Process Safety and Environmental Protection 194 (2025) 807–815

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.journals.elsevier.com/process-safety-and-environmental-protection

Evaluation of simultaneous energy production and biotic and abiotic nitrate removal in microbial fuel cells (MFCs): Selection of the most suitable MFC by a multi-criteria decision methodology

Nevim Genç *, Elif Durna Pişkin

Kocaeli University, Department of Environmental Engineering, Kocaeli University, Kocaeli 41001, Turkey

ARTICLE INFO

Keywords:
Microbial fuel cell
biotic-abiotic nitrate removal
energy production
PROMETHEE

ABSTRACT

Microbial fuel cell (MFC)'s are sustainable resource recovery technologies that produce green energy. While sewage sludge fed with dairy industry wastewater was oxidized in the anode, the energy production and treatment potentials of MFCs in which nitrate was reduced under abiotic-biotic conditions in the cathode compartment were evaluated. It was determined how the performance changed when the conditions of the cathode compartment were changed as biotic (heterotrophic-autotrophic) and abiotic. The performance of the MFC was evaluated by anodic and cathodic coulombic efficiency (CE), maximum power density, chemical oxygen demand (COD) and NO_3^- removal. Considering the MFC performance criteria and the cost of the carbon source added to the catholytes, the preference order of the MFCs was determined using a multi-criterion decision methodology called the PROMETHEE approach, which allowed for pairwise comparison of alternatives on a criterion basis using preference functions. Accordingly, abiotic MFC>autotrophic MFC>heterotrophic MFC preference order was obtained. It was revealed that all criteria except nitrate removal efficiency had a positive effect on the selection of abiotic MFC. Although the nitrate removal efficiency in abiotic MFC was lower than biotic MFCs, the energy production performance was determined to be quite high.

1. Introduction

The effects of climate change have revealed the need to switch to green and low-carbon energy production technologies as soon as possible. However, the performance of energy generation technologies should be evaluated from a new 4E perspective. Energy, exergy, economy and environment are taken into account in the 4E evaluation systems (Wang et al., 2024). MFCs are a series of physically, electrochemically and biologically interconnected processes and are sustainable resource recovery technologies (Esfandyari et al., 2017a; Guo et al., 2023). A 4E analysis of stacked MFC was performed by Nasrabadi and Moghimi (2022). It was determined that by scaling up the system, the maximum power and energy efficiency would be 332 kW and 58 %, respectively. The results showed that the MFC system is more profitable than conventional energy systems. Conventional systems produce 5000 tons of CO_2 per year, while MFCs produce 1 ton of CO_2 (Nasrabadi and Moghimi, 2022). The use of waste in energy production makes the process sustainable in environmental/economic/social terms. Waste sludge disposal in treatment plants is an important problem. Since the organic matter content of sewage sludge is high, its evaluation in the field of energy production has become a preferred approach, although there are many disposal methods. In the most widely used anaerobic digestion method, sludge stabilization is achived along with energy production. MFCs have 4 times the energy production potential compared to anaerobic digestion and offer a sustainable alternative for biomass management. One of the most important obstacles limiting the application of MFCs is their inadequacy in the treatment of wastewater containing high COD (Hassan et al., 2024). MFCs can be integrated into combined systems, allowing for the simultaneous production of energy and treatment of wastewater or organic waste (Esfandyari et al., 2024). Sludge attracts attention as an important substrate source in the anaerobic compartment. Nitrogenous compounds are the main

Abbreviations: COD, Chemical Oxygen Demand; CE, Coulombic Efficiency; $E_{cell,}$, cell voltage; GAIA, Geometrical Analysis for Interactive Aid; $I,$, current; MCDM, Multi-Criteria Decision-Making Process; MFC, Microbial Fuel Cell; MLSS, Mixed Liquor Suspended Solids; MLVSS, Mixed Liquor Volatile Suspended Solids; PROMETHEE, Preference Ranking Organization Method For Enrichment Evaluation; $R_{ext,}$, External Resistance.

* Corresponding author.
E-mail address: ngenc@kocaeli.edu.tr (N. Genç).

https://doi.org/10.1016/j.psep.2024.12.071
Received 3 October 2024; Received in revised form 16 December 2024; Accepted 16 December 2024
Available online 17 December 2024
0957-5820/© 2024 Institution of Chemical Engineers. Published by Elsevier Ltd. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

constituents that support growth thus, nitrogen entry into the receiving aquatic environment through wastewater should be prevented. This process is achieved by denitrifying nitrate, which is the final oxidation step of nitrogen. In addition, when nitrate is taken with drinking water, it may cause health problems such as blue-baby disease in babies. Although there are many advanced nitrate removal methods, denitrification processes are widely used in both wastewater and drinking water treatment. Nitrate serves as an important electron acceptor in MFCs under both biotic and abiotic conditions. Heterotrophic denitrification uses organic carbon as the electron donor while autotrophic denitrification uses hydrogen and sulfur as electron donors. At the biocathode, organic and inorganic C are given to the microorganisms as a carbon source in the heterotrophic and autotrophic denitrification processes, respectively. Since organic carbon residues in water cause problems after heterotrophic denitrification, autotrophic denitrification is offered as an alternative in the presence of inorganic electron donors for nitrate removal from water to be used as drinking water. Nitrate removal is recommended under abiotic conditions where contamination with both organic matter and microorganisms is undesirable. MFC technology is a technology that simultaneously produces energy via nitrate removal and reduces CO_2 emissions and energy consumption (Guo et al., 2023). The most effective factor in high power generation in MFCs is to determine the electron acceptor that will reduce potential losses at the cathode. It is desired that the cathodic electron acceptor has a high redox potential, to be sustainable, to show fast kinetics, to be economically viable and to be easily accessible (He et al., 2015). There has been increased interest in the use of nitrate as an electron acceptor.

In cathode heterotrophic denitrification, electroactive microorganisms transfer the electrons they obtain from the electrode to denitrifiers, thus reducing the need for organic matter. In this way, CO_2 emissions from the system are also reduced. In addition, biocathode autotrophic denitrification does not require electron donor sources such as H_2 or reduced sulfur compounds. The electrons required for nitrate reduction are transmitted to the denitrifiers via electroactive microorganisms (Zhu et al., 2024). The use of low conductivity waters such as groundwater may limit autotrophic denitrification in the biocathode. Irreversible energy losses occur at low conductivity, and resistance to electron and proton transport between compartments occurs. Thus, nitrate reduction is not complete (Puig et al., 2012). Denitrification in MFCs has attracted attention because the reduction potential of nitrate is similar to oxygen. In addition, it has been proven that nitrite, a byproduct of nitrate reduction, can be used as an electron acceptor (He et al., 2015; Puig et al., 2012). Under abiotic denitrification conditions, charge accumulates on the electrode due to capacitance, and with this accumulated charge capacity, nitrate gains five electrons and is reduced to N_2. Reduction is achieved by four different bacterial enzyme. The reduction potential of nitrate is + 0.549 (V vs Ag/AgCl) and the reduction steps are shown by Eq. 1-5 (Al-Mamun et al., 2017; Lefebvre et al., 2008; Vijay et al., 2022). Potential losses may occur in the biocathode as the needs of microorganisms such as growth consume energy. However, the reduced overpotentials resulting from biocatalysis will compensate for this loss (Virdis et al., 2008).

$$NO_3^- + 2e^- + 2H^+ \rightarrow NO_2^- + H_2O \quad E_0 = +0.233 \tag{1}$$

$$NO_2^- + e^- + 2H^+ \rightarrow NO + H_2O \quad E_0 = +0.150 \tag{2}$$

$$NO + e^- + H^+ \rightarrow 0.5N_2O + 0.5H_2O \quad E_0 = +0.975 \tag{3}$$

$$0.5N_2O + e^- + H^+ \rightarrow 0.5N_2 + 0.5H_2O \quad E_0 = +1.155 \tag{4}$$

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O \quad E_0 = +0.549 \tag{5}$$

The traditional approach is to determine MFC performance by outputs such as energy production only or treatment efficiency only. However, the importance of MFC outputs vary in practice. Therefore, statistical approaches are needed. The correct approach is to evaluate simultaneously occurring MFC outputs together according to their importance. Here, nitrate removal was investigated under biotic and abiotic catholyte conditions in an MFC using waste sludge fed with dairy industry wastewater as substrate. MFC outputs such as energy production, treatment potential, and external carbon cost were considered simultaneously and the most appropriate MFC was determined with the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) approach, which is a multi-criteria decision-making process (MCDM). Hence, the MFC outputs that are positively and negatively influential and the MFC output with the highest degree of influence are revealed.

