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ORIGINAL ARTICLE

Oxidation of vegetable waste and organic pollutant degradation to generate energy through microbial fuel cell

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Abstract

The overarching goal of current MFC research is to optimize the production of power output by exploring innovative strategies to enhance electron generation and transportation. The oxidation of the organic substrate produces glucose, which fuels the bacteria in the cell's operational start-up and activates their electrogenic features. Consequently, organic pollutants wastewater in the MFC system may effectively increase the microorganisms' ability to produce electrons. As a result, this research compares the impacts of naphthalene (NAPTH) and formaldehyde (FOMA) as organic pollutants in two separate MFCs that operate continuously for 70 days. The maximum power density (PD) of the system was calculated through the collected voltage. The NAPTH system produces greater power (8.73 mW/m^2) over the FOMA system, having a maximum power density of 7.84 mW/m^2. The cell's performance was assessed using electrochemical tests, such as cyclic voltammetry and the EIS analysis. The specific capacitance (Cp) values were found to be 0.00013 F/g and 0.00019 F/g for the FOMA and NAPTH systems, respectively. Microbial examination of the used anode electrodes was conducted. The dominant specie found were *Leucobacter* sp. and *Pseudomonas* sp. NAPTH degradation efficiency was 70% and FOMA degradation efficiency was 75% after 70 days of operation. This is the first study to investigate the impact of diverse organic pollutant degradation on MFC performance while using vegetable waste as an organic substrate. This study provides a comparative assessment of the findings, and future research directions are recommended.

Keywords Formaldehyde · Naphthalene · Organic substrate · Wastewater · Bacteria

1 Introduction

The world's energy demands continue to rise, and traditional fossil fuels are becoming increasingly unsustainable. Combustion of these non-renewable resources not only contributes to greenhouse gas emissions and climate change but also leads to scarcity and geopolitical instability [1]. In light of these challenges, the need for environmentally friendly, renewable alternative fuels has never been more urgent. With the finite nature of fossil fuels and growing environmental concerns, the search for alternative energy sources is gaining momentum. Such innovations aim to reduce our reliance on fossil fuels and mitigate the negative impact on our planet [2]. Despite all the advances in MFC, the power yield remains exceedingly poor for commercial applications. Attempts are underway to improve MFC performance while investigating optimal system configuration and lowering operational expenses [3–5].

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According to recent research, improving the rate of electron generation by electroactive microbes on anode surfaces is critical for enhancing the power output of MFC. This suggests that optimization of microbial activity and enhancing the anode surface area could potentially boost MFC performance [6]. Although the current study does not explore the use of genetically engineered microbial strains, alterations to the diversity of bacterial in biofilm have previously been employed to boost MFC power production. However, the inadequate extracellular electron flow resulting from electrogenic biofilm bacterial to the electrode surfaces is still a major bottleneck impeding MFC practicality. Therefore, different methods for increasing electrogenicity have been extensively investigated. One potentially crucial approach would be to genetically modify exoelectrogens, which are responsible for electron transmission between a biofilm and the anode, to improve MFC output efficiency [7]. Electron generation is limited by the unstable organic substrates used in microbial activity. Collaboration of the organic substrate with organic pollutants found in wastewater may enhance the electroactivity of anodic microbes. Furthermore, increased industrial activity has contributed to water pollution [8]. Effluents from various industries enter aquatic bodies, either directly or indirectly, starting pollution. The quantity of organic compounds in the natural environment has risen due to the continuous growth of the agricultural and industrial sectors in the last decade, placing a great burden on the general population [9, 10]. Tanneries, petrochemicals, pharmaceuticals, and other industrial activities release a variety of organic contaminants into bodies of water. This organic wastewater, which is highly difficult to biodegrade by nature, can have major effects for the aquatic ecosystem and social shape. Organic pollution produced by several manufacturing units makes up a diverse set of complex contaminants in wastewater. Wastewater resulting from many of these industries is massive in quantity. Using the organic component of such wastewaters to generate bioenergy and value-added goods can pave the way for a more sustainable waste management strategy [11]. The microbial fuel cell (MFC) is an environmentally friendly method that has been shown to add value to the treatment. Thus, the two most pressing global challenges now are energy demand and wastewater treatment [12, 13]. Consequently, MFC has emerged as the most essential electrochemical instrument for tackling these current challenges.

MFC use microbes like bacteria to convert chemical energy into electric form by feeding on a carbon source (the substrate) and producing electrons. The procedure is carried out in a series of reactions that generate electric current. The electrons that are produced are then sent to bioanode and finally to an electron acceptor through the outside circuit [14]. The area equipped with the anode known as anodic chamber is the location that shelters the microbes to populate the MFC. They grow biofilms over the anode and get their carbon from organic substrates. Electrons and protons are generated during the process of metabolism. The proton exchange membrane enables protons to flow into the cathodic chamber, while electrons are transferred to and transported by the anode. In addition to producing electricity, the anodic chamber of an MFC system may biodegrade pollutants. The capacity of MFC to generate green energy while simultaneously biodegrading pollutants has lately aroused the interest of several researchers, making them a promising new technology and the most studied kind of bioelectrochemical method [15, 16]. In terms of removing toxic metals from wastewater, the technology has come a long way. The biodegradation of organic pollutant through MFC technology is a relatively new area of study [17]. The biocatalyst can generate electrons while feeding on the organic substrate, which provides carbon. Simultaneously, these biocatalysts break down organic matter in the system while also remediating wastewater contamination. Bacterial biocatalysts are made up of both degradative and electroactive bacteria [18]. They work individually to carry out the MFC's dual function. Typically, organic substrate stability and anode electrode performance are crucial to the MFC's overall performance. Usually, glucose or in some cases, acetate were widely employed as organic substrates in MFC. Still, leftover food is finding new life as a natural support in MFC as researchers work towards more affordable and environmentally friendly MFC. Several types of food waste have been used, including waste sugar cane, bad rice, palm fruit waste, and so on. The quest for a more stable organic substrate continues [19]. Furthermore, the degraded organic pollutant can have an impact on the system's power performance because it can also serve as a carbon source for bacterial activity.

Degradation of organic pollutants has been accomplished through the application of several standard approaches, including photocatalytic degradation, conventional adsorption, chemical precipitation approach, electrochemical degradation, and sophisticated oxidation techniques [20–22]. A high-energy expense, a lack of environmental affection, process challenges, and cost inconsistency are some of the major drawbacks of these methods, despite the fact that they have made excellent progress in removing organic pollutants from wastewater. For this reason, finding greener ways to break down organic pollutants is the primary objective. Consequently, this study investigates the impact of biodegrading FOMA and NAPTH from their respective synthetic wastewater on the energy generation performance of the MFC. This study seeks to determine the impact of organic pollutants with different molecular weights on the performance of MFC. NAPTH, a polycyclic aromatic hydrocarbon with a high molecular weight, and FOMA, a simple organic compound with a low molecular weight, will be used to compare

the effects of varying molecular weights on the MFC's ability to generate power and remove pollutants. The current work uses rotten sweet potato juice (RSPJ) as an organic fuel, with commercial graphite rods serving as anodes and cathodes. This study paves the way for further research into the impact of organic pollutant degradation on MFC power output.

2 Materials and methods

2.1 Chemicals and materials

Rotten sweet potato (obtained from Fajar Bakti restaurant at the main campus of USM). Pond wastewater (sourced from Tasik Fajar of USM, Penang). Pairs of commercial graphite electrodes (2B-FUDA rod/Lead, USA), digital multi-meter (UNI-T 33A, Beijing), formaldehyde (R&M Chemical, 37–40%), naphthalene (Sigma-Ald S81996, USA), plastic container, copper wire, external resistors and distilled water were used.

2.2 Organic substrate preparation

The vegetable waste serving as the organic substrate employed in this investigation was the prepared RSPJ. First, the rotten sweet potato was brought to the lab, washed, and dried. This was followed by peeling off the outer layer. The sweet potato was chopped into small pieces and blended to obtain the juice. To make blending easier, about 10 ml of water was added for every 100 g of sweet potato. The resultant juice was placed in a plastic bottle and chilled. A 5 ml of the produced juice is used as the organic substrate provided to the MFC on a daily basis. There were no further characterization studies conducted on the RSPJ sample; however, earlier literature has described the mineral characteristics of the rotten sweet potato, which has a high nutritional value for microbial species [23].

2.3 Source of inoculation and preparation

The wastewater enriched with organic contaminants was first gathered straight from the collection pond site as an inoculation source. The collection source effluent appeared cloudy with an awful odour. Pond wastewater has been shown to possess a variety of microbial mixed culture and is employed for inoculation. FOMA was introduced to the wastewater to produce 50 ppm FOMA-supplemented wastewater, and NAPTH was applied to separate wastewater to produce 5 ppm NAPTH-supplemented wastewater, both of which served as an initial inoculation medium in their respective cells. In brief, the laboratory standard 37% purity FOMA solution was obtained, which means that 100 g of this solution equals 37 g of FOMA. Thus, 0.135 g of FOMA solution equates to 50 mg of FOMA. To make 50 ppm FOMA-supplemented wastewater, 0.135 g of FOMA solution was measured into 1000 mL of the wastewater. The waste-water inoculation media colour was still cloudy. As for the 5-ppm NAPTH, 0.03 g of the pure NAPTH was first dissolved in 2.5 L wastewater to obtain 12 ppm NAPTH-supplemented wastewater. Further, a dilution method was used whereby 1 L wastewater was added to the 12-ppm solution to give the 5-ppm NAPTH-supplemented wastewater used in this study.

