Jurnal Penelitian Fisika dan Terapannya (Jupiter), 7 (2), 2026
Available online at: http://jurnal.univpgri-palembang.ac.id/index.php/Jupiter
DOI: 10.31851/jupiter.v7i2. 21298

Fabrication of an Environmentally Friendly Bio-Battery Based on Lime (Citrus aurantifolia) and $MgSO_4$ as Ion Sources with Tapioca Starch as the Matrix

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Received: 24 01 2026. Accepted: 11 02 2026. Published: 02 2026

Abstract

This study aims to develop and evaluate the performance of an environmentally friendly bio-battery based on natural materials, namely lime (Citrus aurantifolia), magnesium sulfate ($MgSO_4$), and tapioca starch as a biodegradable solid electrolyte matrix. Lime extract was utilized as a natural acidic electrolyte source, $MgSO_4$ functioned to enhance ionic conductivity, while tapioca starch served as a structural support for the solid electrolyte system.The bio-battery was synthesized by varying the volume of lime juice (1–7 mL) and the mass of $MgSO_4$ (1–7 g), followed by measurements of voltage, current, and solid electrolyte resistance. The results indicate that increasing the lime juice volume up to 5 mL significantly improved the electrical performance of the bio-battery, yielding a maximum voltage of 0.845 V, a current of 0.23 mA, and the lowest resistance of 15.15 kΩ. Furthermore, the addition of $MgSO_4$ at a fixed lime juice volume (5 mL) demonstrated optimal performance at 3 g, producing a voltage of 0.812 V, a current of 0.33 mA, and a minimum resistance of 11.48 kΩ. Increasing the $MgSO_4$ content beyond this optimum value resulted in higher resistance and reduced electrical output.Overall, the findings demonstrate that the optimal combination of lime extract, $MgSO_4$, and tapioca starch exhibits strong potential for the development of an eco-friendly bio-battery with favorable ionic conductivity characteristics based on renewable resources.

***Keywords**: Bio-battery, solid electrolyte, lime (Citrus aurantifolia), $MgSO_4$, ionic conductivity*

INTRODUCTION

Global electricity demand continues to rise in line with population growth, industrialization, and the rapid advancement of modern technologies. Nearly all sectors, including industry, transportation, and households, rely heavily on the availability of electrical energy to sustain daily activities (IEA, 2022; REN21, 2023). The increasing use of electronic devices and technology-based systems has further accelerated global energy consumption, thereby intensifying the need for energy sources that are efficient, environmentally friendly, and sustainable (Ellabban et al., 2020).

However, this growing demand has not been adequately balanced by sustainable energy supply, as the global energy system remains predominantly dependent on fossil fuels such as oil, natural gas, and coal. These resources are non-renewable and are being progressively depleted due to long-term exploitation. Moreover, their utilization contributes significantly to greenhouse gas emissions and the acceleration of global climate change (IEA, 2022; IPCC, 2021). These challenges highlight the urgency of developing and implementing environmentally sustainable renewable energy systems.

In response, various renewable energy technologies—such as solar, wind, hydropower, and biomass—have been extensively developed. Nevertheless, the large-scale deployment of renewable energy is still constrained by limitations in energy storage technologies. Current energy storage systems are largely dominated by conventional batteries based on heavy metals and synthetic electrolytes, which pose environmental concerns due to toxicity, limited recyclability, and dependence on non-renewable resources (Dunn et al., 2011; Goodenough & Park, 2013). Therefore, the development of alternative energy storage systems that are safe, eco-friendly, and sustainable has become a critical research priority.

One emerging innovation attracting increasing attention is the bio-battery, an energy storage system that utilizes biological or natural materials as electrochemical components, particularly as electrolytes. Through redox reactions occurring at the electrodes, bio-batteries convert chemical energy into electrical energy while potentially reducing environmental impacts compared to conventional batteries (Logan et al., 2019; Zhang et al., 2021). Several studies have reported the utilization of biomass, organic acid solutions, and natural polymers as electrolyte media or matrices in environmentally friendly bio-battery systems (Chen et al., 2020; Rahman et al., 2018).

