

Optimization of Bio-Battery Performance Based on Young Cassava Leaf Electrolyte, Calcium Chloride (CaCl_2) and Lamtoro Leaf with Coconut Stem Powder Matrix

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Received: 12 06 2026. Accepted: 31 07 2026. Published: 07 2026

Abstract

The global energy crisis and the increasing demand for electricity have encouraged the development of sustainable biomass-based alternative energy sources. This study aims to optimize the performance of a bio-battery using a multi-ion electrolyte system composed of young cassava leaves, calcium chloride (CaCl_2) and leucaena leaves with a coconut stem powder matrix. The research method was conducted experimentally through three stages of mass variation, namely young cassava leaves (6–14 g), CaCl_2 (1–3 g) and leucaena leaves (2–10 g), as well as the use of aluminum, copper and zinc anode electrodes with a graphite cathode. The measured parameters included voltage, current and impedance using a multimeter and a YR1035+ Battery Impedance Tester. The results showed that the optimum composition was obtained with 10 g of young cassava leaves, 2 g of CaCl_2 , and 6 g of leucaena leaves using an aluminum anode. Under these conditions, the bio-battery produced a voltage of 0.734 V, a current of 3.96 mA and a minimum impedance of 3.73 Ω . The multi-ion electrolyte system proved capable of increasing ionic conductivity, reducing internal resistance and producing a more stable electrical output, making it a promising environmentally friendly alternative energy source.

Keywords: Bio-battery, multi-ion electrolyte, young cassava leaves, calcium chloride (CaCl_2), leucaena leaves

INTRODUCTION

Global energy demand continues to increase alongside technological advancement, industrialization, and population growth, while the availability of fossil energy resources is becoming increasingly limited and contributes significantly to environmental degradation through greenhouse gas emissions (Jamilatun et al., 2025). This situation has driven the development of alternative energy sources that are environmentally friendly, sustainable, and based on renewable resources. One promising technology is biomass-based bio-batteries (Martins et al., 2019).

Bio-batteries are energy storage devices that convert chemical energy from

biological materials into electrical energy through electrochemical reactions (Cao et al., 2024). This technology utilizes natural, biodegradable, and readily available materials, thereby reducing dependence on synthetic chemicals and heavy metals commonly used in conventional batteries (Sulasminingsih et al., 2023). The performance of bio-batteries is strongly influenced by the characteristics of the electrolyte, which serves as the medium for ion transport between electrodes (Bertaglia et al., 2024).

Numerous studies have explored biomass as a natural electrolyte source, including aloe vera gel (Azmi et al., 2018), coconut water (Valensia et al., 2021), pandan leaf extract

(Rasel et al., 2023), lime juice (Mita et al., 2025), tomatoes (Tanjung et al., 2022), pineapples (Sari et al., 2023), and bilimbi fruit (Fermi et al., 2024). In addition, porous biomass materials such as starch, cellulose, lignocellulose, and agricultural waste-derived materials have been utilized as supporting matrices to enhance electrolyte stability and distribution (Arrieta et al., 2022). Nevertheless, the application of multi-ion electrolyte systems based on combinations of local biomass resources remains relatively limited (Tamo et al., 2025).

Young cassava leaves are known to contain mineral ions such as K^+ , Na^+ , and Ca^{2+} , which contribute to improved ionic conductivity and charge transfer efficiency (Alamu et al., 2022). Likewise, leucaena leaves contain potassium, calcium, and magnesium, which can enhance ion mobility within electrolyte systems (Raju et al., 2025). The potential of these biomasses can be further enhanced through the addition of calcium chloride ($CaCl_2$) as a supporting electrolyte, owing to its ability to provide high concentrations of Ca^{2+} and Cl^- ions, thereby increasing charge carrier density and ionic conductivity (Wei et al., 2022).

The performance of the electrolyte system can be further improved through the use of coconut stem powder as a matrix. This lignocellulosic material possesses a porous structure capable of absorbing and distributing electrolytes uniformly, thereby facilitating ion transport and maintaining electrochemical stability (Rahman et al., 2018). In addition to enhancing bio-battery performance, the utilization of coconut stem waste also supports circular economy principles and sustainable biomass management (Vieira et al., 2024).