2.4 Set up, assembly, and operational procedure of MFC

The MFC arrangement in this investigation is a single-chambered MFC setup. Briefly, a plastic container with a volume of around 3.0 L was obtained for use as the cell. The electrodes which are made up of graphite rods were put on opposing sides of the container. A copper wire was linked between the anode and cathode electrodes. The external resistor was set to 1 kΩ. To ensure a steady flow of electrons, 1 kΩ external resistor was connected to the outer linked circuit. Based on previous research, a 1 kΩ external resistance was selected as it is the optimal choice for MFCs operating at room temperature and pH 7 as it maximizes voltage output [24]. An aquarium pump was connected to the cathode to provide the necessary aeration, but the air flow was controlled by a controller attached to the aquarium pump. Every day, a syringe was used to inject about 5 mL RSPJ into the anode region. Every day, the digital multi-meter was used to measure the cell's output voltage. The system was studied for 70 operational days. Table 1 further shows the characteristics of the wastewater used in this study. Figure S1 shows the MFC set up as used in this study. Furthermore, the flow process of this study is briefly presented in Fig. 1. The electrodes had an average height of 10.0 cm, a diameter of 1.0 cm, and a surface area of 30.2 cm^2. In both cell systems, the working volume of the cell was 2.5 L of the organic pollutant-supplemented wastewater. In simple terms, there are two distinct MFC systems for this operation. One cell contains FOMA as the organic pollutant, whereas the other has NAPTH as the organic pollutant.

2.5 Electrochemical analysis and calculations

The digital multimeter can only measure the voltage. Other electrochemical measurements of the cell, including current density (CD), power density (PD), and internal resistance, are obtained through computations. Equations 1–4 are used to further translate the data acquired from the digital multimeter into additional electrochemical measurements in the MFC.

Table 1 Investigation of the physical characteristics of wastewater used in this study

Properties	Original wastewater	FOMA-supplemented	NAPTH-supplemented
Temperature	25 °C	25 °C	26 °C
Conductivity	50 µS/cm	72 µS/cm	78 µS/cm
Colour	Cloudy	Cloudy	Cloudy
pH	6.96	6.21	6.89
Odour	Very unpleasant	Unpleasant smell	Unpleasant smell
FOMA	0 ppm	50 ppm	-
NAPTH	0 ppm	-	5 ppm

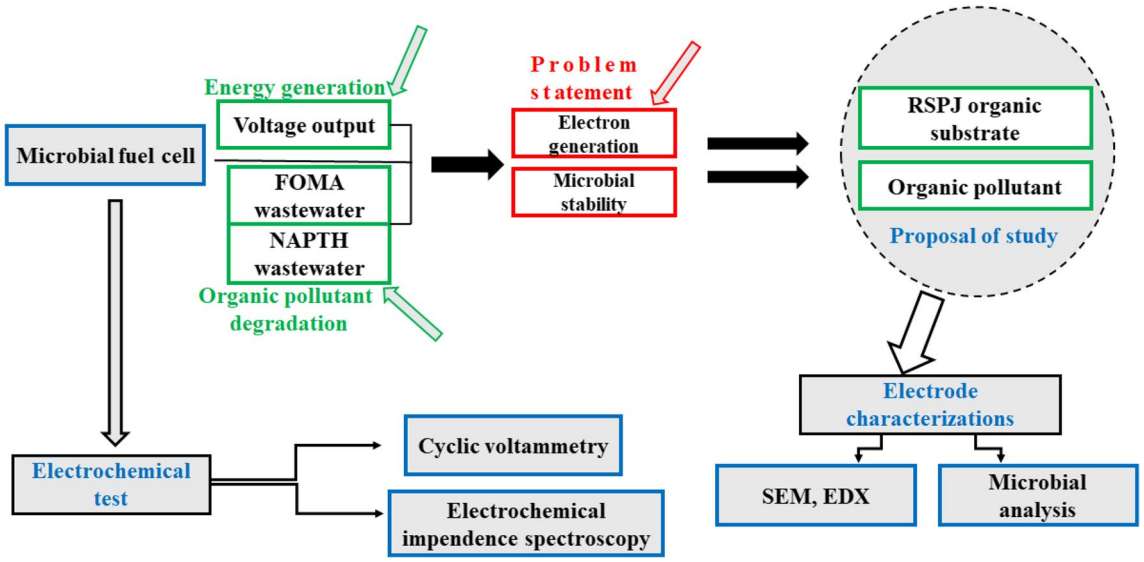


Fig. 1 The operational flow chart of the current study

$$V = IR \tag{1}$$

$$CD = \frac{I}{A} \tag{2}$$

$$PD = \frac{V^2}{RA} \tag{3}$$

$$r = \left(\frac{E - V}{V}\right)R \tag{4}$$

where V is the voltage output, I is the current, R is the external resistance, A is the cross-sectional area, r is the internal resistance, and E is the electromotive force (Emf).

In this work, two electrochemical analyses were used to investigate the cells' performance. The cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) were investigated. The CV is typically investigated to determine the cell's oxidation and reduction potentials, which are dependent on anodic biofilm activities. This CV investigation included the same electrode arrangement, potential range, and scan rate as previously reported [25]. However, the EIS was used to determine the electrodes' charge resistivity. In this situation, a short-amplitude AC of 1.0 mV was used. A narrow frequency range was also used in the EIS to prevent disruption in the anodic biofilm [25].

2.6 Bioremediation efficiency

The bioremediation effectiveness of the system was independently assessed for the FOMA and NAPTH MFC configurations. In brief, at regular intervals, around 1 ml of supplemented wastewater from each cell is taken for UV–vis assessment. The absorbance values obtained from UV–vis are decreasing over time, corresponding to a drop in concentration for each pollutant examined. A syringe was used to carefully collect samples from the MFC for examination. Furthermore, after determining the concentration from the absorbances, the bioremediation efficiency is estimated using Eq. 5.

$$BE\ \% = \frac{C_1 - C_2}{C_1} \times 100 \quad (5)$$

where C_1 is the initial concentration, and C_2 is the final concentration of the supplemented wastewater.

2.7 Microbiological characterization

Scanning electron microscopy, SEM (SEM-Zeiss, model DSM-960, Germany) was employed to investigate the anode surfaces for the presence of biofilms. Cell efficiency in producing electricity and degrading pollutants is enhanced when biofilm is present on anode surfaces. SEM pictures provided solid proof of bacteria growth on electrode surfaces. However, this investigation aims to determine which of the anode electrodes contains the densest biofilm in the two pollutant setups. Prior to SEM examination, the materials were rinsed with phosphate buffer (pH 7) and ethanol solutions (10%, 40%, 80%, and 100%). In addition, the anodes were taken out of their corresponding MFC chambers and rinsed with DI water after 70 days of operation. After sterilising the blade, 1.00 mm of each anode's surface was scraped off to extract microbial biomass from the biofilm. After collecting biofilm samples, 10 mL of sterile water was used to preserve them for the purpose of identifying and characterizing microbes [26].

3 Results and discussion

3.1 Bioelectricity generation performance

The two MFC systems containing NAPTH and FOMA were operating continuously for 70 days to assess power-generating efficiencies. During operation, the cells were placed under an applied load of 1000 Ω. The energy output was evaluated as a unit of voltage (mV) employing a digital multimeter. The voltage potentials in the reactor steadily rise for each pollutant system in their respective cell systems. The output voltage of the reactor increased in proportion to the bacteria growth resulting from an improved daily infusion of 5 mL RSPJ organic substrate in both FOMA and NAPTH systems in a separate MFC set-up. Figure 2A represents the voltage distribution recorded for both cells over a 70-day operation. In the earlier stages, there was no discernible difference in energy output, which may be because of the application of an inoculum source which was fresh and same for the operations. The maximum current of the FOMA system

