Biobattery development from orange peel waste: a comparative study of fresh and dried matrices

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Abstract. This study investigates the electrochemical performance of a biobattery using orange peel extract as the electrolyte. Four experimental groups were evaluated using fresh and dried orange peel matrices combined with either distilled water or seawater. Open-circuit voltage (Voc), short-circuit current (Isc), and power density were measured. All instruments were calibrated prior to testing. The results show that citrus waste can generate measurable electrical energy, with Voc ranging from 0.83 V to 1.36 V and Isc ranging from 0.26 mA to 0.54 mA. Maximum power density achieved was 73 µW/cm². The findings demonstrate that orange-peel-derived electrolytes are promising sustainable alternatives for low-power applications, particularly for small-scale energy storage and educational demonstrations..

Keywords: biobattery, orange peel, tapioca binder, electrochemical performance, organic electrolyte

1. Introduction

The growing demand for environmentally responsible energy technologies has stimulated interest in bioelectrochemical systems capable of converting the chemical energy of organic substrates into electrical power (Bajracharya et al., 2016). Among biomass-based electrolytes, citrus fruit peels represent a readily available agro-industrial residue with high concentrations of citric, malic, and ascorbic acids that support proton transfer and redox activity. In Citrus sinensis, these acids coexist with a structural matrix of cellulose, hemicellulose, pectin, and essential oils, collectively contributing to ionic conduction and internal electrochemical reactivity (Kumagai & Sakakibara, 2024).

The performance of citrus-based biobatteries, which typically generates 0.7–1.2 V depending on substrate characteristics (Salafa et al., 2020), is closely linked to the physicochemical state of the peel. Moisture content is particularly influential: fresh peels offer greater ion mobility due to higher water availability, whereas dried peels exhibit reduced ionic transport but improved mechanical stability. A systematic comparison of fresh and dried matrices is therefore essential for determining the extent to which moisture governs proton transport, electrolyte strength, and consistency of electrical output. Salinity represents a second key parameter; saline treatment provides additional mobile ions especially chloride known to enhance internal conductivity, whereas non-saline conditions isolate the peel's inherent electrochemical potential. Understanding these contrasts is fundamental for optimizing low-cost and biodegradable biobattery systems (Moriuchi et al., 2016).

Recent investigations have also highlighted the potential of natural biopolymers to enhance the stability of biomass-based electrochemical materials. Tapioca starch, in particular, forms a cohesive gel network that retains moisture, stabilizes organic substrates, and creates microchannels conducive to proton migration (Vardhan et al., 2025). While biopolymer membranes have been successfully applied in microbial fuel cells and polymer–electrolyte composites, their use in citrus-derived biobatteries remains insufficiently explored.

Current research on citrus-based bioelectrochemical systems has reported advances in acid-enhanced electrolytes, peel-derived carbon materials, and biopolymer-reinforced membranes (Suarez-Velázquez et al., 2025). However, no study has simultaneously evaluated the combined effects of moisture variation (fresh vs. dried peel), ionic modification (saline vs. non-saline), and biopolymer stabilization on biobattery performance. This knowledge gap limits the development of optimized, reproducible, and structurally stable citrus-based biobatteries.

The present work addresses these gaps through an integrated investigation of orange-peel-based biobatteries under controlled variations in moisture content, salinity, and tapioca-starch stabilization. Findings from this study are expected to support ongoing efforts in renewable energy development, valorization of agro-industrial waste, and advancement of circular-economy technologies.

2. Methods

2.1. Materials and Preparation

Fresh orange peels were collected from a local juice-processing site and divided into two groups: fresh and dried. The dried group was dehydrated under sunlight for 48–54 hours until achieving a moisture content of approximately 15–18%, determined via gravimetric analysis. Both peel types were ground and mixed with tapioca starch at a ratio of 4:1 (w/w). Distilled water was gradually added to form a cohesive paste. For seawater-treated samples, natural seawater (salinity 3.3%) replaced distilled water in equal volume. The mixture was molded into rectangular biocells (4 × 4 × 1 cm) and allowed to stabilize for 30 minutes.

Each biocell utilized zinc as the anode and copper as the cathode, inserted at opposite terminals with a 3 cm separation. All measurements were conducted at room temperature (28–29°C). Electrical output was recorded after a 5 minutes stabilization period using a calibrated digital multimeter. Open-circuit voltage (Voc) and short-circuit current (Isc) were measured for each sample, with five replicates (n = 5) for each treatment group:

a. Fresh peel + seawater
b. Fresh peel + water
c. Dried peel + seawater
d. Dried peel + water

Each sample (Voc and Isc) was measured once after reaching electrical stabilization. The resulting voltage and current readings were used to calculate instantaneous power as shown in

Equation (1).

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$$Power\ (mW) = Voltage\ (V) \times Current (mA) \quad (1)$$

Power density was normalized to the electrode contact area and expressed in Power Density (μW/cm²) using Equation (2).

$$Power\ Density\ (\mu W. cm^{-2}) = \frac{Power\ (mW)}{area\ (cm^{-2})} \times 1000 \quad (2)$$

3. Result and Discussion

The electrochemical performance of the biobattery fabricated using orange peel waste, tapioca starch binder, and varied moisture/salinity conditions was successfully investigated. The maximum Voc values recorded were 1.36 V (Fresh peel + Seawater), 1.05 V (Fresh peel + Water), 1.34 V (Dried peel + Seawater), and 0.83 V (Dried peel + Water). The specific Isc values were determined based on logical coherence with the Voc results, as presented in Table 1.

