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Experimental Investigation of a Passive Direct Polymer Electrolyte Fuel Cell Using L-Ascorbic Acid as a Fuel

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ABSTRACT

The present study involves an experimental investigation of the electrochemical performance of a passive direct ascorbic acid fuel cell (DAAFC), evaluating its potential as a sustainable energy source. A single-cell assembly of DAAFC integrated with a Nafion® 117 membrane measuring 5 cm x 5 cm was fabricated and evaluated. The influence of variation in significant parameters, including ascorbic acid feed concentration, cell positioning (horizontal/vertical), bolt clamping torque, and operating temperature, was investigated. The outcome of the experiment highlights the importance of controlling these parameters for enhanced electrochemical performance of the passive DAAFC system. Different cell AA concentrations were fed to the system from 0.25 M to 1.75 M, at which the maximum power density of 0.633 mW/cm2 was obtained at 1.5 M. Further, this concentration was used for the remainder of the experimentation. For each condition of the cell parameter, a specific experimental procedure is followed to identify the optimum value of the selected parameter. The passive DAAFC shows optimum electrochemical performance when applied with 8 Nm of bolt torque. The horizontal cell orientation and 60°C operating temperature were identified as the optimum parameters among the experimental attributes. The cell produces a maximum power density of 0.838 mW/cm2 at 60°C among all experimental sets. These results demonstrate that careful optimisation of operating conditions significantly enhances the electrochemical performance of DAFC. The results show that each of these parameters significantly affects the electrochemical performance of the passive DAAFC. Moreover, the study confirms the potential of using ascorbic acid as an effective fuel for electricity generation, and the outcome of this study is expected to serve as a useful reference for guiding future research and development efforts in DAAFC systems.

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1. Introduction

The rapid growth of portable electronic devices such as mobile phones, laptops, and medical implants has raised the demand for stable and consistent small-scale power sources (Soloveichik, 2014). Across available promising candidates, polymer electrolyte fuel cells (PEFCs) have gained substantial research interest due to their quick start-stop character, low emissions, sleek design, and high efficiency (Berretti et al., 2023). Extensive research on the electro-oxidation of bio-derived fuels has highlighted direct fuel cells for stationary and portable applications (Umarkar et al., 2024).

Hydrogen is a popular primary fuel for PEFCs due to its high gravimetric energy density (120 MJ/kg) (Valera-Medina et al., 2018). However, hydrogen faces certain limitations, such as challenges in storage and handling,

expensive production, and the need for an external reformer (Xie et al., 2024). To address limitations associated with gaseous hydrogen, direct liquid fuel cells (DLFCs) have been developed, which enable the direct supply of H2-enriched liquid fuel to the fuel cell (Ong et al., 2017). DLFCs offer certain advantages over H2, such as high energy density, ease of storage and handling (Velisala et al., 2015), and membrane hydration (Molavian et al., 2016), making them a favourable candidate for small power applications (Qasem & Abdulrahman, 2024). However, their commercialization is limited by slow reaction kinetics, and fuel crossover (Mallick et al., 2015).

Generally, DLFCs are classified as active and passive systems. Active DLFCs depend on auxiliaries such as pumps and blowers for controlling the flow of reactant, while passive DLFCs utilize gravity action, diffusion, natural convection, and capillary action for the flow of reactant inside the cell structure, thus offering simpler design and lower energy consumption (Shrivastava et al., 2015). Among liquid fuels researched over recent decades, methanol and ethanol have gained the most attention (Maiyalagan & Pasupathi, 2010). Direct methanol fuel cells (DMFCs) exhibit high electrochemical performance but face crossover, catalyst poisoning, and limited durability issues. Ethanol offers advantages such as higher energy density and lower toxicity, but suffers from slower kinetics, incomplete oxidation, and water management issues (Badwal et al., 2015).

Ascorbic acid (AA) has recently evolved as a potential alternative fuel. It is a water-soluble powder, non-toxic, has favourable redox activities and is environmentally friendly (Hasan, 2023). Currently, AA is commercially produced from glucose and can be extracted from natural sources such as citrus fruits (Pappenberger & Hohmann, 2013), AA offers ease in storage, transport and refuelling (Muneeb et al., 2017). It is completely safe and does not produce fuel crossover (Keramati et al., 2021). It makes AA suitable for portable and biomedical applications. Though research on direct ascorbic acid fuel cells (DAAFCs) has accelerated in the last decade, most studies have focused on active DAAFCs, leaving passive systems unexplored. Some parameters influencing the electrochemical performance of DAAFCs were studied, including the effects of catalyst loading, membrane thickness, and fuel concentration (Fujiwara et al., 2007).

This study investigates the potential and feasibility of using ascorbic acid as a fuel for DAAFCs by analysing its performance under specific operating conditions. Ascorbic acid (AA) or vitamin C is a chemically stable and nature-friendly element produced from renewable sources (Deutsch, 2000). It exists in a non-toxic powder form that dissolves easily in water. Transforming glucose is an industrial method to manufacture AA, and it can be extracted from citrus fruits as well (Pappenberger & Hohmann, 2013). It has potential applications in small-scale power utilities, such as electronic devices and human implantable devices. Therefore, ascorbic acid is a promising fuel candidate for DLFC. The DAAFC can be further divided based on the electrolyte used: Acid DAAFC uses a polymer electrolyte membrane to conduct protons from the anode to the cathode. However, alkaline DAFC make use of an anion exchange membrane (AEM) to flow hydroxyl ions from cathode to anode (Fujiwara et al., 2011).

Furthermore, primary electrochemical research has presented the capabilities of ascorbic acid and its oxidation with Pt/Pd catalysts in acidic media to produce electrical power at ambient temperature (Choun et al., 2016). Several studies present the use of non-noble catalyst material for AA oxidation (Uhm et al., 2007). However, limited research is available on a systematic parametric study of the passive AA-PEMFC condition. Some important literature relevant to the present study is presented in Table 1.

Table 1 (a): Literature Review on Passive PEM Fuel Cells (Parameter-Oriented Studies)

Sr. No.	Fuel Type and Cell Configuration	Parameter Studied & Operating Range	Observation and Discussion	Identified Research Gap	References
1	Methanol, Passive PEMFC	Fuel Concentration 0.5-2M	Increase in Concentration Improved Current Density Up to an Optimum Value; Higher Concentrations Led to Severe Fuel Crossover and Voltage Loss. Performance of Cell Start Decreasing after 5 M.	Limited Investigation on Alternative Non-Alcohol Fuels Under Passive Mode.	(Chadge et al., 2016), (Boni et al., 2022)
2	Methanol, Passive PEMFC	Bolt Torque 2–6 N·m	Proper Torque Improved Interfacial Contact Resistance and Reduced Fuel Leakage, Enhancing Power Density. 4 Nm to 7 Nm Optimum Performance Range.	Mechanical Parameters Rarely Optimized Systematically.	(Bates et al., 2013), (Boni et al., 2022)