Although various studies have investigated biomass materials as electrolytes and matrices for bio-batteries, the combination of young cassava leaves, leucaena leaves, and $CaCl_2$ in a multi-ion electrolyte system using coconut stem

powder as a matrix has rarely been reported. The synergistic interaction among these components is expected to enhance ionic conductivity, reduce internal resistance, and produce a more stable electrical output compared to single-electrolyte systems.

Therefore, this study aims to optimize the performance of a bio-battery based on young cassava leaf, $CaCl_2$, and leucaena leaf electrolytes with a coconut stem powder matrix. The study investigates the effects of electrolyte composition and electrode type on the voltage, current, and impedance of the bio-battery, contributing to the development of environmentally friendly and sustainable alternative energy technologies (Sumanzaya et al., 2019).

MATERIALS AND METHODS

The materials used in this study included cassava leaves, leucaena leaves, coconut stem powder as a biomass matrix, and calcium chloride ($CaCl_2$) purchased from the chemical supplier Bumi Agung Kimia, South Tangerang, Indonesia.

The preparation of the solid electrolyte began with a material pre-treatment stage. Fresh cassava leaves were first washed with clean water to remove adhering impurities, then cut into small pieces and blended to obtain a cassava leaf suspension. This suspension served as the natural electrolyte source in the bio-battery system. Subsequently, the cassava leaf suspension was weighed at different masses of 6 g, 8 g, 10 g, 12 g, and 14 g, then placed in a beaker and homogenized to ensure a uniform distribution of ions. Separately, the coconut stem powder used as the supporting matrix was prepared by grinding the material and sieving it through a 100-mesh sieve to obtain a uniform particle size. The coconut stem powder was then gradually added to the cassava leaf suspension until a homogeneous solid electrolyte paste was

formed. The porous structure of the coconut stem powder matrix plays an important role in absorbing and retaining the electrolyte, thereby improving the overall stability of the system. The variation in cassava leaf suspension mass was carried out as the first optimization stage to determine the optimum composition that produced the maximum current and voltage in the bio-battery system, while the masses of calcium chloride (CaCl_2), leucaena leaf suspension, and coconut stem powder, as well as the electrode configuration, were kept constant. The optimum composition obtained in this stage was subsequently used as the basis for the next optimization step.

In the second optimization stage, the optimum cassava leaf suspension composition obtained from the first stage was maintained constant, while the calcium chloride (CaCl_2) content was varied at 1.0, 1.5, 2.0, 2.5, and 3.0 g. The incorporation of CaCl_2 was intended to increase the ionic concentration within the system, thereby enhancing ionic conductivity and improving the electrochemical performance of the bio-battery. The optimum CaCl_2 content obtained in this stage was subsequently used for the next optimization stage.

In the third optimization stage, using the optimum cassava leaf suspension and calcium chloride (CaCl_2) compositions obtained from the previous stages, leucaena leaf suspension was introduced. The leucaena leaves were washed with clean water, cut into small pieces, and blended to obtain a natural electrolyte suspension. The leucaena leaf suspension was then added at varying masses of 2, 4, 6, 8, and 10 g to form a ternary electrolyte system. This optimization was conducted to determine the electrolyte composition capable of producing the highest voltage and current outputs. The optimum electrolyte composition obtained from this stage was subsequently used for the

evaluation of different anode materials.

In each stage, the bio-battery was assembled by uniformly coating the solid electrolyte onto the surface of a graphite sheet serving as the cathode, with dimensions of 3 cm $\times$ 4 cm. The comparison of aluminum (Al), copper (Cu), and zinc (Zn) anodes was performed using the optimum electrolyte composition obtained from the previous optimization stages. Metal sheets of the same dimensions were then used as anodes, namely aluminum (Al), copper (Cu), and zinc (Zn), and placed on top of the solid electrolyte layer based on the coconut stem powder matrix containing cassava leaf suspension, leucaena leaf suspension, and calcium chloride (CaCl_2). The two electrodes were then assembled into a single bio-battery cell and clamped on both sides to maintain structural stability and prevent layer displacement during testing. The total mass of the electrodes coated with the electrolyte was approximately 10 g. The anode and cathode terminals were connected to a multimeter using wires and alligator clips for voltage and current measurements, while the internal resistance was measured using a YR1035+ Battery Impedance Tester.