2. Materials and methods

2.1. Experimental procedure

The mixture of anaerobic sludge taken from a fermentation industry wastewater treatment plant and dairy industry wastewater was used as substrate in the anode compartment. Nitrate was used as an electron acceptor in the cathode compartment. The experiments were conducted in an MFC reactor made of plexiglass with each compartment having an active working volume of 800 mL. Each compartment was divided by a Nafion 117 proton-exchange membrane (Fisher Scientific/Thermo Fisher Scientific, Waltham, MA, USA) with surface area of 10 cm^2. The membrane was pretreated with 30 % H_2O_2 solution at 40 °C for 24 hours before each experiment. Carbon fabric electrodes (FuelCell Store) with a surface area of 22.5 cm^2 (5 cm*4.5 cm) were used as anode and cathode electrodes. The mixture of anaerobic sludge (500 mL) taken from the fermentation industry wastewater treatment plant and dairy industry wastewater (200 mL) was used as substrate in the anode chamber. 100 mL and 50 mL of exoelectrogen rich sludge was added to the anode and biocathode compartment, respectively. Enrichment of sludge in terms of exoelectrogens was carried out as described in a previous study (Durna Pişkin and Genç, 2024). A mixed culture enriched with exoelectrogens was added as an inoculum in the anode compartment and as a microbial population to provide denitrification in the cathode compartment. While the mixed liquor suspended solids (MLSS) values of the anode and cathode were 40 g/L and 10 g/L, respectively, the mixed liquor volatile suspended solids (MLVSS) values were 14 g/L and 3.4 g/L, respectively. A solution containing 40 mg/L NO_3^-N (500 mL) was used in the cathode compartment. A $NaNO_3$ solution was used as NO_3^- source for the cathode. 2125 mg/L K_2HPO_4, and 2600 mg/L KH_2PO_4 buffer solutions were added to the anode and cathode compartments. $NaHCO_3$ (1000 mg/L) and CH_3COONa (1250 mg/L) were used as carbon sources for the microorganisms in autotrophic and heterotrophic denitrification, respectively. Under abiotic conditions, no inoculum or carbon was added to the catholyte. In all experiments, the anode and cathode compartments were mixed with a magnetic stirrer. At the beginning of the experiments, both compartments were swept with N_2 gas to remove oxygen. Before starting the experiments, the anodic and cathodic solutions were adjusted to pH 7.0 with a Mettler-Toledo pH meter and the experiment was carried out at 23 ± 1.5 °C. The electrodes were connected to each other with conductive copper wire. All experiments were carried out using 1000 Ω external resistance. Samples were taken from the anode and cathode compartments under conditions where the voltage remained constant. All chemicals used in the experiments were analytical grade. The MFC experimental setup is shown in Fig. 1.

2.2. Analysis

The voltage between the anode and cathode during 4300 min was determined by a Unit UT8804E Benchtop Digital Multimeter. The voltage and power were calculated according to Ohm's law using Eqs. 6 and 7, respectively. The coulombic efficiency (CE) was calculated by Eq. 8.

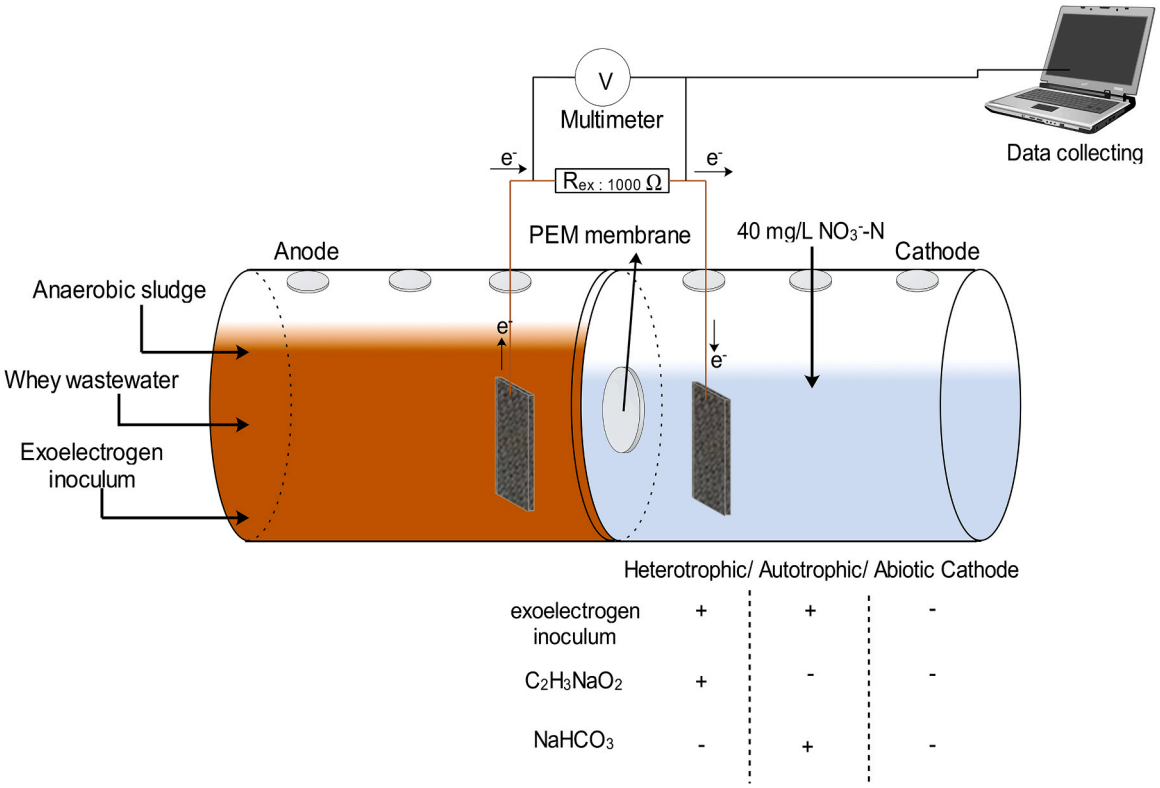


Fig. 1. MFC experimental setup.

$$I = E_{cell}/R_{ext} \tag{6}$$

Here, I is the current, E_{cell} is the voltage measured through an external resistance (R_{ext}).

The power density (P) was determined using Eq. (9) and normalized with the surface area of the electrode.

$$P = I^{*}E_{cell} \tag{7}$$

The coulombic efficiency (%) is expressed as the ratio of the total coulombs transferred from the substrate to the anode to the maximum number of coulombs that can be transferred. The coulombic efficiency was calculated according to Eq. 8 (Peera et al., 2021). The Coulombic efficiency was calculated in the MFC system based on the anode and is also referred to as the anodic coulombic efficiency in some sources (Bhattacharya and Chatterjee, 2024).

$$\text{Anodic CE}(\%) = \frac{8\int_0^{t_b} Idt}{FV_{an}\Delta COD} \times 100 \tag{8}$$

In recent years, the concept of cathodic CE has come to the fore with the use of different electron acceptors. The cathodic coulombic efficiency can be calculated using Eq. 9.

$$\text{Cathodic CE}(\%) = \frac{\int_o^t Idt}{\left(5\frac{\Delta NO_3^- V_c}{M_n}\right)F} \times 100 \tag{9}$$

where I (A) = current generation during the operating time (t, s); Van (L)= active volume of the anode chamber, Vc (L) = active volume of the cathode chamber; F = Faraday constant (96485 C/mol); Mn = nitrogen atomic weight (14 g/mol); ΔCOD is the initial and effluent COD difference (mg/L) at the anode, and ΔNO_3^- represents the initial and effluent NO_3^- difference (mg/L) at the cathode (Bhattacharya and Chatterjee, 2024).

