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Green Solutions using Microbial Fuel Cells for Dye Wastewater Treatment and Bioelectricity Generation

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ABSTRACT

With scientific progression and technological advancements, the newly industrialized world has become increasingly dependent on water use. However, water, a fundamental necessity of life, is being polluted through various means, often returning to the environment carrying hazardous substances that pose serious health risks. Implementing a proper sanitation system is crucial for treating contaminated water and ensuring it is safe for human consumption. Microbial fuel cell (MFC) technology can serve as a low-cost and eco-friendly alternative to current wastewater treatment methods and is gaining traction among modern community planners due to its dual function as both a wastewater treatment and power generation system. Bangladesh, regarded as a haven for textile manufacturing businesses, hosts a large number of garment factories that produce a substantial amount of dyeing wastewater containing high levels of chemical pollutants. This study has been designed to develop a microbial fuel cell (MFC) for treating dyeing wastewater generated by Bangladeshi garment industries, while simultaneously producing bioelectricity. A remarkable BOD and COD removal efficiency of 81.57% and 84.38%, respectively, was achieved. The maximum voltage generated was 1.4 volts during the first hour, which gradually decreased over time due to a decline in microbial activity.

Keywords: Microbial Fuel Cell (MFCs), Salt Bridge, COD, BOD, Bioelectricity, Wastewater Treatment.

Nomenclature:

Symbols/Subscripts	Meaning
MFC	Microbial Fuel Cell
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
pH	Potential of Hydrogen
V	Voltage (Volt)
A	Ampere (Current)
mg/L	Milligram per Liter
NaOH	Sodium Hydroxide
Na_2SO_4	Sodium Sulfate
Pb	Lead (Heavy Metal)
ETP	Effluent Treatment Plant
SEM	Scanning Electron Microscopy

1 INTRODUCTION

The contamination of water is a global concern and contributes to acute health diseases around the world. It is also a major concern for Bangladesh, as approximately 8.5% of the total number of deaths occur due to water-related diseases, many of which are children [1]. Nearly 135 million people are to be affected by water-related diseases [2]. Diarrhea alone is responsible for the deaths of 1.8 million people annually [3]. Cholera accounts for 95000 deaths each year [4]. The morbidity and mortality rates in subcontinental countries such as India, Pakistan, and Bangladesh are alarmingly high due to waterborne diseases like leptospirosis, typhoid, and rotavirus disease [5].

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Water and sanitation systems have become essential for modern communities to maintain hygiene. According to [6, 7], approximately 1.1 billion people worldwide still lack access to proper sanitation systems, with Bangladesh alone accounting for 75.4 million people, making them particularly vulnerable to diseases. In the developing countries, almost 90% of the wastewater is released readily to the environment without any treatment [8]. The physicochemical properties of wastewater in Bangladesh typically range from pH 3.9–14, BOD 10–786 mg/L, and COD 41–2430 mg/L, levels that are harmful enough to pose a serious threat to the aquatic ecosystem if discharged untreated [9]. Wastewater from textile industries is loaded with a wide variety of harmful chemicals, including lubricants, alkaline agents like NaOH, Na_2SO_4, nitrogen-based compounds such as NH_3, sulfur-containing ions S_2-, toxic elements like Pb, and other heavy metals. Very few industries in Bangladesh have ETP, which can be used to treat wastewater [10].

Microbial fuel cells (MFCs) utilize microorganisms that generate electricity through metabolic processes using various organic wastes [11–15]. Although this technology is still in its early stages, it requires significant research and development to be widely adopted at an industrial scale [16]. The simultaneous generation of clean electricity and wastewater treatment makes it particularly appealing to users [17, 18]. As the world transitions from fossil fuels to renewable energy sources, MFC technology holds great potential for future scientific breakthroughs.

