

Comparative Analysis of Aloe Vera and Orange Peel Extracts as Sustainable Electrolytes in a Copper–Zinc Bio-Electrochemical Cell

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ABSTRACT

The need for sustainable energy storage has prompted the study of bio-derived electrolytes as a substitute for traditional battery systems. This paper compares aloe vera and orange peel extracts as natural electrolytes in a 3-compartment copper-zinc electrochemical cell. Voltage output and stability of the electrolytes were analyzed and compared across five dilution ratios (1:1–1:5) under constant conditions. Plant extracts were prepared by blending, dilution with distilled water, and filtration to obtain aqueous electrolytes. Voltage output was recorded on a digital multimeter over seven days to check the stability of the system. The two electrolytes yielded measurable and sustained voltages, which suggested their potential use as natural electrolytes in electrochemical systems. The voltage output was not linearly related to the dilution. The greatest mean voltage was recorded with aloe vera at the 1:1 ratio (1.393 V) and at the ratios of 1:2, 1:3, and 1:5 (1.280–1.294 V). Orange peel achieved its best mean voltage with the most dilute 1:5 ratio (1.314 V) and similar results at 1:1–1:3 (1.166–1.243 V). The performance of both electrolytes was found to be lower at a 1:4 ratio. The results show that the performance of the electrolytes depends on both concentration and properties, including ionic conductivity, viscosity, pH, and interaction with the electrodes. The results support the potential of plant-based electrolytes in Cu–Zn systems and emphasize the need to optimize dilution and composition to improve electrochemical performance.

Keywords: Bio-derived electrolytes, Cu–Zn bio-electrochemical cell, aloe vera extract, orange peel extract.

1. INTRODUCTION

Global energy consumption has been rising continuously, and the growth in electricity consumption has been the highest of all energy sectors in terms of percentage of total energy consumption. In 2024, the world energy demand increased by approximately 2.2 percent, while electricity demand increased by 4.3 percent, the largest absolute increase in electricity demand in history, apart from recession-recovery periods [1]. This rapid development places increasing pressure on energy storage technologies to be both efficient and environmentally friendly. The traditional electrochemical batteries are primarily based on the

use of synthetic chemical electrolytes, which are typically corrosive, toxic, and non-biodegradable [2]. These characteristics are serious environmental and safety concerns in manufacturing, use, and disposal. Unfortunately, the U.S. alone is responsible for 2.11 billion single-use alkaline batteries each year, contributing significantly to the streams of hazards [3]. These issues underscore the necessity of coming up with alternatives in energy storage systems that are eco-friendly and sustainable in a short timeframe.

To address these issues, bio-electrochemical systems have been receiving increasingly more attention as an ecologically friendly alternative to the traditional battery. These systems can use the plant-derived naturally occurring electrolytes or organic waste and have the benefits of biodegradability, low toxicity, local supply, and less processing [4], [5]. Scientists have also investigated plant-derived electrolytes since they possess ions to assist in the flow of charge in galvanic circuits [6], [7]. Previous studies have already shown that fruit extracts, plant gels, and agricultural waste can be used as electrolytes in the low-power bio-battery [8], [9]. Orange peel extract and aloe vera gel are the most promising among them.

Orange peel, which is one of the largest by-products of the food processing sector, is composed of organic acids, minerals, and moisture, making it a desirable electrolyte derived from waste valorization [8]. Several studies have recorded the generation of measurable voltages in copper-zinc bio-electrochemical cells using citrus waste and identified it as a viable source of sustainable energy recovery [9],[10],[11],[12]. Aloe vera gel, on the other hand, contains high amounts of polysaccharides, electrolytes, and water-soluble compounds, from which a gel-based electrolyte with high ionic mobility and long operational stability can be prepared [5] [13]. It also has a viscous nature, which reduces leakage and evaporation, which are important limitations of liquid electrolytes [14].

The electrode pair of copper-zinc (Cu-Zn) is widely used in bio-electrochemical research because it has a completely characterized redox behavior, is cost-effective, and is reproducible [5]. A standard electrode system allows the electrolyte composition to be systematically investigated for the influence of electrochemical performance.

