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A comparative analysis of organic substrates from industrial wastewater streams for enhanced electricity production using a double chamber microbial fuel cell (DCMFC)

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ABSTRACT

This study investigates the startup sequence of a Double Chamber Microbial Fuel Cell (DCMFC) for the treatment of diverse industrial wastewater streams, including biorefinery, dairy, and mixed sources. It presents a comprehensive startup and calibration procedure for the essential electrical components, utilizing MATLAB-SIMULINK to establish typical resistance calibration curves and correlate measured electrical parameters with expected values. This approach enables a robust experimental startup protocol for the DCMFC under psychrophilic and thermophilic conditions. The study explores the impact of fundamental operating parameters on determining the experimental Hydraulic Retention Time (HRT) of the DCMFC. Specifically, it examines the effects of catholyte type (Phosphate $\left(PO_4^{3-}\right)$ buffer) and three distinct organic substrates: dairy wastewater, biorefinery wastewater, and mixed substrates (50% v/v dairy).

Electricity production is evaluated in terms of voltage yield (mV), Columbic efficiency (CE) (%), and overall growth yield (Y). The study also assesses the COD (Chemical Oxygen Demand) mass balance component's influence on COD removal efficiency to establish a viable operating HRT during the startup phase. Key findings include startup experimental voltage yields of 145.2 mV for biorefinery, 85 mV for mixed wastewater, and an impressive 357 mV for dairy wastewater. Columbic efficiencies of 0.92%, 0.77%, and 0.02% were respectively achieved. Furthermore, the study reveals a viable experimental HRT, ranging from 72 to 96 hours, for both biorefinery/mixed and dairy/mixed wastewater sources, facilitating startup electricity generation and efficient removal of organic contaminants. These findings contribute to the advancement of sustainable wastewater treatment and bioelectricity generation, offering valuable insights for practical applications.

Knowledge contribution

The novelty in this research article lies in several aspects of the study related to the start-up sequence and organic substrate comparison for a Double Chamber Microbial Fuel Cell (DCMFC) used for treating industrial wastewater streams. Here are some key points highlighting the novelty of the research:

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1. **Start-up sequence for DCMFC**: The study delves into the detailed start-up sequence of a DCMFC for treating different industrial wastewater sources, including biorefinery, dairy, and mixed streams. While previous studies have explored DCMFC technology, this research provides a comprehensive and well-documented start-up procedure, which is vital for successful implementation.
2. **Calibration of electrical components**: The article outlines a calibration sequence for the essential electrical components of the DCMFC. Calibration is a crucial step in ensuring the accurate measurement of electrical operating variables, and the study presents this process clearly.
3. **Comparison of organic substrates**: The research compares three distinctive types of organic substrates: dairy wastewater, biorefinery wastewater, and mixed substrates (50% biorefinery / 50% dairy) in terms of their suitability for electricity production in the DCMFC. This comparison offers insights into the most effective organic substrate for maximizing voltage yield and columbic efficiency.
4. **Voltage yield and efficiency results**: The study reports voltage yield (mV) and columbic efficiency (%) results for each organic substrate. Notably, it shows that biorefinery wastewater yielded the highest voltage (253 mV) and maintained a constant voltage potential for over 168 hours. This suggests the potential of using raw organic substrates, particularly biorefinery wastewater, as a reliable source of fuel and anolyte.
5. **Hydraulic retention time (HRT) findings**: The research identifies a viable experimental HRT ranging between 72 and 96 hours for both biorefinery/mixed wastewater and dairy/mixed wastewater sources. This finding is crucial for optimizing the start-up process and achieving efficient organic contaminant treatment and electricity production.
6. **Application of MFC technology**: The study emphasizes the feasibility of using raw organic substrates as a source of fuel and anolyte in MFC technology. It suggests that biorefinery wastewater can serve as a better and more reliable electron donor, potentially leading to more sustainable and efficient bioelectricity production.
7. **Future perspectives**: The article presents future perspectives for scaling up bioelectricity production commercially while effectively treating high-strength organic pollutants for zero liquid discharge (ZLED). It highlights the potential areas for further research, including exploring specific bacterial species, optimizing temperature conditions, electrode configuration, catholyte dosing, and circuit design using MATLAB Simulink.

In summary, the novelty of this research lies in its detailed start-up sequence, the comparison of organic substrates, and the practical application of DCMFC technology for electricity production and wastewater treatment. The findings open opportunities for further research and the potential for real-world applications of microbial fuel cell technology in industrial wastewater treatment and sustainable energy production.

1. Introduction

Microbial Fuel Cells (MFCs), despite their promise, have faced a significant hurdle in transitioning from laboratory-scale experimentation to practical, commercial applications. The initial breakthrough in 1999, which eliminated the need for chemical mediators to generate power, (Abed and Alisawi, 2020; Jadhav and Ghangrekar, 2009), ignited the hope that MFCs could revolutionize both wastewater treatment and electricity production (Ahn and Logan, 2010; Gonzalez del Campo et al., 2013; Parthasarathy et al., 1992a, 1992b). The advent of air cathodes offered the possibility of efficient aeration-free wastewater treatment coupled with electrical power generation, further bolstering enthusiasm for MFCs' potential.

However, over a decade has passed since these innovations, and commercial applications of MFC technology are still elusive. One critical impediment to scaling up MFC processes lies in the high cost of electrodes, (Ahn and Logan, 2010). This novel technology holds the key to reducing our reliance on fossil fuels and mitigating the environmental consequences associated with them. It offers a sustainable, renewable, and environmentally responsible solution for wastewater treatment, (Parthasarathy et al., 1992a; Aiyer et al., 2020). However, before it can find widespread use, several challenges must be surmounted, (Ishii et al., 2013; Zhang et al., 2012).

A fundamental bottleneck in MFC operation is the generation of low-power voltage yields. Additionally, the extended start-up times and the costs associated with materials, such as Nafion membranes (CEM/PEM), electrodes, and exogenous components like catalysts, present economic challenges (Zhang et al., 2012; Shabangu et al., 2023; Jadhav et al., 2022; Ahn and Logan, 2013; Min and Logan, 2004a; Logan and Rabaey, 2012a; Logan and Regan, 2006; Rossi et al., 2020). To enhance MFC performance, it is crucial to identify the primary operational factors that influence scalability (Logan and Rabaey, 2012a; Rossi et al., 2020; Katuri et al., 2011; Zhang et al., 2017). These factors encompass a broad spectrum, from the microbial species' nature and population to anodic chamber configurations, exogenous mediators, substrate types and their organic concentrations, operational conditions (including pH, external resistance, temperature, ionic strength of catholyte, aeration, dissolved oxygen dosages, etc.), and the MFC unit's design and configuration (Logan et al., 2006; Cheng et al., 2006a, 2006b; Zuo et al., 2006; Metcalf et al., 2004; Wang et al., 2008).

Psychrophilic conditions typically refer to temperatures ranging from 0 °C to 20 °C, (Abed and Alisawi, 2020; Jadhav and Ghangrekar, 2009; Ahn and Logan, 2010; Gonzalez del Campo et al., 2013). In these conditions, microbial activity tends to be slower compared to mesophilic or thermophilic conditions due to reduced metabolic rates. Mesophilic conditions refer to temperatures ranging from 25 °C to 40 °C or partially higher, (Gonzalez del Campo et al., 2013; Parthasarathy et al., 1992a, 1992b). Microbial activity is significantly enhanced in thermophilic environments due to increased metabolic rates and faster reaction kinetics, (Aiyer et al., 2020; Ishii et al., 2013). The start-up of DCMFCs under psychrophilic conditions may be slower due to the lower metabolic activity of psychrophilic microorganisms. Psychrophilic microbial communities tend to have lower diversity compared to mesophilic or mesophilic communities, which could affect the performance and stability of DCMFCs. Sudden temperature fluctuations or cold shocks could adversely affect microbial activity and electrode reactions, potentially leading to performance fluctuations or instability, (Jadhav and Ghangrekar, 2009; Ahn and Logan, 2010; Parthasarathy et al., 1992b). Psychrophilic DCMFCs may find applications in cold climates or remote regions where low temperatures prevail. Potential applications include wastewater treatment in cold regions, off-grid power generation in polar or mountainous areas, or environmental monitoring in icy environments, (Abed and Alisawi, 2020; Jadhav and Ghangrekar, 2009; Ahn and Logan, 2010).