All measurements were conducted at room temperature (27 ± 2 °C). Each experimental condition was tested in triplicate, and the reported values represent the mean voltage, current, and internal resistance obtained from the three measurements. The experimental data were analyzed descriptively using Origin 7.0 software. The optimum operating condition was identified based on the highest voltage and current outputs together with the lowest internal resistance.

RESULTS AND DISCUSSION

The bio-battery was developed using cassava leaf suspension as the

source of electrolyte ions, with coconut stem powder serving as a solid supporting matrix within the system. The mass of cassava leaves was varied at 6 g, 8 g, 10 g, 12 g, and 14 g, with the addition of 2 mL

of water for each variation. The parameters evaluated included voltage (V), current (mA), and impedance (Ω), as presented in Table 4.1 and Figure 4.1

Table 4.1. Effect of cassava leaf mass variation in a coconut stem powder matrix on the voltage (V), current (mA), and impedance (Ω) of the bio-battery.

Cassava Leaf Mass (g)	Voltage (V)	Current (mA)	Impedance (Ω)
6	0.692	0.66	148.8
8	0.708	1.19	92.0
10	0.716	1.37	48.4
12	0.651	0.96	94.4
14	0.617	0.68	105.0

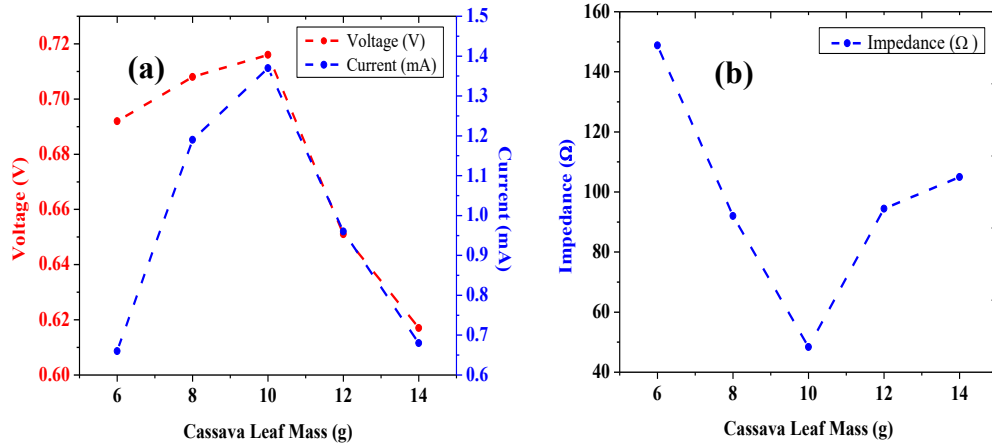


Figure 4.1 Effect of cassava leaf mass on (a) voltage (V), current (mA) and (b) impedance (Ω) of the bio-battery.

Table 4.1 and Figure 4.1 present the measured voltage, current, and impedance of the bio-battery with varying masses of cassava leaves as the ion source in a biomass-based solid electrolyte system. The mass variation was performed to evaluate the influence of biomass quantity on the electrical performance of the bio-battery.

The results show that increasing the cassava leaf mass from 6 g to 10 g significantly improved both current and voltage. The current increased from 0.66 mA at 6 g to 1.37 mA at 10 g, while the voltage increased from 0.692 V to 0.716 V. This improvement is associated with

the higher concentration of ionizable minerals and organic compounds present in cassava leaves, which increase the number of charge carriers and facilitate ion transport within the electrolyte matrix (Abiodun et al., 2023). As a result, ionic conduction becomes more effective, reducing internal resistance and enhancing electrical output (Sibaki et al., 2018).