As textile dyeing industries fall in the "red industry" category according to the Bangladesh Environment Conservation Act-1995, they are mandatorily required to install ETPs combined with their industrial facility [19]. The ETPs that are used in Bangladesh have a percentage removal efficiency for BOD and COD of 87.24% and 90.5%, respectively [20]. ETPs consume a huge amount of electricity, which is seen as a burden to the company, making the policymakers reluctant to install and operate an ETP along with the industrial facility. In contrast to it, microbial fuel cells can produce electricity from the wastewater while treating it, making it more profitable than ETPs [21]. Furthermore, the electricity produced by this process is also eco-friendly, making the technology both economically and environmentally sustainable. As noted by [22], a microbial fuel cell with a double chamber mechanism and a flow rate of 54 m^3/day with a COD removal efficiency of 40 − 90% may have a capital cost of USD10000. This capital cost can easily be reimbursed if the MFC is operated for a long time.

Nafion is commercially used as a proton exchange membrane in MFCs due to its high efficiency, but its high cost makes it impractical for use in developing countries like Bangladesh, where the per capita income is below average [23]. The cost of the proton exchange membrane could be as high as 40% of the total cost of a finished MFC [24]. In this experiment, by addressing this issue, a salt bridge from the agar solution was used as a medium for proton exchange between the anodic and cathodic chambers. This approach helped reduce the overall cost of the cell while still achieving notable BOD and COD removal efficiencies compared to the maximum achievable values. This work aims to maximize pollutant removal efficiency while keeping costs as low as possible, primarily for the wastewater produced by local dyeing industries.

2 EXPERIMENTAL METHODS

2.1 Sample Collection

Textile wastewater samples were collected from Emon Fashion Ltd. (EFL), located in Gazipur, Dhaka, Bangladesh, a facility selected for this study due to the complex composition of its effluents, which typically contain dyes, surfactants, heavy metals, and other organic pollutants that pose challenges to conventional treatment systems. The exterior of the facility is shown in Figure 1(a). Wastewater samples were collected directly from the designated effluent discharge point, as illustrated in Figure 1(b). Before sampling, all collection containers were thoroughly rinsed with deionized water to eliminate the risk of contamination and ensure the reliability of analytical results. Sampling points were carefully chosen based on the operational layout of the treatment units and discharge locations to obtain representative samples for wastewater characterization and treatment performance evaluation.

(a) (b)

Figure 1: (a) Exterior of Emon Fashion Ltd. (EFL), Gazipur, Dhaka, Bangladesh, selected as the textile wastewater sampling site. (b) Collection of textile effluent samples at the discharge point using a pre-rinsed sampling jar to ensure accuracy and representativeness.

2.2 Experimental Setup

A laboratory-scale microbial fuel cell (MFC) was designed to evaluate its performance in treating textile industry wastewater. The MFC consisted of dual polypropylene chambers (3 L capacity each) serving as the anode and cathode compartments. The chamber dimensions are shown in Figure 2(a), and graphite electrodes used as current collectors are shown in Figure 2(b).

An anode and cathode chamber were connected by a salt bridge, which is used to facilitate ion transportation. In the anode chamber, bacteria break down organic matter, which releases electrons that travel through an external circuit to the cathode. This process not only generates electricity but also helps clean the wastewater. A salt bridge was prepared by dissolving 3% agar in 1 M KCl, boiling the solution for two minutes, and casting it into a PVC tube. The completed salt bridge was refrigerated before use and is illustrated in Figure 3. The bridge connected the two chambers to facilitate the transfer of ions.

In the anode chamber, microbial oxidation of organic matter released electrons, which were transferred via an external copper wire to the cathode. A multimeter was connected in the circuit to measure voltage and current. A schematic diagram of the MFC configuration and a photograph of the constructed system are presented in Figure 4.

Figure 2: Structural components of the microbial fuel cell: (a) Dimensions of the anode and cathode containers. (b) Graphite electrodes as anode and cathode, with labeled dimensions and polarity.

Figure 3: Salt bridge assembly for ion transport between chambers: (a) Side view of the salt bridge. (b) Front view of the salt bridge showing cross-section.