Table 1 (b): Literature Review on Passive PEM Fuel Cells (Parameter-Oriented Studies)

Sr. No.	Fuel Type and Cell Configuration	Parameter Studied & Operating Range	Observation and Discussion	Identified Research Gap	References
3	Formic Acid Passive PEMFC	Fuel Concentration 0.25-1.5 M	Optimal Concentration Achieved a Balance Between Reaction Kinetics and Mass Transport; Excessive Concentration Caused Cathode Flooding.	Parametric Study of Fuel Concentration is Not Explored.	(Ha et al., 2006)
4	Ascorbic Acid Passive PEMFC	Fuel Concentration, Orientation, Temperature	Demonstrated Feasibility of Eco-Friendly Fuel; Performance Strongly Governed by Mass Transport Limitations.	Optimization of Mechanical and Thermal Parameters Absent.	(Fujiwara et al., 2011)
5	Ascorbic Acid, PEM-Based DLFC (Lab-Scale)	Fuel Feasibility at Ambient Temperature	Demonstrated Direct Electricity Generation from Ascorbic Acid with Low Crossover and Safe Handling	Power Density Limited; No Parametric Optimization	(Fujiwara et al., 2007)
6	Ascorbic Acid, PEM Half Cell	Pt-Based Catalyst, Acidic Medium	It showed improved oxidation kinetics and Low Poisoning Tendency.	Translation to Full Passive PEMFC not explored.	(Choun et al., 2016)
7	Open Cathode PEMFC	PEMFC Guideline	Optimization Of Torque and Gasket Geometry Improves Cell Performance By 3.4-20.1 %.	Parametric Study of Torque Variation is Not Done.	(Xing et al., 2021)

The present study seeks to bridge this gap by experimentally investigating the effects of operating orientation, bolt torque, and ascorbic acid feed concentration on the performance of a passive DAAFC. A single-cell configuration with a Nafion 117 membrane (25 cm²-sized) was developed and systematically tested. The findings provide insights into performance optimisation and help advance DAAFC technology as a sustainable, safe, and practical power source for next-generation portable devices.

The main purpose of this study is to explore the potential associated with passive DAAFC. The experimental scope is limited to the investigation of a passive direct ascorbic acid polymer electrolyte membrane fuel cell (DAA-PEMFC). A passive DAAFC integrated with a 25 cm²-sized MEA using Nafion 117 membrane was developed for evaluation. The study focuses on determining the optimum character of different operational parameters: concentration of AA fuel, cell orientation (horizontal and vertical), operating temperature, and bolt torque to improve electrochemical performance in a passive system. Performance evaluation is carried out using polarization and power density characteristics of a single-cell configuration without auxiliary devices (Pump, flow controllers, etc.). The investigation is limited to short-duration performance assessment and does not report long-term character, stack-level integration, or catalyst modification. The key finding of this study offers design and operating guidelines for the development of cost-effective, environmentally friendly, portable passive liquid fuel cells.

2. Materials and Methods

2.1 Materials

A platinum catalyst (Pt/C) with a metal loading of 2 mg cm^{-2} was utilized at the cathode, while activated carbon loaded with 2 mg cm^{-2} was utilized as the anode catalyst layer to operate under passive conditions. Catalyst inks were formulated by homogeneously dispersing the catalyst powder in an isopropyl alcohol (IPA) and deionised (DI) water mixture, followed by incorporation of a Nafion ionomer as a proton-conducting binder. The formed ink was ultrasonically stirred to disperse it and subsequently coated onto the gas diffusion layer (GDL) to form a uniform catalyst layer. After evaporation of the solvent, the anode and cathode electrodes were integrated on both sides of the membrane. Subsequently, hot-pressed at 120°C, and subjected to a pressure of 3 MPa, for a duration of 5 min to prepare a MEA with high mechanical strength, increased interfacial contact, and minimized ohmic resistance.

Analytical grade Ascorbic acid ($C_6H_8O_6$) was utilized as the liquid fuel without further processing. Nafion® 117 membrane (thickness 183 µm) was selected as the proton exchange membrane due to its mechanical strength, chemical stability, and high proton conductivity. Carbon cloth gas diffusion layers were employed at both electrodes. Deionized water was used for fuel preparation. Stainless steel SS 314 was used to fabricate the current collectors due to its corrosion resistance.

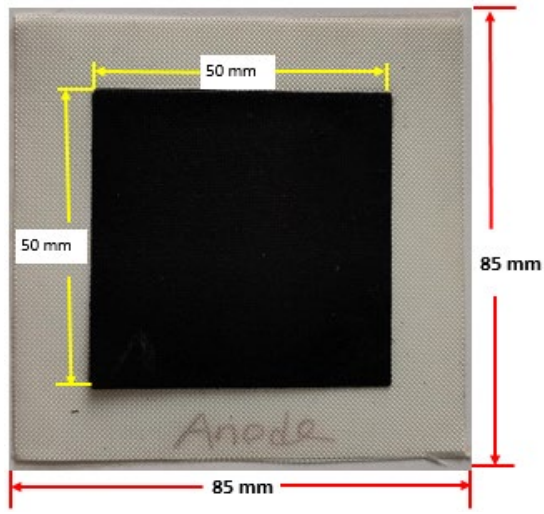


Figure 1: Membrane Electrode Assembly

Figure 1 shows the actual size of the MEA used for the experimentation. The other component of the fuel cell is fabricated to match the MEA size to ensure an exact fit of all components.

2.2 Preparation of Ascorbic Acid Fuel and Concentration Optimization

Ascorbic acid (AA) solutions with concentrations ranging from 0.25 M to 1.75 M were prepared using deionised water and stirred thoroughly to obtain a homogeneous solution of 25 ml per test. The effect of AA fuel concentration on passive PEMFC performance was investigated by preparing polarization and power density curves under predefined operating conditions. Maximum power density and stable voltage are the basic parameters considered for determining the optimum fuel concentration. Ascorbic acid ($C_6H_8O_6$, M = 176.12 g mol^{-1}) solutions of varying molarities (0.25–1.75 M) were prepared using analytical grade AA and deionized water. The required masses of ascorbic acid were calculated according to the relation 1:

$$\text{Mass (m) in gram} = M \times V \times MW \tag{1}$$

Where, Molar mass of ascorbic acid (M) = 176.12 g·mol^{-1}

Table 2: AA Concentration Matrix

Concentration (M)	Mass =(g) /25 ml of solution of AA
0.25 M	1.1
0.50 M	2.2
0.75 M	3.3
1 M	4.4
1.25 M	5.5
1.5 M	6.6
1.75 M	8.8

Table 2 presents the AA weight in grams associated with the respective AA concentration per 25 ml of aqueous solution of AA.