Mesophilic temperatures foster a rich array of mesophilic microorganisms characterized by heightened metabolic activity, (Ahn and Logan, 2010). This microbial diversity is fundamental to the efficient degradation of organic matter and electron transfer, making mesophilic Microbial Fuel Cells (MFCs) adaptable for wastewater treatment and associated purposes, (Gonzalez del Campo et al., 2013; Parthasarathy et al., 1992a). Additionally, maintaining mesophilic temperatures proves energy-efficient, requiring minimal heating and cooling interventions. Conversely, thermophilic conditions stimulate microbial metabolism, accelerating the breakdown of organic matter and electron transfer processes. This leads to increased power output, particularly in the decomposition of complex organic substrates, (Zhang et al., 2012). The resilience of thermophilic microorganisms, renowned for their tolerance to a broader spectrum of environmental contaminants, renders thermophilic MFCs well-suited for specific industrial wastewater treatment scenarios, (Jadhav and Ghangrekar, 2009; Ahn and Logan, 2010; Parthasarathy et al., 1992a; Shabangu et al., 2023).

Optimizing these MFC operating parameters promises not only to reduce operational costs but also to enhance voltage yield and overall viability. This article delves into the comprehensive setup, start-up procedures, and equipment configurations employed in launching an array of accelerated double-chamber microbial fuel cell (DCMFC) benchtop operations within the laboratory. It provides a meticulous account of the experimental methods, the empirical models for real-time data analysis from both physico-electrochemical and purely electrical perspectives. The primary objective of this study is to initiate the experimental start-up sequence and rigorously compare the potential of substrate sources, as well as concurrent viable incubation or retention times (HRT) within the DCMFC unit, spanning both the analytic and cathodic treatment chambers. Furthermore, the article explores the impact of experimental Hydraulic Retention Time (HRT) on the treatment of high-strength organic substrates from three wastewater sources while concurrently generating electricity in the DCMFC. A distinctive feature of this study is the elucidation of the DCMFC's unique configuration, including its circuit design and the series connection of electrical fluke-multimeters for the experimental detection of OCV (open-circuit voltage) and CCV (closed-circuit voltage). In essence, this work aims to unravel the intricacies of MFC technology, providing valuable insights that pave the way for its wider adoption and practical application in solving both environmental and energy challenges.

2. Materials and methods

2.1. Wastewater and proteobacteria and bacteriodota microbes sampling and storage procedure

2.1.1. Sample collection and culture incubation

Industrial wastewater samples, along with mixed bacterial cultures predominantly consisting of Heterotrophs (Proteobacteria and Bacteriodota), were sourced from two local wastewater treatment facilities in Durban, South Africa: Tongaat Hullet Sugar Mill (Biorefinery) in Rossburg, Durban, and Clover Dairy Plant in Queensburgh, Durban, South Africa. Upon collection, these samples were carefully preserved in a controlled temperature environment of approximately 10 °C in the research laboratory. Three distinct sources of industrial wastewater substrates were selected as inoculum to determine the most conductive and suitable analyte (raw organic complex substrate source) for the anodic chamber of the Double Chamber Microbial Fuel Cell (DCMFC). The characterization results of these wastewater streams, particularly their electrogenic capacity and viability as worthy anolytes for enhanced power generation in the DCMFC, have been extensively detailed and previously presented in a study titled "Classification of Taxonomy of Biorefinery & Dairy Wastewater Pollutants: A Case of Phylum Metagenomics – rDNA Identification & Dominance as Potential MFC-Electricity Generation" by Shabangu et al. [2023],(11).

Simultaneously, the freshly harvested microbial cultures were securely stored in 2 ×5 L bucket incubation units, hermetically sealed with aluminium foil. This approach aimed to create a partially adiabatic system, thereby facilitating microbial incubation under anaerobic conditions within the mesophilic temperature range. When commencing a new fed-batch DCMFC operation, the well-acclimated Proteobacteria and Bacteriodota microbial cultures were decanted into a 2 L conical jar. This was followed by a physical pre-separation operation designed to isolate the well-acclimated and densely populated microbial species. This process aimed to prevent biodegradation inhibition and partial sludge bulking within the anodic chamber of the DCMFC, following the procedure established by Kim et al (Feng et al., 2008 Apr; Wang et al., 2013; Ishii et al., 2014; Wang and Han, 2009). To ensure selectivity in favour of the desired microbial populations, the microbes were meticulously strained through appropriate filters, allowing only the microbes suitable for enhancing the growth rate of electrogene needed to enhance electron flow in the anodic chamber. Fig. 1**,** provides visual representations of the mini bucket incubator utilized for biomass acclimatization and the lab-scale bucket incubator employed for continuous biomass acclimation, sourced from local wastewater treatment plants in both the dairy and biorefinery facilities. Fig. 1 is a pictorial layout that encapsulates the multifaceted start-up procedures integral to this study, encompassing full experimental pre-treatment, biomass acclimation, catholyte air aeration, and the physical pre-screening sequence.

2.1.2. MFC unit set-start up sequence and calibration procedure

The MFC unit was thoroughly set up and connected by a professional electrical practitioner, experienced as a Technologist in the field. All electrical configurations were originally set for the improved performance of this research work and wasn't sourced from any previous research work but purely to get optimum desired results from this MFC research work. Details the of Bi-electrodes and other critical MFC

Fig. 1. Start-up sequences for the full experimental set-up (a) Full view of the benchtop DCMFC lab setup; (b) Sieving and pre-separation of bacterial community (Bacteriodota and Proteobacteria; (c) Incubation and blending phase of influent dairy complex substrate; (d) Anodic and Cathodic bi-electrode mounted on the water heat-circulation tubes; (e) Bi-electrode (1,2,3 – Carbon Rod- Copper sheet electrode); (f) Full side view of the main components of the DCMFC including the heating controller with the resistor box.

components with its unique electrode wiring configuration sequence to detect both OCV and CCV voltage readings.

2.2. MFC experimental configuration

The MFC chamber is a dual-chamber design that was fabricated from 2 x Schutt blue cap 1 L bottles. The anode and cathode chamber were separated by Nafion 115 ® Proton Exchange Membrane (PEM) *(Lyntech, United States)* to transfer proton (H^+) from anode chamber to cathode chamber. The copper-bi-electrode electrode augmented with carbon-graphite electrodes was selected as the electrode and was placed at the anode and cathode chamber with a cross-sectional area of 0.237 m^2. The bi-electrode connection was then completed by an external circuit using professional electrical positive and negative wires to transfer electrons produced from organic matter oxidation from the anode chamber to the cathode chamber. An external load of 1000 Ω external resistance is commonly set as reference standard operating threshold to enhance the bacterial activity rate according to previous authors like Logan et al., (2006), (Ahn and Logan, 2010, 2013; Min and Logan, 2004a; Logan and Rabaey, 2012a; Logan and Regan, 2006; Rossi et al., 2020) clearly articulating the methodology and efficient experimental fundamental set-up towards attaining practicable results in a typical MFC system. Based on the above stated reasons, this study adopted a rather higher operating external resistive load capacity of 1,3 KΩ. This was to suffice the bioelectrochemical principle stated by Zhang et al., (2017), (Katuri et al., 2011; Zhang et al., 2017) that microbial fuel cells (MFCs) experiencing a reduction in external resistance during startup exhibited elevated rates of energy gain, energy output, active biomass, and maximum power density. however, there was a decrease in the rate of voltage increase, (Katuri et al., 2011; Zhang et al., 2017). The cathode compartment was filled with a standard 10 mg/L phosphate buffer solution which was combined with slow oxygen sparging as electron acceptors. Figs. 2 and 3***,*** illustrates the start -up experimental process flow diagram and the lab view images of the DCMFC with its distinctive components utilised during the start-up experimental runs.

Fig. 3 was precisely set up for the start-up experimental runs with clear emphasis on the component set up and procedures detailed in above subsections. As per full process description detailed in Section 2.2, this unit was operated at ambient and constantly maintained temperature range to clearly focus on the equipment start up and experimental operating factors set for the duration of the preceding experiments. The experimental HRT and incubation period was clearly digressed and relied on the smooth start up and operation of the DCMFC unit. As shown in the above **Figures 2, 3** all the other basic operating factors were kept at standard operating range as sourced from recent research work e.g., Logan et al. (2006).

2.3. Inoculation and medium

Raw industrial wastewater *(purely organic)* (COD: 250 – 1850 mg/L – biorefinery wastewater and 500 – 3500 mg/L – dairy wastewater, pH = 6 – 7 for both streams) was harvested from a local wastewater treatment plant (Tongaat Hullet, Rossburgh - South Africa and Clover Pty *(Ltd)* Queensburgh, South Africa). The Proteobacteria and Bacteriodota were both seeded as active microbes, electrogene for the bioelectrochemical process.

2.4. DCMFC calibration of measuring instrumentation sequence

Calibration of the measuring instrument was critical to avoid erroneous readings and measurements during the experiment. Fluke True-RMS digital multimeter (DMM) was used. To prepare for proper measurements on the DCMFC, a True-RMS digital multimeter was calibrated according to manufacturer specifications. The DMM was tested on continuity and found to be functional. The DC voltage and AC voltage were tested on known source and the voltage reading matched and ranged closer to the expected values. The 12 VDC voltage was tested from regulated supply and AC voltage was measured on AC wall outlet the results are as shown below in Table 1.