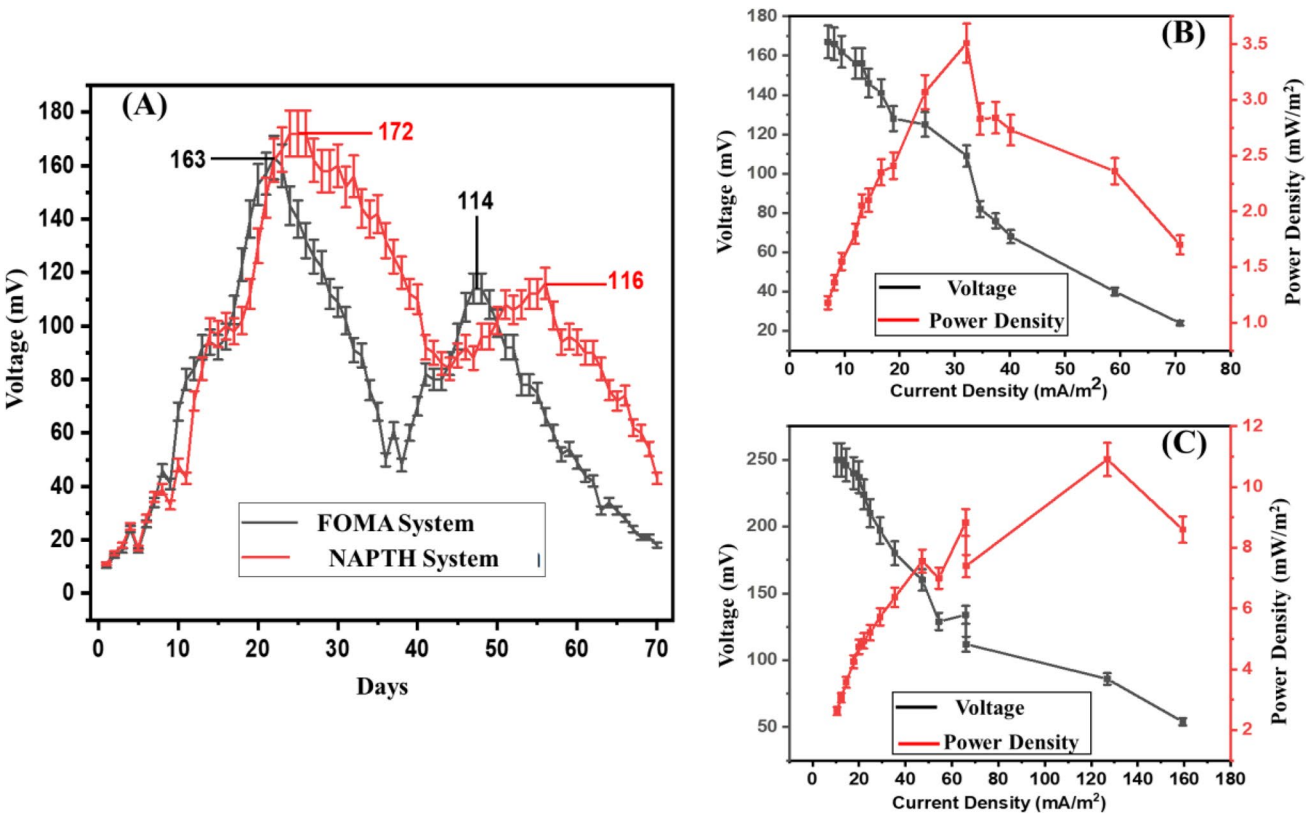


Fig. 2 **A** Voltage pattern trend of the FOMA and NAPTH systems, **B** polarization curve of FOMA system, and **C** polarization curve of NAPTH system

was 0.163 mA delivered on the 22nd day, and that of the NAPTH system was 0.172 mA on the 24th to 26th days. Furthermore, over a period of 70 days of operation, the output pattern in both cells was studied for two cycles. The 56th operation day begins to diminish the highest voltage (172 mV) in the NAPTH system, although a slow rise to 116 mV was recorded. This pattern was repeatedly observed in the case of the FOMA system, that has the initial highest voltage on the 48th day was 163 mV, with the next highest at 114 mV. The FOMA system had a maximum C.D of 48.10 mA/m^2 and a maximum P.D of 7.84 mW/m^2. For the NAPTH system, the maximal C.D and P.D were 50.75 mA/m^2 and 8.73 mW/m^2, respectively.

For both the pollutant systems, their polarization curves describe a relation between voltage performance, current density, and power density with the variable resistant during MFC process. Figure 2B and C shows the plotted of voltage against PD as the applied resistance was changed from 100 Ω to 7 kΩ. When a larger resistance load is supplied to an MFC, electron transport is typically low [27]. However, this process led to a more stable voltage output as the applied resistance increased, however, a reduced in the resistance brought about less stability of the electrical advancement due to robust electron transfer that happens under these conditions. The electrons flow quicker across a cell with lower resistance, resulting in larger currents and power production while maintaining low stability of the voltage. In both cases, poor electron transportation was observed when high external resistance was applied, translating to less current generation but good stability of the voltage, whereas smaller external resistance indicated small electrical progression stability. However, greater current levels were attained due to the quick electron transport. Large electron densities have long been observed over cells with smaller resistances, giving way to larger currents and power performance and low in terms of stability. Additionally, the voltage instability was faster when it was compared with higher external resistances. High voltage destabilization occurred at low resistance due to the quick transfer of electrons to the cathode, resulting in increased current with less voltage stability. In a few MFC studies, including Sarma et al. [28] as a scenario, comparable power patterns have been reported. Unlike the polarisation study that employed varying the resistors, this MFC operation maintained a constant external resistance of 1 kΩ continuously. Koók et al. [29] found that using an appropriate external resistance (1 kΩ) improves MFC power output. The external resistance factor was found as one of the critical component that affects electron flux during transmission, with a considerable impact on the anodic biofilm's electrogenic activities and MFC performance [30].

3.2 Cyclic voltammetry

Cyclic voltammetry (CV) represents an electrochemical assay used for assessing the biofilm effectiveness within the anode and the MFC system's specific capacitance (Cp). The CV experimental process was carried out over a few periods in this investigation, as shown in Fig. 3A and B. The platinum wire and Ag/AgCl electrodes act as counter electrodes and reference electrodes, respectively, in the CV analysis electrode system. The analytical conditions were set at a scan rate of 20 mV/s and a potential range of − 0.8 V and + 0.8 V. In this CV analysis, it is made up of two scans: forward refers to FS, and reverse is RS. Whereas the FS represents the oxidization of the process, the RS represents the system's reduction. The CV curves show that across every anode material, both FS and RS rise over periods of MFC operation. They all had their peak FS and RS values near the final stage of the process. This occurrence suggests that the formation of bacterial biofilms within anode materials accelerates as periods of operation progress [31]. It also shows that the microbial biofilm successfully oxidised the organic RSPJ substrate fed into the cell daily. In general, CV curves that have elevated FS and RS peaks are impacted by the availability of external oxygen, leading to electrons to discharge quickly and with significant neutralisation before contacting the anode [32, 33]. Furthermore, the curves for CV were analysed to establish the greatest specific capacitance (Cp) values for each

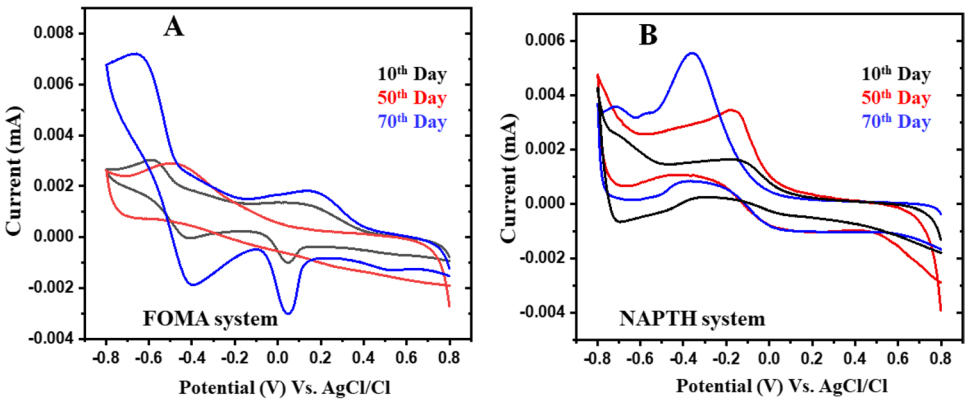


Fig. 3 Cyclic voltammetry curves of the MFC systems on specific days of operation **A** FOMA system and **B** NAPTH system

pollutant system. The FOMA system had the greatest Cp value of 0.00013 F/g, and the NAPTH system with 0.00019 F/g. The higher capacitance of the NAPTH system is possibly due to increasing charge capacity inside the cytoplasm of bacterial cells via redox enzymes on the microorganisms' cell membranes [34–36].

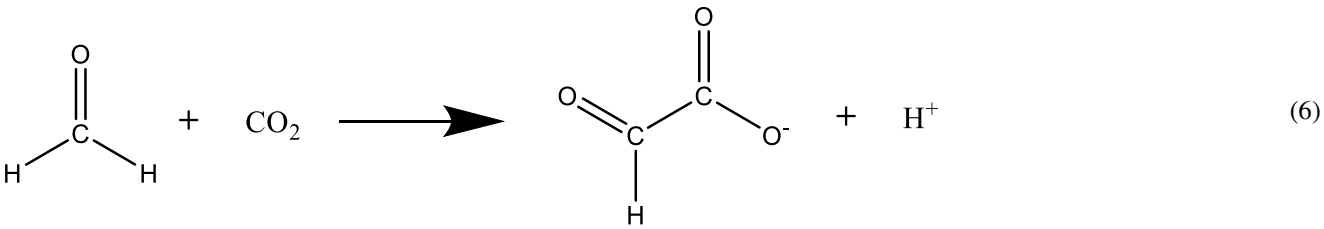
3.3 Electrochemical impendence spectroscopy

The EIS study is represented by the Nyquist plots that was experimented for the 10th and 70th days, as depicted in Fig. 4A and B, respectively. The conditions of the EIS device were fixed at a frequency range of 100 kHz to 100 mHz. The detachments associated with the anode's biofilms tend to happen during EIS investigation, hence a minimal AC signal is needed to reduce them [37]. As a result, a 1.0 mV AC signal has been applied in this analysis. The electron mobility of the system is revealed by the Nyquist plot's Z"imag value. Its high value suggests that the system has poor electronic mobility, whereas its low value shows that the system has great electronic mobility [38]. The Z"imag figure decreased through the day 10 to the day 70 of activity, indicating the ongoing development of biofilms across every anode material until the final day of operation, based on a comprehensive examination of every material using the Nyquist plots. The anodes' Z"imag, on the other hand, was much less, giving rise to improved electron movements in the cells. The slight decrease generally cause in enhancing electron movement across the anode systems [39]. Nonetheless, these CGr anodes have demonstrated weaker electron mobility potential, resulting in lesser power generation during operation.