Fuel concentration (C_f) affects the reaction rate and mass transport at the anode. The current density (J) for moderate concentration can be expressed as:

$$J \propto k\, C_f$$

The current density J was calculated as:

$$J = \frac{I}{A}$$

Where,
I is the measured current (A), and
A is the active area of the fuel cell (cm^2).
Power density was used as the primary performance indicator and calculated using:

$$P_d = \frac{V\ X\ I}{A}$$

Where, P_d is the power density (mW cm^{-2}).
The instantaneous cell voltage V was measured directly across the external load:

$$V = E - \eta_{act} - \eta_{ohmic} - \eta_{mt}$$

Where, E_{OCV} is the open-circuit voltage,
η_{act}, η_{ohmic}, and η_{mt} represent activation, ohmic, and mass transport losses, respectively.

2.3 Fuel Cell Assembly and Orientation Study

The effect of cell orientation (Horizontal and vertical) on the performance of the passive AA PEMFC was assessed by measuring the single-cell performance in both orientations**.** In the horizontal orientation, the MEA was arranged parallel to the bench surface to facilitate uniform fuel distribution, while in the vertical orientation, it was placed perpendicular to study reactant flow management. Measurements of power density were done under stable conditions for both orientations to evaluate their impact on electrochemical performance.

Cell orientation influences gravity-driven mass transport and water/CO_2 removal. The effective mass transport loss is expressed as:

$$\eta_{mt} = f(g, \theta)$$

Where,
g is gravitational acceleration, and
θ is the cell orientation angle (horizontal or vertical).

2.4 Bolt Torque Optimization

The fuel cell assembly was held together with stainless steel bolts that compress each part, forming a rigid, leakproof structure and simultaneously stretching the MEA uniformly. The bolt torque varied between 4 Nm and 11 Nm using a torque wrench. The optimum bolt torque was recorded by correlating torque data with the considered electrochemical performance indicators, ensuring effective surface contact without extreme membrane compression.

Bolt torque (T_b) affects the interfacial contact resistance ($R_c$between cell components. The ohmic loss is given by:

$$\eta_{ohmic} = I\ .R_{cell}$$

where,

$$R_{cell} = R_m + R_c$$

and R_c is inversely related to applied bolt torque up to an optimal value:

$$R_c \propto \frac{1}{T_b}$$

Excessive torque can cause membrane deformation and performance loss.

2.5 Operating Temperature Optimization

A study of the effect of operating temperature on the performance of the passive DAAFC was conducted over a temperature range of 30 °C to 70 °C. The fuel cell is placed in the hot air oven, and the necessary connections are used to maintain a stable operating temperature with an accuracy of ±2 °C. The cell was set to reach thermal equilibrium at each temperature before measurements were monitored. Polarization and power density curves were measured at each temperature under predefined operating conditions.

Operating temperature (T) affects membrane proton conductivity and reaction kinetics. Proton conductivity (σ) follows an Arrhenius-type relation:

$$\sigma = \sigma 0\ exp(-\frac{E_a}{RT})$$

Where, E_a is the activation energy,
R is the universal gas constant, and
T is the operating temperature (K).
An increase in temperature reduces ohmic losses and improves power density under passive conditions.

2.6 Electrochemical Performance Evaluation

Electrochemical performance was assessed by monitoring polarisation and power density using an electronic load (model N 3300A) and a data logger application, as shown in Fig. 2. All measurements were conducted under ambient conditions. The current density was increased gradually, allowing voltage stabilisation at each level. Main performance parameters, including open-circuit voltage, current density, and peak power density, were analyzed.

Figure 2: Electronic DC Load (N 3300A)

Thus, the power density of a passive DAAFC can be expressed as a function of operating parameters:

$$P_d = f\ (C_f, T_b, T, \theta)$$

This relation highlights the combined influence of electrochemical, mechanical, thermal, and geometrical parameters on cell performance.

2.7 Experimental Reproducibility

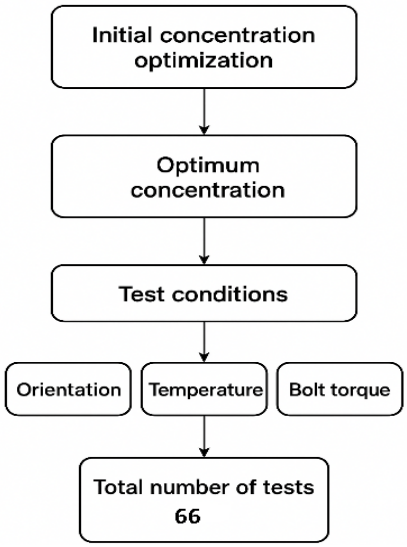


Figure 3: Experimentation Structure

To ensure reliable and reproducible results, each experiment was repeated 3 times at each stage, as shown in the Figure. 3 a total of 66 tests were conducted during the complete experimentation schedule. The reported values show

averaged results, with experimental deviations maintained within ±4%. Table 3 below presents the experimental matrix developed before starting the test.

Table 3: Experimental Matrix and Number of Tests

Stage of Experiment	Parameter Studied	Levels / Range	No. of Levels	Repetitions per Level	Total Tests
Stage I	Fuel Concentration	0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 M	7	3	21
Stage II	Cell Orientation	Horizontal, Vertical	2	3	6
	Operating Temperature	30, 40, 50, 60, 70 °C	5	3	15
	Bolt Torque	4–11	8	3	24
Overall	—	—	—	—	66

Note: All experiments of Stage II were conducted using the optimum fuel concentration obtained from Stage I.

2.8 Single Cell Fixture

Figure 4 shows the exploded view of a single-cell assembly used for experimentation, comprising cathode and anode end plates, bipolar plates, the MEA, and a gasket assembled to form a single-cell structure of the experimental setup.

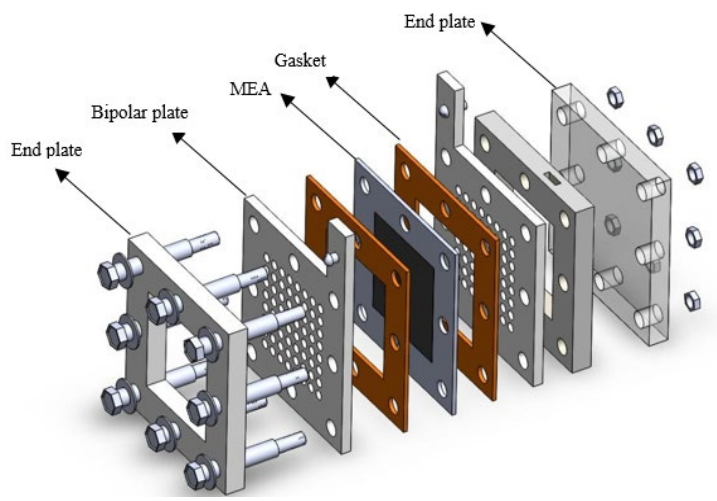


Figure 4: Passive Direct Ascorbic Acid Fuel Cell Assembly Exploded View

2.9 Experimental Setup and Test Conditions

The N3300A Mainframe with the N3302A Module is a DC electronic load used for both open-circuit voltage (OCV) and polarisation tests. Passive DAFC is activated before the test by adding 0.25 M ascorbic acid solution to the reservoir and letting it stand for 48 hours. After 40 hours at constant voltage, 0.35 V is supplied, and the cell is subjected to an I-V polarization test afterwards. Until a stable polarization curve is achieved, this procedure was repeated. The fuel reservoir is filled with ascorbic acid at the proper concentration for the test. After that, the cell is maintained at OCV for 60 minutes to achieve stability. The polarization test is then conducted. To achieve a stable voltage during the test, a 60 s waiting period is applied at each discharging current point. The room temperature for the experiments is between 25°C and 28 °C, and the relative humidity is between 40% and 50%.