The polarization curve was plotted using different external resistances between 1×10^5 and 10 Ω.

COD and NO_3^- analyses were carried out to determine the treatment performance in the anode and cathode chambers, respectively. Nitrate analysis was carried by a Hach DR 6000 spectrophotometer. using the LCK340 - Nitrate Cuvette Tests on the filtrate obtained by filtering the analyte through a 0.45 μm pore diameter filter. COD analysis was conducted according to the standard 5220 closed reflux method. The COD and nitrate removal efficiencies were calculated according to Eq.10.

$$\text{Removal Efficiency}(\%) = \frac{C_0 - C_t}{C_0} \times 100 \tag{10}$$

where C_0 (mg/L) is the initial COD or nitrate concentration, and C_t(mg/L) is the COD or nitrate concentration at reaction time, t (min).

Electrochemical impedance spectroscopy (EIS) measurements were carried out for whole cell using a VersaSTAT 4 potentiostat and VersaSTUDIO electrochemical software. In the test, the anode electrode was used as the working electrode and the cathode electrode was used as the counter and reference electrodes (Lu et al., 2015; Tou et al., 2024).

Measurements were conducted for heterotrophic MFC with a frequency range of 1000 kHz to 0.1 MHz and an amplitude of 10 mV and for abiotic MFC with a frequency range of 10000 kHz to 0.1 MHz and an amplitude of 10 mV. Zsimp software is used to fit the measured EIS data to the equivalent circuit model (Tou et al., 2024).

2.3. PROMETHEE approach

The most suitable MFCs for biotic and abiotic nitrate removal in terms of energy production, treatment efficiency and required C (carbon) cost were determined by PROMETHEE (The Preference Ranking Organization Method for Enrichment Evaluation). The PROMETHEE method is a MCDM method developed by Brans and Vincke (1985). PROMETHEE is a prominent ranking method for ranking and selecting a finite set of alternative actions among often conflicting criteria (Behzadian et al., 2010). The method evaluates the alternatives based on the specified preference functions and determines the priorities of the alternatives. GAIA (Geometrical Analysis for Interactive Aid) plane is a

graphical representation. The GAIA plane, a visual tool, provides a graphical representation of the results obtained with the PROMETHEE method. This tool also helps to understand conflicts between criteria and which criteria are influential in the selection of alternatives (Mareschal and Brans, 1988). The PROMETHEE rainbow visually represents a sliced view of the net ranking achieved with PROMETHEE II. Positive and negative impact criteria can be displayed for each alternative (Tusher et al., 2024). Biotic and abiotic MFCs were evaluated according to CE, maximum power density, C-cost, COD and NO_3^- removal criteria and the most suitable MFC was determined. Alternative MFCs were ranked using the Visual PROMETHEE software.

3. Results and discussion

3.1. Evaluation of MFCs in terms of their energy production potential and treatability

While the dairy industry wastewater and sludge mixture were oxidized in the anode chamber of the MFC, abiotic and biotic (heterotrophic and autotrophic) nitrate reduction was carried out in the cathode section. The energy production and treatment potential of MFCs were evaluated simultaneously. The results are given in Table 1.

COD removal remained at approximately the same levels in all MFCs because the only variable that can affect the degree of organic matter oxidation is the abiotic/biotic condition of the catholyte. MFCs were evaluated with anodic CE calculated based on the electrons generated by the decomposition of organic matter (COD) and cathodic CE calculated based on the electrons required for the reduction of nitrate. It was observed that CE was at the maximum level in the abiotic cathode process where nitrate removal efficiency was at the lowest level. In abiotic MFC where 5 % NO_3^- was removed, anodic and cathodic CE were determined as 15.4×10^{-2} and 67.94, respectively. In heterotrophic and autotrophic MFCs where NO_3^- was removed as 98.5 % and 22.5 %, anodic and cathodic CE were determined as 1.5×10^{-2}, 0.33 and 3.1×10^{-2}, 3.06, respectively. Carbon is generally thought to be an excellent conductor and anti-corrosion material for making electrodes for MFCs. However, because of the poor adhesion of bacteria, electron transport from microbial biofilm to the electrode surface is limited when utilising traditional anodes. This problem affects the MFC's ability to operate by lowering its power output, which impedes the technology's practical application. High internal resistance is the other major drawback (Khan et al., 2024; Soomro et al., 2016). A high salt concentration damages carbon-based electrodes or metal-based current collectors (Li et al., 2018). Here, the anode chamber had a sufficiently high salt concentration to support biodegradation and was not at a level that would damage the electrode. Since the MFCs were operated under practically anticipated operating conditions, no significant change in the electrochemical properties of the electrodes was expected. The only difference between biotic MFC and abiotic MFC was that mixed microbial population that will provide nitrate reduction were used in the cathode compartment of biotic MFC. Electroactive microorganisms carried the electrons they received from the cathode electrode to denitrifiers, providing higher nitrate removal. In abiotic conditions, since electron transfer from the electrode to nitrate was insufficient, nitrate removal efficiency remained low. In the study conducted by Puig et al. (2012), in the MFC fed with sodium acetate in the anode compartment, It was determined that nitrate removal by autotrophic denitrification was approximately 5 times greater than that by abiotic denitrification (Puig et al., 2012). In this study, a 4.5-fold increase in nitrate removal rate was obtained by autotrophic denitrification compared to abiotic conditions. In the study conducted by Jiang et al. (2017), 87.05 % nitrate removal and 1.52 mA/m^3 power density were achieved by autotrophic denitrification (Jiang et al., 2017). The high voltage observed at low NO_3^- removal increased the cathodic CE to the maximum. High COD removal decreased the anodic CE. The high COD in the anode chamber encouraged the growth of fermentation and methanogenesis bacteria, which cannot contribute to electricity production (Nguyen and Babel, 2023). Power production was achieved by reducing nitrate in the cathode compartment. However, the formation and accumulation of intermediate products may lead to loss of oxidation capacity of the electron acceptor, resulting in low CE (Puig et al., 2012). Nitrite is frequently generated during the startup stages of the microbial-driven denitrification process as a result of pH variations, a lack of electron donors, or electrode potential oscillation (Li et al., 2024b). During the stabilization phase, nitrite accumulation is minimal.In MFCs, nitrite's electron consumption is superior to that of nitrate, leading to a greater cathodic coulombic efficiency and a nitrite reduction rate that is up to two times quicker than that of nitrate, hence enhancing the nitrogen removal efficiency (Nguyen and Babel, 2024). In the study conducted by Li et al. (2016), in a MFC with a Pt-free plain electrode, nitrite and nitrate were reduced only 87.2 % on the 4th day with an integrated short-cut nitrification and autotrophic denitrification, the nitrate reduction rate was 0.0028 kg N/m^3d, and the nitrite reduction rate was 0.0068 kg N/m^3 d (Li et al., 2016). Experimental results obtained by Yao et al. (2024) revealed that potential acclimation could efficiently improve denitrification performance by relieving the phenomenon of nitrite accumulation (Yao et al., 2024). The results indicated that potential acclimation was conducive to enhancing denitrifying enzyme activity and that the electron transport system activity could be increased by 5.8 times. After potential acclimation, the nitrite accumulation was efficiently relieved. The accumulation of nitrous oxide in the cathode is the most important reason for the decrease in coulombic efficiency at the cathode. Strategies have to be found to minimize the accumulation of this intermediate. Incomplete denitrification can reduce the coulombic efficiency of the cathodic denitrification due to the reduced number of electron equivalents actually taken up by bacteria at the electrode (Virdis et al., 2008). To achieve the desired level of effluent treatment in the anode and cathode compartments, MFCs need to be operated at high retention times. Longer retention times will reduce the power generation potential. Therefore, the use of MFCs as final treatment units is not feasible. When the initial concentrations of nitrate and nitrite were about 50 mg/L and 23 mg/L, respectively, after around 43 days of operation, the removal efficiency for both NO_3^--N and NO_2^--N in the system stabilized at almost 99.5–99.9 % (Deng et al., 2020). In this study, MFCs were monitored for approximately 10 days. Nitrite levels were determined to be approximately 0.7 mg/L, 2.5 mg/L, and 8 mg/L for abiotic, heterotrophic, and autotrophic MFCs, respectively. By increasing the electron donor without allowing the growth of fermentation bacteria and methanogens in the anode compartment, creating environmental conditions that will support microbial growth in the biocatholyte, and increasing the retention time, complete reduction of denitrification intermediate products will be achieved. Thus, intermediate product accumulation can be prevented.