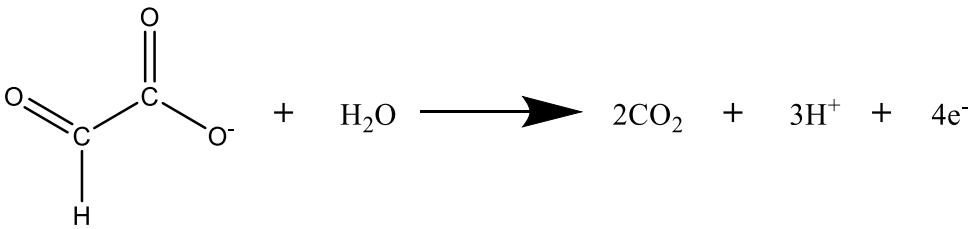
3.4 Bioremediation efficiency

The bioremediation efficiency of the pollutants was investigated for at intervals as the both systems were put through the 70-day operation of MFC containing supplemented 50 ppm FOMA and 5 ppm NAPTH, respectively. Usually, there are two functional microbes involved in the MFC biodegradation route: biodegradative bacteria and electroactive bacteria. These species exist in a mutually stimulating relationship, while other strains perform both roles of biodegradative and electroactive bacterial. The electroactive species terminate the possible generation of more pollutant intermediates, then the biodegradative microbes strike the organic pollutant directly, splitting it down into their derivatives of carboxylic acids [40]. At the end of 70 days, the UV–visible spectrophotometry investigation demonstrated that FOMA biodegradation efficiency was 75%. As shown in Fig. 5A and C, the decline in FOMA concentration was evaluated on the 30th, 50th, and 70th days. The FOMA biodegradation efficiency was 22% on the 30th day. The efficiency climbed to 45% on the 50th day. On the last day of operation, increased biodegradation effectiveness was seen as the operations of the degradative and electroactive bacteria meliorated. The chemical reactions that happen at the anode and cathode in the course of FOMA biodegradation are represented by Eqs. (6–10).

Anodic reactions:



(6)



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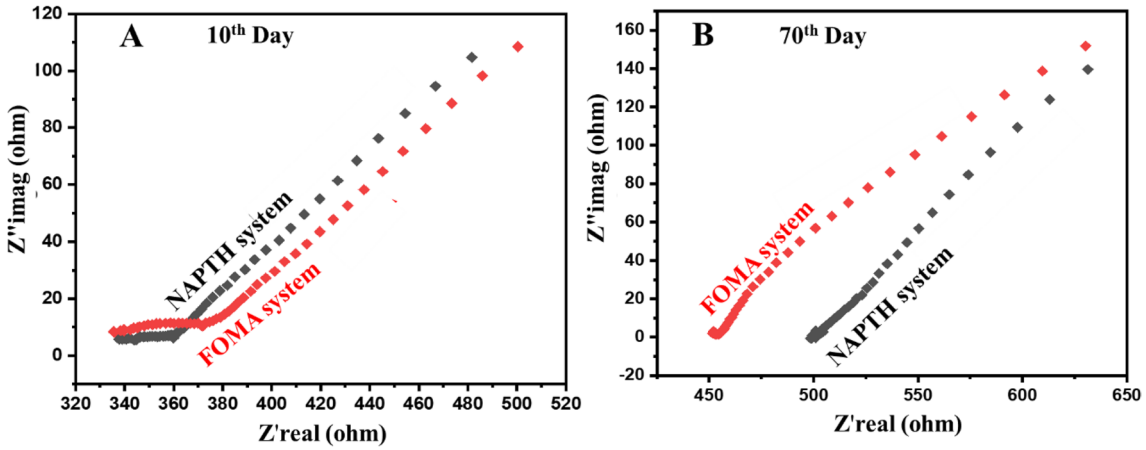


Fig. 4 Nyquist plot derived from the EIS analysis

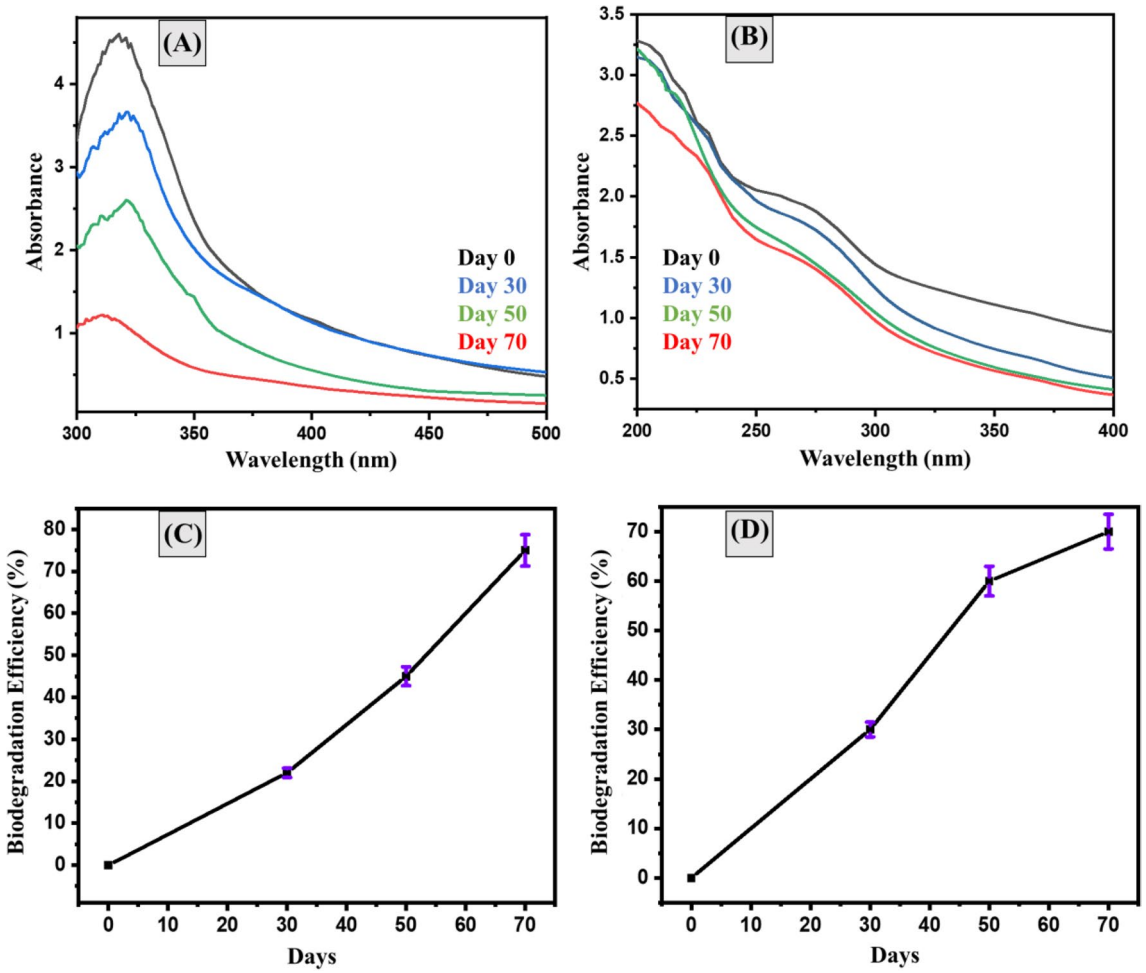
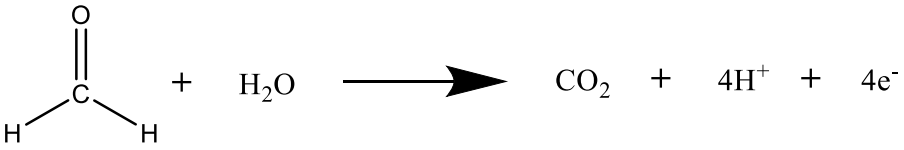


Fig. 5 The spectra of the UV–vis analysis **A** FOMA UV–vis studies from at various intervals, **B** NAPTH UV–vis studies at various intervals, **C** calibration of treated FOMA samples, and **D** calibration of treated NAPTH samples inserted

Total anodic reaction:

