
BIOELECTRICITY GENERATION AND NUTRIENT REMOVAL FROM LANDFILL LEACHATE USING DOUBLE-CHAMBER MICROBIAL FUEL CELLS

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ABSTRACT

wastewater treatment. This study investigated the use of a double-chamber microbial fuel cell (MFC) to simultaneously remove organic matter and nitrogen from landfill leachate while recovering bioelectricity. Raw leachate from Simpang Renggam landfill, Malaysia, was treated in six inoculated MFCs and an uninoculated control under fed-batch conditions.

During biofilm development, the best reactor achieved $80.10 \pm 0.5\%$ COD removal, with 68.12% $\text{NH}_4\text{-N}$ removal and 58.76% total nitrogen removal. Power generation increased as $\text{NH}_4\text{-N}$ concentration increased, reaching an optimum at approximately 800 mg/L, after which power density declined, indicating ammonium inhibition of electroactive microorganisms. Nitrogen removal occurred through multiple biological pathways, including a measurable contribution from anammox. The leachate salinity of 5.58 ppt did not appear to be a major independent limitation. the study demonstrates that MFCs can effectively combine landfill-leachate treatment with energy recovery, but maintaining $\text{NH}_4\text{-N}$ below the identified inhibitory range is important for stable MFC performance.

Keywords: Microbial fuel cell; Landfill leachate; Ammonium nitrogen inhibition; Anammox; Bioelectricity generation

1. INTRODUCTION

Landfill leachate contains high levels of organic matter, ammonium, heavy metals, and salts, with mature leachate often having higher ammonium and more resistant organic compounds (Gokgoz et al., 2023). Conventional treatment can be limited by ammonia, salinity, low C/N ratios, and toxic substances, while MFCs can simultaneously remove pollutants and generate electricity (Hassan et al., 2018). However, excessive $\text{NH}_4\text{-N}$ can inhibit microorganisms and reduce treatment and power generation, with nitrogen removal occurring through pathways such as nitrification, denitrification, anammox, and membrane transport (Hassan et al., 2018; Hiegemann et al., 2018; Zhang et al., 2014). In Nigeria, inadequate waste-management infrastructure and poorly engineered dumpsites increase the risk of leachate contamination of soil and groundwater (Ishaq et al., 2022). MFCs therefore offer potential as a low-cost, decentralized treatment technology, although the $\text{NH}_4\text{-N}$ inhibition threshold remains insufficiently defined (Ishaq et al., 2023). This study evaluates a double-chamber MFC treating raw landfill leachate, focusing on biofilm development, COD, $\text{NH}_4\text{-N}$ and TN removal, Coulombic efficiency, and the $\text{NH}_4\text{-N}$ concentration that inhibits power generation and treatment performance, with the goal of establishing an appropriate operating range for simultaneous leachate treatment and electricity recovery.

2. MATERIALS AND METHODS

2.1 Description of the Study Area and Leachate Sampling

The Simpang Renggam landfill in the Kluang district of Johor, Malaysia, was the source of the leachate used in this study. The site lies approximately two kilometres from the town centre and occupies 14.82 acres, at coordinates 1°53'41" N, 103°22'35" E (Figure 1). The landfill has received approximately 400–500 tonnes of wet solid waste daily for 12 years from Simpang Renggam, Batu Pahat, and Kluang. Its aerated lagoon leachate-treatment system has been inadequate, with previous investigations reporting adverse impacts on a nearby river used by the local community for drinking water, highlighting the urgent need for effective leachate treatment.