The real voltage of a MFC is less than the theoretical one. This decrease is cause by ohmic, concentration and activation over potentials (Esfandyari et al., 2017b). Due to the activation energy required for an oxidation/reduction reaction, activation losses occur during electron

Table 1
Outputs of biotic and abiotic MFCs.

Outputs	Biotic MFC (Heterotrophic denitrification)	Biotic MFC (Autotrophic denitrification)	Abiotic MFC
Anodic CE (%)	1.5×10^{-2}	3.1×10^{-2}	15.4×10^{-2}
Cathodic CE (%)	0.33	3.06	67.94
Max power density (mW/m^2)	0.99	5.65	95.34
COD removal (%)	45.00	47.00	50.00
NO_3^- removal (%)	98.50	22.50	5.00

transfer to or from a reacting compound at the electrode surface. Ohmic losses are the resistance of the electrodes and their junctions to the flow of electrons and the resistance of the flow of ions through the proton conducting membrane (PEM), anode and cathode electrolytes (Teoh et al., 2023). Concentration losses are limitations on current production due to the rate of mass transport of a species to or from the electrode (Esfandyari et al., 2017b). In particular, the change in conductivity associated with nitrate in the catholyte is likely to cause significant changes in ohmic losses.

The significant increase in voltage observed in the abiotic MFC was due to the high potential difference between the anode (biotic) and cathode (abiotic). In biotic MFCs, low voltage occurred because the potential difference between the anode (biotic) and cathode (biotic) remained at lower levels. Polarization curves are used to determine the dependence of MFC performance on resistance. The polarization represents the change between voltage (V) and current density (mA/m^2) using the projected area of the electrode (Benghernit et al., 2022). The polarization curves of MFCs are shown in Fig. 2. The maximum power density in the abiotic MFC was determined as 95.34 mW/m^2, whereas it was determined as 0.99 mW/m^2 and 5.65 mW/m^2 in heterotrophic and autotrophic MFCs. In the polarization graph of the three MFC experiments, it is seen that in the heterotrophic MFC (Fig. 2(a)) the voltage decreased suddenly in the high external resistance region. The losses in this region were caused by the initiation energy of oxidation/reduction reactions frequently observed in biochemical processes and are expressed as the fast voltage loss region (Choudhury et al., 2021). It is seen that the least voltage loss in this region was in the abiotic MFC. When the polarization curve of the abiotic MFC is examined (Fig. 2(c)), it is seen that ohmic and mass transfer losses were more intense. While ohmic losses expressed the resistance of the electrodes and their connections to the flow of electrons and the resistance of the flow of ions passing through the proton conducting membrane (PEM), anode and cathode electrolytes, mass transfer losses generally occurred due to the concentration losses of chemical substances limited by diffusion to the electrode surface (Guo et al., 2021). The cathodic losses incurred in MFCs have been a challenge to achieve the desired performance, mainly with biocathodes. Therefore, it is possible to overcome this with special applications. For example, it was determined that the use of granular activated carbon acting as an electrochemical capacitor doubled the rate of autotrophic denitrification and increased the maximum power density from 37.6 ± 4.8 mW/m^2 to 379.2 ± 7.4 mW/m^2 (Thapa et al., 2024). In the heterotrophic MFC and autotrophic MFC, which have biotic cathodic chambers, voltage losses were determined more in the high resistance region (Fig. 2(a) and (b)). It can be said that activation losses are evident for these two MFCs. In the abiotic MFC (Fig. 2(c)), voltage losses originating from ohmic and mass transfer are seen to be more evident. Since no biological reduction occurs in the cathode in the abiotic MFC, these losses are thought to be lower compared to biotic MFCs.

In MFCs where both the anode and cathode compartments were biotic, the maximum power density was lower than in abiotic MFCs since the potential difference between the two biotic chambers was low. The internal resistance of the MFCs was calculated from the slope of the linear region of the voltage-ampere curve. The internal resistances for heterotrophic, autotrophic and abiotic MFC were calculated as 1405.6, 4422 and 654.87 Ω, respectively. It was compatible to obtain the highest maximum power density with the abiotic MFC having the lowest internal resistance. In the study conducted by Zhu et al. (2016), in

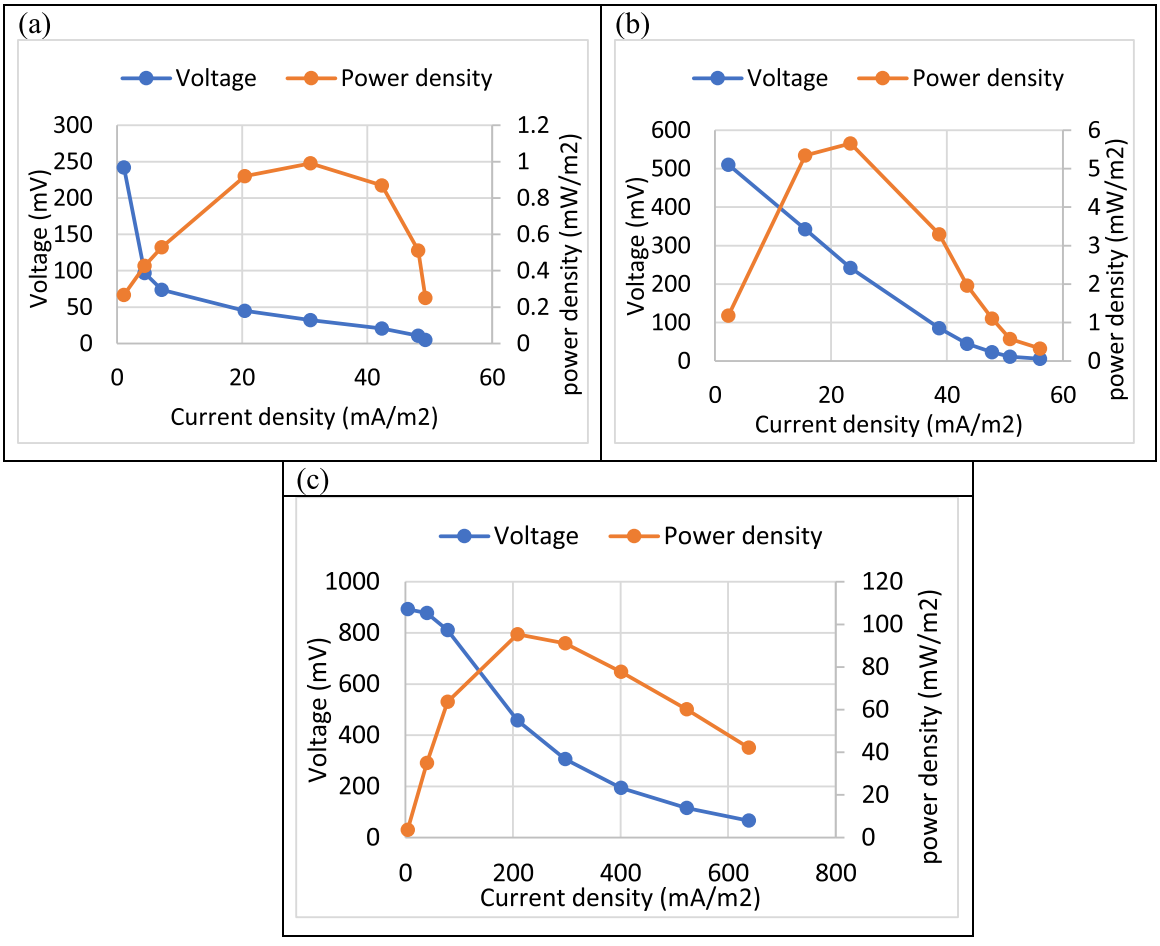


Fig. 2. Polarization graphs of MFC's: (a) Heterotrophic, (b) Autotrophic, (c) Abiotic).