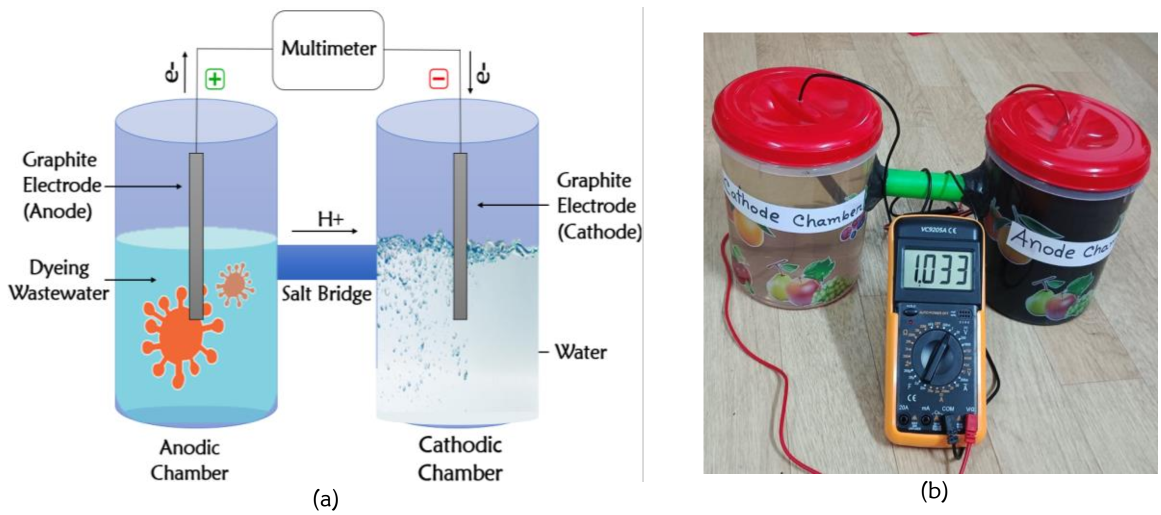

Figure 4: Design and assembly of the microbial fuel cell: (a) Schematic diagram of the dual-chamber MFC with electrodes, salt bridge and external circuit. (b) Photograph of the constructed MFC setup, showing the anode and cathode chambers, salt bridge, and electrical connections.