3. Result and Discussion

3.1 Effect of Ascorbic Acid Feed Concentration

The effect of ascorbic acid feed concentration on the cell performance is shown in Fig. 5. Ascorbic acid solutions of seven different concentrations, 0.25 M, 0.5 M, 0.75 M, 1 M, 1.25 M, 1.5 M, and 1.75 M, are used in this investigation. Figure 5 shows the variation in OCV with ascorbic acid concentration. After feeding the ascorbic acid solution into the anode-side fuel reservoir, the OCV is observed until it stabilises; this usually takes 60 minutes. The

ascorbic acid solution concentration of 0.25 M gives the lowest OCV (0.292 V), and 1.5M gives the highest OCV (0.365 V).

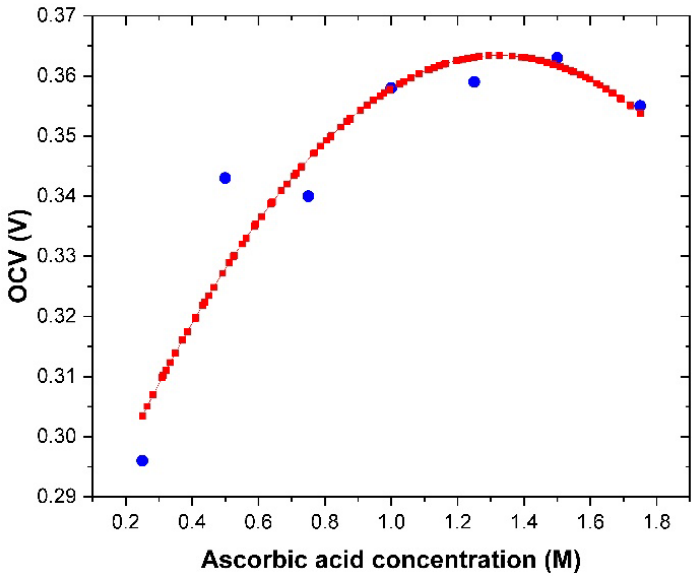


Figure 5: Open–Circuit Voltage Vs AA Concentration

Ascorbic acid is stored in the fuel reservoir; it disperses through the current collector and the diffusion layer and reaches the anode catalyst layer, where the electrochemical reaction takes place. The ascorbic acid directly reacts with oxygen and produces nontoxic product dehydroascorbic acid (DHA) at the cathode. Other reactions, like the hydrolysis of DHAA to diketogulonate and its degradation to 5 and 4-carbon species, have been reported (Deutsch, 2000).

The OCV initially increases rapidly across all concentrations, then gradually stabilises over time for each molarity. At higher concentrations (1 M to 1.75 M), OCV starts at a higher voltage and stabilises more quickly than at lower concentrations.

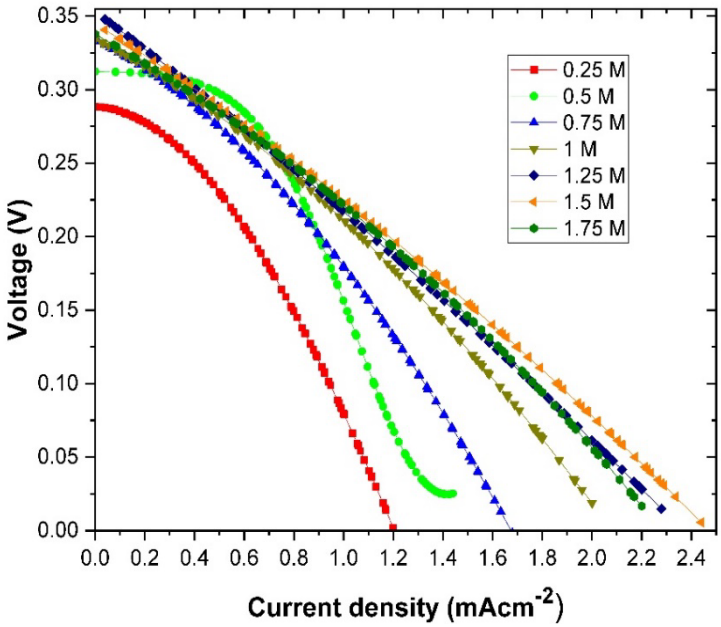


Figure 6: Current Density- Voltage (I-V) Curve

Figure 6 shows the current density vs voltage plot. At low concentrations (0.25 M and 0.5 M), the cell shows lower

current density and an early drop in voltage, highlighting a fuel shortage in the anode catalyst layer. General prediction in this situation: a restriction in the oxidation of ascorbic acid occurs, leading to lower power output. At the range of 0.75M -1 M, a significant improvement in cell performance is observed.

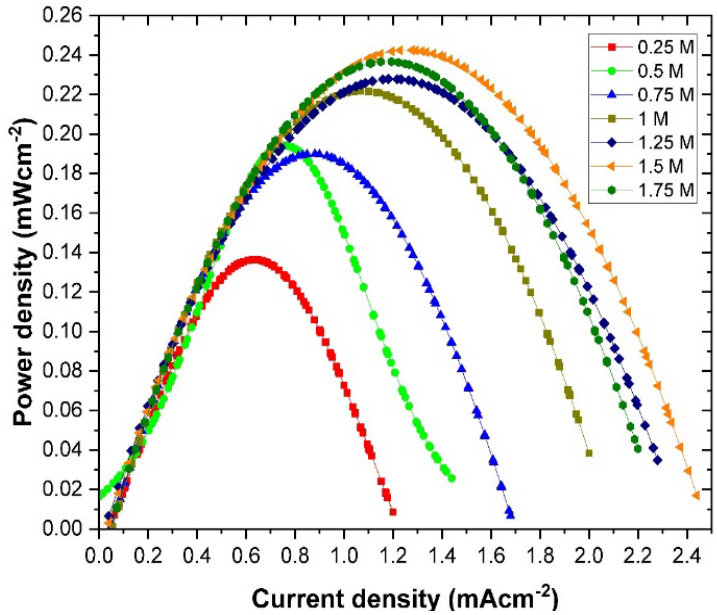


Figure 7: Current Density-Power Density (I-P) Curve for Different Concentrations of AA.

For concentrations of 1 M, 1.25 M, and 1.5 M, the behaviours are very similar, except that 1.25 M shows greater fluctuation in the later stages. 1.5 M reaches the highest OCV, stabilizing around 0.365 V. For concentrations of 1 M and above, the system stabilizes more quickly, reaching a nearly constant OCV value between 40-60 minutes. Lower concentrations result in a lower final OCV and a longer time to stabilise.