A calibration test results plot was further done on using MATLAB Simulink software as presented in Fig. 4 below. Fig. 4 shows the parameters obtained during the calibration of Fluke True-RMS digital multimeter (DMM). The 0.1 Ω was obtained for estimated 0.05 Ω. The 0.1 Ω was deemed acceptable considering the factors such as the test lead length, cross- sectional area and type of copper present in the test leads. The silicon rectifier diode (1N4007) was used for calibration of DC mV and the 600 mV was measured on DMM. The 600 mV was acceptable, and it was within the range of breakdown voltage, in addition, the rectifier diode is made of silicon, the most common material found in most electronic components. The advantage of silicon can be doped to be insulator or conductor. For 1N4007 the silicon is insulated with the silicon that breaks down at the minimum of 300 mV. The 11.94 V was measured from regulated power supply and the results were less than 5% to the expected value as shown in Table 1. The AC voltage read to 19.59 V on the low side of the transformer and AC mains supply got to 238 V as anticipated for household voltage.

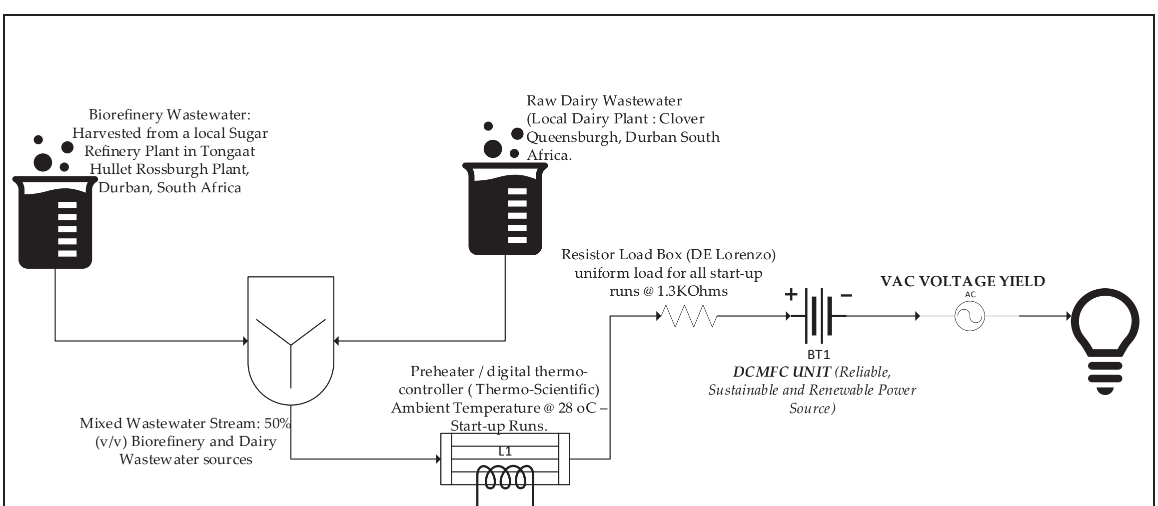


Fig. 2. Illustrative Process Block Flow Diagram for the laboratory / bench top DCMFC operation for the generation of bioelectricity from treating biorefinery and dairy wastewater substrates.

Fig. 3. MFC Experimental Set-up; Images of the start-up operation for the DCMFC system; component sections; aerator pump; DCMFC configuration chambers; Temperature controlling unit; Resistor box and water circulation set-up.

Table 1
Calibration test for DCMF Unit Operation.

Parameter	Expected values	Measured values	Scale
Continuity test (Ω)	0.05	0.1	200
DC voltage (mV)	0.7	0.6	1000
DC voltage (V)	12	11.94	20
AC voltage low voltage (V)	20	19.59	20
AC wall voltage (V)	220	238	1000

2.4.1. Resistive load test

It was important to conduct an electrical test on the resistive load to determine its behavior, stability, and accuracy about temperature internal and external factors during the experiment. Table S2 in the supplementary section best describes the behavioral response of the resistance dynamics at fixed temperature of 18 ° C. This temperature is considered below ambient conditions, hence within the psychrophilic zone. The DCMFCs effect within psychrophilic to thermophilic zone in this case would be covered as the lowest temperature point calibration

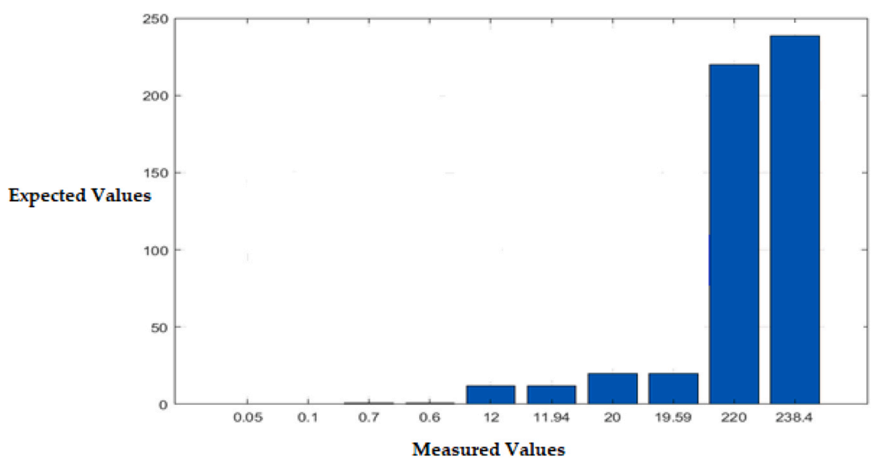


Fig. 4. MATLAB-SIMULINK Calibration test results.

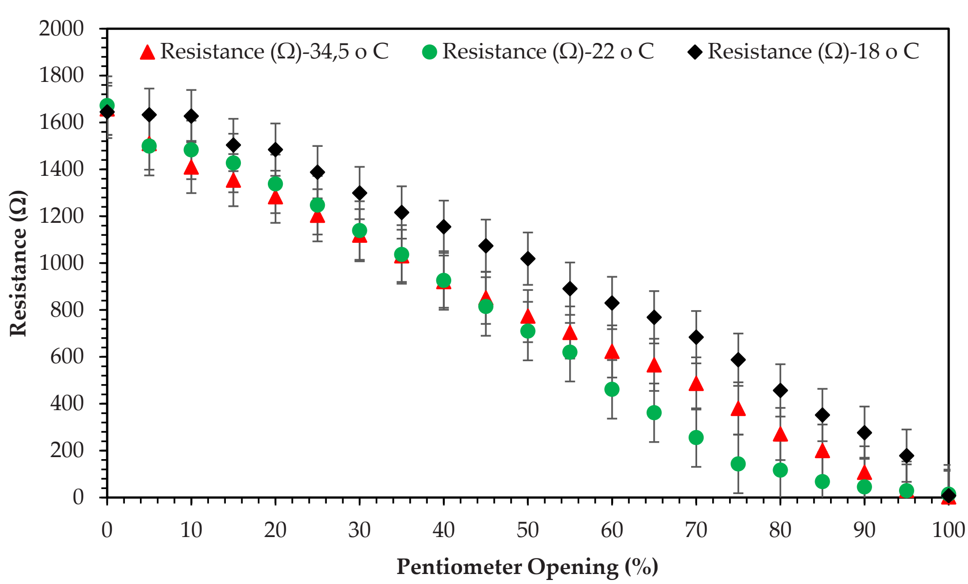


Fig. 5. Resistance calibration test at 18 ° C, 22 ° C and 34.5 ° C.

sequence has been covered. Due to the operation sequence adopted from Logan et al (Cheng et al., 2006a). and the other studies hence stated in the above process description, this unit was mostly operated at 1 300 Ω at start-up and was kept constant throughout the start-up experimental runs. Part of the objective calibration sequence is the observation derived by the effect of temperature on the overall resistivity of this unit. At different temperature gradients one observes different resistance loads at rather sample % openings. Hence Fig. 5 below, best presents the behavioral sequence of the resistance box at 18 ° C, 22 ° C and 34.5 ° C proving the criticalness of the calibration curve towards deriving the desired percentage load opening at that specific temperature through extrapolation from the presented calibration curve measurement.