3 RESULTS AND DISCUSSIONS

3.1 Scanning Electron Microscopy (SEM) Analysis

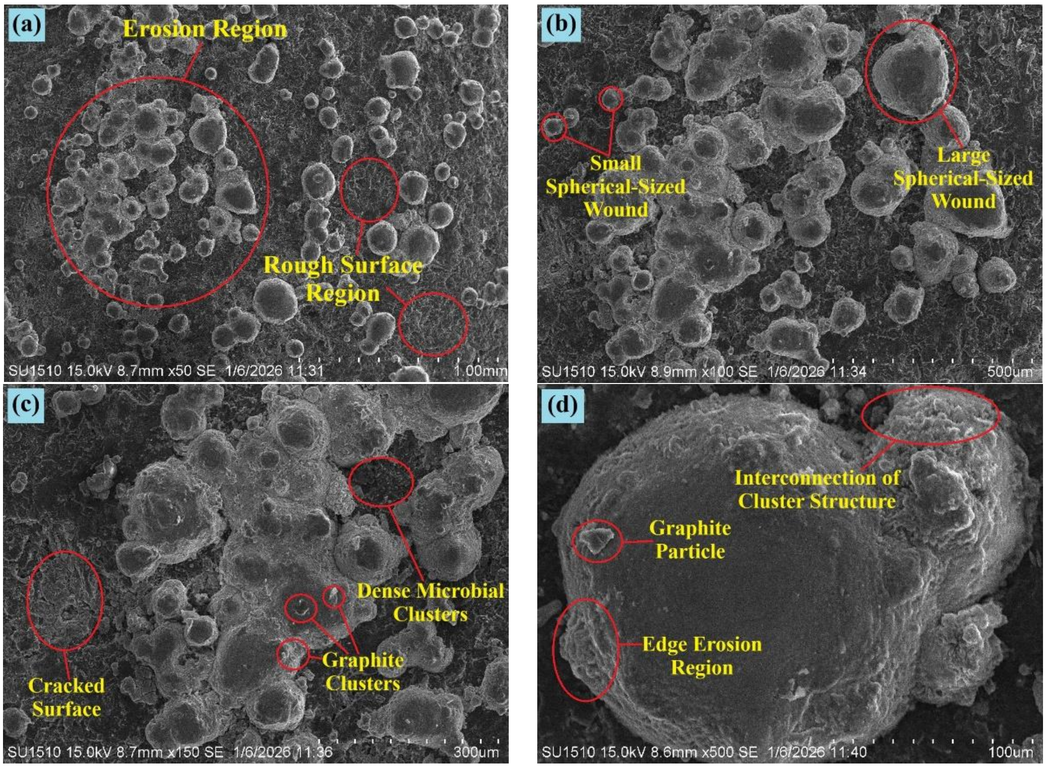

Figure 5: SEM micrograph erosion of graphite anode rod after use in MFC fuel cell at (a) 50x, (b) 100x, (c) 150x, (d) 500x magnification.

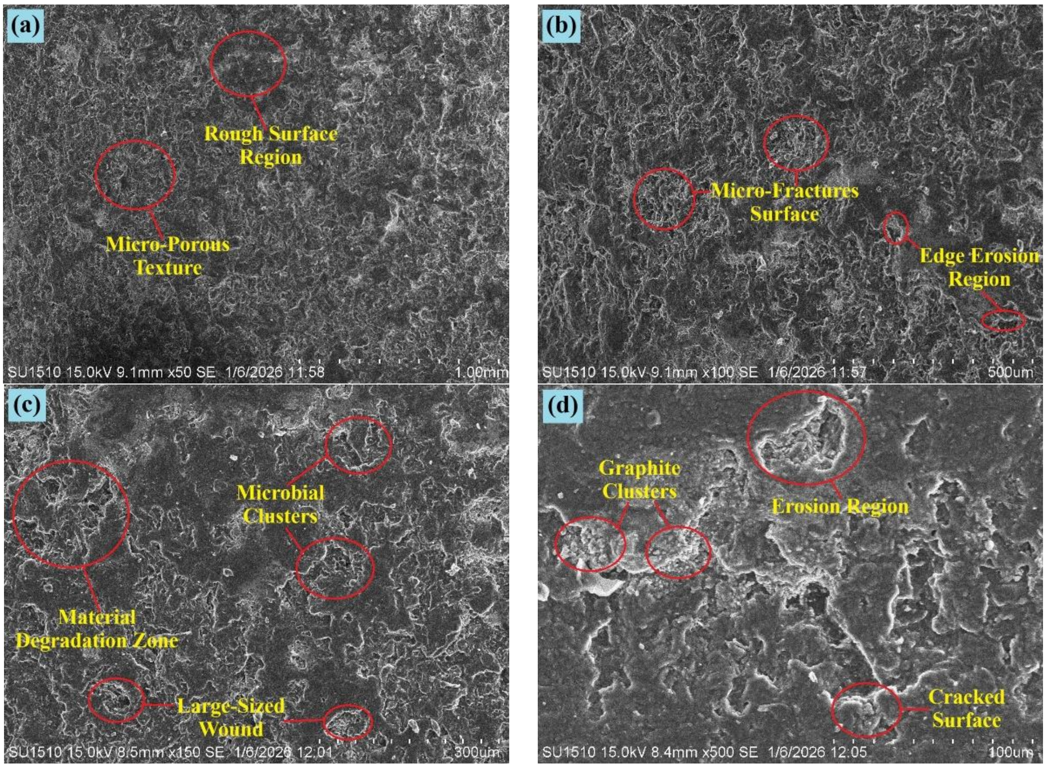

Figure 6: SEM micrograph erosion of graphite cathode rod after use in MFC fuel cell at (a) 50x, (b) 100x, (c) 150x, (d) 500x magnification.