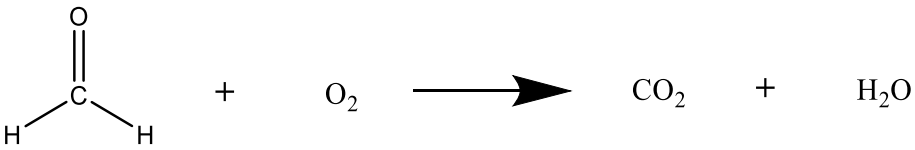


(8)

Cathodic reactions:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (9)$$

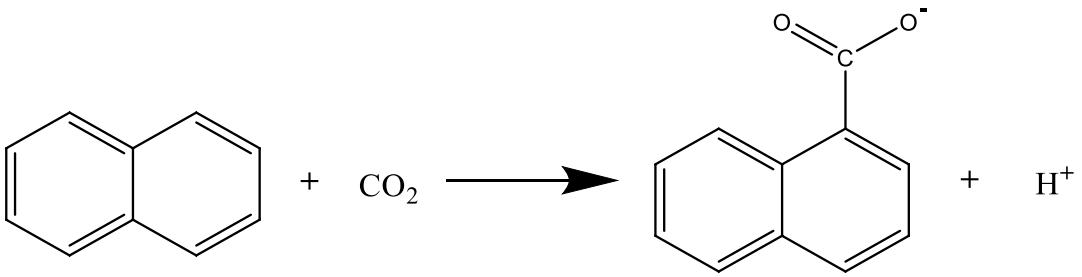
The total reaction in the MFC.



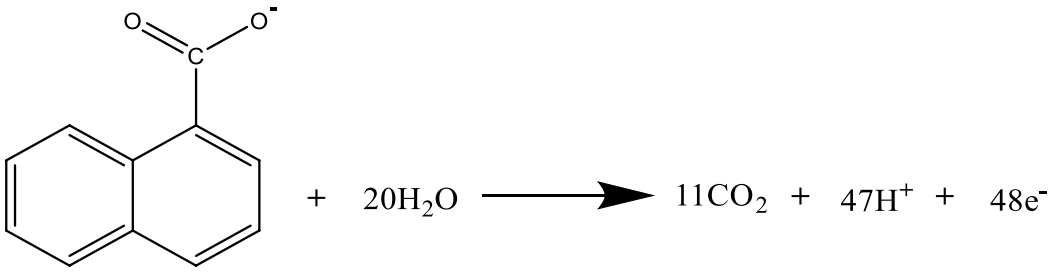
(10)

The UV–vis spectrophotometry investigation demonstrated a total NAPTH degradation efficiency of 70% at the end of 70 days of operation. Figure 5B and D depicts the observation of the drop in NAPTH concentration over time. The degradation efficiency of NAPTH was 30% on the 30th day. Similarly, by the 50th day, degradation efficiencies have increased to 60%. The chemical reactions taking place at the anode and cathode for the NAPTH degradation are depicted in Eqs. (11–15).

Anodic reactions:



(11)



(12)

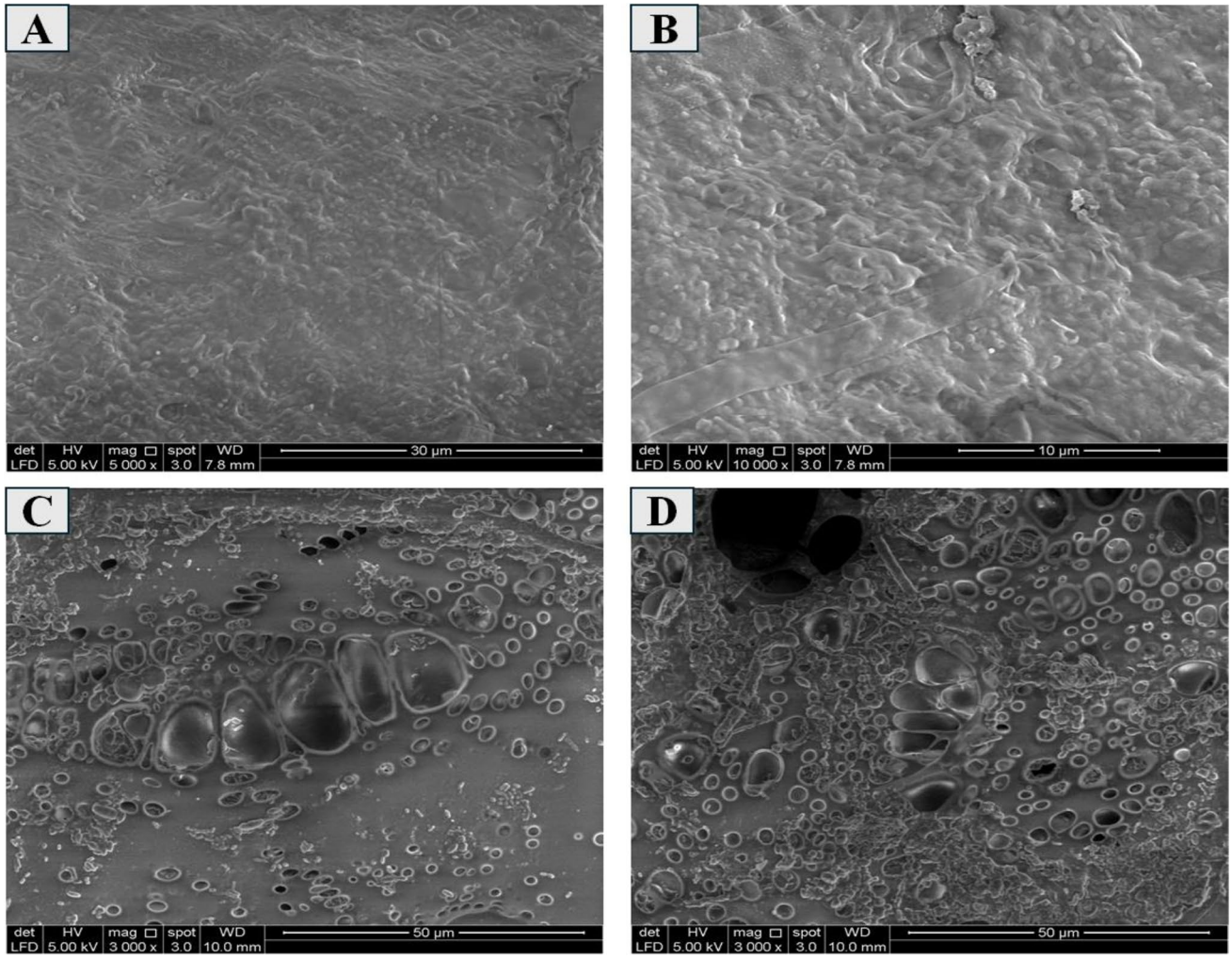
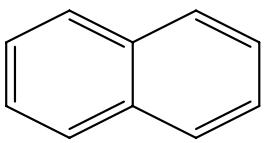


Fig. 6 SEM images showing microbial biofilm of **A** FOMA system anode, **B** NAPTH system anode, **C** FOMA system cathode, and **D** NAPTH system cathode

Total reaction at the anode:

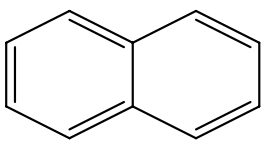


$$+ \quad 20H_2O \longrightarrow 10CO_2 + 48H^+ + 48e^- \tag{13}$$

Reaction at the cathode:

$$12CO_2 + 48H^+ + 48e^- \rightarrow 24H_2O \tag{14}$$

The total reaction in the MFC:



$$+ \quad 12O_2 \longrightarrow 10CO_2 + 4H_2O \tag{15}$$

3.5 Microbiological analysis

The MFC operation was completed after a duration of 70 days, thereafter, the SEM examination was performed to analyse the biofilm features on both anodes of each pollutant system, as shown in Fig. 6. Particularly, biofilms were seen on all of the anode electrodes, indicating a vigorous growth of microbial organisms on the system's anode surfaces. These biofilms have an identity of morphology with tubes and rod-like structures throughout the filaments and characteristic wrinkling cells, as shown in SEM images. Previous survey has demonstrated a link connecting this kind of structures on the surface of electrodes and the prevalence of exo-electrogenic nano-wire species, that perform a critical function in promoting the transport of electrons from bacterial biofilms to surfaces of anodes [41]. However, in the corresponding cathode electrodes, there were no filamentous structures observed in the micrograph. Only some characteristic rough surfaces of the cathode were seen, implying that major growth of the biofilms occurred around the anode electrodes. The anode electrode surfaces allow for excellent interaction with organic pollutants and exoelectrogens, as well as efficient adsorption through the electrode pores [42]. SEM investigation revealed that the organic pollutants, which had initially accumulated on the anode's surface, were remediated during the experiment. From the SEM images, microbial colonies can be found on the anode's surface