The impedance data further support this trend. The impedance decreased from 148.8 Ω at 6 g to 92.0 Ω at 8 g and reached its lowest value of 48.4 Ω at 10 g. The reduction in impedance indicates improved charge-

transfer efficiency and lower internal resistance, allowing greater current generation within the system (Weiss et al., 2020). These findings demonstrate that increasing the availability of mobile ions up to an optimum level contributes positively to bio-battery performance. However, when the cassava leaf mass was increased beyond 10 g, the electrical performance declined. At 12 g and 14 g, the impedance increased to 94.4 Ω and 105.0 Ω , respectively, while the generated current decreased. This behavior suggests that excessive ion concentration no longer enhances conductivity. Instead, stronger ion-ion interactions, ion-pair formation, and non-uniform ion distribution can restrict the mobility of free charge carriers, leading to higher diffusion resistance and reduced ionic conductivity (Kaiser et al., 2018; Ma et al., 2019).

This non-linear relationship between ion concentration and conductivity has been widely reported in electrolyte systems. Zhang et al. (2020), observed that ionic conductivity in a $\text{CaCl}_2\text{-PC-H}_2\text{O}$ electrolyte increased with concentration until reaching an optimum value and subsequently decreased due to ion-pair formation and stronger interionic interactions. Similar findings were reported by Al-Salih & Abu-Lebdeh, (2024), in aqueous acidic electrolytes, where conductivity

declined beyond the optimum composition because of intensified interionic interactions and hydrated phase formation. Likewise, Herbers et al. (2023), demonstrated that excessive salt concentration in PEOA-based polymer electrolytes promoted ion-cluster formation, which hindered ion mobility and reduced conductivity.

Overall, the performance of the bio-battery is governed by the balance between ion availability and ion mobility within the electrolyte matrix. A cassava leaf mass of 10 g represents the optimum condition, producing the highest current, maximum voltage, and lowest impedance. These results confirm that electrolyte composition plays a critical role in determining charge transport efficiency and electrical performance in cassava leaf-based bio-batteries.

After obtaining the optimum composition of cassava leaves, calcium chloride (CaCl_2) was added as a supporting electrolyte to enhance the performance of the bio-battery. The masses of CaCl_2 used were 1, 1.5, 2, 2.5, and 3 g, mixed with 10 g of cassava leaves and 5 g of coconut stem powder, with the addition of 2 mL of water to each sample. The measured electrical parameters, including current, voltage, and impedance, are presented in Table 4.2 and Figure 4.2.

Table 4.2. Effect of CaCl_2 mass variation at the optimum cassava leaf composition in a coconut stem powder matrix on the voltage (V), current (mA), and impedance (Ω) of the bio-battery.

CaCl_2 Mass (g)	Voltage (V)	Current (mA)	Impedance (Ω)
1	0.694	1.63	10.54
1.5	0.706	2.38	7.45
2	0.710	2.83	4.24
2.5	0.653	2.27	5.54
3	0.642	2.08	6.20

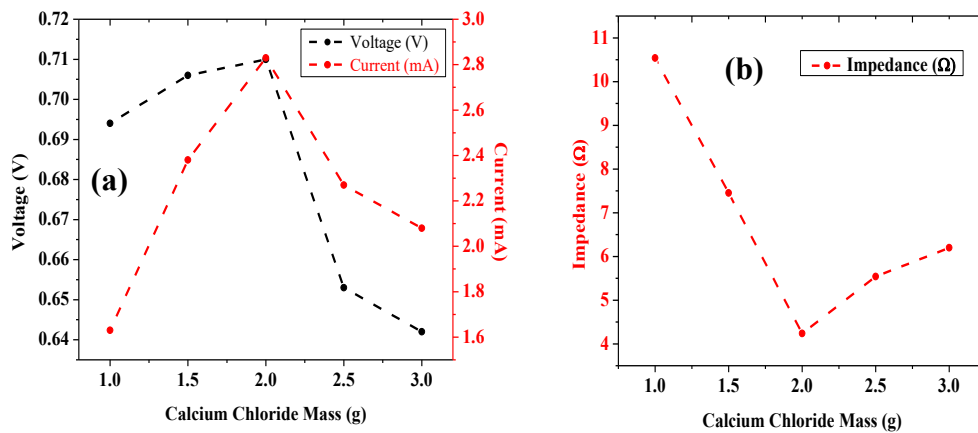


Figure 4.2. Effect of CaCl_2 mass variation at the optimum cassava leaf composition on (a) voltage (V) and current (mA), and (b) impedance (Ω) of the bio-battery.

