

Charcoal Ash as an Alternative pH Buffer in Single-Chamber Microbial Fuel Cells: Effects on Open Circuit Voltage and Substrate pH Dynamics

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Article Info	ABSTRACT
Article history: Received , 23/03/2026 Revised , 28/05/2026 Accepted , 03/06/2026	The escalating cost of commercial pH buffer reagents remains a critical impediment to the large-scale commercialization of microbial fuel cell (MFC) technology. This study evaluates charcoal cooking ash as a low-cost, locally available alternative pH buffer in single-chamber MFCs fed with domestic sewage substrate. Two identical single-chamber MFCs were operated at 35 °C for seven days using carbon rod anodes and aluminium rod cathodes. Ash was added incrementally in 2 g doses at 10-minute intervals, and open circuit voltage (OCV) was continuously monitored. In the ash-supplemented cell, OCV increased progressively from 722 mV (Day 1) to a peak of 986 mV (Day 5), stabilising at 909 mV at Day 7. Substrate pH rose monotonically from 7.82 (0 g ash) to a maximum of 11.63 (180 g), before stabilising at pH 10.98 at the buffering saturation point of 324 g. In contrast, the unsupplemented control exhibited a sustained voltage decline from 737 mV to 543 mV over the same period. These results demonstrate that charcoal ash exerts a dual buffering and ion-conductivity-enhancing function, sustaining favourable cathodic conditions and extending the operational lifetime of the cell. The findings propose charcoal ash as a viable, zero-cost buffer substitute with competitive electrochemical performance relative to conventional commercial buffers, warranting further investigation for decentralised wastewater treatment applications.
Keywords: Single chamber microbial fuel cell; Charcoal ash; Cost effective pH buffer; Open circuit voltage; Electrochemical reactions.	

I. Introduction

The global proliferation of decentralised energy and sanitation challenges has renewed interest in bioelectrochemical systems capable of simultaneously generating electricity and treating wastewater. Among these, microbial fuel cells (MFCs) stand out as a dual-function technology that harnesses the metabolic activity of electroactive microorganisms to convert the chemical energy stored in organic substrates directly into electrical energy [1]. Despite notable advances in electrode materials, reactor configurations, and microbial community engineering, the commercialisation of MFC technology remains constrained by several performance-limiting

parameters, including substrate pH, temperature, salinity, membrane costs, and electrode conductivity [2,3].

The pH of the anode compartment substrate exerts a profound influence on microbial community activity, proton transport kinetics, and the thermodynamic potential of both anodic and cathodic half-reactions. Under neutral to slightly alkaline conditions (pH 6.5–8.0), electroactive bacteria—predominantly from genera such as *Geobacter* and *Shewanella*—exhibit optimal metabolic rates and electron transfer efficiencies [4]. Conversely, the cathodic oxygen reduction reaction (ORR) is thermodynamically favoured at alkaline pH, creating an inherent tension between anodic and cathodic pH optima in single-chamber configurations where both electrodes share a common electrolyte [5]. Puig et al. demonstrated this complexity in air-cathode MFCs treating urban wastewater over 30 days, reporting peak power production of 1.8 W/m³ at a sustained pH of 9.5 [1].

Tremouli et al. reported a maximum power density of 50.6 mW/m² at an anolyte pH of 9 in a dual-chamber MFC, with an optimal Coulombic efficiency (CE) of 15% at pH 7 [2]. Igboamalu et al. extended this analysis across pH values of 6–9, identifying a maximum voltage of 197.2 mV and power density of 10.3 mW/m² at pH 9 in a batch dual-chamber MFC inoculated with anaerobic digester sludge [6]. In a double-chamber MFC, Ren et al. found that power production declined significantly when pH dropped to 5.2 due to acidic fermentation products, recovering promptly upon restoration to pH 7 [4]. These findings collectively establish pH management as a primary determinant of MFC performance.