heterotrophic denitrification using decomposed Cyanobacteria solution as substrate, a 0.064 ± 0.005 kg TN/m^3d nitrogen removal rate and 1.28 mW/m^2 power density were obtained (Zhu et al., 2016). It can be said that this value is compatible with the maximum power density value obtained with the waste substrate mixture in the current study. In heterotrophic and autotrophic cathodic denitrification where sodium acetate was used as an electron donor, the nitrate removal rate and power density were obtained as 2.06 kg NO_3^--N/m^3d, 3.02 W/m^3 and 0.13 ± 0.011 kg NO_3^--N/m^3d, 207.05 ± 5 mW/m^3, respectively (Vijay et al., 2019). In abiotic denitrification, it is known that the electrode acts as an electron donor and removes nitrate at certain levels. For biocathode systems, it is stated that the bacteria in the biocathode system could use electrons which are provided by their own metabolism to perform denitrification. When evaluated from this perspective, the denitrification rate is higher in biotic cathode systems (Li et al., 2024b). In this study, the power density obtained by autotrophic denitrification was 5.7 times higher than that obtained by heterotrophic denitrification. The reactor configuration affected electron supply and indirectly nitrate removal. In the study conducted by Bhattacharya and Chatterjee (2024), a power density of 370 mW/m^3 was obtained in the H-type reactor at the cathode where autotrophic denitrification took place. This value increased to 1441 mW/m^3 when the reactor configuration was cube-shaped (Bhattacharya and Chatterjee, 2024). Different strains and environmental factors may affect the denitrification abilities of cathodic electroactive bacteria that can exchange electrons with electrodes (Shi et al., 2024). The use of high-performance denitrifiers will positively affect the process. With autotrophic denitrification with a mixed culture, a maximum output voltage of 120 ± 5 mV at 1000Ω over 400 h and approximately 70 % NO_3-N removal were obtained. It is reported that this value was increased to 93 % by the isolated strain *Lyy (S.stutzeri)* (Li et al., 2024a).

When the voltage versus time curves of the three MFCs are examined, the voltage increased rapidly and reached the maximum value due to the usable substrate in the anode compartment (dairy industry wastewater). This increase was determined at 1081 min (46.12 mV), 841 min (88.89 mV) and 1200 min (448 mV) in heterotrophic, autotrophic and abiotic MFCs, respectively. At the point where soluble and usable substrate was depleted, the endogenous phase began for the microorganisms present in the sludge. In endogenous respiration, it was observed that the voltage value decreased rapidly because the substrate consumption rate was slow. Between 2000 and 4300 minutes, the voltages for heterotrophic, autotrophic and abiotic MFCs remained stable at 40, 80 and 450 mV, respectively. This situation was accepted as the steady state. Since the anode conditions were constant and the cathode conditions changed in the examined MFCs, the potential difference between the two compartments created this change.

3.2. Determining the most suitable MFC with the PROMETHEE approach

Biotic and abiotic MFCs were evaluated in terms of energy production, treatment performance and C cost, and the most suitable MFC was selected with the PROMETHEE approach. The PROMETHEE analysis was based on the data presented in Table 1. In the calculation of the cost of organic and inorganic C added in the cathode compartment, the sales price in Türkiye was taken into account. The costs of carbon added to the cathode in heterotrophic and autotrophic MFCs were taken as € 0.034 and € 0.0019. No carbon addition was made in the abiotic MFC. Here, all criteria determining the performance of the MFC were taken as equal weights and the PROMETHEE analysis was performed to obtain the preference ranking. The weighting of the criteria can be done by decision makers. In practice, the weighting of the criteria will of course change when the desired treatment efficiency, energy efficiency of the process and cost are taken into account. By changing the weighting of the criteria, the MFCs were analyzed and the preference rankings presented in Table 2 were obtained. As can be seen, the change in the criteria weighting did not affect the ranking insignificantly, and in every case, the Abiotic MFC was selected.

Table 2
PROMETHEE rankings obtained with different weightings.

Response (weight)	Ranking
Anodic CE (%) (1), Cathodic CE (1), Max power density (1), COD removal (1), NO_3^- removal (1), Cost* (1)	Abiotic MFC>Autotrophic MFC>Heterotrophic MFC
Anodic CE (%)(2), Cathodic CE (2), Max power density (2), COD removal (1), NO_3^- removal (1), Cost* (1)	Abiotic MFC>Autotrophic MFC>Heterotrophic MFC
Anodic CE (%) (1), Cathodic CE (1), Max power density (1), COD removal (2), NO_3^- removal (2), Cost* (1)	Abiotic MFC>Autotrophic MFC>Heterotrophic MFC
Anodic CE (%)(1), Cathodic CE (1), Max power density (1), COD removal (1), NO_3^- removal (4), Cost* (1)	Abiotic MFC>Heterotrophic MFC>Autotrophic MFC

Cost*: The cost of organic and inorganic carbon added in the cathode compartment

In PROMETHEE II, the net flow is shown in a single column (Fig. 3 (a)). Alternatives are shown as horizontal lines in the flow columns. At the top of the ranking is the abiotic MFC. Accordingly, the order of preference was determined as abiotic MFC>autotrophic MFC>heterotrophic MFC. As seen in Fig. 3(a), the net Phi score of the abiotic MFC, which ranks first among the alternatives in the study (Phi = 0.5833), is greater than all of them. The net superiority values of the autotrophic MFC and heterotrophic MFC are negative and are Phi = −0.1207 and Phi = −0.4627, respectively.

As shown in Fig. 3(b), alternative MFCs are shown as square boxes in the GAIA plane, criteria are shown as vectors, and the decision axis is shown as a red vector. More detailed results can be obtained in the GAIA plane. For example, the longer the criterion axis, the greater the discrimination power. Criterion vectors in the same direction represent similar preferences, while criterion vectors in opposite direction represent conflicting preferences (Agustin et al., 2022). The alternative abiotic MFC closest to the red decision bar appears to be the most suitable MFC. All criteria except maximum power density were approximately the same length and affect the choice to the same degree. The maximum power density criterion can be interpreted as the criterion that affects the performance more because it is closer to the decision vector and longer. In general, if the vector lengths of the criteria are short, it is interpreted as the discriminative power of the criteria being low. It is clearly seen that the discriminative power of all criteria except the maximum power density is low.

PROMETHEE rainbow provides a visual representation of the criteria that influence the alternatives. The alternatives are listed from left to right in order of preference and divided by criterion slices from bottom to top (Fig. 4). For example, in the Abiotic MFC alternative on the far left, the anodic CE, cathodic CE, max. power density, C- cost and COD removal criteria in the upper part [+ 1/0] have a positive contribution on the selection of this alternative. The nitrate removal criterion in the lower part [-1/0] has a negative contribution on the selection of this alternative. Heterotrophic MFC was ranked last in the preference ranking. All criteria except nitrate removal had a negative effect on this selection. In autotrophic denitrification, the criteria had no significant effect. While C-Cost, COD and NO_3^- removal positively affected the selection, anodic and cathodic CE and maximum power density criteria negatively affected the selection.