Figure 7 shows the I–P curve for the concentration of AA. At the initial level (0.25 M and 0.5 M), a small amount of power density is observed, reaching approximately 0.132 and 0.186 mW cm^{-2}, respectively. Insufficient fuel at the anode may cause the early decline in power output at higher current densities. These restrict the AA oxidation rate and lead to dominant concentration polarisation effects. The power density increases significantly with concentration from 0.75 M to 1.0 M, reaching values of 0.179–0.211 mW cm^{-2}.

The findings show that the OCV is clearly influenced by solution molarity. OCV values are greater and more stable in solutions with higher molarity. This could be due to higher ionic conductivity, which improves charge distribution in the system. A faster OCV stabilization indicates that the system is becoming more electrochemically stable as the molarity rises. This shows that the electrolyte promotes more effective ion transport at higher concentrations, resulting in a quicker attainment of equilibrium. Some minor fluctuations in the 1.25 M and 1.5 M solutions after stabilization might indicate either local changes in electrode behavior or interactions within the solution at these concentrations, which could require further analysis. At higher concentrations (1.75 M), as shown in Figure 5, the observed slight decline in OCV may suggest that the electrolyte becomes overly concentrated, potentially leading to increased viscosity or other factors that impede ion mobility. Additionally, it could indicate the occurrence of side reactions or the degradation of electrode materials due to elevated ascorbic acid levels.

A high and steady OCV can be obtained by varying the ascorbic acid content between 1 M and 1.5 M. After this point, additional concentration increases have no effect on OCV and may even produce a small drop. Future studies could focus on the exact processes operating between 0.25 M and 0.5 M, as well as on strategies for maintaining or improving OCV above 1.5 M.

3.2 Effect of Ambient Temperature

The cathode end of a passive direct ascorbic acid fuel cell is exposed to atmospheric air; therefore, variations in ambient temperature affect the cell's electrochemical activity and performance. Five distinct ambient temperatures are used to measure cell performance: 30 °C to 70 °C, with an increment of 10 °C. Figure 8 shows the OCV values for different temperature conditions. It is observed that the OCV steadily increases as the ambient temperature rises from 30 to 60 °C, then significantly decreases at 70 °C.

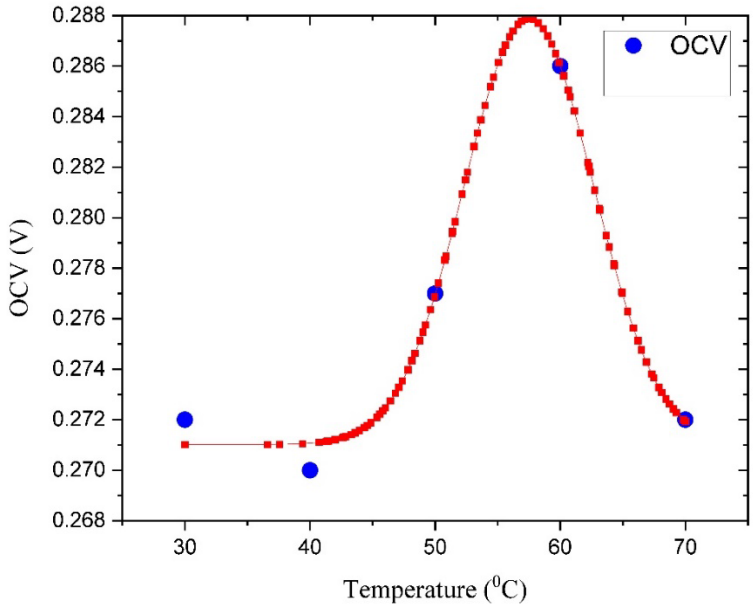


Figure 8: Maximum OCV Value at Different Temperature Conditions.

The passive DAAFC is operated at a predetermined temperature in a convection oven to measure the effect of ambient temperature on the cell's electrochemical performance. A 1.5 M AA feed concentration is used for testing. An identical trend is observed for the I-V and I-P curves, as shown in Figures 9 and 10, respectively. Cell performance improves as the cell temperature rises from 30°C to 60°C. The cell gives the highest output at 60 °C. The cell's performance declines as the temperature rises to 70 °C. The maximum power density is 46.72% higher at 60 °C (0.336 mW cm^{-2}) than it is at 30 °C (0.229 mW cm^{-2}). This demonstrates the significance of ambient temperature in improving cell performance. The following consequences arise from an increase in the ambient temperature: (i) A greater ambient temperature raises the temperature of the cell by slowing the rate at which heat dissipates from it. Cell performance is enhanced, and the electrochemical reaction rate is increased by increasing the cell temperature. (ii) As the cell temperature rises, the internal resistance of the cell falls, lowering ohmic loss and enhancing cell function. (iii) As the temperature rises, the cathode's water evaporation rate increases, removing the water more quickly and improving oxygen accessibility.

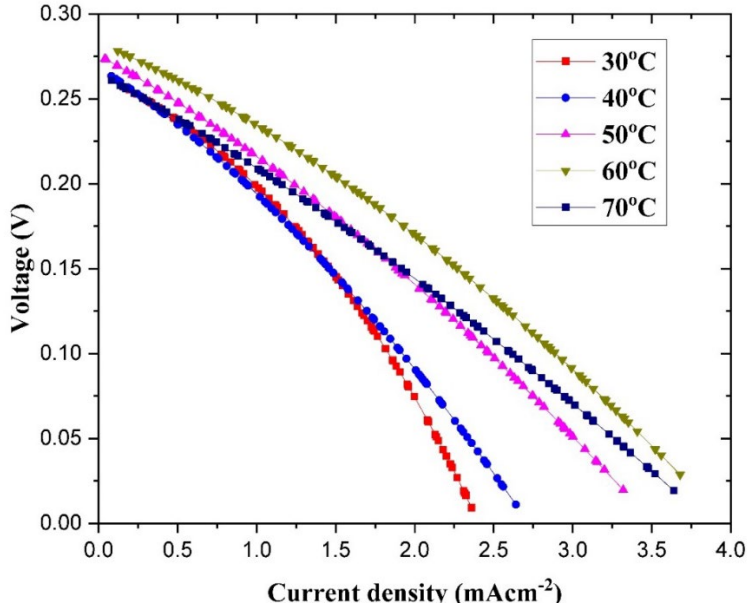


Figure 9: Current Density Vs Voltage for Different Temperature Conditions.