Phosphate buffer solution has historically been the reagent of choice for pH stabilisation in laboratory-scale MFC studies. However, the concentrations required for effective pH control (typically 0.1–0.2 M) introduce substantial chemical costs and environmental phosphate loading, rendering commercial buffers unsuitable for practical wastewater treatment applications [7]. Bicarbonate buffers have emerged as a lower-cost alternative: Fan et al. reported a maximum power density of 1,550 W/m³ at pH 9 in cloth electrode assembly (CEA) MFCs, representing a 38.6% increase over equivalent phosphate-buffered systems at 0.2 M [7]. Nevertheless, both options remain prohibitively expensive for decentralised deployment in low-resource settings.

Natural materials derived from combustion residues have recently attracted interest as near-zero-cost pH modifiers. Wood ash exerts significant alkalinising effects: Bang-Andreasen et al. observed strong increases in soil pH and electrical conductivity upon wood ash addition, with bacterial numbers peaking at 22 t/ha and declining at higher doses [8]. Tiwari et al. demonstrated the utility of wood ash as a functional additive to earthen MFC membranes, achieving 93% COD removal and a power density of 1,450 mW/m³ whilst replacing costly Nafion membranes [9]. Charcoal ash, distinct from wood ash by its higher fixed-carbon content and alkali-generating species (K₂CO₃, Ca(OH)₂) formed during high-temperature combustion, has not been characterised as a primary electrolyte buffer in single-chamber MFCs.

This study therefore aims to: (i) characterise the dose–response relationship between incremental charcoal ash addition and substrate pH in a single-chamber MFC; (ii) compare the OCV evolution over a seven-day operational period between ash-buffered and unbuffered control MFCs; and (iii) assess the potential of charcoal ash as a viable, cost-effective buffer substitute, particularly in the context of decentralised wastewater treatment in developing economies where charcoal combustion ash is abundantly available as a waste product.

II. Materials and Method

II.1. Substrate Collection and Characterisation

Domestic sewage substrate was collected from the wastewater outfall of the Technical University of Mombasa (TUM), Mombasa, Kenya. The substrate was transported in sealed polyethylene containers and used within 24 hours of collection. Initial substrate pH was measured as 7.82 ± 0.05 using a calibrated HANNA digital pH meter (HI 9813-6). No additional pre-treatment was applied.

II.2. Charcoal Ash Preparation

Charcoal ash was obtained by complete combustion of commercially available coconut-shell charcoal, the predominant cooking fuel along the Kenyan coast. The resulting ash was cooled to room temperature, sieved through a 2 mm mesh to remove coarse char fragments, and stored in sealed polyethylene bags pending use. No chemical pre-treatment or modification was applied.

II.3. MFC Construction and Configuration

Two identical single-chamber MFCs were constructed from rectangular polyethylene containers (nominal reactor volume: approximately 1.5 L). Carbon rods ($\varnothing 0.8 \text{ cm} \times 5.6 \text{ cm}$) served as anode electrodes, and aluminium rods ($\varnothing 1.3 \text{ cm} \times 5.8 \text{ cm}$) served as cathodes. Sea sponge was used as a separator/membrane, as was used in reported literature [13]. Both reactors were inoculated with equal volumes of the collected sewage substrate and placed in a thermostatically controlled water bath maintained at $35 \pm 1 \text{ }^{\circ}\text{C}$ throughout the seven-day experimental period.

One MFC was designated the ash-supplemented experimental cell; the second operated as an unsupplemented control. Electrodes were connected to external circuit wires for OCV measurement; no external resistance was applied during measurement.

II.4. Ash Addition Protocol

For the experimental MFC, charcoal ash was added incrementally in 2 g portions at 10-minute intervals using a calibrated analytical balance (Model TX4202L; precision $\pm 0.01 \text{ g}$). Substrate pH was recorded immediately following each addition using the calibrated HANNA pH meter. Additions continued until no further change in pH was observed across three consecutive measurements. The cumulative ash dose at which this saturation criterion was met was identified as the buffering saturation point.

II.5. Electrochemical Measurements

Open circuit voltage was recorded at 5-minute intervals during Day 1 of operation using a TOTAL digital multimeter (Model TMT460012; resolution 1 mV). Daily peak OCV was subsequently recorded at a fixed time each morning across the seven-day operational period. All OCV measurements were performed in open-circuit configuration (no applied external load) to obtain thermodynamic potential values unaffected by Ohmic and activation losses.