Although individual studies on aloe vera and orange peel as electrolytes have been carried out, direct comparisons of the two under matched experimental conditions appear limited in the available literature. There is a lack of systematic comparison, which hinders identification of better natural electrolytes for bioelectrochemistry applications. Therefore, the present study aims to compare the electrochemical properties of aloe vera gel and orange peel extract as electrolytes in a bio-electrochemical cell of Cu-Zn.

2. MATERIALS AND METHODS

2.1 Experimental Design

An experimental study was done at the lab scale to assess the electrochemical activity of plant-derived electrolytes in a copper-zinc bio-battery. The aloe vera gel extract and orange peel extract were used as

electrolytes, and the performance was tested in a concentration series. Cell voltage served as the dependent variable, while electrolyte type and dilution ratio were the independent variables.

2.2 Preparation of Electrolyte Extracts

2.2.1 Aloe vera Extract

The fresh leaves of aloe vera were soaked in deionized (DI) water and dried using laboratory-grade paper towel. The outer rind was removed and the inner gel was scooped out with a spoon. The gel was homogenized in a laboratory blender to get a uniform slurry. The aloe vera extract was then filtered to remove fibrous material and coarse particulates, yielding a clarified extract of aloe vera [15]. The extract was stored in an airtight container and used immediately after preparation (within 30 minutes) to minimize the oxidative and dehydrating effects.

2.2.2 Orange Peel Extract

The oranges were peeled and washed with deionized water (DI) and then dried. The peels were cut into small pieces and mixed with a small amount of DI water (<10 mL) to be homogenized. This slurry was then filtered to remove solid material, and a stock orange peel extract was prepared. The extract was prepared in airtight containers and used within 30 minutes of preparation.

2.3 Preparation of Electrolyte Dilutions

Five different ratios of electrolyte: DI water (v/v) were used for each electrolyte type with a total volume of 150 mL of water per sample. The dilution ratios were 1:1, 1:2, 1:3, 1:4, and 1:5, the dilution values shown in Table 1. All samples were labelled and mixed thoroughly for approximately 30 seconds to ensure homogeneity before cell assembly

Ratio (Electrolyte: Water)	Volume of Aloe Vera/Orange Peel (mL)	Volume of Distilled Water (mL)
1:1	75 mL	75 mL
1:2	50 mL	100 mL
1:3	37.5 mL	112.5 mL
1:4	30 mL	120 mL
1:5	25 mL	125 mL

Table 1: Electrolyte dilution ratios used in the experiment

2.4 Assembly of the Copper–Zinc Electrochemical Cell

A three-compartment setup connected in series within a single 3D-printed housing was used to construct the electrochemical cell. The anode (negative terminal) was made of zinc electrodes, and the cathode (positive terminal) was made of copper.

Before assembly, copper and zinc plates were washed with DI water and allowed to dry so that they were cleaned of their surface contaminations. Each compartment had one copper and one zinc electrode placed

in it. In all experiments, the same volume of electrolyte was poured into each compartment to ensure the electrodes were immersed to the same depth. The electrical connection between the compartments was achieved by connecting the zinc electrode of one compartment in series with the copper electrode of the next compartment, with one external zinc electrode and one external copper electrode to record the measurements [16]. Each compartment held 50 mL of electrolyte, giving a total of 150 mL across the three compartments, and had internal dimensions of approximately $30 \times 50 \times 45$ mm, corresponding to a fill depth of approximately 33 mm. The copper and zinc electrodes were rectangular plates of approximately 40×20 mm, giving an immersed surface area of roughly 6.6 cm^2 per face, and were positioned approximately 20 mm apart within each compartment. Electrical connections were made using insulated single-core copper wire soldered to the electrode tabs. The same set of electrodes was reused across all trials; between runs the plates were rinsed with deionised water and dried.