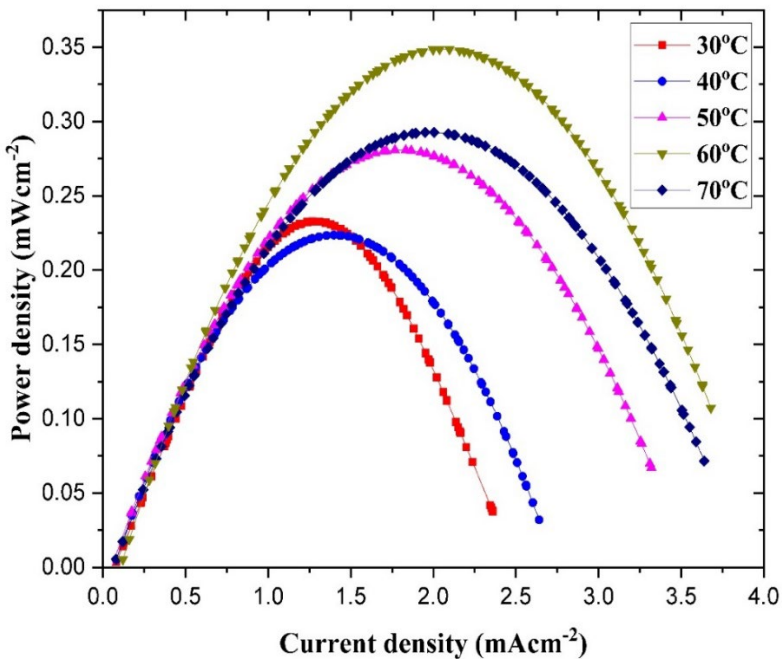


Figure 10: Current Density Vs Power Density for Different Temperature Conditions.

3.3 Effect of Bolt Torque

All parts of the fuel cell were held together tightly with 8 Nos. SS bolts, each with predefined torque values. An adequate bolt torque is necessary to ensure correct contact between fuel cell components, making it a crucial element to investigate. Initially, a bolt torque of 3 Nm was applied; however, fuel leakage was observed, indicating that the applied torque was insufficient. After that, the dripping is halted by increasing the torque to 4 Nm. As a result, the initial torque in the trials is 4 Nm. Thereafter, seven distinct bolt torque values, all above 4 Nm, are employed for the test. Figure 11 indicates the OCV for different torque values.

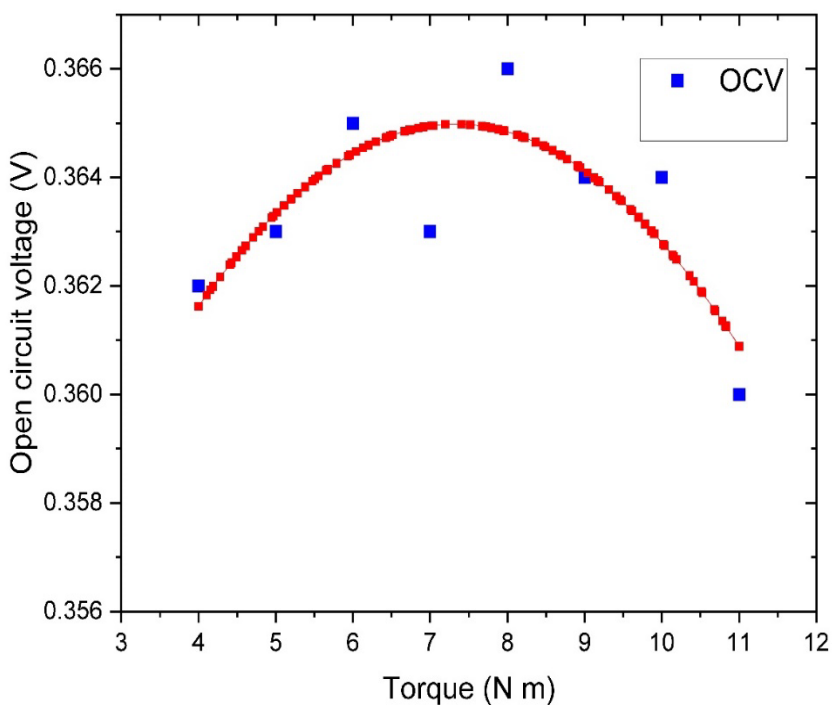


Figure 11: OCV for Different Torque Values.