II.6. Data Analysis

Descriptive statistics were computed for all measurement series. The dose–response relationship between ash content and substrate pH was analysed graphically and divided into distinct phases based on the rate of pH change per gram of ash added. Voltage trends were compared between the two cells using daily peak OCV as the primary metric. All calculations and plotting were performed using Microsoft Excel 2019.

III. Results and Discussion

III.1. Day 1 Open Circuit Voltage Dynamics

Table 1 and Figure 1 below present the OCV profiles of both MFCs during the first 200 minutes of operation. At $t = 0 \text{ min}$, the ash-supplemented cell recorded an OCV of 722 mV and the control 737 mV—values within 2.1% of each other, confirming equivalent electrochemical initialisation. Both cells exhibited a characteristic initial voltage decline attributable to rapid consumption of readily biodegradable organic fractions and the associated drop in substrate redox potential as the anodic biofilm equilibrates [3].

By $t = 200 \text{ min}$, the ash-supplemented cell had recovered to 333 mV compared to 290 mV for the control – a 14.8% differential. This divergence, apparent even on the first day, suggests that the initial alkalinisation of the substrate by dissolved ash species begins to shift cathodic kinetics favourably within hours of inoculation. The transient fluctuations observed between $t = 115$ and 160 min in both cells are consistent with biofilm restructuring and substrate depletion dynamics characteristic of early-phase single-chamber MFC operation [5].

Table 1: Open circuit voltage (OCV) of ash-supplemented and control MFCs during Day 1 at 5-minute intervals.

Time (min)	OCV – Ash Sample (mV)	OCV – Control (mV)
0	722	737
5	591	584
10	598	597
15	445	422
20	457	457
25	495	479
30	400	365
35	399	369
40	406	364
45	350	317
50	320	294
55	322	293
60	326	294
65	328	291
70	297	262
75	275	242
80	308	272
85	293	263
90	284	257
95	285	253
100	285	261
105	287	259
110	288	262
115	239	232
120	257	251
125	265	251
130	253	233
135	259	258
140	262	250
145	280	277
150	284	276
155	234	234
160	227	225
170	246	245
180	268	257

Time (min)	OCV – Ash Sample (mV)	OCV – Control (mV)
185	289	275
190	304	285
195	311	281
200	333	290

OCV vs. time for Day 1 (0–200 min). Both cells exhibit characteristic initial voltage decay; the ash-supplemented cell maintains a 14.8% higher terminal OCV (333 mV vs. 290 mV at $t = 200$ min).

