



Orange Peel Waste as Natural Electrolyte for Bio-Batteries: Experimental Evaluation of Energy Storage Performance

I Wayan Suriana^{1*}, Ida Ayu Dwi Giriantari², Wayan Gede Ariastina², I Nyoman Setiawan²

¹Department of Electrical Engineering, Faculty of Engineering and Informatics, Universitas Pendidikan Nasional, Jl. Bedugul No. 39, Denpasar Selatan, Bali, 80224, Indonesia

²Department of Electrical Engineering, Faculty of Engineering, Universitas Udayana, Jl. Raya Kampus UNUD, Jimbaran, Bali, 80361, Indonesia

* wayansuriana@undiknas.ac.id

Abstract. This study aims to explore the potential of orange peel waste as an alternative electrolyte solution in environmentally friendly bio-battery systems. The significance of this research lies in the use of abundant and often discarded organic materials as active components for energy storage. Orange peel is extracted to obtain citric acid and bioactive compounds, then processed into an electrolyte gel to enhance ionic stability. Experimental methods were used to test the electrolyte performance in a Cu–Zn electrode configuration. The test results showed that the orange peel solution produced a maximum voltage of 0.9 V, while the gel formulation reached 1.0 V with voltage stability for up to 12 hours. The gel form showed better ionic conductivity and durability compared to the liquid solution. These findings confirm the potential of orange peel waste as a sustainable source of bioelectrolyte and support the application of circular economy in energy storage technology.

Keywords: Bio-battery, circular economy, natural electrolyte, orange peel waste, renewable energy.

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1. Introduction

To face global challenges in the energy sector, technological innovations are needed that can support sustainable development in the future [1]. Various studies and advancements have been undertaken lately to devise renewable power sources, highlighting the critical role of efficient battery technology in the generation and storage of sustainable electrical energy [2].

Despite major historical progress in battery technology, its ongoing development is hindered by issues such as overcoming negative environmental effects and sustaining stable, efficient performance over long periods to fulfill contemporary energy needs [3]. The battery itself is an electronic device that converts chemical energy into electrical energy through an electrochemical process known as a redox reaction [4]. One promising innovation is the development of bio-batteries, which have great benefits given our dependence on batteries in our daily lives [5].

The role of bio-batteries in the future will be increasingly vital in meeting global energy needs [6–12]. Renewable energy is now the main hope for addressing the challenge of increasing energy availability, with advantages such as sustainability, abundant availability, and environmental friendliness [1,13–15]. In this context, bio-batteries emerge as a potential solution to replace conventional batteries based on synthetic chemicals [14–18].

Compared to commercial batteries, bio-batteries are considered safer and more environmentally friendly [16,19]. Conventional batteries can contaminate soil and water if disposed of in landfills and pose a risk of fire and explosion due to uncontrolled chemical reactions [1,16,20]. Therefore, the development of safer and renewable alternative energy sources has become a focus of research in various fields. One innovation that has received much attention is the use of natural materials in bio-battery systems, which are devices that convert chemical energy into electrical energy through redox reactions using biological materials [21–23].

In battery systems, electrolytes play an important role as ion-conducting media, whose conductivity is influenced by the number of ions, ion mobility, oxidation number, and temperature [24–27]. Several studies have shown that fruits and vegetables contain organic acids such as citric acid and hydrochloric acid, which can be broken down into ions in water, thus potentially becoming effective natural electrolytes [16,28,29]. Based on this, various studies have utilized natural materials such as oranges, mangoes, banana peels, and plant waste as substitutes for synthetic electrolytes in bio-battery systems [21–23].

In general, batteries are classified into wet cells and dry cells based on the type of electrolyte [30–32]. Wet cells, such as accumulators that use H_2SO_4 solutions, have high efficiency but pose environmental risks due to their corrosive and toxic properties [20,33,34]. This condition has encouraged the development of safer and more sustainable natural electrolytes to replace these strong acid-based materials. Based on this problem, citrus fruits are potential candidates due to their abundant availability and high citric acid ($\text{C}_6\text{H}_8\text{O}_7$) content [24,35,36]. Several previous studies have shown the potential of citrus peel as a natural electrolyte. Research reports that orange peel with a pH of 3.8 is capable of producing a voltage of 0.81 V and a current of 0.049 mA with a resistance of 4.7 k Ω [32,37]. Other findings also prove that orange waste can be used as an alternative energy source using copper (Cu) and zinc (Zn) electrodes [2,24].