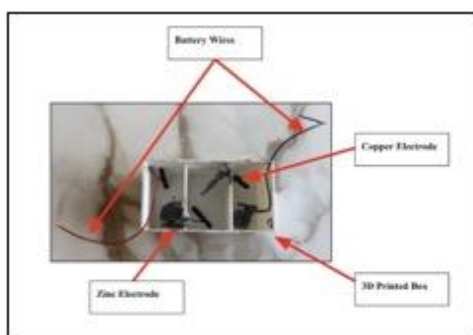


Figure 1: Experimental setup of the Cu–Zn bio-battery cell.

An experimental Cu–Zn bio-battery assembled in a 3D-printed chamber. Copper and zinc electrodes were connected via external wires, and the chamber was filled with the respective bio-electrolyte (aloe vera or orange peel extract) during testing. The setup was used to measure the voltage output and electrical performance of the bio-electrochemical system over the experimental period.

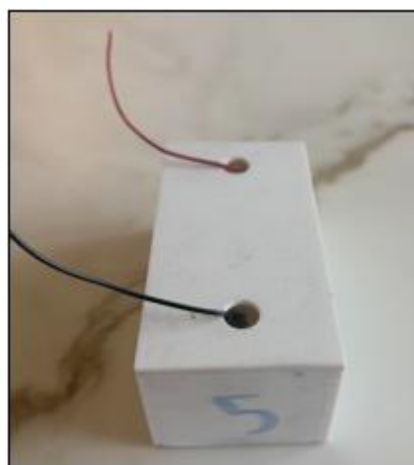


Figure 2: External side-on view of bio-battery

2.5 Electrochemical Measurements

The voltage of the cell (V) was measured by a calibrated digital multimeter across the external terminals of the three-compartment series cell. For each electrolyte type and dilution ratio, voltage was recorded five times per day at fixed time intervals under ambient laboratory conditions, and each daily value reported in Tables 2 and 3 is the mean of these five readings. The depth of immersion of the electrodes and the volume of the electrolyte were kept the same to achieve uniformity in all experiments. To minimise cross-contamination, electrode and cell housings were washed between experiments with DI water. A seven-day monitoring window was selected, consistent with previous bio-battery research [17], in order to capture short-term drift and stabilisation of the bio-electrochemical output. In addition, a control cell was assembled and measured under identical conditions using deionised water alone in place of plant extract; this control produced a reference voltage of 0.50 V.

2.6 pH Measurement

The pH of the individual dilutions of the electrolytes was measured using pH indicator strips prior to electrochemical testing. These measurements were conducted to compare the acidity of the electrolytes with the changes of cell voltage that were observed. pH indicator strips resolve to approximately ± 0.5 pH units, so the values obtained are indicative rather than precise. pH was therefore used only to describe the relative acidity of the two extracts and was not used quantitatively in interpreting voltage output. Resolving acidity differences between individual dilutions would require a calibrated pH meter, which is recommended for future work.

2.7 Quality Control and Reproducibility

All experiments were standardized in the dimension, position, and spacing of the electrodes. Measurements were made with the same multimeter, and experiments were conducted at room temperature to avoid environmental variation. Each of the ten conditions (two extracts $\times$ five dilution ratios) was tested in a single cell, and replicate cells were not run. The mean voltages reported therefore describe one seven-day run per condition rather than an average across independent trials, which limits assessment of experimental variability. This is acknowledged as a limitation of the study.

3. RESULTS AND DISCUSSION

Daily voltage outputs were recorded for aloe vera and orange peel electrolytes across five dilution ratios (1:1 to 1:5). Mean voltages over the full measurement period are summarized in Tables 2 and 3, with a control reference of 0.50 V for both electrolytes.

3.1 Time-Dependent Voltage Behaviour

The voltage output of both electrolytes showed a clear time-dependent pattern during the seven-day observation period (Tables 2 and 3).