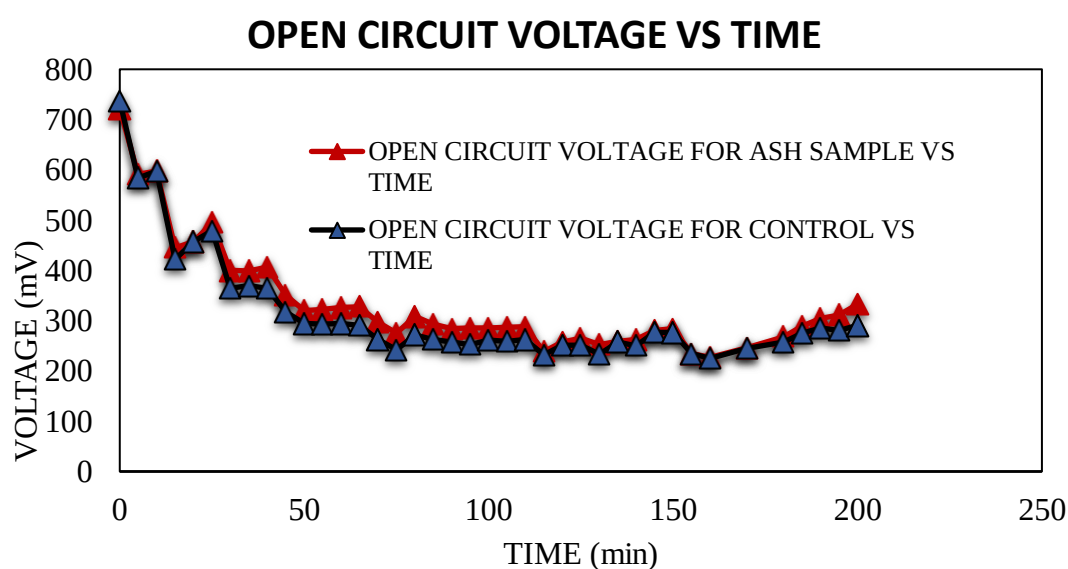


Figure 1: A graph of open circuit voltage for the first day

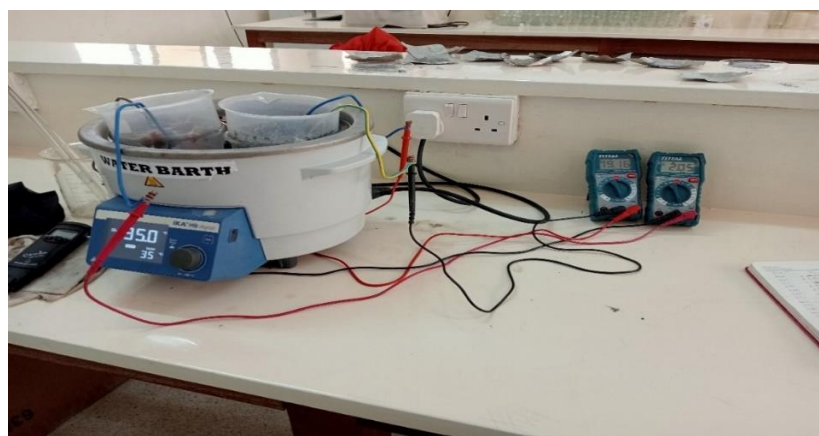


Figure 2: Experimental setup of MFCs in a water bath

III.2 Seven-Day Open Circuit Voltage Trend

Table 2 and Figure 2 below summarise the daily peak OCV for both cells over the seven days. The ash-supplemented cell demonstrated a net OCV increase from 722 mV (Day 1) to 909 mV (Day 7), with a peak of 986 mV on Day 5 - a 36.6% overall gain relative to Day 1. This progressive ascending trend reflects both the maturation of the electroactive biofilm on the carbon anode and the sustained alkaline pH facilitated by the ash buffer, which thermodynamically favours cathodic ORR in the cathode configuration.

In marked contrast, the control MFC exhibited a monotonic OCV decline from 737 mV (Day 1) to 543 mV (Day 7) - a 26.3% deterioration. This decay is attributable to progressive acidification of the substrate as fermentation acids accumulate without buffering, inhibiting electroactive bacterial activity, as documented by Ren et al., who reported significant power decline at pH 5.2 [4]. The cumulative OCV differential between cells widened from near-parity at Day 1 to 167 mV at Day 7, demonstrating that the buffering effect of ash is sustained - and indeed amplified - across the operational period rather than being limited to the initial dosing event.

The peak OCV of 986 mV at pH 10.7 substantially exceeds reference values from pH-optimised MFCs using conventional buffers: Jung et al. reported 741 mV at pH 7 [10], and Igboamalu et al. obtained 197.2 mV at pH 9 [6]. Morton and Ieropoulos recorded 747 mV at pH 10 using dipotassium hydrogen orthophosphate [12]. While direct quantitative comparison is complicated by differences in reactor geometry, electrode surface area, and substrate composition, the ash-supplemented OCV values are competitive with - and in some cases exceed - those from commercial buffer systems, suggesting that ionic enrichment from dissolved ash species contributes a conductivity-enhancing effect supplementary to the pH-mediated voltage improvement.

Table 2: Daily peak OCV for ash-supplemented and control MFCs over a seven-day operational period.

Day	OCV - Ash Sample (mV)	OCV - Control (mV)
1	722	737
2	845	578
3	750	384
4	896	235
5	986	306
6	830	370
7	909	543

Daily peak OCV vs. operational day. The ash-supplemented cell demonstrates a net ascending trend (722 mV to 909 mV; peak 986 mV on Day 5), whilst the control declines monotonically (737 mV to 543 mV).