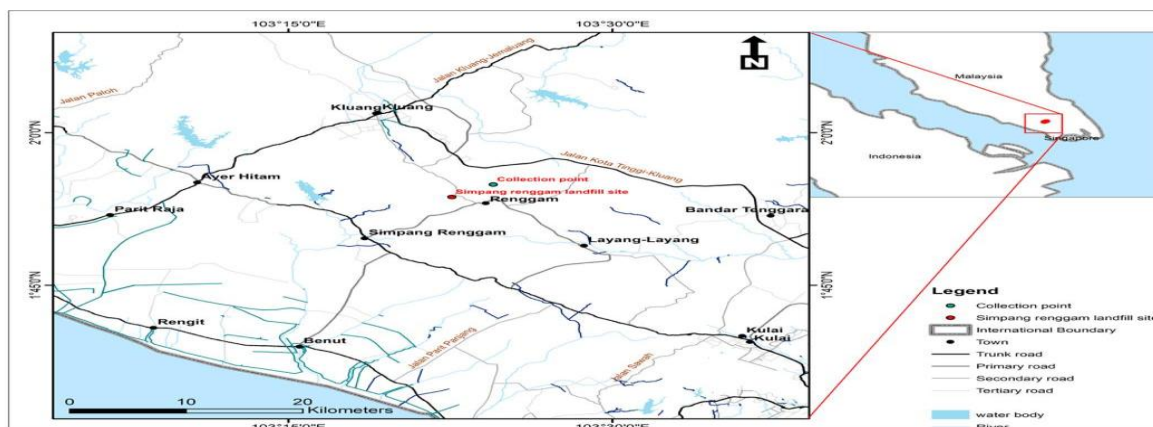


Figure 1: Location of the Simpang Renggam landfill and leachate collection point, Johor, Malaysia.

2.2 MFC Configuration and Operation Mode

H-type dual-chamber MFCs were constructed using modified designs from Nor et al. (2015) and Hassan et al. (2018). Each Plexiglas reactor consisted of separate 125-mL anode and cathode chambers with a 100-mL working volume, carbon-felt electrodes, and a Nafion 117 proton-exchange membrane separating the chambers. The Nafion membrane was pre-treated by sequential soaking in 0.1 M H_2SO_4 and 0.1 M H_2O_2 for 60 minutes at 60 °C, followed by rinsing with deionized water, following Bakhshian et al. (2011).

2.4 Pre-treatment of Anode and Cathode Materials

Electrode assemblies were submerged in 5% ethanol ($\text{C}_6\text{H}_6\text{O}$) for 10 minutes to prevent contamination, rinsed thoroughly with distilled water, and exposed to UV light for 15 minutes (Hassan et al., 2018; Nor et al., 2015). To enhance porosity and reduce the influence of surface impurities, the anode and cathode were then submerged in acetone for 24 hours, rinsed with deionised water, and air-dried overnight (Özkaya et al., 2013).

2.5 MFC Reactor Set-up and Operation

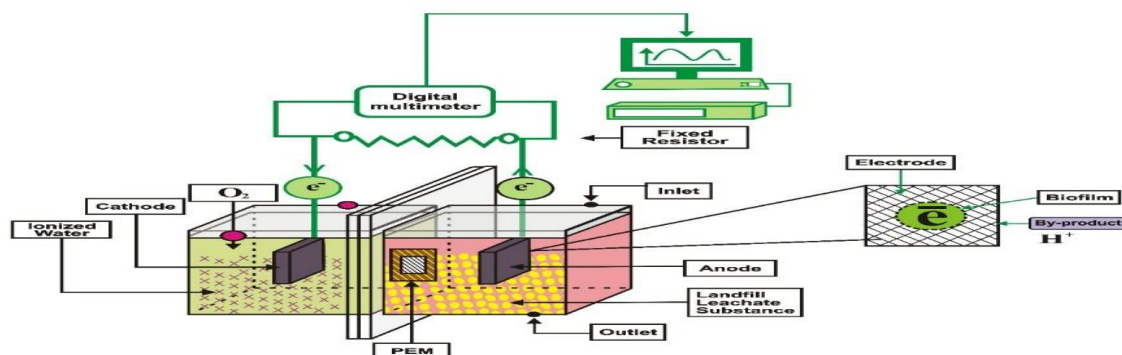


Figure 2: Schematic layout of the double-chamber MFC reactor used in this study.