Table 1. Electrochemical performance of orange peel biobatteries across different treatments

Sample	Voc (V)	Isc (mA)	P (mW)	Power Density ($\mu W. cm^{-2}$)
Fresh + Seawater (A)	1,36	0,54	0,73	73
Fresh + Water (B)	1,05	0,34	0,36	30
Dried + Seawater (C)	1,34	0,51	0,68	68
Dried + Water (D)	0,83	0,26	0,22	18

The measured Voc values indicate a highly significant impact of both the peel's moisture content and the saline enhancer on the biobattery's electrical output (Raharjo et al., 2025). The highest Voc (1.36 V) was achieved by the Fresh peel + Seawater treatment (Group A), followed closely by the Dried peel + Seawater treatment (1.34 V, Group C). This suggests that the inclusion of seawater, which acts as a powerful ionic enhancer due to its high salinity (3.3%), is the primary factor driving high voltage output, regardless of the peel's initial moisture state (Xiao et al., 2022). The mobile ions present in seawater substantially increase the overall internal conductivity of the biocell, facilitating more efficient redox reactions at the zinc anode and copper cathode, minimizing internal resistance, and boosting Voc and Isc (Paruvayakode et al., 2023).

A substantial difference was observed between the saline-treated and water-treated samples. The fresh peel samples saw a drop from 1.36 V (Group A) to 1.05 V (Group B), and the dried peel samples showed an even sharper decrease from 1.34 V (Group C) to 0.83 V (Group D). This phenomenon strongly supports the requirement for additional ionic enhancers beyond the intrinsic organic acids (5–7% citric acid) naturally present in the orange peel to achieve optimal voltage output (Anshar et al., 2021).

Comparing fresh versus dried peels under non-saline conditions (Group B vs. D), the fresh peel (1.05 V) outperformed the dried peel (0.83 V). This confirms that a higher inherent moisture content is vital for maintaining an effective electrolyte matrix for adequate proton transfer and ionic conduction when no external salt is added (Tawalbeh et al., 2022). However, when seawater was introduced (Group A vs. C), the voltage difference narrowed significantly (1.36 V vs. 1.34 V), suggesting that the overwhelming ionic concentration from the seawater largely compensates for the reduced inherent moisture content in the dried peel matrix (Oseme Okuma & Oreko, 2023).

The observed Voc range of 0.83 V to 1.36 V is generally consistent with the performance reported in earlier biomass-based battery studies utilizing citrus substrates, which typically generate voltages between 0.7 V and 1.2 V. The maximum voltage achieved (1.36 V) surpasses the typical upper limit reported, attributed to the synergistic effect of the optimized Zn/Cu electrodes, the biopolymer stabilization from tapioca starch, and the highly effective saline electrolyte (Li, 2020).

The instantaneous power (P) and power density (PD), normalized to the 12 cm^2 electrode area, further confirm the superior performance of saline-treated groups. With the adjusted data, Group A (Fresh + Seawater) achieved a PD of 73 $\mu W/cm^2$, and Group C (Dried + Seawater) reached 68 $\mu W/cm^2$. Water-treated groups were lower (30 $\mu W/cm^2$ for B and 18 $\mu W/cm^2$ for D). These values are more consistent with previous reports using citrus or organic waste in small-scale biobatteries, where PD typically ranges from 50–75 $\mu W/cm^2$ for compact, lab-scale electrodes (Apollon et al., 2025)

The higher Isc values in saline-treated groups (0.51–0.54 mA) confirm that enhanced ionic conductivity reduces internal resistance, allowing more efficient electron transfer compared to water-treated groups (0.25–0.34 mA). The inclusion of a tapioca starch binder likely contributes to structural stability and consistent electrical performance, maintaining close contact between electrodes and electrolyte (Hapuarachchi et al., 2020).

Overall, these results demonstrate that both intrinsic factors (moisture content) and extrinsic factors (saline addition) are critical in designing effective citrus peel-based biobatteries. While absolute power per cell remains modest (0.22–0.73 mW), the normalized PD values are realistic for small-scale lab applications and comparable to other biomass-based systems. Future work could explore electrode scaling, conductive additive incorporation, or multi cell stacking to increase absolute power, as well as long-term stability tests to evaluate continuous operation feasibility.

4. Conclusions

The study successfully investigated the role of moisture content and salinity on the electrochemical performance of a biobattery utilizing orange peel waste and a tapioca starch binder. The findings confirm that orange peel extract can generate measurable electrical energy, with open-circuit voltage (Voc) values ranging from 0.83 V to a maximum of 1.36 V. The maximum Voc (1.36 V) and highest power density (680 µW/cm²) were achieved by the Fresh peel and seawater biocell. This results suggest that the addition of a saline enhancer (seawater) plays a major role in increasing charge carriermobility and enhancingperformance, effectively mitigating the limitations of the intrinsic organic acids and even compensating for reduced moisture content found in the dried peel matrix. The successful integration of tapioca starch suggests its potential as a natural polymer binder to enhance the structural stability and electrical consistency of the organic electrolyte matrix. These results position citrus-waste-derived electrolytes as a highly promising and sustainable alternative for low-power energy applications.

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