The use of biodegradable polymers such as starch in bio-battery systems has been shown to enhance mechanical stability and maintain structural integrity of solid electrolytes, thereby facilitating more stable ion transport (Avérous & Halley, 2009; Tharanathan, 2003). In addition, natural acidic electrolytes derived from biological sources contain active ions that play a crucial role in improving ionic conductivity in electrochemical systems (Zhang et al., 2021; Liu et al., 2021).

Despite these advancements, the electrical performance of previously reported bio-batteries remains relatively low and highly dependent on the type and combination of materials employed. In particular, studies integrating natural acidic electrolyte sources, environmentally benign inorganic supporting salts, and biodegradable polymer matrices into a single optimized bio-battery system are still limited. This indicates a clear research gap in optimizing natural material compositions to enhance ionic conductivity while maintaining structural stability within bio-battery systems (Rahman et al., 2018; Zhang et al., 2021).

Based on this research gap, the present study aims to develop an eco-friendly bio-battery based on lime (Citrus aurantifolia), magnesium sulfate ($MgSO_4$), and tapioca flour. Lime juice is utilized as a natural acidic electrolyte source providing active ions, $MgSO_4$ serves as a supporting electrolyte to enhance ionic conductivity, and tapioca flour functions as a biodegradable polymer matrix to improve the stability and structural integrity of the solid electrolyte. The novelty of this study lies in the integration of lime, $MgSO_4$, and tapioca flour into a simple, natural-material-based bio-battery system that is readily available, environmentally friendly, and potentially biodegradable, as well as in the systematic evaluation of its electrical performance as a sustainable small-scale energy storage alternative.

MATERIALS AND METHODS

This study utilized lime (Citrus aurantifolia) fruits of uniform ripeness as a natural electrolyte source, technical-grade magnesium sulfate ($MgSO_4$) as a supporting electrolyte, tapioca flour as a biodegradable polymer matrix, and distilled water (aquadest). Graphite and aluminum were employed as the cathode and anode, respectively. All electrical measurements were conducted using a digital multimeter (CD800A) under laboratory room temperature conditions (±27 °C).

Preparation of the natural electrolyte began by washing the lime fruits under running water to remove surface impurities. The fruits were then cut and manually squeezed to extract the juice, which was subsequently filtered through a fine sieve to remove pulp residues, yielding a homogeneous electrolyte solution. Based on preliminary optimization, the volume of lime juice used in each treatment was fixed at 5 mL.

The bio-battery electrolyte was prepared by dissolving magnesium sulfate ($MgSO_4$) into 5 mL of lime juice with mass variations of 1 g, 2 g, 3 g, 4 g, and 5 g. The mixture was stirred using a magnetic stirrer for approximately 10 minutes until a homogeneous solution was obtained. Subsequently, 10 g of tapioca flour was gradually added while continuously stirring until a uniform solid-state electrolyte paste was formed. This paste functioned as a natural polymer matrix capable of absorbing and retaining the electrolyte solution while facilitating uniform ion distribution within the system.

The bio-battery cell was assembled by placing the solid electrolyte paste between two electrodes—graphite as the cathode and aluminum as the anode—with dimensions of 3 cm × 4 cm. The electrode surface area and inter-electrode distance were kept constant across all treatments to ensure experimental consistency. The assembled configuration constituted a single bio-battery cell, which was connected to the digital multimeter using alligator clip cables for electrical measurements.

The electrical performance of the bio-battery was evaluated by measuring the open-circuit voltage (OCV), current, and internal resistance. Internal resistance was calculated based on the relationship between voltage and current according to Ohm’s law. Each $MgSO_4$ mass variation was tested in triplicate ($n = 3$) to ensure data reliability. The independent variable in this study was the mass of $MgSO_4$ added to the electrolyte system, while the dependent variables were voltage (V), current (mA), and internal resistance (Ω). Controlled variables included the volume of lime juice (5 mL), mass of tapioca flour (10 g), electrode type and surface area, inter-electrode distance, ambient temperature, and cell configuration.