The MFC reactors were sealed and equipped with sampling ports, while the electrodes were cleaned and connected using copper wires. The anode chambers were nitrogen-purged to maintain anaerobic conditions and filled with raw landfill leachate (Jagaba et al., 2021). A 1 k Ω external resistor was used, and voltage was monitored every 30 seconds with a LabJack U3-HV multimeter. The cathode chambers contained distilled water and were continuously aerated for 24 hours to provide oxygen and mixing.

2.6 Leachate Characterization

Prior to use as MFC substrate, the physicochemical quality of the raw leachate was characterized, including BOD, COD, BOD₅/COD ratio, NH₄-N, turbidity, pH, temperature, conductivity, nitrate and nitrite nitrogen, and salinity. The measured characteristics are summarized in Table 1.

Table 1: Physicochemical characteristics of the landfill leachate used as MFC substrate.

Parameter	Unit	Concentration
Biochemical oxygen demand (BOD)	mg/L	112 $\pm$ 7
Chemical oxygen demand (COD)	mg/L	1322.5 $\pm$ 5
BOD ₅ /COD ratio	–	0.0845 $\pm$ 0.0014
Ammonium nitrogen (NH ₄ -N)	mg/L	411 $\pm$ 6
Turbidity	NTU	134.95 $\pm$ 8
pH	–	6.88 $\pm$ 0.3
Temperature	°C	30 $\pm$ 2.5
Conductivity	μ S/cm	107 746 $\pm$ 7.4
Nitrate nitrogen (NO ₃ -N)	mg/L	70 $\pm$ 5.5
Nitrite nitrogen (NO ₂ -N)	mg/L	110 $\pm$ 8.5
Salinity	Ppt	5.58

2.7 Biofilm Development for MFC Enrichment

The experiment involved three phases, starting with a 62-day acclimatization period for seven MFC reactors, including 14 days under open-circuit conditions. Raw leachate was continuously supplied without pH adjustment, dilution, or nutrient supplementation, while a 1 k Ω resistor was used during closed-circuit operation. Ammonium-oxidizing microorganisms were enriched using ammonium sulphate and sodium nitrite at an NH₄-N:NO₂-N ratio of 1:1.32 (Hassan et al., 2018), with 10% (v/v) anaerobic sludge inoculum added to each reactor (Damiano et al., 2014). Reactors were maintained at 27–30 °C and near-neutral pH until stable voltage production indicated successful acclimatization.

2.8 Ammonium Nitrogen (NH₄-N) Inhibition Study.

After acclimatization, the MFCs were operated under controlled conditions using a one-factor-at-a-time (OFAT) design to evaluate NH₄-N inhibition of electricity generation. NH₄-N concentrations were adjusted to 600–1600 mg/L using NH₄Cl, while COD was maintained at approximately 1327 mg/L. The initial pH was adjusted to 6.88 when necessary but was not continuously controlled, with only modest variation (6.88 $\pm$ 0.3) during batch cycles. Power density was measured at each NH₄-N concentration to identify the concentration at which MFC performance began to decline.

3. RESULTS AND DISCUSSION.

3.1 Physicochemical Characteristics of the Landfill Leachate

The leachate had moderate salinity (5.58 ppt), which was suitable for MFC operation and could enhance conductivity and reduce internal resistance (Gokgoz et al., 2023; Kumar et al., 2020). However, excessive salinity combined with high ammonia may inhibit electroactive microorganisms through osmotic stress, membrane disruption, and enzyme interference. the moderate salinity, near-neutral pH, high conductivity, and substantial ammonium and organic content provided suitable baseline conditions for evaluating biofilm development and ammonia inhibition in the MFCs

3.2 Power Generation and Treatment Performance during Biofilm Development

During the 48-day acclimatization period, COD and NH₄-N removal progressively increased across operating cycles, indicating successful microbial growth and biofilm development. The improvement was attributed to the enrichment of electrogenic bacteria, organic-matter-oxidizing microorganisms, and anammox-related populations on the anodes. Table 2 presents the MFC performance during biofilm development across the operational cycles, with each cycle consisting of two batch operations.