Table S1 shows the calibration test results when the pentiometer was tested at the temperature of 18℃, the resistor was adjusted from 0% to 100% and values were measured using DMM. Fig. 5 summarizes the calibration profile test over three sets of temperature ranges from psychrophilic to partial thermophilic range. The percentage setting on x-axes is basically plotted against the resistor values over the above stated temperature range. When resistor was tested at 34.5 ° C the results are as shown in Fig. 5 Overall, the curves are not linear as expected for an ideal resistor. The results obtained in Table S1, Table S2 and Table S3 showed that when the resistance is selected at 0% the maximum values are 1645 Ω, 1672 Ω and 1658 Ω respectively. This means that there are slight changes at the room temperature. Similarly, when resistor is adjusted to 100% the values are 7.5 Ω, 14.2 Ω and 2.4 Ω were obtained in Table S1, Table S2 and Table S3. This translates that the resistance changes slightly at room temperature. According to the manufacturer specification, DL2108T11 can be adjusted from the minimum resistance of 330 Ω to a maximum 1930 Ω. Overall the test results were deemed acceptable because are within the range of Manufacturer's specification.

2.4.2. DCMFC installation

The DCMFC was connected as shown in Figure S1, in the supplementary section. This is the electronic connection circuit diagram for the DCMFC connection sequence towards a proper flow of currency around the bioelectrochemical system. This schematic consists of electrodes labelled 1 and 2 connecting wires and resistive load. The DCMFC connection was routinely checked for connection tightness, rust, and electrical connection so that each experiment ran independently without affecting each other in any way. The test results for each run are as shown in Table S1 in the supplementary section. The test results were obtained using the DMM and were deemed acceptable and within the range. When comparing 0.3 Ω to 0.1 Ω obtained in Table S1 above, it is near and within the manufacturer specification for continuity resistance. The 1672.4 Ω is the ohmic value including ohmic of connecting wires in left chamber similarly with 1672.4 Ω in the right chamber connecting wire are also included in the results. Overall, the electrical test conducted went according to the expected results and guided by test results in Table S1, and calibration results in Table S2, Table S3 and Table S4 as presented in the supplementary section.

The resistive load calibration test was a crucial step in the DCMFC experiment to ensure accurate resistance measurements and prevent errors during the experimental runs. The DL 2107 resistive load, with a manufacturer-specified range of 0–1600 Ω, was employed for this purpose. Previous studies on MFCs indicated that experiments typically utilized resistance values exceeding 1000 Ω to sustain microbial life within the chamber, (Katuri et al., 2011; Zhang et al., 2017). In this study, temperatures were set at varying levels below ambient, medium, and high to replicate real-life conditions found in wastewater environments. Given the significant role of temperature in MFCs, instruments were utilized to monitor temperature variations in real-time, ensuring accurate readings and detection of any deviations. The instruments employed for this purpose included in a pictorial layout of Fig. 6: ***(a)*** – ***(e)*** below.

2.5. DCMFC data analysis

The real time performance monitoring data for the DCMFC unit was captured and calculated using the following electrochemical models and expressions as reported and used by Logan et al (Logan et al., 2006; Cheng et al., 2006a, 2006b; Zuo et al., 2006)., by measuring electrical current (I) and voltage (V) using a multi-meter every 5 hours for precisely 48 hours optimum incubation period, (Logan et al., 2006).

$$I(mA) = V/R_{ext} \quad (1)$$

Where $R_{ext,}$ was the resistance of an external resistor that value was equal to 1000 Ω. V (mV) is the voltage capacity, closed circuit voltage of the MFC unit.

$$\Delta G_r \quad (J) = \Delta G_r^0 + RT\ln(\pi) \quad (2)$$

Where $\Delta G_r \quad (J)$is Gibbs free energy for specific conditions, $\Delta G_r^0 \quad$ (J) is the Gibbs free energy under standard conditions usually defined by 298.15 K, 1 bar- pressure, and 1 M concentration for all species, R (8.31447 $J/mol^\circ K$) is the basic universal gas constant, T (° K) is the absolute temperature calculated as the activities of the products divided by those reactants. The standard Gibbs free energy is calculated from tabulated energies of formation for organic compounds in water, sources available (19).

$$E_{emf}(mV) = -\frac{\Delta G_r}{nF} \quad (3)$$

Where all biodegradation reactions transpire under standard conditions hence: $\pi = 1$, then equation simplifies further:

$$E^0_{emf}(mV) = -\frac{\Delta G^0_r}{nF} \quad (4)$$

$$P(mW) = IE_{cell} \quad (5)$$

Fig. 6. Presents calibration test instrumentation (a) Infrared digital thermometer (b) Contact thermo-couple thermometer (c) Resistive load (DL2108T11 (d) Fluke digital multimeter (DMM) (e) Thermo-Scientific temperature controller for the DCMFC system.

Where $P(mW)$, is the overall power of the MFC unit. Normally the voltage is measured across a fixed external resistor (R_{ext}, while the current is calculated from Ohms law: $I(mA) = E_{cell}/R_{ext}$. By Logan et al. (19):

$$\epsilon_{Cb}(\%) = \frac{M\int_0^{t_b} Idt}{Fbv_{anode}\Delta COD} \quad (6)$$

Where M = 32, the molecular weight of oxygen, F is Faraday's constant, $b = 4$ is the number of electrons exchanged per mole of oxygen, V_{An} is the volume of the anodic chamber, and ΔCOD (mgCOD/L) is the change in COD over time t_b sourced from Logan et al (Logan et al., 2006). The above listed empirical models and equations for bio-electrochemical calculations in the startup of the DCMFC for the generation of electricity in this manuscript were sourced from Logan et al (Logan et al., 2006).: The organic loading rate (OLR) for the DCMFC process was calculated as per following model that was sourced from Metcalf & Eddie, (Metcalf et al., 2004).

$$OLR = \frac{(Daily\quad Mass\quad Basis\quad COD\quad Throughput)(\frac{mg}{L})}{\left(\dot{V}_{daily}\right)} = \frac{(gCOD)(\frac{mg}{L})}{L.d} \quad (7)$$

The biomass growth yield for monitoring the effect of active bacterial population growth in the MFC unit during processing which involved 7 - day incubation period for optimum biodegradation of organic pollutants strength was calculated as below (19):

$$Y = \frac{OLR(gCOD)}{\Delta COD(\frac{mg}{L})} = \frac{(gCOD)}{(\frac{mg}{L})} \quad (8)$$

Where Y is the exact biomass growth yield for the active population in the DCMFC unit, and ΔCOD is the change in COD assay from influent fresh feed to the final effluent point. The overall COD mass balance to monitor the real time data on the performance of the DCMFC unit in biological biodegrade the high strength organic substrates of these wastewater sources was calculated as per below empirical models, (Logan et al., 2006).

$$\varphi = (1 - (\%)CE - Y) \quad (9)$$

Where φ is the fractional COD mass balance in correlation with the coulombic efficiency (%) CE, and the biomass growth yield (Y), (Logan et al., 2006).

3. Results and discussion

3.1. DCMFC start-up mode of operation classification

The basic mode of operation sequence for the experimental start-up sequence for this research work was adopted from Logan et al (Logan and Regan, 2006; Logan et al., 2006; Cheng et al., 2006a, 2006b; Zuo et al., 2006).; Wang et al (Cheng et al., 2006a; Wang et al., 2008; Feng et al., 2008 Apr). Precisely, this current study operated on fed-batch mode and transient or unsteady state and integral biodegradation principle of pollutants removal capacities. The raw industrial organic substrates from dairy, biorefinery and mixed streams were harvested and blended as described in above sections then inoculated into the DCMFC chambers in batches of 500–800 ml of the homogeneous raw substrates. The working volume was kept almost constant within the above stated rang, but fed in batches at the end of each run that was drained and left with about 150 ml of previous batch supernatant towards the healthy inoculation and acclimation of the Proteobacteria and Bacteriodota biomass in the DCMFC. Prior; these substrates were adjusted to a standard working pH of 7, kept constant as adopted from Wang et al., (Wang et al., 2008; Feng et al., 2008 Apr). The nature of the substrates biological and physicochemical parameters was already clinically addressed by Shabangu et al (Jadhav et al., 2022). Precisely the theory of this manuscript is to set an experimental hydraulic retention time that will correlate with the efficient generation of power of bioelectricity concurrently to wastewater treatment in the DCMFC unit. The hypothesis is that at ultimate voltage yield and optimum organic pollutants strength parameters removal from these wastewater sources will mark the efficient operation residence time in the DCMFC unit.