Table 4.2 and Figure 4.2 show that variations in CaCl_2 mass directly influence the electrical characteristics of the bio-battery at the optimum cassava leaf composition. Increasing the CaCl_2 mass from 1 g to 2 g enhanced the current from 1.63 mA to 2.83 mA, while the voltage increased from 0.694 V to 0.710 V. However, beyond this condition, both current and voltage declined, reaching 2.08 mA and 0.642 V, respectively, at 3 g. These results indicate that CaCl_2 addition is beneficial only up to an optimum level, after which system performance decreases.

Impedance analysis further supports this trend. The impedance decreased from 10.54 Ω at 1 g to 7.45 Ω at 1.5 g and reached its minimum value of 4.24 Ω at 2 g, indicating reduced internal resistance and more efficient ion transport. However, impedance increased again to 5.54 Ω at 2.5 g and 6.20 Ω at 3 g. This increase in resistance is consistent with the observed decline in current, suggesting that the overall system resistance rises when the ion concentration exceeds the optimum condition.

From an electrochemical perspective, the performance improvement within the 1–2 g range is attributed to the increased number of free ions generated by the dissociation of

CaCl_2 into Ca^{2+} and Cl^- ions. The higher ion concentration enhances charge transport within the electrolyte, reduces internal resistance, and improves system conductivity. Under these conditions, ion distribution remains relatively homogeneous, allowing high ion mobility.

In contrast, increasing the CaCl_2 mass beyond 2 g leads to a decline in performance. The higher ion density strengthens electrostatic interactions among ions, particularly involving divalent Ca^{2+} species (Ilic et al., 2024). This promotes the formation of ion pairs and ion clusters, reducing the number of free ions available for charge conduction (Kang et al., 2022). Furthermore, increased ion concentration may lower ion diffusion coefficients and increase electrical resistance (Kim et al., 2024). These effects are reflected in the higher impedance and lower current observed at the 2.5–3 g mass range.

The present findings are consistent with previous studies. Taminato et al. (2024), reported that the addition of LiPF_6 to a PEO–LiTFSI polymer electrolyte improved conductivity up to an optimum concentration, but excessive LiPF_6 reduced conductivity due to increased

ion association. Similarly, Yang et al. (2021) found that a $\text{LiPF}_6\text{-LiDFP}$ dual-salt electrolyte exhibited reduced impedance and improved electrochemical performance up to an optimum composition, followed by a decline resulting from lower ionic conductivity. Boroujeni et al. (2024), also demonstrated that conductivity in multisalt systems increased at low-to-moderate concentrations but decreased at higher concentrations because of ion association and crowding effects that hinder ion mobility.

Overall, bio-battery performance is governed by the balance between ion availability and ion mobility within the electrolyte system. A CaCl_2 mass of 2 g represents the optimum condition, producing the highest current, maximum voltage, and lowest impedance. These

results confirm that electrolyte composition is a critical factor in enhancing charge transport efficiency and electrical output stability in cassava leaf-based bio-batteries.

After the optimum composition of coconut stem powder, cassava leaves and CaCl_2 had been established, *Leucaena* leaves were added at varying masses to further improve the performance of the bio-battery. The addition of this biomass was intended to utilize the mineral ions and ionizable compounds present in *Leucaena* leaves, which have the potential to enhance charge transport within the electrolyte system. The effect of *Leucaena* leaf mass variation on the electrical parameters of the bio-battery is presented in Table 4.3 and Figure 4.3.

Table 4.3. Effect of *Leucaena* leaf mass variation at the optimum cassava leaf and CaCl_2 composition in a coconut stem powder matrix on the voltage (V), current (mA) and impedance (Ω) of the bio-battery.