MFC	Cycle	Operating time (d)	CE (%)	Influent COD conc. (mg/L)	COD removal (%)	Influent NH ₄ -N conc. (mg/L)	NH ₄ -N removal (%)	TN removal (%)
A	1	0–7	19.08	1327 ± 7.0	26.76 ± 0.5	411 ± 8.5	23.90 ± 0.1	18.21
	2	7–24	15.13	1327 ± 9.5	35.15 ± 0.3	411 ± 7.5	31.68 ± 0.2	28.31
	3	24–36	11.64	1327 ± 8.5	43.74 ± 0.5	411 ± 5.2	39.14 ± 0.1	31.23
	4	36–48	14.33	1327 ± 5.3	47.09 ± 0.5	411 ± 6.5	41.70 ± 0.0	20.54
B	1	0–7	19.76	1327 ± 7.0	32.43 ± 0.3	411 ± 8.5	32.14 ± 0.0	25.01
	2	7–24	13.74	1327 ± 9.5	47.80 ± 0.3	411 ± 7.5	44.85 ± 0.3	35.35
	3	24–36	11.52	1327 ± 8.5	55.64 ± 0.4	411 ± 5.2	51.82 ± 0.1	37.63
	4	36–48	13.88	1327 ± 5.3	59.92 ± 0.5	411 ± 6.5	55.31 ± 0.2	28.71
C	1	0–7	16.09	1327 ± 7.0	62.42 ± 0.3	411 ± 8.5	57.09 ± 0.2	34.41
	2	7–24	13.05	1327 ± 9.5	75.37 ± 0.5	411 ± 7.5	62.79 ± 0.2	45.05
	3	24–36	9.82	1327 ± 8.5	79.99 ± 0.3	411 ± 5.2	64.01 ± 0.1	51.61
	4	36–48	12.04	1327 ± 5.3	80.10 ± 0.5	411 ± 6.5	68.12 ± 0.0	58.76
D	1	0–7	15.55	1327 ± 7.0	52.81 ± 0.4	411 ± 8.5	45.87 ± 0.2	31.09
	2	7–24	12.72	1327 ± 9.5	61.76 ± 0.4	411 ± 7.5	55.33 ± 0.1	17.23
	3	24–36	9.93	1327 ± 8.5	69.29 ± 0.5	411 ± 5.2	58.79 ± 0.1	49.64
	4	36–48	12.31	1327 ± 5.3	69.85 ± 0.4	411 ± 6.5	61.50 ± 0.0	44.45
E	1	0–7	17.14	1327 ± 7.0	51.59 ± 0.5	411 ± 8.5	49.85 ± 0.1	30.12
	2	7–24	13.71	1327 ± 9.5	63.46 ± 0.3	411 ± 7.5	53.87 ± 0.2	50.25
	3	24–36	11.10	1327 ± 8.5	68.41 ± 0.9	411 ± 5.2	59.28 ± 0.1	37.98
	4	36–48	13.56	1327 ± 5.3	71.20 ± 0.2	411 ± 6.5	62.47 ± 0.0	41.43

MFC	Cycle	Operating time (d)	CE (%)	Influent COD conc. (mg/L)	COD removal (%)	Influent NH ₄ -N conc. (mg/L)	NH ₄ -N removal (%)	TN removal (%)
F	1	0–7	15.73	1327 ± 7.0	57.56 ± 0.3	411 ± 8.5	50.36 ± 0.1	29.12
	2	7–24	12.46	1327 ± 9.5	69.91 ± 0.5	411 ± 7.5	55.82 ± 0.1	38.34
	3	24–36	9.69	1327 ± 8.5	71.71 ± 0.5	411 ± 5.2	60.36 ± 0.2	47.91
	4	36–48	12.05	1327 ± 5.3	70.20 ± 0.2	411 ± 6.5	64.55 ± 0.3	49.48
Control	1	0–7	18.81	1327 ± 7.0	22.44 ± 0.3	411 ± 8.5	19.7 ± 0.3	12.14
	2	7–24	18.10	1327 ± 9.5	29.59 ± 0.2	411 ± 7.5	24.08 ± 0.2	18.86
	3	24–36	16.56	1327 ± 8.5	32.12 ± 0.2	411 ± 5.2	23.35 ± 0.1	17.27
	4	36–48	16.64	1327 ± 5.3	38.36 ± 0.0	411 ± 6.5	26.76 ± 0.0	21.39