3.2. DCMFC performance during start-up sequence

3.2.1. Comparison graphs for overall voltage yield between the three wastewater sources

Following inoculation, voltage was generated in the DCMFC unit within 168 hours of incubation in the 1 L anodic chamber that has been seeded with well acclimatised Proteobacteria for the biorefinery wastewater treatment and Bacteriodota for the dairy wastewater treatment sequences. As shown in Fig. 7 there were 2 successfully operated fed-batch runs for the dairy wastewater treatment with a maximum voltage yield of 357 mV which was operated at 0.2 N KOH as an interim catholyte instead of pure air aeration, this type of catholyte was chosen as more of an electrolyte controller within the cathodic chamber. Hence with the seeding of KOH a strong base medium, one anticipated a basic pH medium of pH 7 to be maintained in this chamber. The potassium hydroxide was also seeded in the anodic chamber to sort off adjust the pH and assist the dairy based Bacteriodota dominant specie microbes' pH buffering capacity, (Metcalf et al., 2004). Unfortunately, the buffering capacity as was targeted resulted to the total sludge bulking of the microbes hence total failure and mostly dead microbes as observed from 96 hours the bioelectrochemical process was almost done due to dead microbes and totally bulked up. Although, the first 48 hours of inoculation and incubation in the bioreactor proved feasible in terms of bioelectricity production. The external resistance was kept constant at 1000 Ω, adapted from Wange et al (Wang et al., 2013; Ishii et al., 2014; Wang and Han, 2009; Wang and Ren, 2014, 2013; Wang et al., 2009). and Logan et al (Ahn and Logan, 2010, 2013; Min and Logan, 2004a; Logan and Rabaey, 2012a; Logan and Regan, 2006; Rossi et al., 2020; Cheng et al., 2006a, 2006b; Zuo et al., 2006; Feng et al., 2008 Apr; Cheng and Logan, 2007; Ren et al., 2014; Kim et al., 2005; Cheng et al., 2007; HaoYu et al., 2007 Sep 27; Logan et al., 2007; Zuo et al., 2007). and Alterman et al (Aelterman et al., 2006a).; Kim et al (Kim et al., 2005; Hyun et al., 2021; McCarty et al., 2011; Kim et al., 2007 Sep; Zuo et al., 2008; Dec et al., 2008). and Rabaey et al (Logan and Rabaey, 2012a; Aelterman et al., 2006a; Rabaey and Rozendal, 2010; Rabaey et al., 2005; Rozendal et al., 2009; Aelterman et al., 2006b; Foley et al., 2010; Pham et al., 2006; De Schamphelaire et al., 2008). Shown in Fig. 8 is the 3 – fed batch operation of the biorefinery inoculated DCMFC experimental runs. The highest voltage 255 mV within the 3 - fed batch experimental runs. Mostly observed is the reliability and sustainability of the complex substrates in terms of its electrical conductivity throughout the 7 - day period. Unlike the dairy wastewater source which shot up for the first 48 hours then dropped drastically and vanished, biorefinery wastewater help up its average voltage potential of 145 mV on the higher end and 85 mV on the lower end. As stated by Kolev et al (Slavov, 2017; Kolev Slavov, 2017)., dairy wastewater holds very low electrical conductivities and hence this studies start-up comparison runs have proven that theory. Fig. 9***, below*** shows the trends of the combined organic substrates; dairy, biorefinery and mixed wastewater power potentials. Clearly observed is the high peak attained from dairy wastewater that vanishes within 48 hours. Biorefinery wastewater is seen to exude average and sustainable power potentials together with the mixed wastewater substrates. These trends suffice the choice that biorefinery and mixed wastewater substrates are mostly viable DCMFC anolytes choices for sustainable and improved or scaling up the generation of bioelectricity in the DCMFC unit.

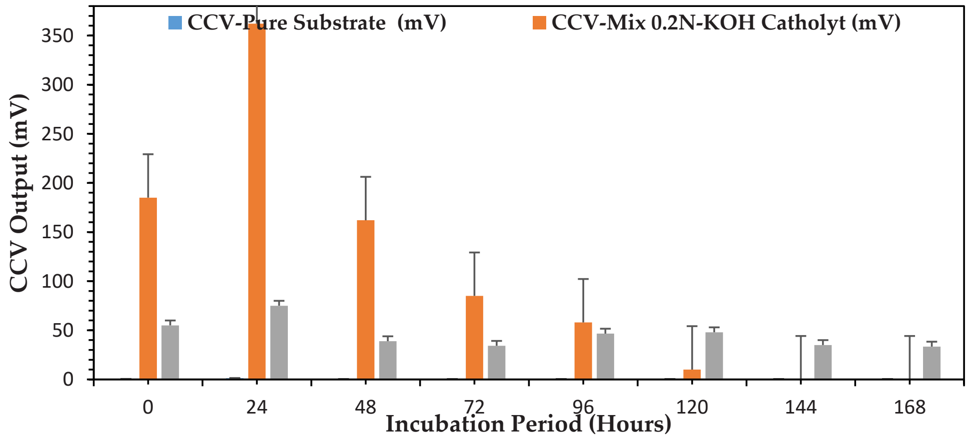


Fig. 7. Dairy wastewater comparison trends with Mix wastewater for Closed Circuit Voltage Generation in a DCMFC unit.

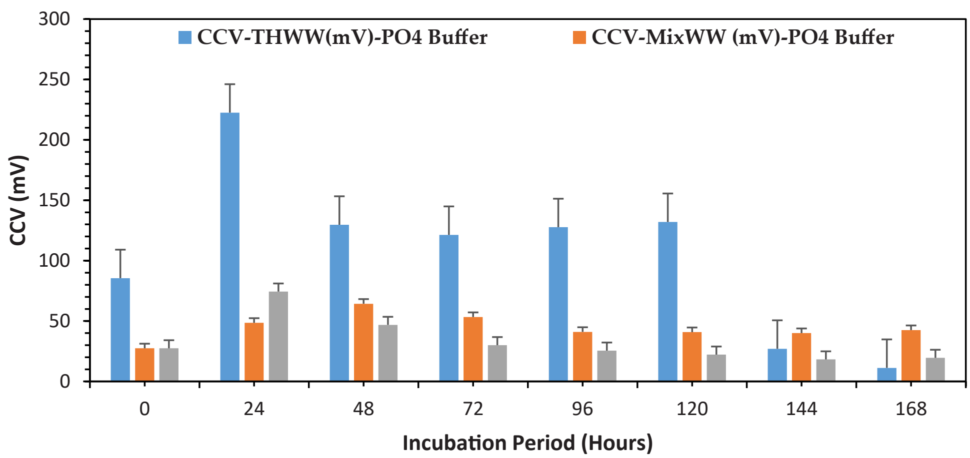


Fig. 8. Biorefinery wastewater comparison trends with Mix wastewater for Closed Circuit Voltage Generation in a DCMFC start-up sequence.

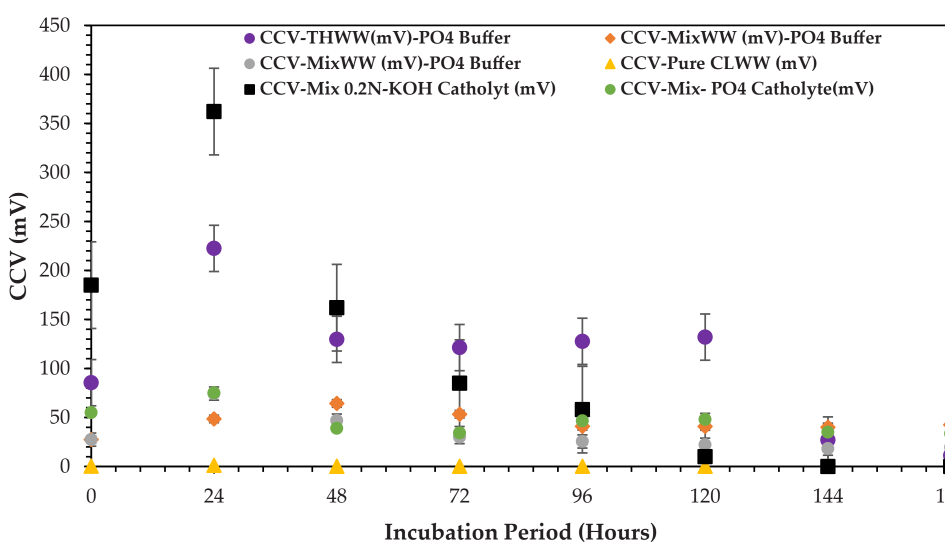


Fig. 9. Electrical Power Generation (Closed Circuit Voltage- CCV) in a DCMFC unit Comparison graph for all types of wastewater sources within a 7-day incubation period.