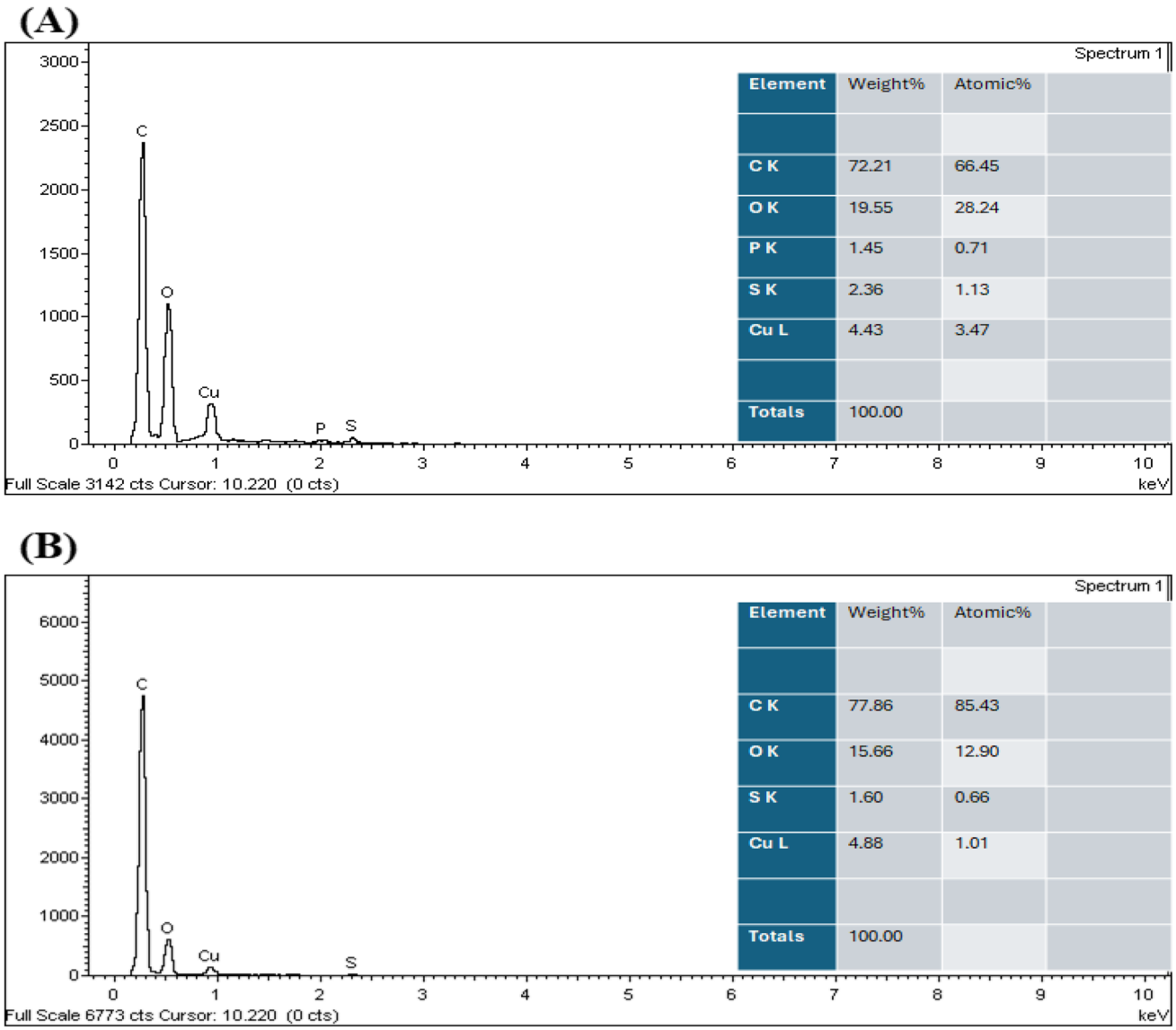


Fig. 7 EDX spectra of the anodes at the completion of the MFC operation **A** FOMA system and **B** NAPTH system

as well as in its internal pores. As bacteria proliferated and multiplicated on the anode surface, they finally grow into the biofilms. The formed biofilm is apparent at high magnification in the SEM images. However, after being introduced into MFC systems, the pollutants served as an energy reliance for the microorganisms in the organic substrate, and the ensuing degradation of the pollutants stimulated the discharge of electrons as biofilms continue to proliferate. These released electrons were sent straight to the bioanode side, reducing internal resistance and producing voltage. The biofilms were significantly denser in the NAPTH system cell. A huge number of these bacteria are utilized in MFCs, however, the utilization of a pure or mixed bacterial culture has been effectively proven in some MFC operations [43, 44]. In one instance, Saha et al. [45] used the MFC operating through a 30-day period and examined the anode's biofilms, which featured Bacillus sp. The cell operated well, delivering its maximum voltage at 5.8 V with a mean current output of 5.0 mA. Similarly, Dongre et al. [46] evaluated the efficiency of MFC by introducing their bioanode with *Bacillus* sp. to serve the biocatalyst, which improved electro-activity and general cell efficiency. On day 16 of operation, the MFC produced the highest level of electricity (455 mV), with current and power density values of 51.8 A/cm^2 and 4.3 W/cm^2, respectively. The source carbon derived from the organic pollutant causing bacterial proliferation on anode surfaces was been oxidised by microbes to produce metabolites including protons, CO_2 and the electrons [47]. In this context, electrons are delivered to the microbe cell through the electron transfer pathway and then to the cytochromes', which is positioned around the membrane. The electrons are subsequently transmitted to the anode via a method referred to direct electron transfer or mediated electron transfer [48]. Exo-electrogenic bacteria link up the organic pollutants in their surroundings, enabling them to seek carbon for development and metabolise in settings that would otherwise be inaccessible to them. Hence, several genetically and metabolically distinct bacteria have proven to develop various types of linkages. Exoelectrogenic microbes are most suited for organic pollutant biodegradation in MFC due to its proclivity for Extracellular Electron Transfer (EET) from the inner bacterial cell's to the anode electrode [49].

Furthermore, according to Fig. 7, EDX was evaluated to determine the impact RSP juice caused on the anodic microfilms' outer layer at the final stage. It was observed that certain mineral components found in RSPJ accounted for the biofilms' increased healthy growth. The EDX analysis shows a greater concentration of oxygen and carbon within the biofilm anodic surfaces, alongside trace levels of phosphorus, sulphur, and copper. Santos et al. [50] delved into the mineral content of sweet potatoes and detected these minerals as their vital components. Also, due to the carbon material concentration of the anodes and the oxygen supply, the carbon and oxygen percentages were substantially larger. This suggests that RSP juice is a suitable organic substrate potentially proposed for robust effects on MFC microbial species. Furthermore, the EDX result showed no hazardous component, implying that there was no toxicity consequence for the electrodes.

According to the bacterial analysis, the most common species in both systems was *Leucobacter* strain for the FOMA system and *Pseudomonas* strain for the NAPTH system. However, the anode's surface contained only a few bacterial species. The phylogenetic tree of the bacteria species isolate is presented in Fig. 8. Sturm et al. [51] investigated *Leucobacter* sp. and discovered a highly

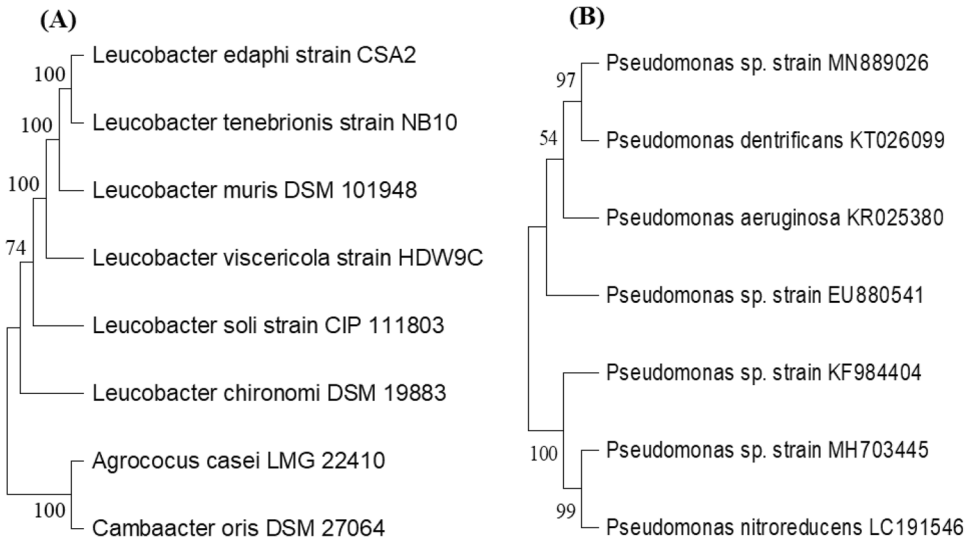


Fig. 8 The constructed phylogenetic tree derived from the sequence **A** FOMA MFC anode and **B** NAPTH MFC anode