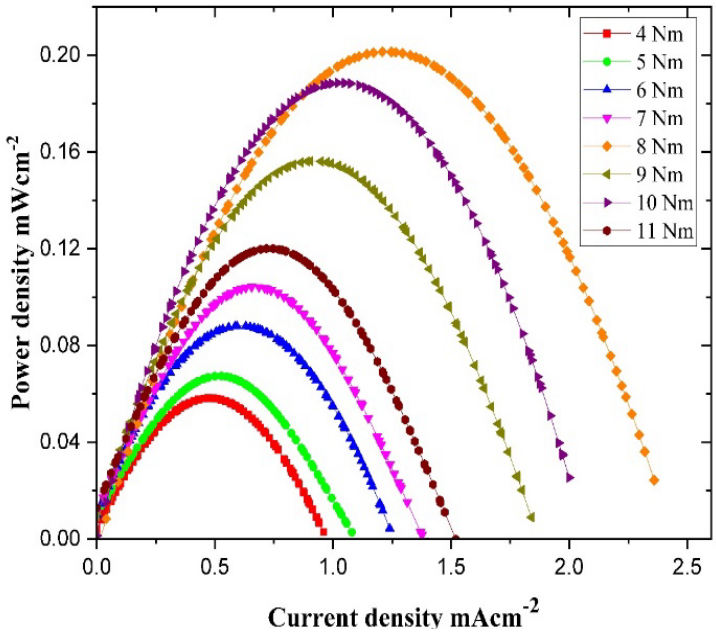


Figure 12: Current Density and Power Density (I-P) Curve

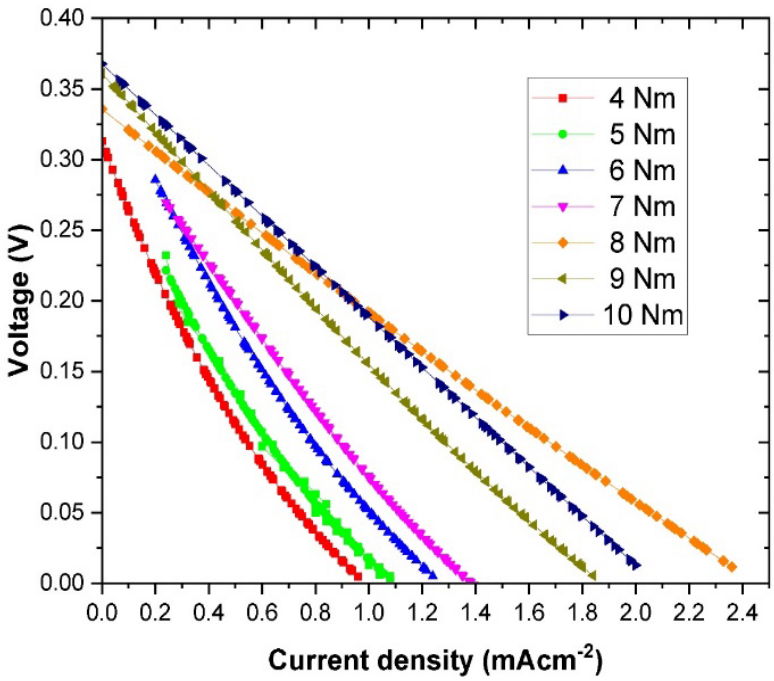


Figure 13: Current Density-Voltage (I–V) Curve

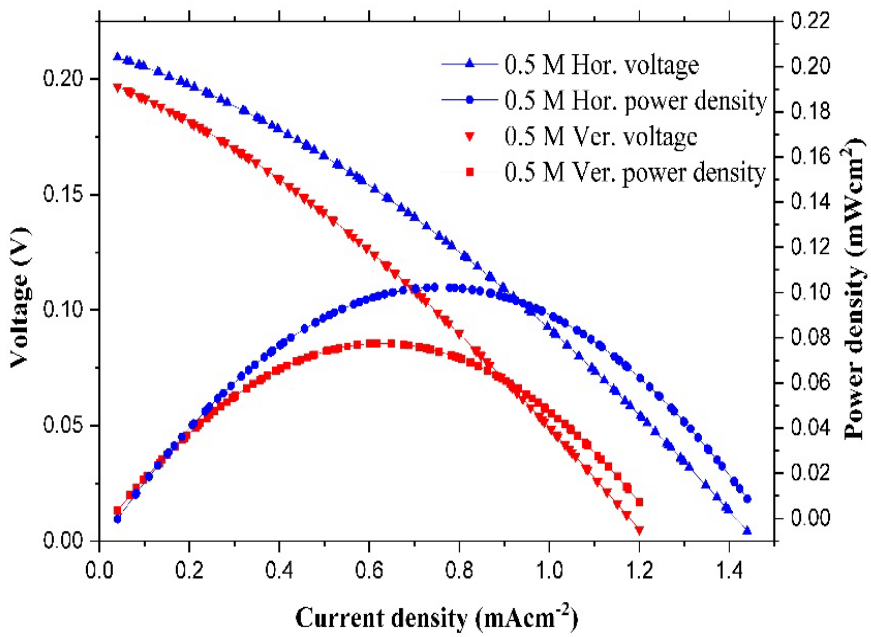
For the applied torque range, the open-circuit voltage varies from 0.358 V to 0.366 V for 4 nm to 11 Nm, respectively. The maximum open-circuit voltage, 0.366 V, was achieved at 8 Nm torque, and the minimum, 0.358 V, was observed at 11 Nm. Indicates that increasing torque above 11 Nm is not appropriate based on cell performance and subsequently raises mechanical stresses on other components. The graph shows a significant reduction in OCV as torque exceeds a certain threshold**.** Initial observations indicate that the cell's performance improves when the bolt torque is increased from 4 to 6 Nm. At 7 Nm, cell performance suddenly declines. Figures 12 & 13 show the power density, current density, and voltage at different applied torque values. The maximum power density of 0.19984 mW/cm^2 is achieved at 8 Nm torque. After reaching its maximum value, the performance curve steepens at 10 and 11 Nm. The mass transport loss due to acute compression of the diffusion layer is most likely the reason for the declining

performance.

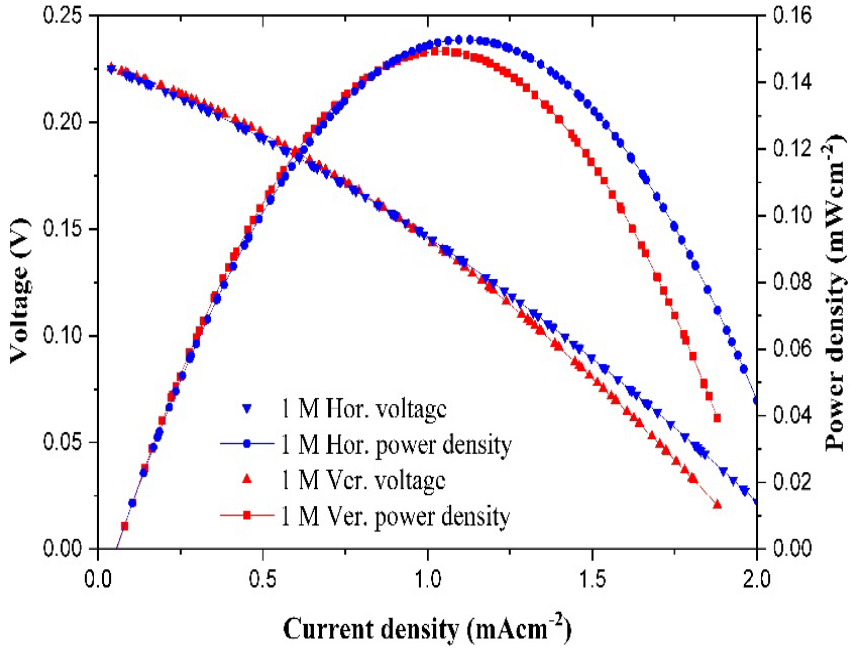
The peak torque range is about 8 N·m, and the ideal torque range for obtaining the maximum OCV is between 6 and 9 N·m. There is a noticeable decrease in OCV when operating at higher torque levels, particularly above 10 N·m. This could be a sign of mechanical inefficiency or stress at higher torques.

3.4 Effect of Cell Orientation

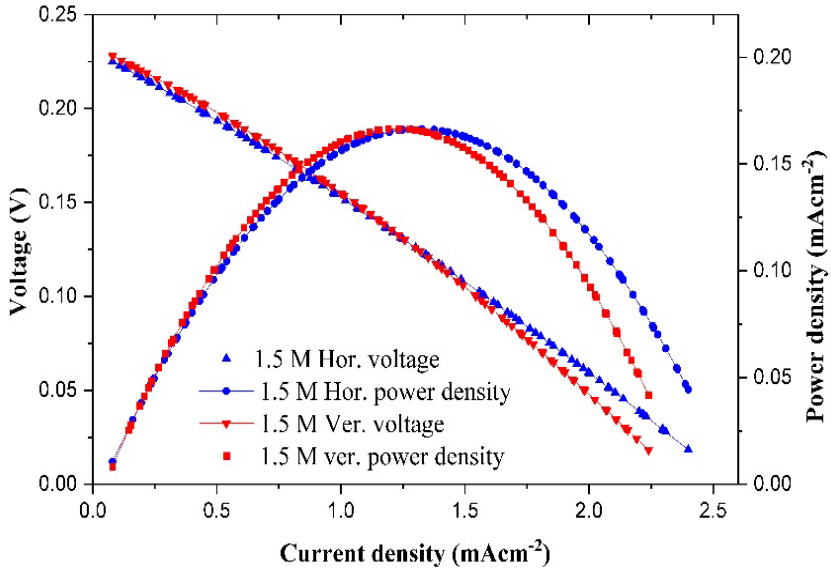
The effect of cell orientation on passive DAAFC performance is shown in Figure 14. The Test was conducted in two orientations: horizontal (anode facing up) and vertical (MEA perpendicular to the bench surface). Three different concentrations, 0.5 M, 1 M, and 1.5 M, are used to understand implications related to the gravity-driven effect on fuel distribution and product accumulation.