3.2.2. Experimental HRT based on COD-OLR variations for all three wastewater sources

The hydraulic retention time (HRT) has been theoretically reported and experimentally proven as a function of organic pollutant strength removal by many authors in previous research when dealing with industrial organic wastewater treatment. The context of this start-up sequence for the DCMFC unit has chosen to base the retention time or incubation period within the DCMFC fed-batch operation cycles on the experimental capacity of this unit in treating the fresh feed of the complex substrates from its high strength organic pollutants while generating electricity as the measure of the biological residence time needed for a complete biodegradation process. Shabangu et al (Khaya Pearlman Shabangu and Babatunde Femi Bakare, 2019). clearly articulated the strong significance of experimental COD - HRT for biological wastewater treatment in treating very high strengths effluent system from a local South African brewery successfully. The context of experimental COD - HRT has thus been adopted from findings of Shabangu et al (Khaya Pearlman Shabangu and Babatunde Femi Bakare, 2019). As seen in Fig. 10 ***(a)*** to ***(c),*** this principle of COD - HRT has once again been proven only this time a consideration of voltage yield is concurrently observed. From an electrical efficiency point of view, a practical retention time on average of 92 hours was deemed feasible based on findings of Fig. 10. From a biological treatment perspective, precisely a rapid organic removal is achieved within the first 48–72 hours with an almost flat removal capacity moving forward to 168 hours retention time. The findings of both biological and electrical perspectives on these graphs suffice the principle of experimental HRT. Shown in Fig. 11 ***(a)*** and ***(b)*** is the same phenomenon and theory of experimental COD - HRT. Precisely in both runs, the average COD rapid removals capacity more than 80% COD removal was achieved within the first 48 hours of the retention period. These experimental HRTs sufficed literature citing alluded by Shabangu et al (Jadhav et al., 2022; Bakare et al., 2017; Kwaku Armah et al., 2021). and other researchers in the field of bioelectrochemical technology concepts like Kim et al (Ahn and Logan, 2013; Min and Logan, 2004a; Cheng and Logan, 2007). and Logan et al (Ahn and Logan, 2010, 2013; Min and Logan, 2004a; Logan and Rabaey, 2012a; Logan and Regan, 2006; Rossi et al., 2020; Cheng et al., 2006a; Cheng and Logan, 2007).

3.2.3. Active biomass – proteobacteria-bacteriodota growth yield comparison MFCs Faraday's efficiency for all three wastewater sources

The Faradays Efficiency or coulombic efficacy is the measure primarily of the efficiency of the overall power output yield and energy recovery of the MFC system. This parameter is reported to have a theoretical range of 0.02 – 0.8% for most MFCs units Logan et al (Ahn and Logan, 2010; Logan and Rabaey, 2012a; Rossi et al., 2020; Cheng et al., 2006a; Cheng and Logan, 2007). The Coulombic efficiency, $\epsilon_{Cb}(\%)$ is defined as the ratio of total Coulombs transferred to the anode from the substrate to maximum possible Coulombs if all substrate removal produced current. The total Coulombs obtained is determined by integrating the current over time, so that the Coulombic efficiency for an MFC run in fed-batch mode, $\epsilon_{Cb}(\%)$ evaluated over a period *tb*, Logan et al. (2006); Rabaey et al (Logan et al., 2006; Aelterman et al., 2006b; Foley et al., 2010; Pham et al., 2006; De Schamphelaire et al., 2008; Rozendal et al., 2008; Rabaey et al., 2007; Guo et al., 2014).; Cheng et al (Cheng et al., 2006a, 2006b, 2007; Logan et al., 2007; Zuo et al., 2007; Cheng et al., 2016). Cell growth will reduce *CE*-($\epsilon_{Cb}(\%)$ due to diversion of electrons into biomass. The substrate utilization for growth is measured by the net (or observed) cell yield, (*Y (gCOD/ (mg.* L^{-1}*))* as sourced from Logan et al (Kim et al., 2005; Min et al., 2005). Subsequently it is noted that the overall biomass growth yield is inversely proportional to the substrate strength in terms of COD (mg/L) and directly proportional to the daily fed-batch organic loading rate (ORL (gCOD/L.d)). Subsequently a decrease in the loading rate or substrate loading impairs the active bacterial specie growth rate thereby increase the overall coulombs generated on the daily basis of the organic substrate quantities. Figure S2 ***(a)*** to ***(c)*** presents as significant correlation between the faraday efficiency and the substrate growth yield for biorefinery wastewater respectively as: $R^2 = 0.92$ and 0.92% ($\epsilon_{Cb}(\%)$; $R^2 =$ 0.58 and 0.044 ($\epsilon_{Cb}(\%)$ and $R^2 = 0.77$ and 0.045 ($\epsilon_{Cb}(\%)$. These findings present highly significant correlation factor at the highest coulombic efficiency with correlating growth yields. As Logan et al (Kim et al., 2005; Min et al., 2005). reported, the higher the coulombic efficacy the increase in terms of complex substrates growth yields. The same sequence at these DCMFC start-up runs was attained for dairy wastewater presented by Figure S3 ***(a)*** and ***(b);*** the Faraday efficiency and the substrate growth yield were respectively achieved as: $R^2 = 0.98$ and 0.0014% ($\epsilon_{Cb}(\%)$; $R^2 = 0.99$ and 0.020 ($\epsilon_{Cb}(\%)$. These findings present strong correlation capacity between the coulombic yield of the DCMFC with respect to the substrate or active bacterial growing mechanism over the start-up sequence retention times. Once again, the theory of Logan et al (Kim et al., 2005; Min et al., 2005). is sufficed by these start-up experimental runs. But clearly, biorefinery substrates presented the highest faradays/coulombic efficiency rations compared to the dairy wastewater substrates. This presents the viability of biorefinery as the perfect electron donor to suffice improved power density and high current densities in the DCMFC unit on full experimental mode operation.

3.3. DCMFC COD mass balance in relation to Coulombic efficacy and proteobacteria-bacteriodota growth yields as a start-up sequence performance measure

Once the efficiencies for electricity generation in terms of power density and current density is attained to assessed on its the feasibility for overall DCMFC on start – up sequence in terms of bioelectrochemical and biological treatment capacities was carried out as a yard stick measure of this unit's success at start-up sequence. The COD and biomass production are completed in this bioelectrochemical process is presented as the mass balance fraction (ϕ) in Figs. 12 and 13 for biorefinery and dairy wastewater start-up sequences. Precisely, this is the exact fraction of 3 gCOD that was removed by the unknown processes transpiring during both the biodegradation and bioelectrochemical processes transpiring within the DCMFC anolyte and cathodic chambers within the given retention times. As seen in the Figs. 12 and 13, the ϕ yardstick limitation is 1, hence the worst performing feedback process in terms of COD removal batch 1 of the diary wastewater presented in Fig. 12 showed a very slight deviation from the theoretical fraction of the value ϕ. The second preceding batch presented an observable deviation which showed an improved capacity form both Faraday and the growth yield efficacies. The same observation was derived from Fig. 13 of the biorefinery stream. Hence, from the COD mass balance ϕ, the capacity of the unknown fractional processing presented by the COD mass balance is highly insignificant and non-congruent to the retention time of the fed batch DCMFC process. But rather the higher the coulombic capacity and active biomass growth yields to significant deviation of the fractional COD mass balance. This concept has been gathered and reiterated by Logan et al., (Kim et al., 2005; Min et al., 2005) and other bioelectrochemical research specialist.

4. Comparison of the industrial wastewater sources for efficient MFC start-up and operation sequence

Table 2 present studies reported in literature on the treatment of wastewater using different microbial fuel cells (MFCs) configurations strategies to attain a start-up electrical energy production in (Ahn and Logan, 2013; Min and Logan, 2004a; Logan and Rabaey, 2012b; Min and Logan, 2004b). The CE (%) efficiency, voltage yields, power densities and current densities as shown in Table 2 are within mostly reported MFC operational standards (Ren et al., 2014; Kim et al., 2005; Cheng et al., 2007; HaoYu et al., 2007 Sep 27; Logan et al., 2007; Zuo et al., 2007; Aelterman et al., 2006a; Hyun et al., 2021; McCarty et al., 2011; Kim et al., 2007 Sep; Zuo et al., 2008). This can be complemented by the positive organic's removal presented in the above sections for this study and reported by Min et al (Dec et al., 2008)., Wend et al (Kim et al., 2007 Sep). and Hyun et al (Khaya Pearlman Shabangu and Babatunde Femi Bakare, 2019). The findings of the MFCs accelerated or basic start-up operations are detailed in Table 2 below.