3.3. Electrochemical analysis of biotic and abiotic MFCs

Electrochemical impedance spectroscopy (EIS) is an effective and non-destructive characterization method widely used to characterize electrochemical processes quantitatively and qualitatively (Borole et al., 2010; Sekar and Ramasamy, 2013). Electrochemical impedance spectroscopy (EIS) was performed for the most preferred alternative MFC (abiotic) and the least preferred alternative MFC (heterotrophic)

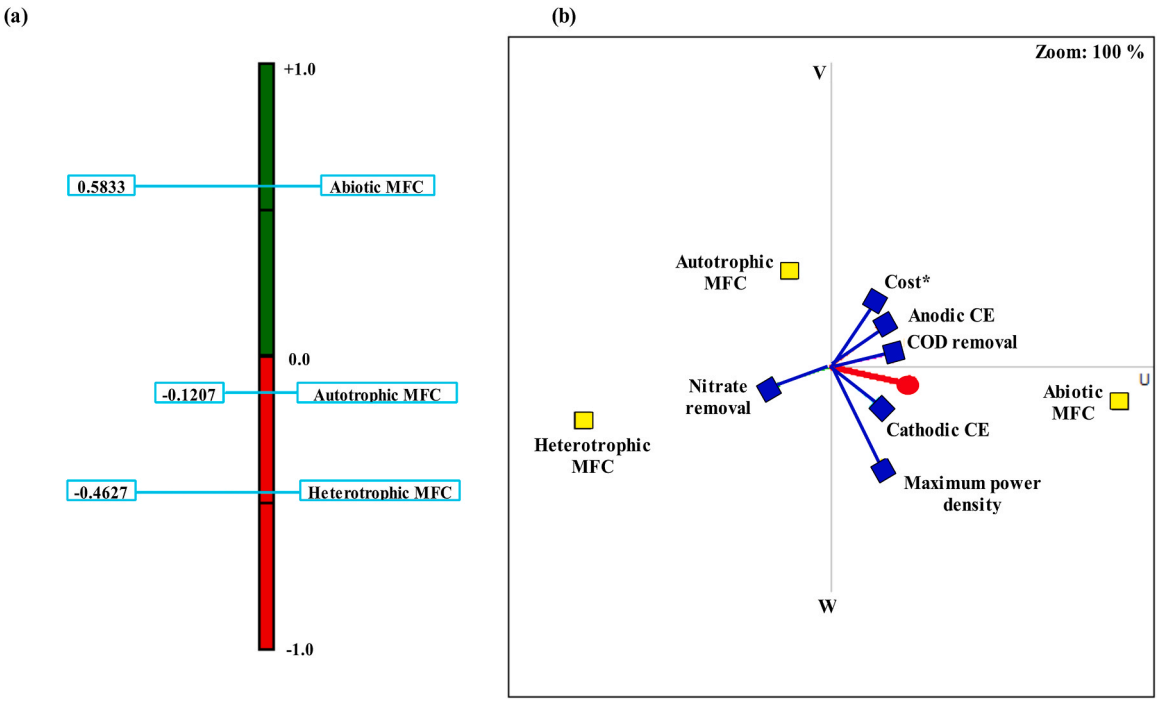


Fig. 3. PROMETHEE II net ranking and GAIA plane.

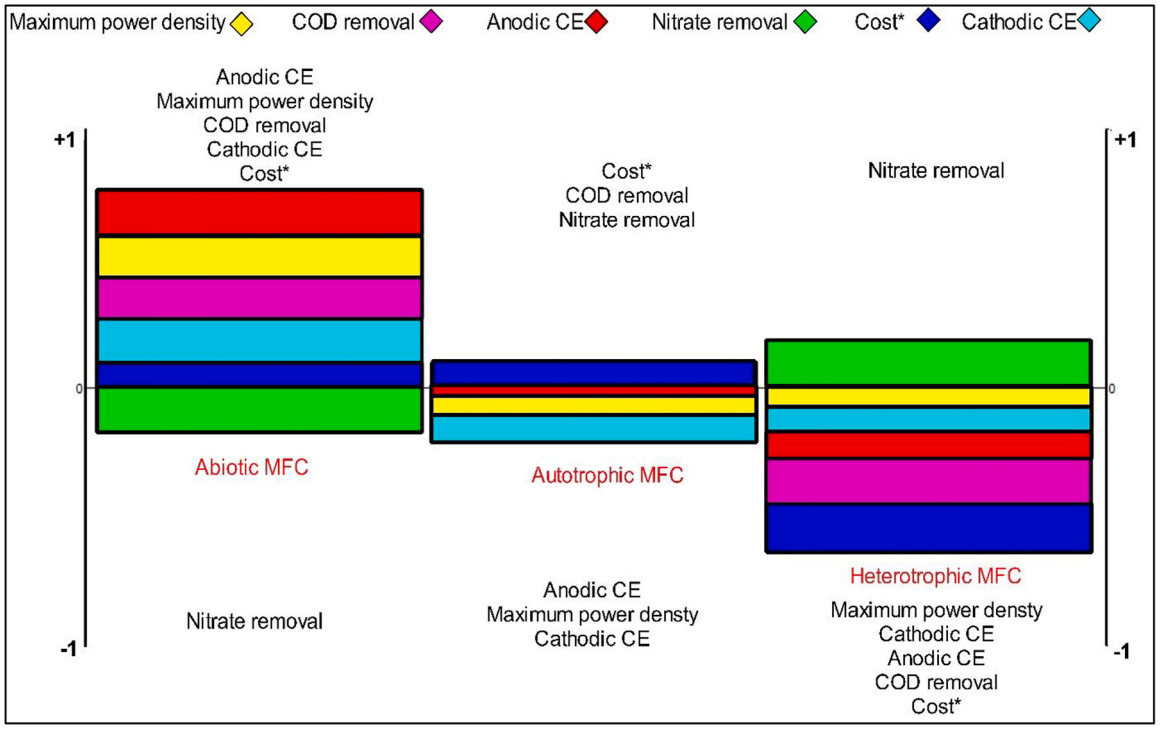


Fig. 4. PROMETHEE Rainbow.

according to the PROMETHEE ranking. After the polarization curve was created, EIS was performed on the day the experiments reached maximum voltage. Fig. 5 shows Nyquist plots of the heterotrophic and abiotic MFCs. Zsimp software was used to fit the measured electrochemical impedance data using an equivalent circuit. The equivalent circuit consists of the ohmic total resistance, a Constant Phase Element-Resistor parallel pair (these two groups represent a typical Randles circuit) and finally a Warburg element to represent diffusion effects (Sindhuja et al., 2016; Wang et al., 2022). In the equivalent circuits of MFCs, the first resistor R1 represents the total ohmic loss, which includes and represents both electronic and ionic resistances in all components (electrodes, proton exchange membrane, and anolyte). R2 can represent the charge transfer losses caused by the activity of the biofilm of the anode, while R3 represents the charge transfer losses in the cathode, and the Warburg element represents the diffusion resistance in the substrate, oxygen, or other reactants (Chen et al., 2018).

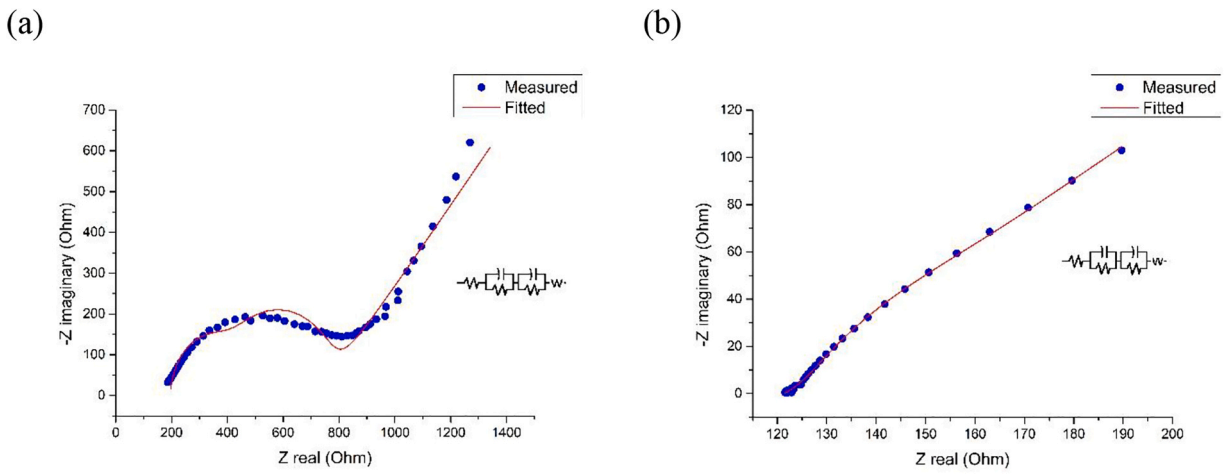


Fig. 5. Nyquist plots of abiotic and heterotrofic MFCs.

Nyquist plots for abiotic and heterotrophic MFC are given in Fig. 5. For the two MFC experiments the equivalent circuit provided good agreement with the measured impedances.