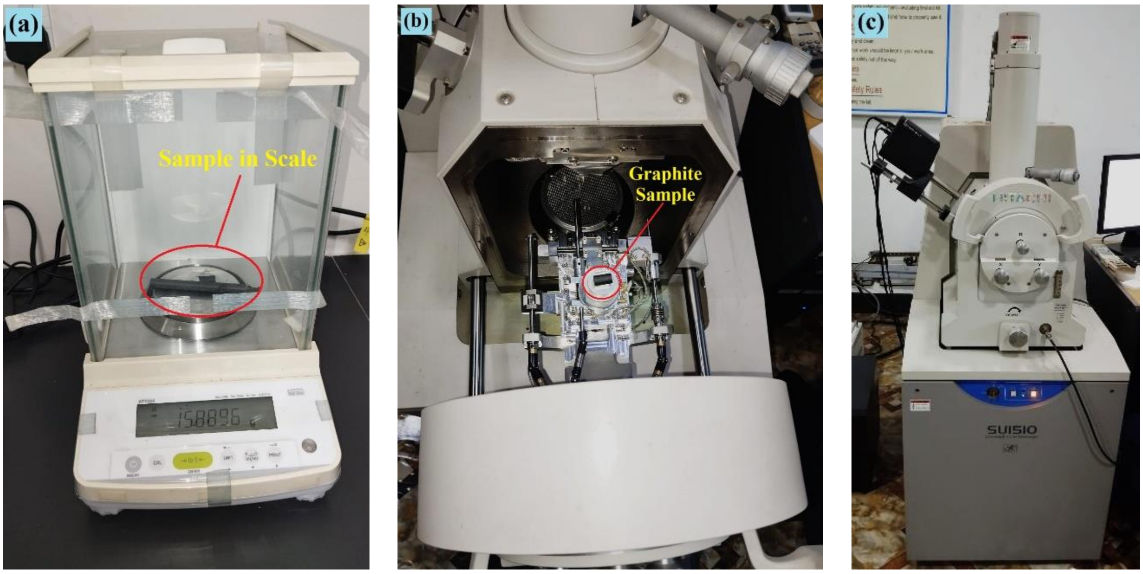

Figure 7: SEM micrograph of anode and cathode; (a) High precision weighing scale, (b) SEM machine, (c) Sample inside the SEM machine.

The structural integrity and surface characteristics of the graphite electrodes were analyzed using Scanning Electron Microscopy (SEM) to evaluate the physical impact of the 14-day microbial fuel cell operation. As detailed in Figure 7, the characterization workflow involved high-precision weight measurement of the sample on a scale to track mass loss, shown in Figure 7 (a), followed by the positioning of the sample within the SEM vacuum chamber for microscopic inspection, displayed in Figure 7 (b) and Figure 7 (c). Anode characterization in Figure 5 revealed a complex, textured landscape at magnifications ranging from 50x to 500x, where prominent graphite clusters and irregular protrusions indicated robust microbial colonization and the successful establishment of an electroactive biofilm, essential components for the oxidation of organic pollutants and efficient electron transfer. In contrast, the cathode micrographs in Figure 6 depicted significant physical degradation, with distinct erosion regions and an overall rough surface resulting from continuous electrochemical reduction reactions and prolonged exposure to hazardous dyeing wastewater constituents, such as NaOH and heavy metals (Pb). This observed surface degradation underscores the intense chemical environment the cathode must withstand to facilitate the completion of the electrochemical circuit while maintaining system performance.