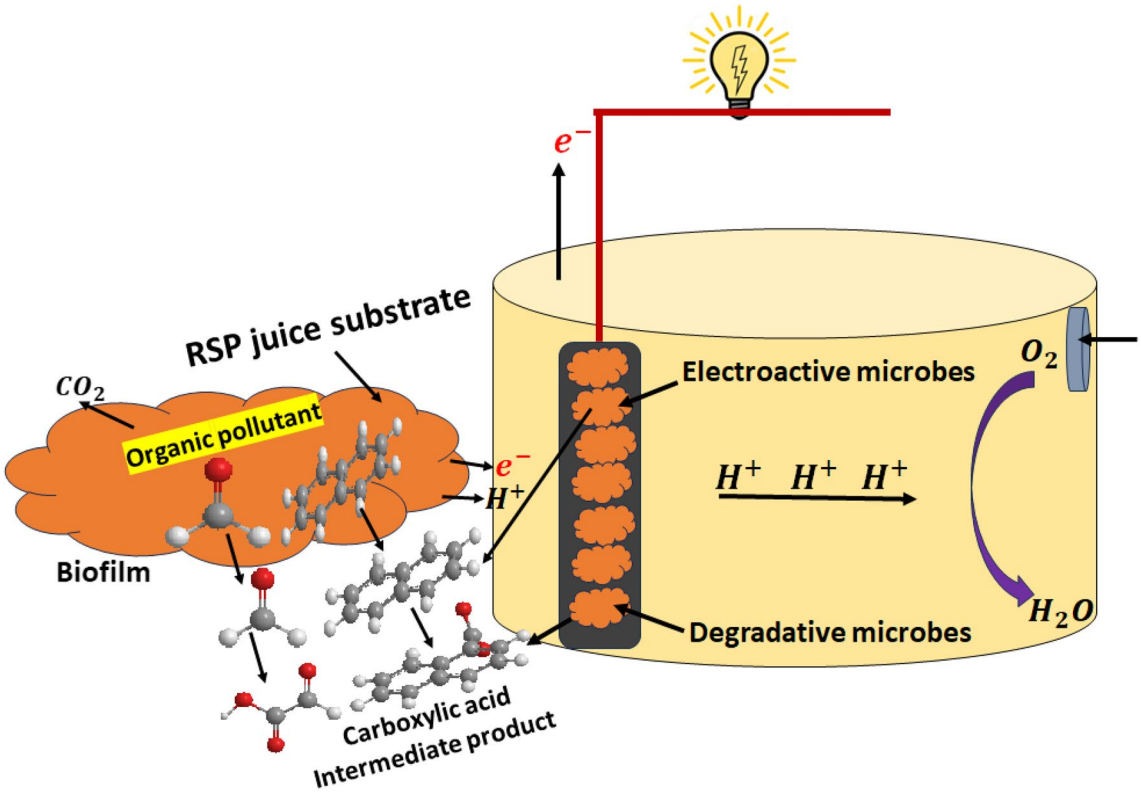


Fig. 9 Proposed component interactions mechanism in the MFC system

pollutant-resistant strain. The presence of *Leucobacter* sp. biofilm on the anode's surface significantly reduced pollutant sensitivity. As a result, *Leucobacter* sp. can be employed to bioremediate organic pollutants, a harmful environmental contaminant. However, the current study demonstrated that *Leucobacter* sp. functioned as a unique biocatalyst, generating electricity while simultaneously biodegrading organic pollutants in the wastewater system. The restricted variety of species of bacteria in MFC demonstrates that this technology is highly efficient and promising in the biodegradation process [52]. Furthermore, *Pseudomonas* sp. has earlier been reported to be actively involved in the biodegradation of benzene through the MFC [53]. This study employs a mixed culture from the wastewater inoculum at the beginning of the MFC process. In subsequent studies, it is proposed that these bacteria can be used as a pure culture inoculum to investigate their effects on MFC performance, both degradative and electroactive potentials. The duration of the MFC studies is determined by their performance over time, which is significantly influenced by the electroactivities of the anodic bacteria. Bacteria have a lifespan, and once they reach their prime, their electroactivity declines, and they are unable to generate electrons to continue the process. However, in order to maintain that state of balance, research into the stability and durability of anodic bacteria is underway.

3.6 Oxidation mechanism of the substrate

The RSPJ produced during this study was utilised on a regular basis to support anodic microorganism development and activity. The juice was extracted from the potatoes with water and a blender. The organic substrate breakdown and oxidation mechanism during MFC operation was previously presented by Aleid et al. [54]. The substrate juice extract was originally made up of polysaccharide, then as its metabolism advanced, they eventually broke down forming glucose. Microbe species subsequently oxidise the monosaccharide, producing electrons as well as protons. Prior to injecting the substrate juice, the juice's COD analysis was likely reflected on the organic substrate content, enabling validation for every anode type in the operational cells had a comparable degradable organic load. This however will be explored in future study. This investigation discovered oxidation/reduction techniques, as depicted in the chemical reaction pathways of Eqs. 16–18. The generated protons and electrons are then transported to the cathode throughout the oxidisation process, as illustrated in Fig. 9. Proton is known to have a clean passage from anode to cathode in single-chamber MFC such as the current consideration. The compositional value of a material utilized as an organic substrate in MFC must be capable of providing nutritional

value as a source of energy for anodic bacteria to thrive. As a result, carbohydrate-rich materials are anticipated to offer the glucose bacteria species require to perform their functions in the MFC [55].

Oxidation reaction:

$$Sweet\ potato\ juice \rightarrow C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \quad (16)$$

Reduction reaction:

$$24H^+ + 24e^- + 6O_2 \rightarrow 12H_2O \quad (17)$$

Overall reaction:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Electricity \quad (18)$$

The juice substrate offered to the anode's section biofilm that handles metabolism is principally responsible for preserving the dense population of microbes on the anodic surface. These bacteria are characterised by their responsibilities in MFC: some performed the degrading operation, sometimes called as degradative bacteria, and some were in the grip of electro-activities. Previous studies identified the two major microorganisms in MFC as degrading and electroactive bacterial [56]. For example, a recent study examined the biodegradation of toluene utilising benthic MFC. A study reported that when energy was generated, the toluene degradation efficiency was more than 80% [57]. Electroactive microbes inhibit the production of further pollutant product intermediates, while degrading bacteria breakdown the organic pollutant producing carboxylic acid derivatives [58]. Figure 9 depicts the elements required in the biodegradation of the organic pollutant used in the current study. The study's findings showed that the amounts of organic pollutant steadily decreased over time. The degradative and electro-active bacteria' performance improves over time, resulting in increased biodegradation efficiency towards the completion of the investigation.

3.7 Comparative discussion

MFC has been widely utilised to remove potentially toxic metals from wastewater. Only lately has its potential in the biodegradation of organic contaminants been examined [59, 60]. In general, the power performance of the FOMA and NAPTH systems in the present study was slightly lower than that of the most investigated organic pollutants in MFC. Other parameters that may influence the MFC's power performance include electrode type, MFC setup, and ambient conditions. The strategy of using MFC for organic pollutant biodegradation is more appealing because the biodegradation process can boost the system's power generation. This is because the biodegraded organic pollution can also serve as a carbon source for the microorganisms, hence enhancing the bacteria' activity in tandem with the existing organic substrate. However, the performance of MFC is also affected by environmental parameters such as temperature, pH, and nutrient availability, among others. These variables have a substantial impact on the biocatalyst choice and microbial community composition in MFCs. Fermentation activities, for example, dominate electrogenesis when the anode voltage is very low and the concentration of redox mediators in the anode chamber is low, resulting in negligible power generation in MFC due to electron movement inside the bacteria [61]. The bacteria' actions are not restricted to the biodegradation process; they are also responsible for generating electrons and transporting them to anodes. For rapid electron transfer to occur, the anode must be both good conducting and microbially biocompatible [62]. Consequently, in this study, both the FOMA and NAPTH systems works to provide carbon to the bacteria via the RSPJ organic substrate. However, the naphthalene system was observed to perform higher. This can be due to the fact that NAPTH has more conjugated carbons and is a polycyclic aromatic hydrocarbon, whereas FOMA is a simple hydrocarbon. For instance, in terms of energy generation in the first cycle, the FOMA system delivers less energy than seen in the first cycle of the NAPTH system. The overall energy generation performance was higher in the NAPTH system than in the FOMA system. The scenario differs in terms of biodegradation efficiency, though. The biodegradability of a complex polycyclic aromatic structure, such as NAPTH, was found to be lower than that of the simple hydrocarbon FOMA. The FOMA system achieves a 75% biodegradation efficiency, which is higher than that of NAPTH (70%). Table 2 shows the comparative performance profile of the pollutant systems in the current study. Furthermore, microbial analysis of the SEM images revealed a higher density of microbial growth in the NAPTH MFC system. All of these characteristics indicate that microorganisms are more active in the NAPTH system than in the FOMA system.