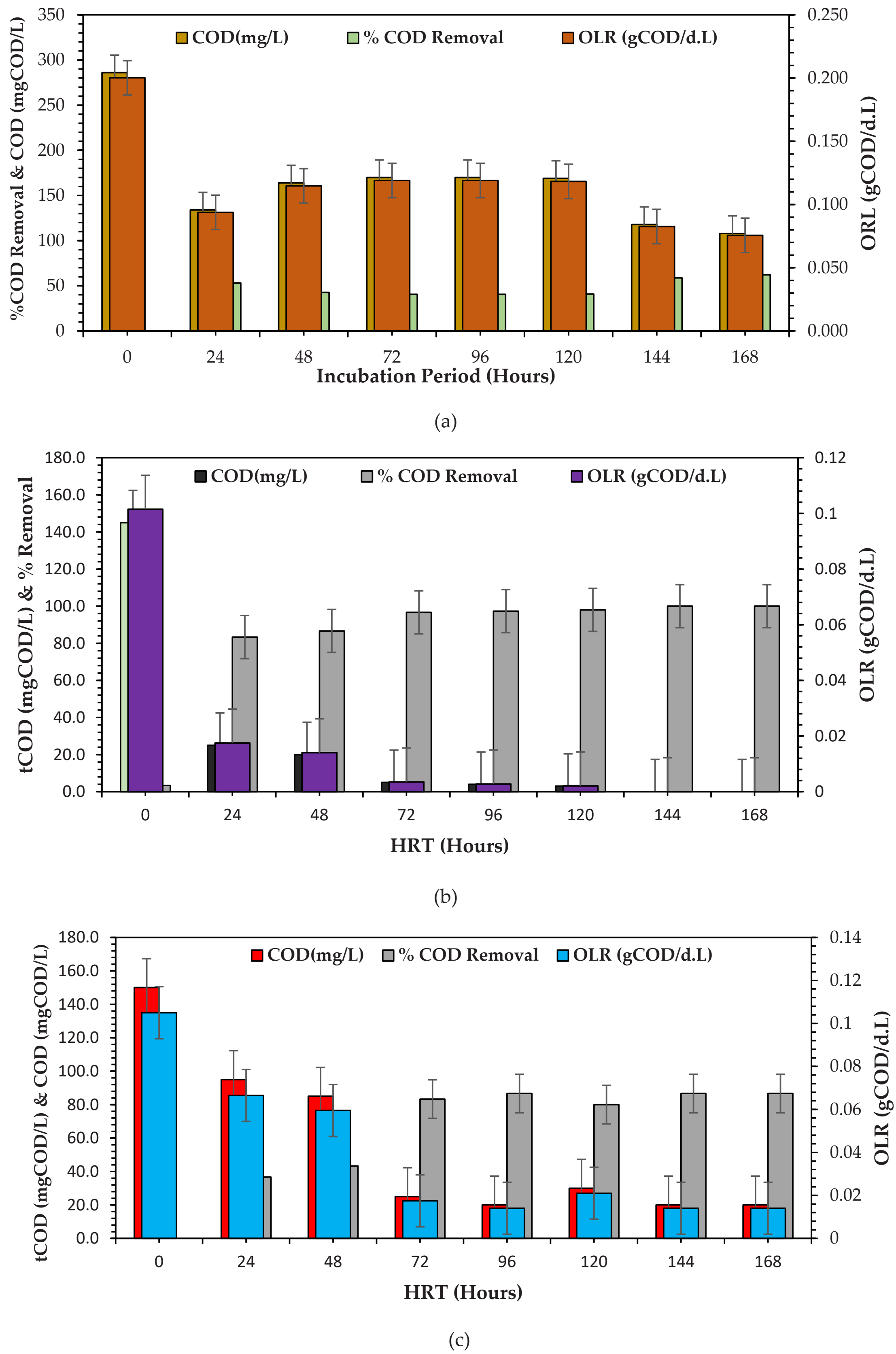
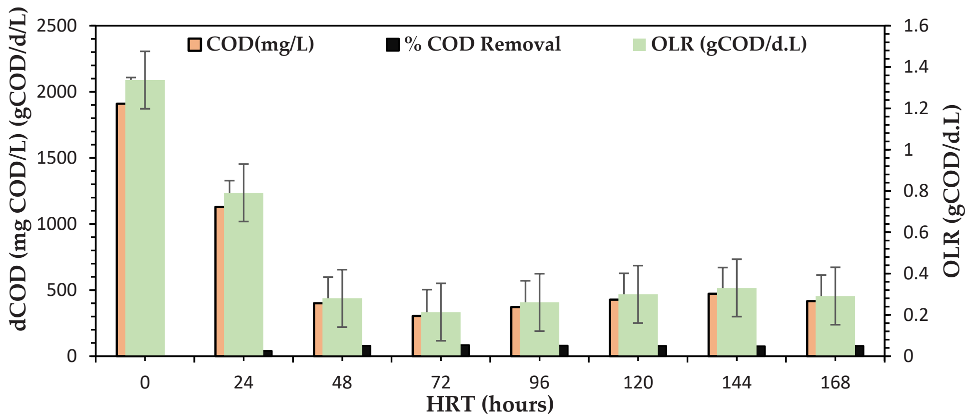
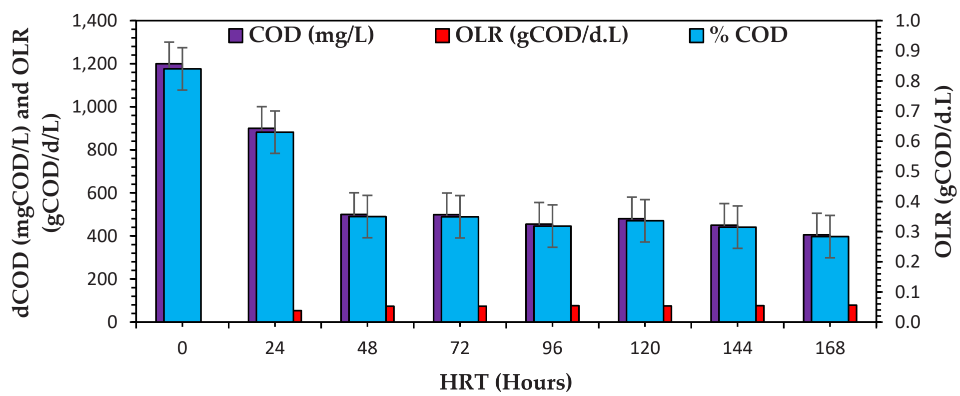


Fig. 10. (a) Experimental HRT Based On COD-OLR Variations for Mixed Complex WW (TH-CL) Batch#7, (b) Experimental HRT based on tCOD vs OLR for THWW Batch#6 and (c) Experimental HRT based on OLR vs tCOD for THWW Batch#5.



(a)



(b)

Fig. 11. (a) COD - HRT for Dairy WW in DMFC Air Cathode- Batch#1 and (b) Batch#3 CLWW start-up HRT-COD -OLR Trends.

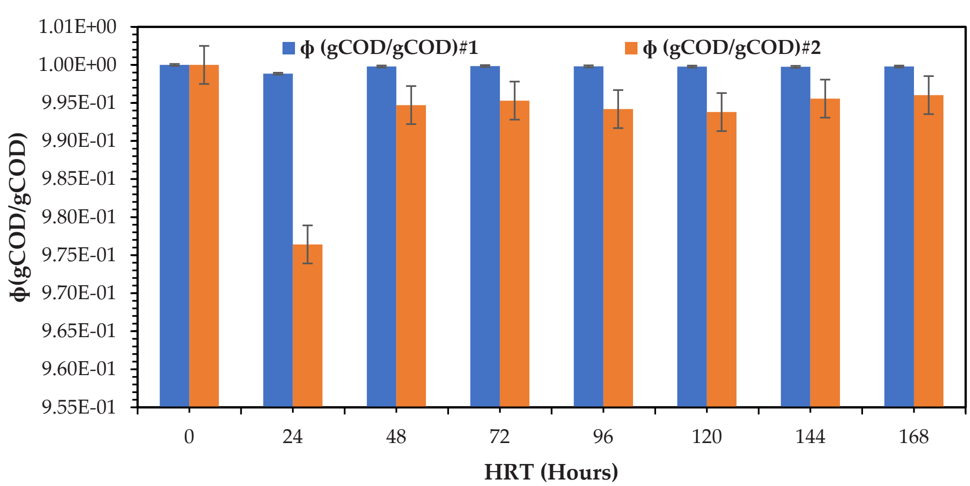


Fig. 12. ϕ (gCOD/gCOD) Mass Balance Vs HRT for Dairy Wastewater.