However, most previous studies have focused on liquid electrolytes, which have the disadvantages of rapid evaporation and voltage instability during electrochemical reactions. Only a few studies have investigated gel electrolytes, even though gel media have the potential to increase ionic stability, reduce evaporation rates, and extend battery life. Previous research found that an increase in acid concentration in citrus fruit peel is directly proportional to an increase in voltage, where pure lime juice (pH 1.55) produces a voltage of 6.00 V, and after the addition of NaCl and Na-EDTA, it increases to 7.40 V [38,39]. These findings indicate that chemical composition has a significant effect on electrolyte performance.

Based on these gaps, this study focuses on optimizing the use of orange peel waste as a natural electrolyte in gel form. The main innovation of this research lies in the formulation of an electrolyte gel based on orange peel waste, which is expected to increase voltage stability and reduce evaporation rates compared to liquid solutions. This approach not only improves the efficiency and lifespan of bio-batteries but also supports the concept of a circular economy by converting organic waste into an environmentally friendly renewable energy source.

2. Methods

The goal of this experimental study is to evaluate the effectiveness of utilizing orange peel extract as a natural electrolyte in a bio-battery system, incorporating a gel for voltage stabilization. The experimental method was chosen as it facilitates an optimal design for harnessing renewable energy. After the fresh and fermented orange peel-based electrolytes were swapped into the cell, voltage and current readings were taken. The battery was constructed with copper (Cu) acting as the positive terminal (anode) and zinc (Zn) functioning as the negative terminal (cathode).

2.1 Materials and Equipment

The main materials used in this study include:

1. Orange peel extract, as a natural electrolyte source containing citric acid, flavonoids, and polyphenols.
2. Copper (Cu) and zinc (Zn) electrodes, functioning as the cathode (+) and anode (–), respectively.
3. Carboxymethyl cellulose (CMC) and pectin, used as gel-forming agents.
4. Distilled water and acetic acid (CH_3COOH), as solvents and pH regulators.

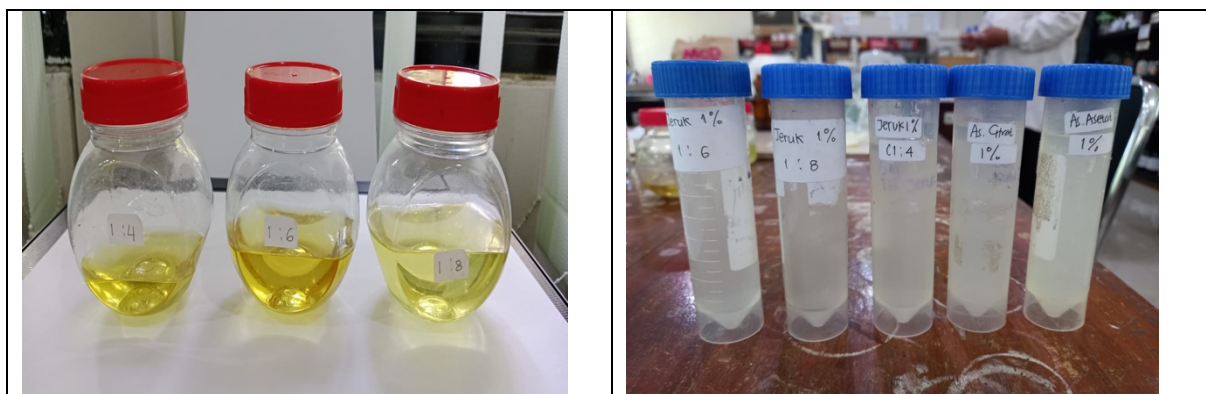
The main tools used consist of a digital multimeter to measure voltage (volts) and current (amperes), a pH meter to measure the acidity level of the solution, and a conductivity meter to determine the electrical conductivity of the electrolyte solution.

2.2 Extraction and Preparation of Electrolyte Gel

The orange peel is separated from the fruit flesh, cut into small pieces, and then blended into a homogeneous mixture. The extraction process is carried out by adding distilled water in three different ratios (1:4, 1:6, and 1:8 w/v) to determine the most optimal formulation. The mixture is heated to 60–70°C while stirring continuously. During heating, 1.5–2.5 grams of CMC or pectin is added until it dissolves completely and forms a stable gel. This preparation process is shown in Figure 1, which consists of:

- (a) Cutting and crushing orange peel,
- (b) Filtering the extraction results,
- (c) Forming a liquid electrolyte solution, and
- (d) Forming an orange peel electrolyte gel.