Table 2 Comparative profile of performances in the current study

Maximum performance	FOMA system	NAPTH system
Voltage (mV)	163	172
Current (mA)	0.163	0.172
Current density (mA/m^2)	48.10	50.75
Power density (mw/m^2)	7.84	8.73
Biodegradation efficiency (%)	75	70

4 Challenges and future perspectives

MFCs are increasing in popularity, and this type of technology can be employed in a variety of areas. Hassan et al. [63] have discussed the latest model challenges and limitations

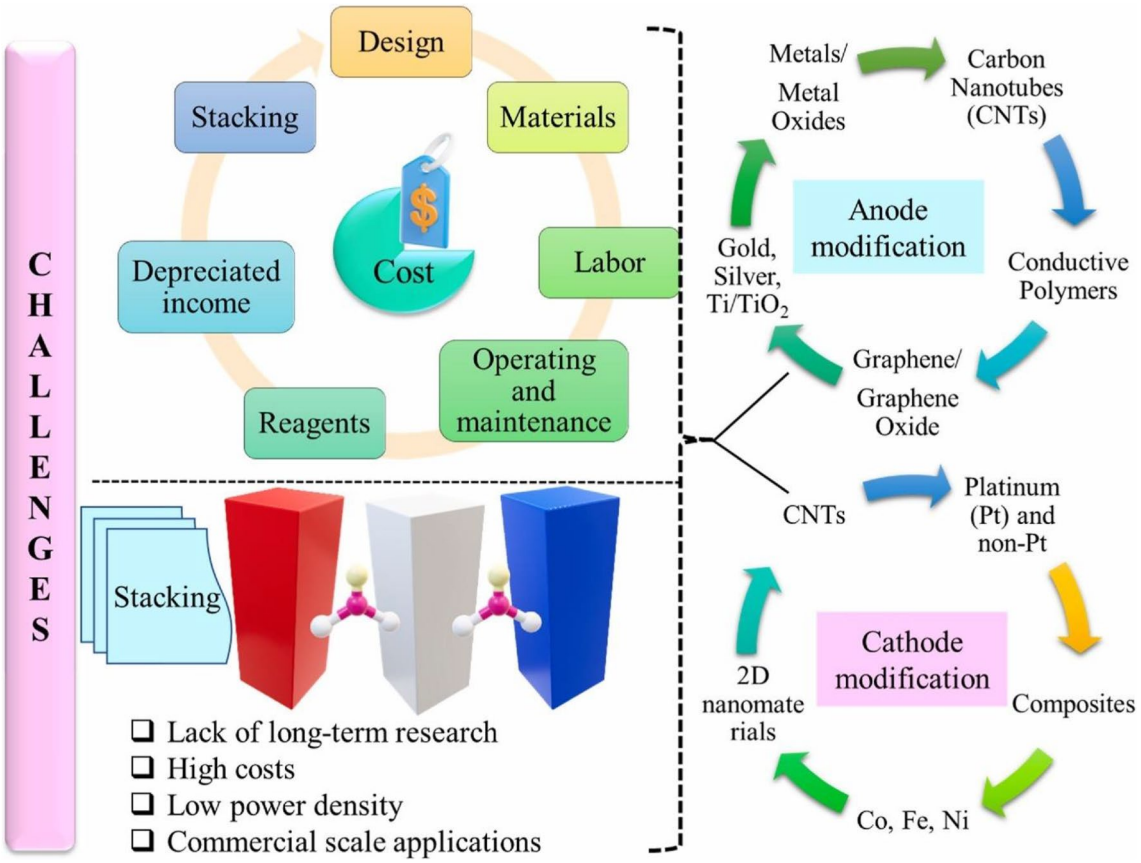


Fig. 10 Most emerging challenges and limitations of MFC (Figure adapted from reference [63] with Elsevier permission)

linked with MFC energy generation and wastewater treatment. They took a comprehensive sight with an obvious future indication. Figure 10 depicts an overview of Hassan et al.'s identified problems and constraints, with a more comprehensive description accessible in the reference [45]. Notwithstanding, MFC continues to face hurdles due to electrode design that does not meet electron transport demands and the organic substrate's instability in activating microorganisms [64]. The invention of high-performance anode materials in conjunction with an adequate organic substrate, as well as modifications, may improve the standing of the MFC technique in wastewater treatment and pollutant removal. These unstable organic substrates can further be complemented by utilizing the organic pollutant wastewater inoculated in the MFC. The MFC is a novel process that can provide the globe with reliable, safe, and sustainable energy while also helping to preserve the natural world [65, 66]. Recent studies focus on modifying electrodes to improve MFC performance. Some of these advancements have been reported in this revised manuscript. Researchers are altering the anode materials specification to improve their biocompatibility and conductive qualities, hence increasing the possibility of electron transfer [67, 68]. Furthermore, considering MFC are a relatively new field of science research, significant effort and time are required necessary before they can be considered economically feasible. The interaction of organic pollutants and microbial species has not been thoroughly explored in order to maximise efficiency and improve MFC performance. The current study produced positive results; however, it was difficult to operate the systems for more than 70 days as a result of the low voltage output during this period. Large-scale MFC requires an organic substrate that is stable over time, as well as the collaboration of organic pollutant carbon supply. The amount of organic pollutant supplemented in the MFC wastewater is also a crucial concern for preventing detrimental impacts on microbial metabolism. The current setup uses a single chamber MFC design. According to reports, the distance between the anode and cathode electrodes influences performance. Hence, this study suggests that reconfiguring the MFC such that the electrodes are closer together and using vegetable waste as an organic substrate may improve the MFC's performance [69]. Furthermore, scientists in the field have reported the combination of MFC systems with different approaches for the efficient degradation of those organic contaminants. MFC-photocatalysis platforms,

photosynthesis MFC frameworks, and MFC-biofilms electrode systems would require an external light source to operate. It is also mentioned in the previous article that the majority of organic contaminants exposed to biodegradation in MFC were supplied from polluted samples of soil sites; research on organic pollutant biodegradation from wastewater discharges was insufficient [70]. The biodegradation of organic pollutants utilising the MFC approach is a viable strategy to enhancing the cell's energy efficiency since the organic pollutant that is degraded additionally serves as the microorganisms' supplementary carbon provider. In addition, some reports have found that slow biodegradation of organic pollutant leads to increased power performance. During the gradual degradation pathway, bacteria continue to consume the organic pollution as a carbon supplier, producing electrons and protons for and increasing the generation of electricity. Initially, organic substrates such as glucose were widely employed in MFC set-up. Researchers advanced their quest of a more cost effective MFC system, understanding the necessity to substitute common organic substrates with bio-derived organic matter generated from biomass-based products such as biowastes. This technique is interesting not just due to its cost feasibility and sustainability, but it has further proven to be an appropriate organic substrate for bacteria in MFC, as shown by recent research in terms of MFC performance. The MFC research community must focus more on intensive research on the biodegradation of organic pollutants in wastewater. Further study must be dedicated toward the design of larger-scale MFC configurations for improved global bioremediation procedures and renewable energy generation.

Exploring new substrates is critical for the advancement of MFC, particularly in the context of microbial stability. Furthermore, using biowaste products as a substrate in MFC allows for cost savings and potential large-scale deployment. The selection of microbial species is critical to the production and transport of electrons across the anode and cathode within the MFC [71]. Researchers have demonstrated the successful use of mixed consortium in wastewater treatment, resulting in more efficient oxidation of organic substrates than with pure cultures. Innovations in genetic engineering are predicted to improve the properties of electrogenic microbes, resulting in improved oxidation of organic substrates and greater MFC power efficiency. A complete system for energy management is required to measure output power and minimize possible power loss during MFC generation [72]. As such, future improvements in integrated and very effective circuits are expected to significantly boost the energy output potential of MFC. Additionally, MFC integrated with other technologies, like anaerobic digestions, Microbial electrolysis cells, membrane reactors, and others, have been shown to produce more energy than independent counterparts [66]. However, the biggest challenge with effortlessly linking two dissimilar systems is the possible expense involved.

5 Conclusion

In conclusion, this study demonstrated the positive impact of organic pollutants on the energy generation of MFCs. Two organic pollutants, FOMA and NAPTH, were used to compare the MFC's energy-generating performance. In both cases, RSPJ organic substrate was used to provide carbon to the bacteria. Electrochemical measurements such as the CV were used, and they confirmed that oxidation and reduction reactions were effectively catalyzed by the microorganisms in the organic pollutant systems. This suggests that the RSPJ organic substrate is effective at promoting biofilm formation. The MFC operation in each system was conducted for 70 days and at every interval, the decline in the pollutant degradation was analysed. Overall, naphthalene had a lower biodegradation efficiency of 70% than FOMA, which had a biodegradation efficiency of 75%. However, the gradual biodegradation of NAPTH generates more energy than the FOMA. The maximal PD in the naphthalene system was 8.73 mW/m^2, but in the FOMA system, it was 7.84 mW/m^2. In both cases, rapid formation of biofilms was observed on the anode surfaces. However, it is clearer and denser in the naphthalene system. On the laboratory scale, bacterial biodegradation of organic pollutants using the MFC methodology proofs more effective than previous bioremediation approaches. Many variables limit the effectiveness of anodic bacterial degradation of organic pollutants. This article also aims to address several key issues that require an extensive knowledge of organic pollutant biodegradation through MFCs, such as the reaction mechanism of the degrading organic pollutant and ways which organic pollutant degradation affects the energy performance of the MFC. Therefore, whereas MFC systems have immense potential for organic pollutant degradation, their large-scale use remains an obstacle. This study provides valuable insights into the potential of organic pollutants as substrates for MFCs, leading to improved energy generation and sustainability. These findings provide future study directions for enhancing MFC power output production through effective organic pollutant biodegradation. The biodegradable organic pollutant influences the MFC's power-generating performance.

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Data availability The authors declare that the data supporting the conclusions are completely accessible without any limitations.

Declarations

Ethics approval and consent to participate Not applicable.

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