During acclimatization, COD removal increased substantially, reaching $80.10 \pm 0.5\%$ in MFC C by cycle 4, compared with $71.71 \pm 0.5\%$ in MFC F. However, higher COD removal did not always correspond to higher Coulombic efficiency, indicating that some organic matter may have been removed through non-electrogenic processes such as methanogenesis (Hassan et al., 2018; Oliveira et al., 2013; Cecconet et al., 2018). The uninoculated control showed lower COD removal, confirming the importance of microbial inoculation. NH₄-N removal reached its maximum of $68.12 \pm 0.0\%$ in MFC C in cycle 4, with improved performance associated with biofilm growth and maturation. Later declines were likely related to changing substrate conditions, nitrogen loading, and inhibitory or shock effects (Hassan et al., 2019), with membrane transport and mature biofilm activity also contributing to nitrogen removal (Puig et al., 2011; Sehar & Naz, 2016). Biofilm maturation enhanced COD and NH₄-N removal, although treatment stability decreased under changing operating conditions.

3.3 Optimal NH₄-N Concentration and Inhibition of Power Generation

Building on the biofilm-development results, the inhibition study examined how varying influent NH₄-N concentration (600–1600 mg/L, adjusted with NH₄Cl) affected power output under continuous operation at constant COD and pH. Average power densities of the respective MFCs across the tested NH₄-N fractions are presented in Figure 3.

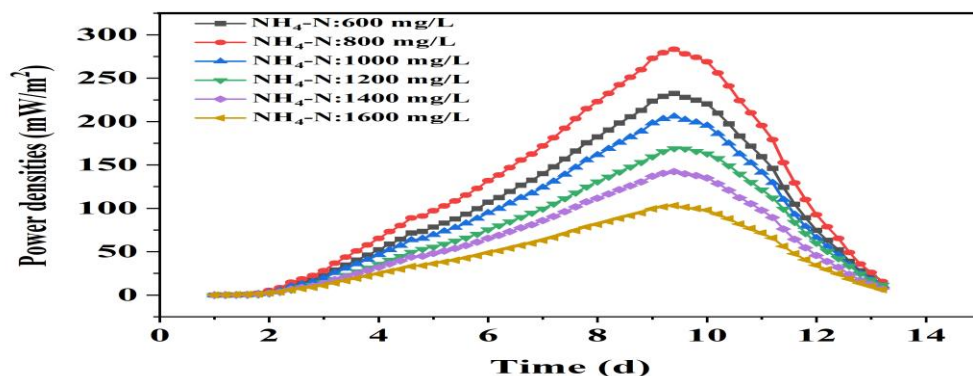


Figure 3: Average power density profiles of the MFCs at different influent $\text{NH}_4\text{-N}$ concentrations (600–1600 mg/L).

During acclimatization, $\text{NH}_4\text{-N}$ removal was enhanced by cation exchange through the membrane and maturation of the anode biofilm, which improved microbial interactions and electron transfer (Puig et al., 2011; Sehar & Naz, 2016). Power generation increased during the early operating period before declining as substrates became depleted. $\text{NH}_4\text{-N}$ concentration showed a non-monotonic effect on electricity generation, with maximum power density of 283 mW/m^2 at 800 mg/L, compared with 233 mW/m^2 at 600 mg/L. Above 800 mg/L, power density progressively declined to 103 mW/m^2 at 1600 mg/L. This indicates that moderate $\text{NH}_4\text{-N}$ concentrations can support microbial activity, whereas higher concentrations cause ammonia toxicity and disrupt microbial and electron-transfer processes (Gu et al., 2021; Hiegemann et al., 2018; Ren et al., 2021). Thus, 800 mg/L was the optimum $\text{NH}_4\text{-N}$ concentration, while 1600 mg/L caused approximately 64% lower power generation, confirming significant ammonium inhibition.