(c) **Figure 1.** Preparation Process

2.3 Spectroscopic Analysis and Chemical Characterization

The prepared electrolyte solution was analyzed using UV-Vis spectroscopy to identify the main compounds such as flavonoids and phenolics. Absorption peaks (absorbance) were used to confirm the presence of citric acid and evaluate the optical purity of the solution, which affects the electrochemical performance of biobatteries.

2.4 Bio-Battery Cell Configuration

The bio battery cell was assembled using a Zn–Cu electrode pair immersed in an electrolyte solution from orange peel, as shown in Figure 2. The distance between the electrodes was kept constant at 2 cm to ensure optimal ion movement. As a comparison, a control cell with 0.5 M H_2SO_4 electrolyte was used to evaluate the relative efficiency of natural electrolytes compared to standard electrolytes.

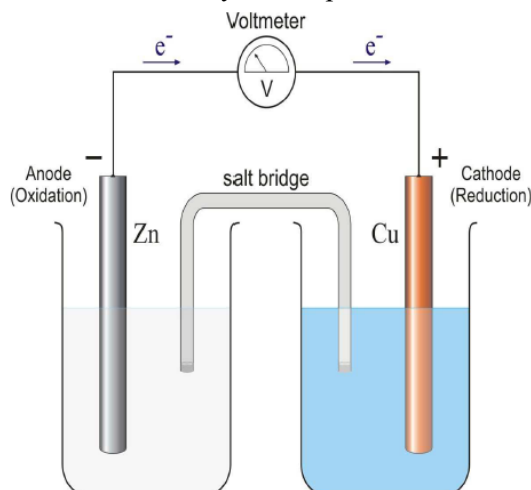


Figure 2. Diagram of battery cell for the experiment

2.5 Measurement and Performance Evaluation

Electrical voltage and current are measured using an automatic digital multimeter immediately after the battery cell is assembled. Measurements are taken every 5 minutes for 1 hour, then averaged from three replicates. The voltage value indicates the potential difference between the Zn and Cu electrodes, while the current value describes the flow of electrical charge generated. These results are used to assess the efficiency and stability of the bio-battery system.

3. Results and Discussion

The results of the test showed that orange peel juice is suitable for use as an electrolyte solution for biobatteries, with a suitable pH, stable viscosity, and good electrical conductivity. Although its efficiency is not as good as conventional electrolytes, the biobattery using orange peel juice as an electrolyte still shows satisfactory performance in generating electricity, underlining the interesting potential of orange as an electrolyte material. Furthermore, UV-Vis spectroscopy analysis showed a strong relationship between the citric acid content in orange peel solution and the absorbance at a wavelength of 320 nm, as seen in Figure 3.

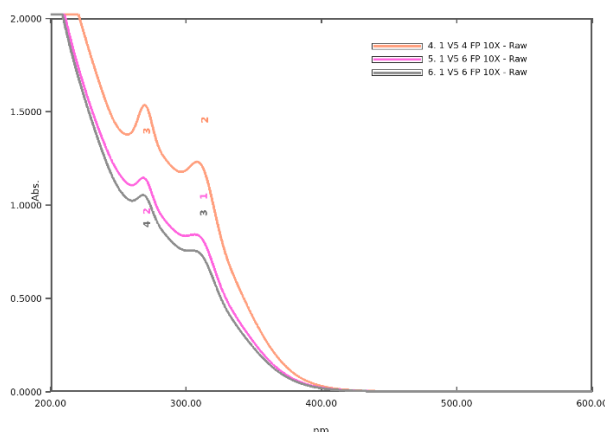


Figure 3. UV-Vis spectrum of citric acid and lime peel solution

This correlation indicates the strong potential for using citrus peel solution as a natural electrolyte, supported by the electrochemical characteristics of citric acid commonly found in citrus fruits. This finding is reinforced by previous studies confirming that the use of citrus peel and fruit waste as biomass can produce low-cost, environmentally friendly, and effective electrochemical energy storage materials for battery applications [40].

Other research shows that the use of citric acid in redox flow battery systems can reduce charge transfer resistance, thereby increasing ionic conductivity efficiency [41]. Additionally, studies on the fermentation of fruit peel waste such as oranges, mangoes, papayas, and lemons also prove the effectiveness of organic compounds such as citric acid in dissolving more than 90% of active metals from battery waste and recovering up to 85% of them, with stable electrochemical performance results after more than 100 cycles [42]. Thus, the strong correlation between citric acid content and lime peel extract confirms its suitability as a potential electrolyte for bio-batteries, with the ability to support redox reactions and accelerate ion transfer, contributing to improved bio-battery system efficiency.