Comparing the shapes of the abiotic and heterotrophic Nyquist plots, it can be understood at first glance that the shape of the abiotic MFC is a typical shape consistent with the literature, with a semi-arc at high frequencies and then a typical Warburg behavior at low frequencies. However, this shape was deformed for the heterotrophic MFC and the first half of the arc depressed. It was found that the current drawn was better in the case of abiotic MFC; this is thought to be mainly due to the increased potential difference allowing the current to flow quickly due to the anaerobic anode and abiotic cathode of abiotic MFC.

4. Conclusions

Nitrate is a pollutant and an important electron acceptor in microbial fuel cell (MFC)'s. MFCs with biotic and abiotic nitrate reduction were compared in terms of energy production potential, treatability and added C (carbon) cost criteria. The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) approach, one of the multi-criteria decision-making method, was used for selection. The MFC with the highest energy production and treatability, and the lowest C cost was determined which was the abiotic MFC. The abiotic MFC stood out in the selection with its advantages such as power generation and not requiring carbon addition. It was determined that heterotrophic and autotrophic MFCs showed a higher treatment performance compared to an abiotic MFC. The heterotrophic MFC provided a higher NO_3^- removal than the abiotic MFC. It was determined that all criteria except nitrate removal had a positive contribution on the selection of the abiotic MFC. The PROMETHEE approach is recommended to select the most suitable one among all alternative methods/equipment that will improve the performance of the MFC and remove the obstacles to its commercialization. There is a need to evaluate alternatives that will minimize energy losses in the operation of MFCs in the future. The PROMETHEE approach can be used safely to select the most suitable one from the perspective of environmental and economic sustainability among all alternatives, including the biotic/abiotic cathode status, the configuration of the MFC unit and its location in the waste treatment plant, the type of electron acceptor and electrode, and the pretreatment method applied to the substrate.

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

This research is supported by the Department of Scientific Research Projects of Kocaeli University under contract number of FBA-2023–3495.

CRediT authorship contribution statement

Elif Durna Pişkin: Writing – review & editing, Visualization, Software, Formal analysis, Data curation. **Nevim Genç:** Writing – original draft, Project administration, Methodology, Conceptualization.

Data Availability

Data will be made available on request.

References

Agustin, E.A.S., Martini, R., Setiyono, B., 2022. Evaluating rural tourism competitiveness: application of PROMETHEE-GAIA method. Cogent Econ. Financ 10. https://doi.org/10.1080/23322039.2022.2054526.

Al-Mamun, A., Baawain, M.S., Dhar, B.R., Kim, I.S., 2017. Improved recovery of bioenergy and osmotic water in an osmotic microbial fuel cell using micro-diffuser assisted marine aerobic biofilm on cathode. Biochem Eng. J. 128, 235–242. https://doi.org/10.1016/J.BEJ.2017.09.020.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: a comprehensive literature review on methodologies and applications. Eur. J. Oper. Res 200, 198–215.

Benghernit, M., Kameche, M., Zerhouni, F.Z., Krim, F.Z., Sahraoui, T., Innocent, C., 2022. The study of the performance of a microbial fuel cell: a progress towards the improvement of low electrical bioenergy output by using an amplification system. Biotechnol. Lett. 44, 1359–1378. https://doi.org/10.1007/s10529-022-03304-4.

Bhattacharya, A., Chatterjee, P., 2024. Impact of Reactor Configuration on Autotrophic Denitrification Performance in a Microbial Fuel Cell. J. Hazard., Toxic., Radio. Waste 28, 04024013. https://doi.org/10.1061/JHTRBP.HZENG-1314.

Borole, A.P., Aaron, D., Hamilton, C.Y., Tsouris, C., 2010. Understanding long-term changes in microbial fuel cell performance using electrochemical impedance spectroscopy. Environ. Sci. Technol. 44, 2740–2745. https://doi.org/10.1021/es9032937.

Brans, J.P., Vincke, P., 1985. Note-a preference ranking organisation method. Manag. Sci. 31, 647–656. https://doi.org/10.1287/MNSC.31.6.647.

Chen, Y.M., Wang, C.T., Yang, Y.C., 2018. Effect of wall boundary layer thickness on power performance of a recirculation microbial fuel cell. Energies 2018 11, 1003. https://doi.org/10.3390/EN11041003.

Choudhury, P., Ray, R.N., Bandyopadhyay, T.K., Basak, B., Muthuraj, M., Bhunia, B., 2021. Process engineering for stable power recovery from dairy wastewater using microbial fuel cell. Int. J. Hydrog. Energy 46, 3171–3182. https://doi.org/10.1016/j.ijhydene.2020.06.152.

Deng, Q., Su, C., Lu, X., Chen, W., Guan, X., Chen, S., Chen, M., 2020. Performance and functional microbial communities of denitrification process of a novel MFC-granular sludge coupling system. Bioresour. Technol. 306, 123173. https://doi.org/10.1016/j.biortech.2020.123173.