3.4 Nitrogen Species Removal: $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$, and Total Nitrogen

Nitrogen removal was strongly influenced by influent nitrogen loading. $\text{NH}_4\text{-N}$ removal increased to about 75% in cycle 2 but declined to 62% by cycle 6 as concentration increased from approximately 600 to 1,640 mg/L. Similar trends occurred for nitrite and TN, with maximum removals of about 74% and 72%, respectively, before declining at higher nitrogen loads. The reduced performance was likely associated with biofilm loading limitations, incomplete nitrogen transformation, nitrification, and anammox-related processes (Wei et al., 2011). Overall, nitrogen removal was highest under moderate loading and decreased with increasing $\text{NH}_4\text{-N}$ concentrations, indicating the involvement of interacting anammox, nitrification, and nitrite/nitrate transformation pathways, consistent with previous studies (Lu et al., 2020, 2021; Gu et al., 2021; Wei et al., 2011).

Table 3: $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$, and total nitrogen (TN) removal efficiencies per operating cycle (values derived from Figure 4).

Cycle	$\text{NH}_4\text{-N}$ removal (%)	$\text{NO}_2\text{-N}$ removal (%)	TN removal (%)
1	70	68	68
2	75	74	72
3	72	73	69
4	67	71	67
5	64	68	63
6	62	66	61

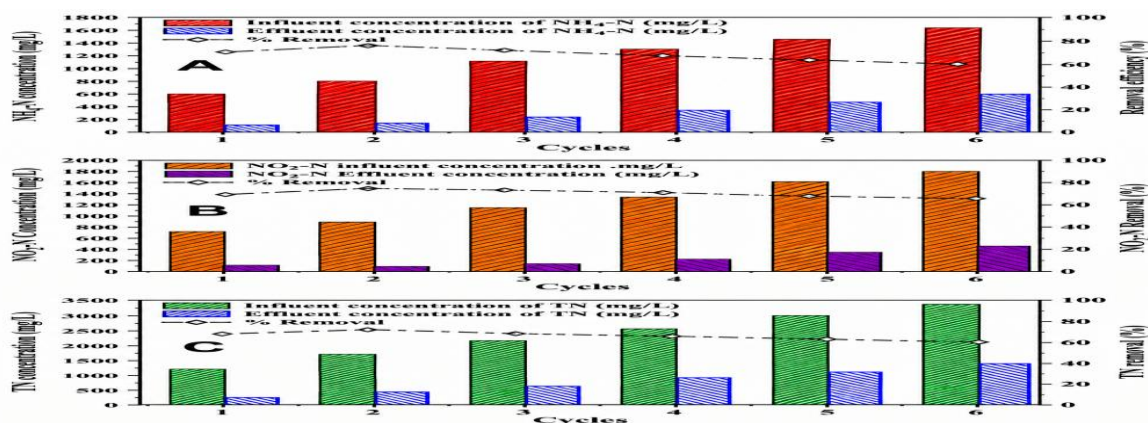


Figure 4: Influent and effluent profiles of (A) NH₄-N, (B) NO₂-N, and (C) total nitrogen (TN), together with the corresponding removal efficiencies (%) across the six operating cycles.

4. CONCLUSION

This study showed that double-chamber MFCs can effectively treat raw landfill leachate while generating electricity. The best reactor achieved 80.10% COD, 68.12% NH₄-N, and 58.76% TN removal, with maximum power density of 283 mW/m² at about 800 mg/L NH₄-N. Higher ammonium concentrations inhibited electricity generation. The findings indicate potential for MFC application in Nigeria, particularly at poorly managed dumpsites where conventional treatment and electricity infrastructure are limited. However, low power output, expensive materials, and scale-up challenges remain major limitations. Pilot studies using Nigerian leachate, low-cost materials, and detailed energy and economic assessments are recommended before full-scale implementation.

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