(a)



(b)



(c)

Figure 14: Effect of Cell Orientation on DAFC Performance for Ascorbic Acid Feed Concentration 0.5 M (a), 1 M (b), and 1.5 M (c)

The cell performance curves (I-V and I-P) are shown in Fig. 14a- c, for all three AA concentrations. It is observed that the cell in horizontal orientation performs better than the one in vertical orientation at the given concentrations. The horizontal orientation reached the maximum power density of 0.0988, 0.1464, and 0.1636 mW/cm2, compared to 0.07504, 0.14732, and 0.1632 mW/cm2 for the vertical orientation at 0.5 M, 1 M, and 1.5 M ascorbic acid feed concentration, respectively. The horizontal orientation shows about 30% better performance than the vertical one. Horizontal orientation may facilitate more effective gas removal and fluid dispersion—no fuel crossover observed between vertical and horizontal orientations. The cell performance difference is wider at higher current density, as shown in plots 12a-c. The initial performances for 1 M and 1.5 M are almost identical, whereas for 0.5 M, a considerable difference is observed at higher current densities. At higher current densities, the horizontal arrangement achieves higher peak power density and greater stability than the vertical configuration. This shows that, for the given condition, the horizontal orientation is more effective in producing power.

Table 4 below show all the final average value for different set of experimentation.

Table 4 (a): Experimental Observations

Sr. No.	Parameter		Experimental Output			Outcomes
			OCV (V)	Power Density (mW/cm^2) Overall, the MEA area is 25 cm^2	Power Density (mW/cm^2) Active Area of 10 cm^2	
1.	AA Concentration	0.25 M	0.296	0.132	0.329	• Maximum values of OCV and power density are obtained for 1.5 M Concentration. • The optimum value lies between 1 M and 1.5 M • Precipitation AA occurs at 1.75 M, and OCV stars decline.
		0.5 M	0.336	0.186	0.446	
		0.75 M	0.345	0.179	0.448	
		1 M	0.344	0.211	0.528	
		1.25 M	0.349	0.225	0.562	
		1.5 M	0.353	0.253	0.633	
		1.75 M	0.346	0.226	0.566	
2.	Operating Temperature	30 °C	0.269	0.179	0.446	• Maximum power density over all the tests is obtained at 60 °C operating temperature. • Electrochemical performance of the cell is optimum within a 50 °C-70 °C temperature range.
		40 °C	0.268	0.168	0.42	
		50 °C	0.277	0.264	0.658	
		60 °C	0.286	0.335	0.838	
		70° C	0.265	0.286	0.702	

Table 4 (b): Experimental Observations

Sr. No.	Parameter		Experimental Output: OCV (V)	Power Density (mW/cm^2): Overall, the MEA area is 25 cm^2	Power Density (mW/cm^2): Active Area of 10 cm^2	Outcomes
3.	Bolt Torque Variation	4 Nm	0.362	0.0638	0.159	• Lower bolt torque values are not in favour of the electrochemical performance of the cell. • 8 Nm torque shows the maximum value of OCV and power density. • A higher torque value increases the mechanical stress on bolt components and the excess compression of the diffusion layer.
		5 Nm	0.363	0.0696	0.174	
		6 Nm	0.365	0.0884	0.221	
		7 Nm	0.357	0.11	0.275	
		8 Nm	0.366	0.199	0.497	
		9 Nm	0.358	0.166	0.415	
		10 Nm	0.364	0.190	0.475	
		11 Nm	0.358	0.126	0.315	
4.	Cell Orientation	Horizontal	0.231	0.156	0.39	• Horizontal orientation produces the optimum value of OCV and power density.
		Vertical	0.288	0.148	0.37	

The outcomes of the present work need to be validated to some extent for assurance of accuracy and reproducibility. Although research on passive DAAFC is limited, the present work is evaluated alongside established literature on methanol, ethanol, and ascorbic acid in Table 5 below.

Table 5: Validation of Direct Ascorbic Acid Fuel Cell Performance with Literature Data

Sr. No.	Parameter	Present Study	Literature	Discussion	Reference
1.	Ascorbic Acid concentration (M)	1.5 M	0.1 – 1.0 M	Several studies reported concentrations up to 1.0 M; a higher concentration of 1.5 M is justified in passive operational conditions to compensate mass-transport limitations, provided no fuel crossover or flooding is observed.	(Fujiwara et al., 2007), (Hasan, 2023)
2.	Operating Temperature (°C)	50 °C-70 °C	25 °C – 70 °C	Optimum operating temperatures are within the typical PEMFC low-temperature regime; moderate heating enhances reaction kinetics and ionic conductivity without membrane dehydration.	(Fujiwara et al., 2007)
3.	Cell Orientation	Horizontal	Mostly Horizontal; Limited Studies on Orientation Effects	No literature on orientation optimisation for passive DAAFC. The concentration may disperse evenly in both the horizontal and vertical directions; however, it may be affected by gravity. Horizontal orientation is reported in several studies, where orientation significantly influences fuel distribution, water management, and reactant transport.	(Shrivastava et al., 2017), No data on DAAFC.
4.	Bolt Torque / Compression (N·m)	8 N.m	3–7 N·m (small lab-scale PEMFCs)	The torque range is on the higher side of the reported values for PEMFC assembly practice; optimised torque ensures sufficient sealing and controlled contact resistance without membrane damage.	(Bates et al., 2013)
5.	Catalyst	Pt/C (Cathode), C (Anode)	Pt/C, PdCu/C	Pt-based catalysts are most commonly reported for acidic ascorbic acid PEMFCs due to favourable oxidation kinetics.	(Uhm et al., 2007)

4. Conclusion

This work reports on an experimental investigation of a passive DAFC. The study uses a passive DAAFC with a MEA cross-section of 25 cm². The impact of bolt torque, cell orientation, operating temperature, and ascorbic acid concentration on the performance of the cell is investigated. Variations in different influential parameters are carried out to identify the optimum performance position- horizontal and vertical cell orientations, change in bolt torque from 4 Nm to 11 Nm, and an ascorbic acid feed concentration are investigated systematically. It has been discovered that each of these factors has a significant impact on cell performance. The maximum power density produced in the horizontal setup is 30% higher than that in the vertical configuration. Cell performance increases steeply initially and remains stable at higher concentrations, starting to decline after 1.5 M (the highest OCV). Optimal cell performance in this investigation is achieved at an ambient temperature of 60 °C, a bolt torque of 8 Nm, and a feed concentration of 1.5 M ascorbic acid. Based on the findings, it is advised to carefully select the cell's operating settings to maximise cell performance. The ascorbic acid fuel cell shows promise as an alternative energy source; addressing its limitations through continued experimentation and innovation is crucial for its practical implementation.

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