their applications in aquatic environmental monitoring. *Sens. Bio-Sens. Res.* 100642.
- Wang, J., Ren, K., Zhu, Y., Huang, J., Liu, S., 2022. A review of recent advances in microbial fuel cells: Preparation, operation, and application. *Biotech* 11 (4), 44.
- Ahmed, J., Kim, S., 2024. Polyaniline nanofiber: an excellent anode material for microbial fuel cells. *RSC Adv.* 14 (46), 34498–34503.
- Kanungo, S.B., Tripathy, S.S., Mishra, S.K., Sahoo, B., et al., 2004. Adsorption of CO_2 , Ni^{2+} , Cu^{2+} , and Zn^{2+} onto amorphous hydrous manganese dioxide from simple (1–1) electrolyte solutions. *J. Colloid Interface Sci.* 269 (1), 11–21.
- Wu, G., Yin, Q., Guo, F., Hu, Z., 2020. Slow growers possess a high pollutant removal potential through granule formation for wastewater treatment. *Water Cycle* 1, 63–69.
- Li, W., Liu, H., Deng, L., Zhang, Y., Ma, Y., Chen, Y., 2023. Recent advances in treatment refinement of kitchen digested wastewater: Feasibility, prospects, and technicalities. *Water Cycle*.

- Osman, A.I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D.W., Yap, P.-S., 2023. Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ. Chem. Lett.* 21 (2), 741–764.
- Ye, H., Hu, Z., Yin, R., Boyko, T.D., Liu, Y., Li, Y., Li, C., Lu, A., Li, Y., 2024. Electron transfer at birnessite/organic compound interfaces: mechanism, regulation, and two-stage kinetic discrepancy in structural rearrangement and decomposition. *Geochim. Cosmochim. Acta*.
- Rathinavel, N., Samuel, J.O.E., Veleeswaran, A., Nallathambi, S., Ponnuchamy, K., Muthusamy, G., Raja, R., Ramalingam, K.R., Alagarsamy, A., 2024. Exploring the key factors enhancing the microbial fuel cell performance. *Process Saf. Environm. Protect.*
- Umar, M.F., Abbas, S.Z., Mohamad Ibrahim, M.N., Ismail, N., Rafatullah, M., 2020. Insights into advancements and electrons transfer mechanisms of electrogens in benthic microbial fuel cells. *Membranes* 10 (9), 205.
- Saeed, T., Miah, M.J., Yadav, A.K., 2022. Free-draining two-stage microbial fuel cell integrated constructed wetlands development using biomass, construction, and industrial wastes as filter materials: Performance assessment. *Chem. Eng. J.* 437, 135433.
- Yang, H., Yeom, W., Oh, J., Kim, H., Beuchat, L.R., Ryu, J.-H., 2023. Antimicrobial effects of essential oil vapors on *Bacillus cereus* on nutrient agar and iceberg lettuce. *Food Biosci.* 53, 102580.
- Jatoi, A.S., Hashmi, Z., Usman, T., Mubarak, N.M., Mazari, S.A., Karri, R.R., Koduru, J.R., Dehghani, M.H., 2024. Role of carbon nanomaterials for wastewater treatment—a brief review. *Water Treatm. Using Eng. Carbon Nanotubes* 29–62.
- Le, G.T., Mohamed, H.O., Kim, H., Yoo, K., Eisa, T., Jadhav, D.A., Nguyen, H.T., Eam, H., Myung, J., Castano, P., et al., 2024. Microbial symbiotic electrobioconversion of carbon dioxide to biopolymer (poly (3-hydroxybutyrate)) via single-step microbial electrosynthesis cell. *Chem. Eng. J.* 500, 156635.
- Khandare, R.V., Govindwar, S.P., 2015. Phytoremediation of textile dyes and effluents: current scenario and future prospects. *Biotechnol. Adv.* 33 (8), 1697–1714.
- Nitisoravut, R., Regmi, R., 2017. Plant microbial fuel cells: A promising biosystems engineering. *Renew. Sustain. Energy Rev.* 76, 81–89.
- Gil, G.-C., Chang, I.-S., Kim, B.H., Kim, M., Jang, J.-K., Park, H.S., Kim, H.J., 2003. Operational parameters affecting the performance of a mediator-less microbial fuel cell. *Biosensors Bioelectron.* 18 (4), 327–334.
- Logan, B.E., Hamelers, B., Rozendal, R., Schroder, U., Keller, J., Freguia, S., Aelterman, P., Verstraete, W., Rabaey, K., 2006. Microbial fuel cells: methodology and technology. *Environm. Sci. Technol.* 40 (17), 5181–5192. <https://doi.org/10.1021/es0605016>.
- Peleg M, Advanced quantitative microbiology for foods and biosystems: models for predicting growth and inactivation, CRC Press, 2006.



DSPACE

<https://dspace.org/>

Dual-Chamber microbial fuel cell for Azo-Dye degradation and electricity generation in Textile wastewater treatment

Ndive, Julius N.; Eze, Simeon Okechukwu; Nnabuike, Somtochukwu Godfrey; Kuang, Boyu; Rana, Zeeshan A.

2025-09

Elsevier

<https://doi.org/10.1016/j.wmb.2025.100195>

Ndive JN, Eze SO, Nnabuike SG, et al., (2025) Dual-Chamber microbial fuel cell for Azo-Dye degradation and electricity generation in Textile wastewater treatment. Waste Management Bulletin, Volume 3, Issue 3, September 2025, Article number 100195