Durna Pişkin, E., Genç, N., 2024. Multi response optimization of waste activated sludge oxidation and azo dye reduction in microbial fuel cell. Environ. Technol. https://doi.org/10.1080/09593330.2023.2179422.
Esfandyari, M., Fanaei, M.A., Gheshlaghi, R., Akhavan Mahdavi, M., 2017b. Mathematical modeling of two-chamber batch microbial fuel cell with pure culture of Shewanella. Chem. Eng. Res Des. 117, 34–42. https://doi.org/10.1016/J.CHERD.2016.09.016.
Esfandyari, M., Fanaei, M.A., Gheshlaghi, R., Akhavan Mahdavi, M., 2017a. Dynamic modeling of a continuous two-chamber microbial fuel cell with pure culture of Shewanella. Int. J. Hydrog. Energy 42, 21198–21202. https://doi.org/10.1016/J.IJHYDENE.2017.07.042.
Esfandyari, M., Jafari, D., Azami, H., 2024. Microbial fuel cells for energy production in wastewater treatment plants-a review. Biofuels 15, 743–753. https://doi.org/10.1080/17597269.2023.2294227.
Guo, C., Zhang, X., Zhao, W., Han, Y., Pei, L., Hou, Y., Peng, D., 2023. Study on the performance of anodic desulfurization and cathodic denitrification coupled electricity generation in microbial fuel cell. J. Water Process Eng. 54, 103932. https://doi.org/10.1016/j.jwpe.2023.103932.
Guo, F., Luo, H., Shi, Z., Wu, Y., Liu, H., 2021. Substrate salinity: a critical factor regulating the performance of microbial fuel cells, a review. Sci. Total Environ. 763.
Hassan, M., Kanwal, S., Singh, R.S., Ali SA, M., Anwar, M., Zhao, C., 2024. Current challenges and future perspectives associated with configuration of microbial fuel cell for simultaneous energy generation and wastewater treatment. Int. J. Hydrog. Energy 50, 323–350. https://doi.org/10.1016/J.IJHYDENE.2023.08.134.
He, C.S., Mu, Z.X., Yang, H.Y., Wang, Y.Z., Mu, Y., Yu, H.Q., 2015. Electron acceptors for energy generation in microbial fuel cells fed with wastewaters: a mini-review. Chemosphere 140, 12–17. https://doi.org/10.1016/J.CHEMOSPHERE.2015.03.059.
Jiang, C., Yang, Q., Wang, D., Zhong, Y., Chen, F., Li, Xin, Zeng, G., Li, X., Shang, M., 2017. Simultaneous perchlorate and nitrate removal coupled with electricity generation in autotrophic denitrifying biocathode microbial fuel cell. Chem. Eng. J. 308, 783–790. https://doi.org/10.1016/j.cej.2016.09.121.
Khan, R., Bhadra, S., Nayak, S., Bindu, A., Prabhu, A.A., Sevda, S., 2024. Emerging Trends in fabrication and modification techniques for bioelectrochemical system electrodes: a review. J. Taiwan Inst. Chem. Eng. 165, 105748. https://doi.org/10.1016/j.jtice.2024.105748.
Lefebvre, O., Al-Mamun, A., Ng, H.Y., 2008. A microbial fuel cell equipped with a biocathode for organic removal and denitrification. Water Sci. Technol. 58, 881–885.
Li, R., Ren, X.P., Fan, X., Zhang, Z., Gao, T.P., Liu, Y., 2024. Efficient enriching high-performance denitrifiers using bio-cathode of microbial fuel cells. iScience 27. https://doi.org/10.1016/j.isci.2024.110965.
Li, X., Li, Yue, Zhao, X., Weng, L., Li, Y., 2018. Cation accumulation leads to the electrode aging in soil microbial fuel cells. J. Soils Sediment. 18, 1003–1008. https://doi.org/10.1007/s11368-017-1785-2.
Li, Y., Williams, I., Xu, Z., Li, B., Li, B., 2016. Energy-positive nitrogen removal using the integrated short-cut nitrification and autotrophic denitrification microbial fuel cells (MFCs). Appl. Energy 163, 352–360. https://doi.org/10.1016/j.apenergy.2015.11.021.
Li, Y., Zhang, H.M., Tian, Y., 2024. Sulfur-driven microbial fuel cells denitrification system for targeted treatment of nitrate-containing groundwater: performance and mechanism. Chem. Eng. J. 496, 154328. https://doi.org/10.1016/j.cej.2024.154328.
Lu, Z., Girguis, P., Liang, P., Shi, H., Huang, G., Cai, L., Zhang, L., 2015. Biological capacitance studies of anodes in microbial fuel cells using electrochemical impedance spectroscopy. Bioprocess Biosyst. Eng. 38, 1325–1333. https://doi.org/10.1007/S00449-015-1373-Z/FIGURES/7.
Mareschal, B., Brans, J.P., 1988. Geometrical representations for MCDA. Eur. J. Oper. Res. 34, 69–77. https://doi.org/10.1016/0377-2217(88)90456-0.
Nasrabadi, A.M., Moghimi, M., 2022. 4E analysis of stacked microbial fuel cell as a component in power plants for power generation and water treatment; with a cost-benefit perspective. Sustain Energy Technol. Assess. 53, 102742. https://doi.org/10.1016/J.SETA.2022.102742.
Nguyen, H.D., Babel, S., 2023. A novel coupled microbial fuel cell operation for organic and nitrogen removal with simultaneous energy recovery from wastewater. Sustain Energy Technol. Assess. 55, 102981. https://doi.org/10.1016/J.SETA.2022.102981.
Nguyen, H.D., Babel, S., 2024. Bioelectricity recovery through isolation and removal of nitrogen from wastewater by shortcut nitrification-denitrification in a coupled microbial fuel cell system. Fuel 359, 130497. https://doi.org/10.1016/j.fuel.2023.130497.
Peera, S.G., Maiyalagan, T., Liu, C., Ashmath, S., Lee, T.G., Jiang, Z., Mao, S., 2021. A review on carbon and non-precious metal based cathode catalysts in microbial fuel cells. Int J. Hydrog. Energy 46, 3056–3089. https://doi.org/10.1016/j.ijhydene.2020.07.252.
Puig, S., Coma, M., Desloover, J., Boon, N., Colprim, J., Balaguer, M.D., 2012. Autotrophic denitrification in microbial fuel cells treating low ionic strength waters. Environ. Sci. Technol. 46, 2309–2315. https://doi.org/10.1021/ES2030609/ASSET/IMAGES/MEDIUM/ES-2011-030609_0001.GIF.
Sekar, N., Ramasamy, R.P., 2013. Electrochemical impedance spectroscopy for microbial fuel cell characterization. J. Micro Biochem. Technol. 5. https://doi.org/10.4172/1948-5948.s6-004.
Shi, X., Liang, Y., Wen, G., Evlashin, S.A., Fedorov, F.S., Ma, X., Feng, Y., Zheng, J., Wang, Y., Shi, J., Liu, Y., Zhu, W., Guo, P., Kim, B.H., 2024. Review of cathodic electroactive bacteria: species, properties, applications and electron transfer mechanisms. Sci. Total Environ. 946, 174332. https://doi.org/10.1016/J.SCITOTENV.2024.174332.
Sindhuja, M., Kumar, N.S., Sudha, V., Harinipriya, S., 2016. Equivalent circuit modeling of microbial fuel cells using impedance spectroscopy. J. Energy Storage 7, 136–146. https://doi.org/10.1016/J.EST.2016.06.005.
Soomro, R.R., Ndikubwimana, T., Zeng, X., Lu, Y., Lin, L., Danquah, M.K., 2016. Development of a two-stage microalgae dewatering process – a life cycle assessment approach. Front Plant Sci. 113. https://doi.org/10.3389/FPLS.2016.00113.
Teoh, T.P., Ong, S.A., Ho, L.N., Wong, Y.S., Lutpi, N.A., Tan, S.M., Ong, Y.P., Yap, K.L., 2023. Enhancement of energy recovery from caffeine wastewater in constructed wetland-microbial fuel cell through operating conditions. Environ. Sci. Pollut. Res 30, 84397–84411. https://doi.org/10.1007/S11356-023-28362-7/TABLES/3.
Thapa, B.Sen, Pandit, S., Gurung, A., Ashun, E., Ko, S.Y., Oh, S.E., 2024. Granular activated carbon assisted biocathode for effective electrotrophic denitrification in microbial fuel cells. Chemosphere 352, 141341. https://doi.org/10.1016/J.CHEMOSPHERE.2024.141341.
Tou, I., Azri, Y., George, I.F., Bouzid, O., Khemili-Talbi, S., Sadi, M., Kebbouche-Gana, S., Anzil, A., Laichouchi, A., 2024. Bacterial community issued from a Chlorophytum plant-microbial fuel cell for electricity generation. Biofuels 15, 495–504. https://doi.org/10.1080/17597269.2023.2261751.
Tusher, H.M., Munim, Z.H., Nazir, S., 2024. An evaluation of maritime simulators from technical, instructional, and organizational perspectives: a hybrid multi-criteria decision-making approach. WMU J. Marit. Aff. 23, 165–194. https://doi.org/10.1007/S13437-023-00318-1/TABLES/4.
Vijay, A., Chhabra, M., Vincent, T., 2019. Microbial community modulates electrochemical performance and denitrification rate in a biocathodic autotrophic and heterotrophic denitrifying microbial fuel cell. Bioresour. Technol. 272, 217–225. https://doi.org/10.1016/J.BIORTECH.2018.10.030.
Vijay, A., Sonawane, J.M., Chhabra, M., 2022. Denitrification process in microbial fuel cell: a comprehensive review. Bioresour. Technol. Rep. 17, 100991. https://doi.org/10.1016/J.BITEB.2022.100991.
Virdis, B., Rabaey, K., Yuan, Z., Keller, J., 2008. Microbial fuel cells for simultaneous carbon and nitrogen removal. Water Res. 42, 3013–3024. https://doi.org/10.1016/J.WATRES.2008.03.017.
Wang, H., Long, X., Sun, Y., Wang, D., Wang, Z., Meng, H., Jiang, C., Dong, W., Lu, N., 2022. Electrochemical impedance spectroscopy applied to microbial fuel cells: a review. Front Microbiol. 13, 973501. https://doi.org/10.3389/FMICB.2022.973501/BIBTEX.
Wang, Y., Shi, L., Song, M., Jia, M., Li, B., 2024. Evaluating the energy-exergy-economy-environment performance of the biomass-photovoltaic-hydrogen integrated energy system based on hybrid multi-criterion decision-making model. Renew. Energy 224, 120220. https://doi.org/10.1016/J.RENENE.2024.120220.
Yao, J., Qi, J., Sun, J., Qian, X., Chen, J., 2024. Enhancement of nitrate reduction in microbial fuel cells by acclimating biocathode potential: performance, microbial community, and mechanism. Bioresour. Technol. 398, 130522. https://doi.org/10.1016/j.biortech.2024.130522.
Zhu, G., Chen, G., Yu, R., Li, H., Wang, C., 2016. Enhanced simultaneous nitrification/denitrification in the biocathode of a microbial fuel cell fed with cyanobacteria solution. Process Biochem. 51, 80–88. https://doi.org/10.1016/J.PROCBIO.2015.11.004.
Zhu, H., Zhou, L., Wang, H., Sun, S., Sun, J., Cai, J., Li, T., 2024. Fate of nitrogen in bioelectrochemical systems: a review. J. Environ. Chem. Eng. 12, 113582. https://doi.org/10.1016/J.JECE.2024.113582.