The experimental data were analyzed quantitatively by calculating the mean values for each treatment variation. The relationship between $MgSO_4$ mass variation and electrical parameters was examined to determine the optimum composition yielding the best bio-battery performance. Furthermore, performance variations were interpreted based on ionic conductivity mechanisms within the natural-material-based solid electrolyte system.

RESULTS AND DISCUSSION

The measured values of current, voltage, and solid electrolyte resistance for the tapioca flour–based bio-battery with varying volumes of lime (Citrus aurantifolia) juice are presented in Table 4.1. The data indicate that increasing the lime juice volume from 1 mL to 5 mL resulted in a rise in voltage from 0.609 V to 0.845 V and current from 0.06 mA to 0.23 mA. Simultaneously, the solid electrolyte resistance decreased from 18.40 kΩ to 15.15 kΩ. These results suggest that the increased concentration of H^+ ions supplied by the lime juice enhanced the ionic conductivity of the system, reaching an optimum at 5 mL. However, when the volume was further

Table 4.1. Measurement results of current, voltage, and solid electrolyte resistance for variations in lime (Citrus aurantifolia) juice volume

Variation Volume of Lime Juice (ml)	Voltage (Volt)	Current (mA)	Solid Electrolyte Resistance (kΩ)
1 ml	0,609	0,06	18,40
3 ml	0,704	0,10	17,75
5 ml	**0,845**	**0,23**	**15,15**
7 ml	0,625	0,19	16,35

The data indicate that increasing the lime juice volume from 1 mL to 5 mL resulted in a rise in voltage from 0.609 V to 0.845 V and current from 0.06 mA to 0.23 mA. Simultaneously, the solid electrolyte resistance

However, when the volume was further increased to 7 mL, the voltage decreased to 0.625 V and the current to 0.19 mA, accompanied by an increase in resistance to 16.35 kΩ. This trend indicates that electrolyte conductivity does not increase linearly with increasing acidic electrolyte volume. Excessive ion concentration may lead to strong ion–ion interactions, thereby reducing ionic mobility within the natural polymer (tapioca) matrix. This phenomenon is consistent with solid polymer electrolyte conductivity theory, which states that increasing salt or ion-source concentration enhances conductivity up to an optimum point before declining due to ion pairing and

decreased from 18.40 kΩ to 15.15 kΩ. These results suggest that the increased concentration of H^+ ions supplied by the lime juice enhanced the ionic conductivity of the system, reaching an optimum at 5 mL.
restricted ionic mobility (Kadir et al., 2018; Hassan et al., 2020).

These findings confirm that the optimum lime juice volume in this system is 5 mL. At this condition, the ion concentration is sufficient to enhance conductivity without causing excessive ion aggregation. Tapioca flour functions as a biodegradable biopolymer matrix that maintains structural stability and facilitates uniform ion distribution within the solid electrolyte system.

The effect of $MgSO_4$ addition on bio-battery performance at the optimum lime juice volume (5 mL) is presented in Table 4.2.

Table 4.2. Measurement Results of Voltage and Solid Electrolyte Resistance for Variations in $MgSO_4$ Mass

Variation		Voltage (Volt)	Current (mA)	Solid Electrolyte Resistance (kΩ)
Volume of Lime Juice (ml)	$MgSO_4$			
5 ml	1 gr	0,668	00,29	13,13
5 ml	3 gr	0,812	00,33	11,48
5 ml	**5 gr**	**0,710**	**00,18**	**12,76**
5 ml	7 gr	0,565	00,10	15,35