3.2 Wastewater Treatment

The implementation of Microbial Fuel Cells (MFCs) has proven to be highly effective in mitigating the pollutants present in dyeing wastewater. A comprehensive analysis was conducted by measuring the concentrations of pollutants both before and after the MFC treatment process, revealing a substantial reduction in their levels. The recorded data, as illustrated in the table below, underscores the noteworthy impact of the MFC process on various parameters. The pH level demonstrated a reduction of 0.18 units, indicating the positive influence of MFCs on optimizing the wastewater's acidity. Furthermore, the Chemical Oxygen Demand (COD) exhibited a remarkable decrease of 273 units, while the Biochemical Oxygen Demand (BOD) saw a significant reduction of 144 units. These findings highlight the MFC's ability to reduce organic and chemical contaminants in wastewater. Perhaps most notably, the Dissolved Oxygen (DO) content exhibited a substantial increase of 4.33 mg/L post-MFC treatment. This enhancement in oxygen availability is a crucial indicator of improved water quality, suggesting a more conducive environment for aquatic life. In summary, the observed changes in pH, COD, BOD, and DO underscore the efficacy of the MFC process in substantially reducing pollutants and enhancing the overall quality of dyeing wastewater. These results contribute to the growing body of evidence supporting the viability and efficiency of MFCs in sustainable wastewater treatment applications.

Table 1: Typical pollutant concentrations before and after MFC treatment and corresponding removal efficiency

Parameter	Before MFC (mg/L)	After MFC (mg/L)	Removal (%)
pH	6.89	6.71	2.61
COD	448	70	84.38
BOD	190	35	81.57
Dissolved Oxygen (DO)	1.35	5.68	--

Typical pollutant concentrations before and after microbial fuel cell (MFC) treatment, showing significant reductions in COD and BOD levels and a minor pH adjustment in Figure 8. Removal efficiencies are displayed in a graph for each parameter.

3.3 Electricity Generation

The main objective of the experiment was to eliminate pollutants from the dyeing wastewater. However, during the process, electricity was generated from the substrate through MFC. A multimeter was attached to the electrical circuit between the anode and cathode to measure the electricity generation. The graph that was obtained shows the gradual reduction in voltage generation with time. The voltage generated during the first hour on the first day was 1.04 V, but by the 312^{th} hour, the voltage generation had decreased to almost zero in 14 days, as shown in Figure 9.

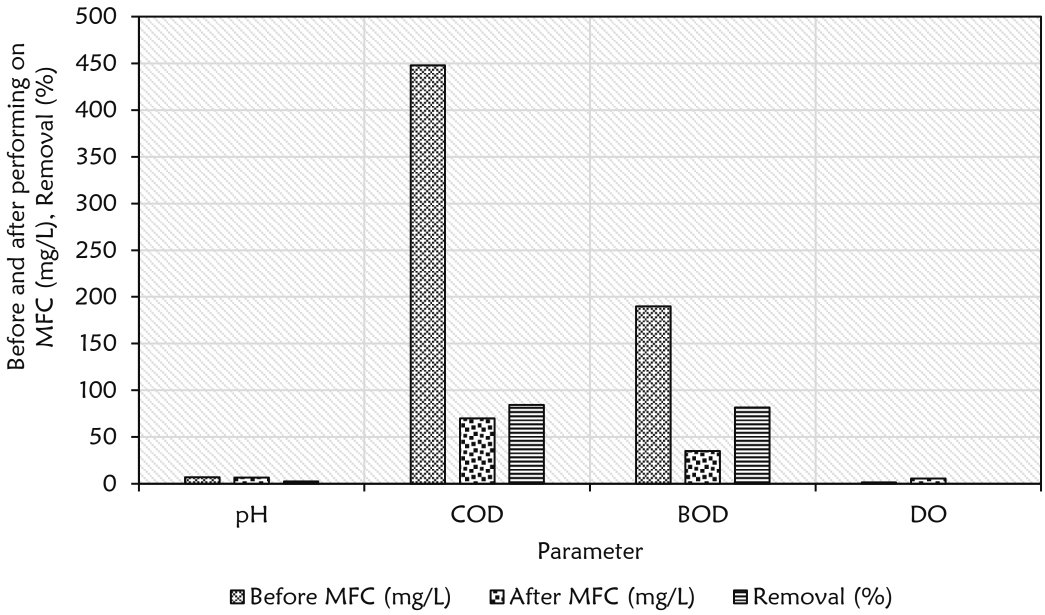

Figure 8: Typical pollutant concentrations before and after MFC treatment and corresponding removal efficiency.