Generally observed from the yeast MFC operation is the prolonged HRT which as per literature favours the optimum biodegradation of the wastewater pollutants strength removal. But as shown, Hyun et al (Khaya Pearlman Shabangu and Babatunde Femi Bakare, 2019). attained profound magnitudes of the overall power density derived from the operating polarization curve. This could be attributed by the active growth mechanism that was maintained in this yeast MFC unit. Then, the performance of MFCs using biocatalysts including yeast cells grown on different thick CFs is measured to investigate how the growth pattern of yeast cells affects the performance of MFCs, (Khaya Pearlman Shabangu and Babatunde Femi Bakare, 2019). Hence, this observation led was sufficed by the linear response of the overall power densities towards the cell growth yeast that acted as the MFC biocatalyst favouring the overall thermodynamic shift of electrons towards power generation. Min et al (Dec et al., 2008). also reported convincing results as seen within very small HRTs of at most 4 hours and average 1.2 hours. The

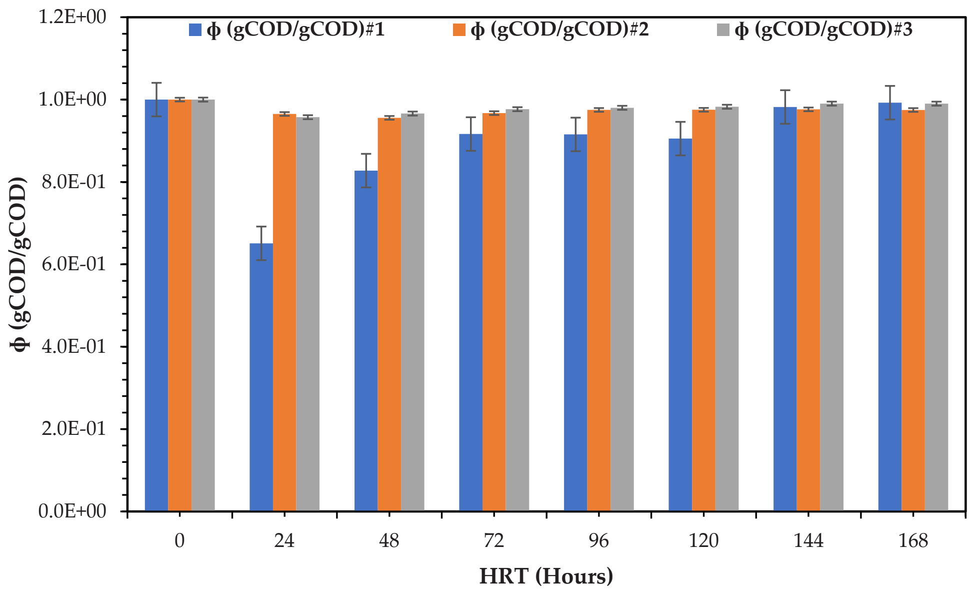


Fig. 13. ϕ (gCOD/gCOD) COD Mass Balance vs Experimental HRT for Biorefinery WW.

Table 2
Start -up studies on MFC for Electricity Generation using Raw Wastewater.

MFC Start-up Performances							
Experimental Configuration & Start-up	Wastewater Source	Voltage Yield *(mV)*	CE *(%)*	Power Density *(mW/m^2)*	Current Density *(mA/m^2)*	HRT *(days)*	References
DCMFC	Biorefinery	145	0.92	-	-	3–4	Present Study
DCMFC	Dairy	357	0.02	-	-	3–4	
DCMFC	Mixed	85	0.77	-	-	3–4	
DCMFC	Domestic WW	620	-	*9.33	*1.66	52	(Kim et al., 2007 Sep)
MFC	Yeast	-	-	*417.17	-	-	(Khaya Pearlman Shabangu and Babatunde Femi Bakare, 2019)
FPMFC	Domestic WW	-	-	43.1	-	*4	(Dec et al., 2008)

* Power density (mW/m^2), *Current Density (mA/m^2) and *HRT (hours)

present study relates mostly to the findings of Min et al (Dec et al., 2008). in-terms of power generation and the overall biodegradable contaminants removal.

Cell growth can reduce Coulombic efficiency due to electrons being diverted into biomass, with substrate utilization for growth measured by the net cell yield, (Fan et al., 2007; Hashemi and Samimi, 2012). The overall biomass growth yield is inversely proportional to substrate strength in terms of Chemical Oxygen Demand (COD) and directly proportional to the daily fed-batch organic loading rate. The findings of this study as presented in Table 2 above reveals a significant correlation between Faraday efficiency and substrate growth yield for both biorefinery and dairy wastewater. Scientifically, higher coulombic efficacy corresponds to increased growth yields, particularly with complex substrates, (Fan et al., 2007). The Biorefinery substrates demonstrated higher Faraday/coulombic efficiency ratios compared to dairy wastewater, suggesting their suitability as electron donors for improved power density and current densities in DCMFC operation. These findings present the potential of biorefinery substrates for enhancing MFC performance in full experimental start-up mode as compared to above previous studies in domestic and yeast wastewater treatment.

5. Conclusions and future perspectives

In this pioneering study, the focus was on an exploration of the start-up sequence for the Double Chamber Microbial Fuel Cell (DCMFC) in the treatment of industrial wastewater (IWW). The vision extends beyond the laboratory, envisioning the commercial scaling-up of bioelectricity production while concurrently addressing the formidable challenge of effectively treating high-strength organic pollutants, ultimately aiming for zero liquid discharge (ZLD).

The start-up methodology, while drawing inspiration from the works of Wang et al (Cheng et al., 2007; HaoYu et al., 2007). and Logan et al (Wang and Ren, 2014, 2013; Wang et al., 2009; Cheng and Logan, 2007; Kim et al., 2005)., was characterized by unique strategies that underscore the originality of the experimental approach. This distinctiveness emanated from the tailored experimental set-up, electrode configuration, and the selection of raw organic substrates. The findings of this work heralded Biorefinery and Mixed wastewater streams as the optimal candidates for raw organic wastewater substrates, serving as reliable sources of electron donors and anolytes within the MFC. A noteworthy highlight of this study was the remarkable biorefinery voltage yield, peaking at an impressive 253 mV, maintained consistently over an extended period of 168 hours. This exceptional outcome was further validated by the achieved peak coulombic efficiency of 0.045%. These findings strongly endorse the application and viability of MFC technology when utilizing raw organic substrates as both fuel and anolyte.

The theory of biorefinery as a more viable electrogenic or complex substrate sources against dairy wastewater and mixed wastewater streams, due to its dependable, and sustainable active electron donor and anolyte was solidly substantiated through this pioneering start-up experimental studies of this study. Importantly, this study has offered conclusive insights into the selection of the most suitable raw organic complex substrates and the determination of feasible incubation or hydraulic retention times, setting the stage for scalable methodologies within the DCMFC.

This overall approach, grounded in experimental evidence, has unequivocally demonstrated reliable organic removal and efficient voltage yield generation, substantiated by Hydraulic Retention Time (HRT) findings ranging convincingly from 72 to 96 hours. These results, as showcased in Figs. 11 and 12 and Figs. S2 – 3 (supplementary section), have set the conviction in both biorefinery and dairy wastewater sources as pivotal factors in the scaling-up methodology of the DCMFC.

Consequently, it is recommended for more comprehensive laboratory-scale experimental runs to validate the above-mentioned findings and set a robust benchmark for the scaling-up aspects of the MFC system. This encompasses considerations such as active bacterial species (Proteobacteria and Bacteroidetes), optimal temperature ranges spanning mesophilic to psychrophilic conditions, electrode configuration optimization for enhanced voltage yield in the MFC, judicious catholyte dosing to maximize DCMFC efficiency, and the meticulous design and empirical modelling of operational circuits in MATLAB Simulink. The culmination of this successful start-up methodology for the DCMFC opens the door to an exciting array of future perspectives, with the potential to revolutionize bioelectricity generation and industrial wastewater treatment on a larger scale.

Institutional review board statement

Not applicable to this study since it did not involve humans or animals.

Informed consent statement

Not applicable to this study since it did not involve humans or animals.

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Author statement

The manuscript has been thoroughly revised as per the reviewers' comments and/or recommendations, kindly see the attached detailed amendments in the revised manuscript done via track changes and accept changes accordingly. Due to the severity of the revisions and amendments or additions, track changes were implemented to best highlight the revisions than responding via a mini report. Note, suplementary materials have been added due to moving some figures and tables to the supplementary section as per reviewer's recommendations to remove from main manuscript body.

Moreso, English editing was manually done via proofreading this article in grammarly, hence all obvious typos were edited accordingly. Moreover, we confirm that neither the attached manuscript nor any parts of its content are currently under consideration used published in another journal. Please note that, all authors have approved the manuscript and agree with its submission to Energy reports. Grateful for your anticipated understanding and cooperation.

Moreover, we confirm that neither the attached manuscript nor any parts of its content are currently under consideration used published in another journal. Please note that, all authors have approved the manuscript and agree with its submission to Energy Reports Journal in Elsevier. Grateful for your anticipated understanding and cooperation.

CRediT authorship contribution statement

Khaya Pearlman Shabangu: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Manimagalay Chetty:** Funding acquisition, Supervision. **Nhlanhla Mthembu:** Data curation, Software, Visualization. **Joseph Bwapwa:** Conceptualization, Writing – review & editing. **Babatunde Femi Bakare:** Funding acquisition, Project administration, Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Khaya Pearlman Shabangu reports financial support was provided by Mangosuthu University of Technology Faculty of Engineering.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2024.02.054.

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