Leucaena Leaf Mass (g)	Voltage (V)	Current (mA)	Impedance (Ω)
2	0.680	2.63	7.46
4	0.702	3.11	7.38
6	0.734	3.96	3.73
8	0.718	1.30	6.28
10	0.710	0.41	7.34

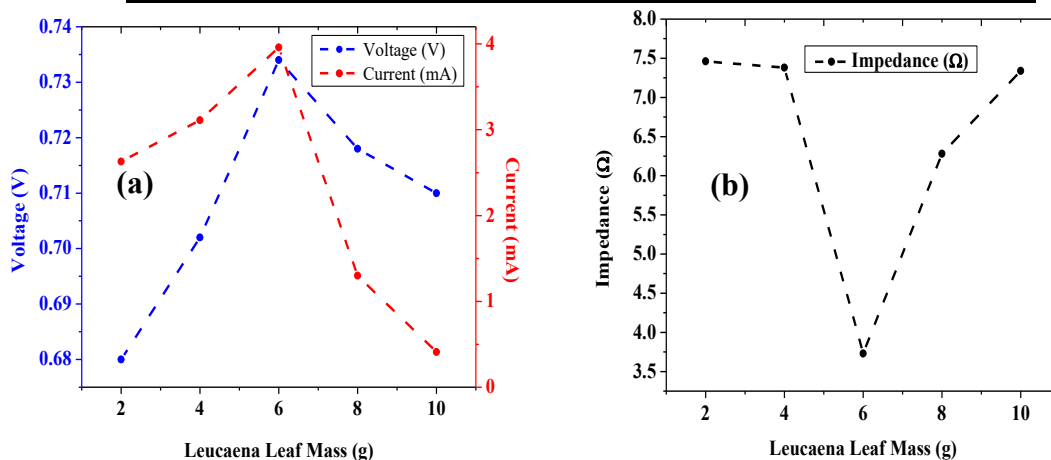


Figure 4.3. Effect of *Leucaena* leaf mass variation at the optimum CaCl_2 and cassava leaf composition on the (a) voltage (V) and current (mA), and (b) impedance (Ω) of the bio-battery.

Impedance analysis further supports this trend. The impedance decreased from $7.46\ \Omega$ at 2 g to $7.38\ \Omega$ at 4 g and reached its minimum value of $3.73\ \Omega$ at 6 g, indicating reduced internal resistance and more efficient charge transfer. However, impedance increased to $6.28\ \Omega$ at 8 g and $7.34\ \Omega$ at 10 g, corresponding to the observed decline in current output. This behavior suggests that the overall system resistance increases when the leucaena leaf mass exceeds the optimum condition.

The improvement in performance up to 6 g can be attributed to the mineral ions and ionizable organic compounds present in leucaena leaves, including K^+ and Ca^{2+} ions, which increase the number of charge carriers within the electrolyte system (Ammar et al., 2024). The combination of ions originating from cassava leaves, $CaCl_2$, and leucaena leaves forms a multi-ion electrolyte system that enhances charge transport efficiency and reduces internal resistance.

In contrast, excessive addition of leucaena leaves decreases system conductivity. Higher ion concentrations intensify electrostatic interactions among ions, reducing the mobility of free charge carriers. Furthermore, ion association and increased diffusion resistance limit charge transport efficiency, resulting in higher impedance and lower bio-battery performance.

This phenomenon is consistent with previous studies, Hadi et al. (2025) reported that ionic conductivity in a PVA–CS–FSG/NaSCN ternary solid polymer electrolyte increased up to an

optimum NaSCN concentration and subsequently decreased due to ion-pair formation. Similar behavior was observed by Homma et al. (2020), in a Li_3PO_4 – Li_3BO_3 – Li_2SO_4 ternary electrolyte system, where conductivity reached a maximum value at an optimum composition before declining at higher concentrations. Likewise, Atik et al. (2021) demonstrated that the addition of a third component in a PEO/LiTFSI/ionic liquid electrolyte enhanced ionic conductivity by increasing charge carrier concentration and ion mobility, highlighting the importance of maintaining a balance between ion availability and ion mobility.

Overall, the electrolyte can be classified as a complex multi-ion system in which interactions among ions derived from cassava leaves, $CaCl_2$, and leucaena leaves determine bio-battery performance. The optimum condition was achieved with 6 g of leucaena leaves, producing the highest current and voltage as well as the lowest impedance, indicating maximum electrolyte conductivity and the most efficient charger transfer process.

Variations in electrode pairs influence the voltage, current, and internal resistance of the system, as indicated by the impedance values. In this study, graphite was used as the cathode, while aluminum, copper, and zinc were used as anodes with different electrochemical properties, resulting in variations in bio-battery performance. The electrical measurement results are presented in Table 4.4.