	Voltage (V)
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	Aloe gel: Water ratio				
Duration	1:1	1:2	1:3	1:4	1:5
Day 1	2.3	2.32	2.08	2.07	2.4
Day 2	1.37	1.24	1.08	0.62	1.18
Day 3	1.25	1.06	1.27	0.54	1.12
Day 4	1.2	1.08	1.25	0.53	1.1
Day 5	1.23	1.13	1.15	0.49	1.06
Day 6	1.18	1.08	1.09	0.61	1.07
Day 7	1.22	1.11	1.14	0.52	1.03
Mean Voltage	1.393	1.289	1.294	0.769	1.280

Table 2: Voltage Output of Aloe Vera Electrolyte Across Different Dilution Ratios

	Voltage (V)				
	Orange Peel: Water ratio				
Duration	1:1	1:2	1:3	1:4	1: 5
Day 1	1.65	1.46	1.32	1.41	1.75
Day 2	1.43	1.28	1.26	1.31	1.48
Day 3	1.37	1.19	1.18	1.01	1.29
Day 4	0.97	1.18	1.21	0.87	1.34
Day 5	1.03	0.98	1.26	0.74	1.07
Day 6	0.82	1.02	1.27	0.57	1.21
Day 7	0.91	1.05	1.2	0.61	1.06

Mean Voltage	1.169	1.166	1.243	0.931	1.314
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Table 3: Voltage Output of Orange Peel Electrolyte Across Different Dilution Ratios

Day 1 registered a high voltage across all dilution ratios, after which the voltage decreased and leveled off for the rest of the days. In the case of aloe vera, the voltages ranged from 2.07 V to 2.40 V on Day 1, then fell to 1.1–1.3 V on Day 3. The maximum mean voltage was observed at the 1:1 ratio (1.393 V), followed by 1:3 (1.294 V), 1:2 (1.289 V), and 1:5 (1.280 V). The poorest result was at 1:4 (0.769 V). Orange peel electrolytes followed a similar pattern. Day 1 voltages ranged from 1.32 V to 1.75 V and then decreased gradually. The maximum mean voltage was 1:5 (1.314 V) and then 1:3 (1.243 V). The 1:1 and 1:2 ratios gave closely comparable results (1.169 V and 1.166 V). Similar to aloe vera, the 1:4 ratio performed poorest (0.931 V). The elevated Day 1 voltages are likely related to initial electrode activation as the new electrolyte is introduced to the metal electrodes. Once this step has been completed, the voltage becomes stabilized as the electrochemical system attains a more stable state.

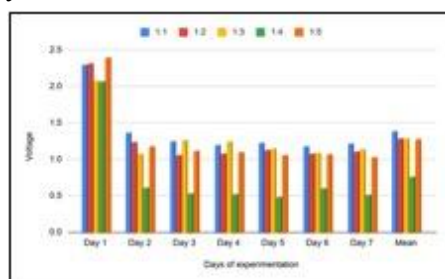


Figure 3: Time-Dependent Voltage Output of Aloe Vera Electrolyte

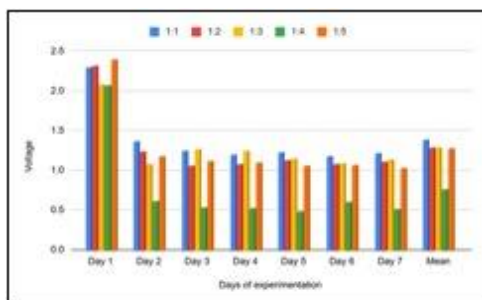


Figure 4: Time-Dependent Voltage Output of Orange Peel Electrolyte

3.2 Effect of Dilution on Voltage Output

The interaction between the dilution and the voltage production was not linear with either of the electrolytes. The experiment found that aloe vera generated the greatest mean voltage at the least dilute condition (1:1), which suggests that a higher concentration of dissolved ions favours charge transport. The mean voltages at moderate dilution (1:2 and 1:3) were similar (1.289 V and 1.294 V), suggesting that small variations in dilution had little effect on the electrochemical response across this range. No statistical test was performed, so this similarity is a descriptive observation rather than a claim of statistical equivalence.

On the contrary, the most dilute condition (1:5) was the most effective with orange peel. Dilution can cause a decrease in the internal resistance and increase the ion mobility of the electrolyte solution. This is consistent with reports that moderate dilution can enhance ionic conductivity in plant-based electrochemical systems [7].