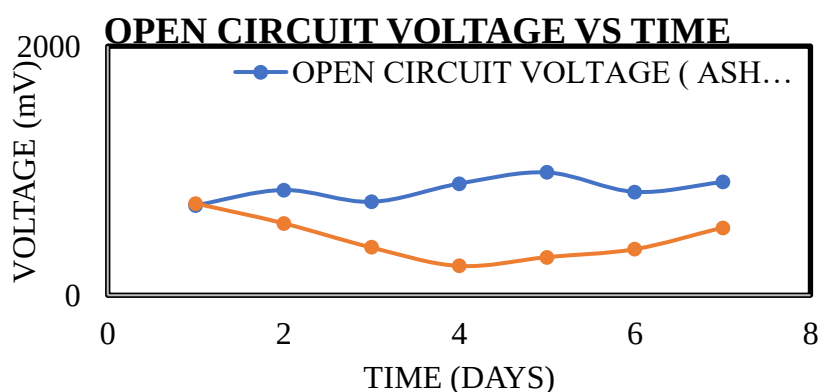


Figure 3: A graph of open circuit voltage vs time for one week



Figure 4: MFC with ash and control setup without ash

III.3 Dose–Response Relationship Between Ash Content and Substrate pH

Table 3 and Figure 3 below illustrate the substrate pH response to incremental charcoal ash addition. From an initial pH of 7.82, the substrate exhibited a near-monotonic increase to a maximum of 11.63 at 180 g cumulative ash. Beyond this point, pH exhibited fluctuating stabilisation within the range 10.98–11.41 between 246 g and 324 g, at which point no further change was detected across three consecutive additions - defining the buffering saturation threshold of this system.

Three distinct phases are identifiable in the dose–response profile: (i) a rapid alkalinisation phase (0–80 g; pH 7.82 → 10.06), consistent with swift dissolution of highly soluble alkali species such as K_2CO_3 and $\text{Ca}(\text{OH})_2$ from the ash matrix; (ii) a buffering plateau phase (80–180 g; pH 10.06 → 11.63), characterised by diminishing marginal pH increments per gram as the carbonate/bicarbonate equilibrium is approached; and (iii) a stabilisation phase (>180 g; pH declining from 11.63 to ~10.98), reflecting pH self-regulation through carbonate precipitation and the limited aqueous solubility ceiling of the ash alkalisating components.

These results compare favourably with commercial buffer benchmarks: Li et al. achieved 1,221 mW/m² maximum power output at pH 10.5 using bicarbonate buffer [11], whilst Morton and Ieropoulos recorded 747 mV OCV at pH 10 using dipotassium hydrogen orthophosphate [12]. The ash-supplemented system in this study achieved an OCV of 909 mV within the stabilised pH range of 10.98–11.41, using a zero-cost material. The identified saturation dose of approximately 180–246 g per 1.5 L of substrate (equivalent to ~120–164 g/L) provides a practical dosing reference for scaled-system design. Future work should investigate whether intermittent ash addition can maintain pH within an optimal operational window (pH 9–11) without reaching saturation, thereby maximising buffering efficiency.

Table 3: Substrate pH as a function of cumulative charcoal ash addition (selected measurements at representative intervals).

Ash Content (g)	pH
0	7.82
20	9.43
40	9.76
60	9.91
80	10.06
100	10.22
120	10.56
140	10.90

Ash Content (g)	pH
160	11.40
180	11.63
200	11.49
220	11.39
240	11.41
246	11.41
260	11.29
280	10.98
300	11.11
324	10.98

Substrate pH vs. cumulative charcoal ash addition. Three phases are identifiable: rapid alkalinisation (0–80 g), buffering plateau (80–180 g), and pH stabilisation (>180 g). Maximum pH of 11.63 at 180 g; buffering saturation at 324 g (pH 10.98).