Table 4.4. Effect of Anode and Cathode Pair Variations on the Electrical Parameters of the Bio-Battery under Optimum Electrolyte Conditions.

Anode and Cathode Variations	Voltage (V)	Current (mA)	Impedance (Ω)
Graphite-Aluminium	0.734	3.96	3.73
Graphite-Copper	0.003	0.05	2.28
Graphite-Zinc	0.704	0.04	8.32

Table 4.4 presents the effect of electrode pair variations on the voltage, current, and impedance of the bio-battery under optimum electrolyte conditions. The results show that the graphite–aluminum electrode pair exhibited the best overall performance, producing a voltage of 0.734 V, a current of 3.96 mA, and an impedance of 3.73 Ω . In contrast, the graphite–copper pair showed the poorest performance, generating only 0.003 V and 0.05 mA despite having the lowest impedance value of 2.28 Ω . Meanwhile, the graphite–zinc pair produced a voltage of 0.704 V, a current of 0.04 mA, and an impedance of 8.32 Ω , indicating a relatively high voltage but greater internal resistance.

These differences are closely related to the electrochemical properties of the electrodes, particularly their standard reduction potentials and tendency to undergo oxidation. Aluminum is more reactive than zinc and copper, enabling a greater flow of electrons within the electrochemical system (Ikeuba et al., 2024). In contrast, copper is more stable and less susceptible to oxidation, resulting in lower current generation (Jun et al., 2024).

In the graphite–aluminum pair, aluminum acts as a highly reactive anode, allowing oxidation to occur more effectively and generating a substantial electron flow toward the graphite cathode. Consequently, higher current and voltage values are achieved. The relatively low impedance further indicates efficient charge-transfer processes within the system. For the graphite–zinc pair, zinc also functions as the anode; however, the higher impedance suggests greater internal resistance, which limits charge transfer and results in a low current output despite the relatively high voltage generated. Conversely, in the graphite–copper pair, the lower tendency of copper to oxidize restricts

electrochemical reactions, leading to very low voltage and current values. Although the impedance is relatively low, the limited release of electrons results in poor overall performance.

Overall, these findings demonstrate that electrode characteristics play a critical role in determining bio-battery performance. Electrode combinations that provide a large potential difference and low internal resistance promote more efficient charge transfer. Based on the obtained results, the graphite–aluminum electrode pair represents the optimum configuration, producing the highest current and voltage while maintaining relatively low impedance.

CONCLUSION

The biomass-based bio-battery developed in this study was successfully fabricated using a coconut stem powder matrix combined with young cassava leaves, leucaena leaves, and calcium chloride (CaCl_2) as electrolyte components. The results demonstrate that variations in electrolyte composition have a significant effect on the electrochemical performance of the system. The optimum condition for young cassava leaves was obtained at 10 g, producing a voltage of 0.716 V, a current of 1.37 mA, and an impedance of 48.4 Ω . For CaCl_2 addition, the optimum performance was achieved at 2 g, resulting in 0.710 V, 2.83 mA, and 4.24 Ω , while leucaena leaves showed the best performance at 6 g, yielding 0.734 V, 3.96 mA, and 3.73 Ω . In general, increasing electrolyte mass initially enhances ion availability and conductivity; however, excessive addition leads to reduced ion mobility and increased ion–ion interactions, which negatively affect performance.

In addition, the choice of electrode pair strongly influenced the

bio-battery output. The graphite–aluminium combination exhibited the highest performance, achieving 0.734 V, 3.96 mA, and 3.73 Ω , which is attributed to the higher electrochemical reactivity of aluminium that facilitates more efficient electron transfer. In contrast, graphite–zinc and graphite–copper configurations showed lower performance due to less favorable redox behavior and reduced charge transfer efficiency.

Overall, the study highlights that

both electrolyte optimization and electrode selection play crucial roles in determining the electrochemical performance of biomass-based bio-batteries. The combined optimization of these parameters effectively enhances ion transport, increases voltage and current output, and reduces internal resistance. These findings indicate that coconut stem powder-based bio-batteries have strong potential as a sustainable and environmentally friendly alternative energy system.

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