The voltage of both electrolytes exhibited a marked reduction at the 1:4 dilution, indicating that the ratio can cause poor conditions in ionic transportation or electrode contact.

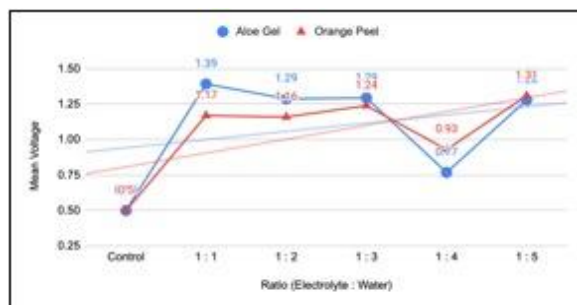


Figure 5: Mean Voltage Comparison Across Dilution Ratios

3.3 Comparison with Previous Studies

The voltages obtained in this study are higher than those reported in several earlier Cu–Zn systems using plant substrates. Previous studies on similar lines have reported aloe vera system voltages of approximately 0.17 V for undiluted extract [5] and 0.94 V for orange waste substrates [9]. These higher voltages may be due to differences in electrolyte preparation and dilution, which could have improved ionic conductivity and lowered internal resistance in the electrochemical cell.

These findings demonstrate the role of the composition of electrolytes and dilution in influencing the performance of plant-based electrochemical systems.

3.4 Comparative Electrolyte Performance

In general, aloe vera electrolyte is more effective at a higher concentration, whereas orange peel is more effective at a higher dilution.

Aloe vera resulted in the highest mean voltage at the 1:1 ratio. At this ratio, the voltage output is 1.393 V. Aloe vera also resulted in similar voltage output in several dilution ratios.

The maximum mean voltage output for the orange peel electrolyte occurs at the 1:5 ratio. At this ratio, the voltage output reaches 1.314 V. However, there is a larger variability in voltage output for the orange peel electrolyte in comparison to the aloe vera electrolyte.

These differences may be attributed to variation in the organic acids, ions, and other compounds present in the two plant extracts, which influence ionic conductivity and electrode kinetics.

3.5 Key Findings:

1. Both extracts produced a measurable and sustained voltage over a period of seven days, suggesting their potential use as natural electrolytes.
2. The highest mean voltage of 1.393 V was recorded in aloe vera at the 1:1 ratio, and the highest mean voltage was recorded in orange peel at the 1:5 ratio.
3. Averaged across all five dilution ratios, aloe vera produced a slightly higher mean voltage (1.205 V) than orange peel (1.165 V).
4. Both electrolytes performed poorest at the 1:4 ratio of dilution, which suggests that this condition may hinder effective ion transport.
5. The results show that dilution alone does not determine electrolyte performance, which also depends on factors such as ion availability, electrolyte composition, and internal resistance.
6. The voltages produced in this study are higher than those reported for comparable plant-based electrochemical systems [18], [19].

4. CONCLUSION

The study demonstrates the potential of orange peel and aloe vera extracts as natural electrolytes for a Cu-Zn biobattery with three compartments. Aloe vera showed the highest mean voltage of 1.393 V at a 1:1 ratio, while orange peel showed the highest voltage at a 1:5 ratio with a mean voltage of 1.314 V. When the average of all ratios of the dilution is considered, aloe vera showed a total average voltage of 1.205 V, which is slightly higher than the average voltage of 1.165 V, as observed with the orange peel extract.

The study also indicated that electrolyte performance depends on both the dilution and the chemical composition of the plant extract, rather than on concentration alone. Although measurable voltages were observed throughout the experiment, only the open-circuit voltage was recorded; current, power density, internal resistance, and performance under load were not measured. In addition, each condition was tested in a single cell without replication, so the findings reported here should be regarded as preliminary. To improve the stability and minimize the leakage of the electrolytes, it is suggested that the liquid extracts be converted into gel or polymer forms of electrolytes, as this may improve their performance. The results of the study show the sustainability of plant-based electrolytes as cost-effective and eco-friendly electrolytes for simple bio-electrochemical energy generation.

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