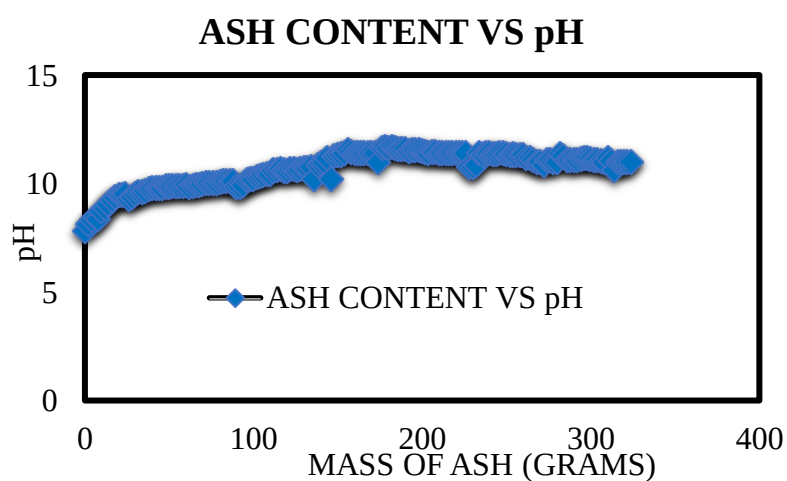


Figure 5: A graph of ash content vs pH



Figure 6: Experimental setup with pH meter reading

III.4 Mechanistic Considerations

The alkalis capacity of charcoal ash arises principally from dissolution of inorganic constituents - predominantly potassium carbonate (K_2CO_3), potassium hydroxide (KOH), calcium oxide (CaO), and calcium hydroxide ($Ca(OH)_2$) - generated during high-temperature combustion of the lignocellulosic biomass. Dissolution produces hydroxide ions (OH^-) that raise substrate pH while simultaneously increasing ionic strength and electrical conductivity [8]. Enhanced ionic conductivity reduces the internal resistance of the MFC, a primary determinant of power output in single-chamber configurations [7].

In single-chamber MFCs, the alkaline conditions established by ash addition are thermodynamically favourable for the cathodic ORR, which proceeds more readily at elevated pH on carbon-based cathodes [5]. The sustained OCV improvement in the ash-supplemented cell is therefore attributable to a synergistic combination of: (i) direct thermodynamic enhancement of cathode half-reaction potential; (ii) prevention of acidification-driven anodic inhibition through sustained alkaline buffering; and (iii) reduced internal resistance via elevated substrate conductivity. The eventual pH declines at doses >180 g likely reflects insoluble carbonate precipitation and/or ionic equilibrium saturation, which set a natural ceiling on alkanisation without introducing acute inhibitory effects on the anodic biofilm.

IV. Conclusion

This study has demonstrated that charcoal cooking ash functions as an effective, dose-responsive pH buffer in single-chamber MFCs, producing sustained improvements in both substrate pH and open circuit voltage relative to unsupplemented controls. The principal findings are summarised as follows:

- Incremental charcoal ash addition raised substrate pH monotonically from 7.82 to a maximum of 11.63 (at 180 g), with buffering saturation achieved at 324 g cumulative dose (pH 10.98).
- The ash-supplemented MFC demonstrated a net OCV increase from 722 mV (Day 1) to 909 mV (Day 7), with a peak of 986 mV on Day 5, whilst the control declined from 737 mV to 543 mV over the same period - representing a 167-mV advantage at Day 7.
- Ash-supplemented OCV values are competitive with or superior to values reported for commercial phosphate- and bicarbonate-buffered MFC systems at comparable pH ranges.
- The buffering mechanism involves simultaneous pH elevation and ionic conductivity enhancement through dissolution of alkali species (K_2CO_3 , $Ca(OH)_2$), jointly enhancing cathodic performance in single chamber MFC configurations.

These findings establish charcoal ash as a promising, zero-cost buffer candidate for MFC applications in resource-limited settings, particularly in sub-Saharan Africa, where charcoal combustion ash is abundantly available as a waste product currently discarded without value recovery. Recommended directions for future research include: (i) chemical characterisation of charcoal ash composition and buffering kinetics across different charcoal types; (ii) optimal intermittent dosing strategies for pH control within a defined operational window; (iii) long-term effects on anodic biofilm community structure and diversity; and (iv) techno-economic assessment of ash-based buffering relative to conventional reagents at pilot scale.

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