The results shown in Figure 4 reinforce that orange peel solution has great potential as an environmentally friendly electrolyte in bio-battery systems. UV-Vis analysis indicates the presence of active compounds that support ionic conductivity, while battery cell testing yielded a voltage of 0.9 V in the solution and 1 V in the gel medium, with currents of 0.035 mA and 0.050 mA, respectively. The stable voltage output and consistent current flow indicate promising system efficiency, although it is still below that of conventional electrolytes.

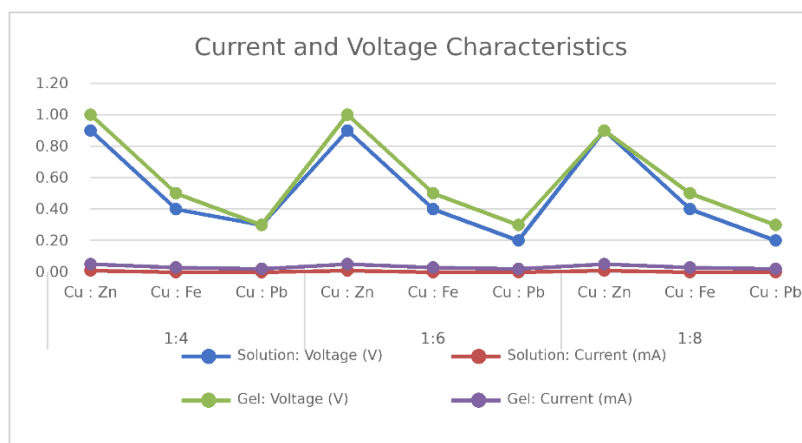


Figure 4. Voltage and current measurement results of the battery cell

Data from this study's voltage measurements on bio-batteries utilizing lime peel solution is presented in Table 1, covering a 12-hour timeframe. The table shows the electrical voltage results for samples with and without gel, tested using Cu-Zn, Cu-Fe, and Cu-Pb electrode combinations.

Table 1. Data on Electrical Voltage Measurement Results of Lime Peel Solution with and without Gel Addition

Type of Solution	Volume (ml)	Electrode	Electrical Voltage (Volts) at Time			
			0 Hours	4 Hours	8 Hours	12 Hours
Without Gel	15	Cu–Zn	0.9	0.9	0.9	0.9
Without Gel	15	Cu–Fe	0.4	0.4	0.39	0.39
Without Gel	15	Cu–Pb	0.3	0.3	0.3	0.29
With Gel	15	Cu–Zn	1.0	1.0	1.0	1.0
With Gel	15	Cu–Fe	0.5	0.5	0.5	0.5
With Gel	15	Cu–Pb	0.3	0.3	0.3	0.3

Based on the data in Table 1, the orange peel solution with gel addition showed more stable and higher voltage compared to the solution without gel, especially in the Cu-Zn electrode pair, which consistently reached 1.0 V for 12 hours. Conversely, the solution without gel showed lower voltage stability, particularly in the Cu-Fe and Cu-Pb electrodes. These results indicate that the addition of gel plays an important role in improving the stability and efficiency of orange peel solution-based bio-battery systems. Previously, there have been studies on biomass-based polymer gels, such as pectin-based gels (biopolymers) used as polymer electrolyte gels (PEGs), which show ionic conductivity of up to ~43 mS/cm and good electrochemical performance [43]. Thus, combining your research results with this literature confirms that biomass-based gel formulations particularly those derived from fruit peels are a promising step in the development of more stable and environmentally friendly bio-battery electrolytes.

4. Conclusion

This study confirms the potential of orange peel waste as a natural electrolyte in bio-battery systems through experimental approaches and UV-Vis spectroscopy analysis. The relationship between citric acid content and solution concentration shows that this material is suitable for use as an electrolyte medium. Battery cell performance test results show that the Cu–Zn electrode configuration provides the most optimal performance. An important finding from this study is that the gel-form electrolyte formulation is able to increase voltage stability and maintain better ionic conductivity compared to the liquid form, making it a major innovation in the development of organic-based bio-batteries. However, this study still has limitations, such as a relatively short testing duration and low current output. Therefore, further studies should focus on optimizing the gel composition, increasing energy density,

and conducting long-term durability testing to assess its potential application in large-scale sustainable energy storage systems.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work, the authors used Claude.ai (Anthropic) to assist with language editing, grammar improvement, and enhancing the clarity and readability of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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