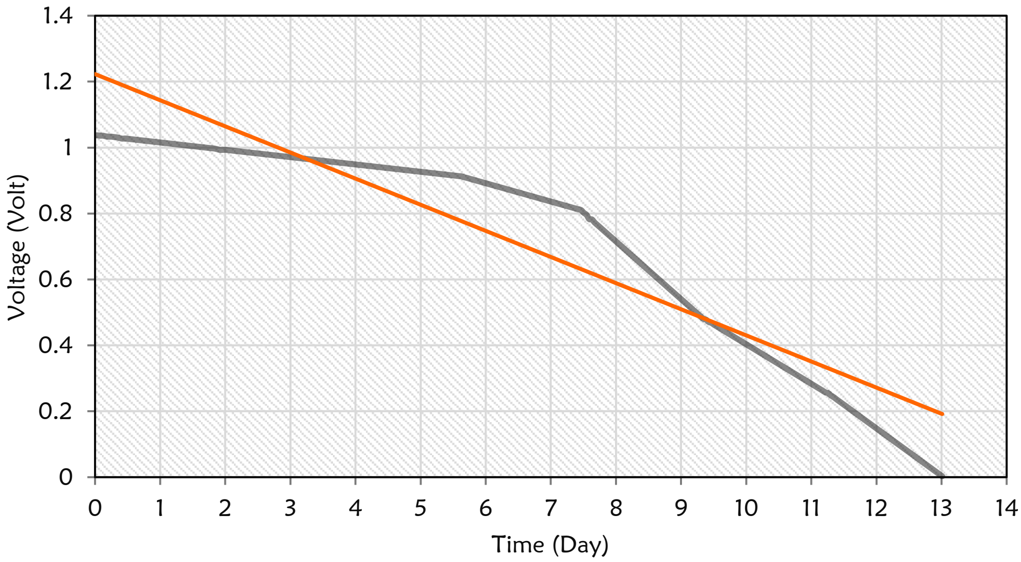

Figure 9: Voltage generation curves over the experimental period

4 CONCLUSIONS

This study successfully demonstrated the application of a double-chamber microbial fuel cell utilizing a low-cost salt bridge for the treatment of textile dyeing wastewater and concurrent bioelectricity generation. The key findings and implications are summarized as follows:

i. The developed double-chamber microbial fuel cell effectively treated textile dyeing wastewater, achieving high removal efficiencies of 81.57% for BOD and 84.38% for COD, thereby reducing the effluent to a much safer level.
ii. The system demonstrated an initial maximum voltage of 1.04 V, which gradually decreased over time due to declining microbial activity.
iii. A significant improvement in dissolved oxygen levels, an increase of 4.33 mg/L indicated enhanced water quality and a more favorable environment for aquatic life.
iv. The adoption of a salt bridge as a proton exchange medium proved to be a low-cost alternative to Nafion membranes, making the system more economically viable for developing countries like Bangladesh.
v. MFC technology provides a dual benefit: wastewater treatment and renewable electricity generation, offering a sustainable alternative to conventional energy-intensive effluent treatment plants.
vi. While large-scale deployment in Bangladesh remains challenging due to financial and technical constraints, small-scale MFCs can be piloted in rural and semi-urban areas to promote community-level wastewater management.
vii. Future research should focus on improving long-term stability, microbial activity, and scalability of MFC systems to enhance their efficiency and ensure economic feasibility.

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