The results show that increasing $MgSO_4$ mass from 1 g to 3 g enhanced the voltage from 0.668 V to 0.812 V and the current from 0.29 mA to 0.33 mA, while the solid electrolyte resistance decreased from 13.13 kΩ to 11.48 kΩ. These results indicate that 3 g of $MgSO_4$ represents the optimum concentration for increasing the number of free ions and improving ionic mobility within the system. However, further increases to 5 g and 7 g led to decreases in voltage (0.710 V and 0.565 V, respectively) and current (0.18 mA and 0.10 mA), accompanied by increases in resistance to 12.76 kΩ and 15.35 kΩ. This behavior suggests that excessively high ion concentrations increase local viscosity and promote excessive inter-ionic interactions, thereby hindering ion transport within the solid polymer electrolyte matrix.

These results are consistent with previous studies on polymer electrolytes containing inorganic salts, which report a non-linear relationship between salt concentration and ionic conductivity. Hassan et al. (2020) demonstrated that increasing magnesium salt concentration in biodegradable polymer systems enhances conductivity up to an optimum value before declining due to reduced ion mobility. Similarly, Kadir et al. (2018) reported that salt incorporation into biopolymer matrices increases charge carrier density; however, at high concentrations, ion aggregation reduces effective conductivity. Jaya Saputra et al. (2023) further reported that a PVA system containing 20% $LiClO_4$ achieved the highest conductivity of 4.8×10^{-5} S/cm, while higher concentrations led to conductivity reduction due to ion interaction effects. Riyanto et al. (2018) also observed that a chitosan–PVA polymer electrolyte containing 35 wt% ammonium nitrate achieved an optimum conductivity of 2.2×10^{-5} S cm^{-1}, whereas conductivity was significantly lower without salt addition. The enhancement was attributed to an increased number of free ions and improved ionic mobility within the polymer matrix.

In the present study, the solid electrolyte formed from the combination of $MgSO_4$, lime juice, and tapioca flour functions as an ion-conducting medium. $MgSO_4$ provides Mg^{2+} and SO_4^{2-} ions, while lime juice contributes H^+ ions derived from citric acid. The interaction among these components forms a solid electrolyte system capable of effective ion transport. The observed inverse relationship between electrolyte resistance and electrical output confirms that bio-battery performance is strongly governed by ionic conductivity.

Overall, the results presented in Tables 4.1 and 4.2 demonstrate that the optimum composition was achieved at 5 mL of lime juice and 3 g of $MgSO_4$. This combination produced the highest voltage and current, along with the lowest internal resistance, thereby yielding the best bio-battery performance. Determining the optimum composition is crucial to ensure sufficient ion concentration for enhanced conductivity while preventing adverse effects caused by excessive ion interactions.

CONCLUSION

The fabrication of a bio-battery utilizing lime (Citrus aurantifolia) juice and tapioca starch as a biodegradable solid electrolyte was successfully carried out and evaluated through measurements of current, voltage, and electrical resistance to assess the effectiveness of the natural electrolyte system. The results indicate that the optimum volume of lime juice is 5 mL, producing the highest voltage and current of 0.845 V and 0.23 mA, respectively, along with the lowest resistance of 15.15 kΩ. Increasing the lime juice volume beyond 5 mL led to a decrease in voltage and current output, accompanied by an increase in electrolyte resistance.

Furthermore, the addition of $MgSO_4$ to the optimum lime juice volume (5 mL) demonstrated optimal performance at a mass of 3 g, yielding a voltage of 0.812 V and a current of 0.33

mA, with the minimum resistance recorded at 11.48 kΩ. Increasing the $MgSO_4$ mass above 3 g resulted in a decline in bio-battery performance, as indicated by reduced voltage and current output and increased internal resistance.

Overall, the combination of lime juice, $MgSO_4$, and tapioca starch as a solid electrolyte matrix in the bio-battery exhibits promising potential. This study demonstrates that natural acidic electrolytes and inorganic salts embedded in a biopolymer matrix can be effectively utilized to produce an environmentally friendly, low-cost, and sustainable bio-battery with favorable ionic conductivity characteristics.

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