

Development of a Hybrid Bio-Battery Based on the Combination of Guava Leaf Electrolyte, CaCl_2 and Banana Leaves on a Duck Eggshell Powder Matrix

Neli Sartika¹, Andi Arif Setiawan², Dui Yanto Rahman^{1*}

¹Department of Physics, Faculty of Science and Technology, Universitas PGRI Palembang, Palembang 30166, Indonesia

²Department of Environmental Science, Faculty of Science and Technology, Universitas PGRI Palembang, Palembang 30166, Indonesia

*e-mail: duiyantorahmanmsi@gmail.com

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Abstract

The increasing demand for electrical energy, along with the limitations of conventional energy sources, has driven the development of sustainable biomaterial-based alternative energy. This study aims to optimize the performance of a bio-battery through a multi-ion electrolyte system composed of guava leaves, calcium chloride (CaCl_2), and banana leaves, utilizing a duck eggshell powder matrix. The research was conducted using a stepwise experimental method by varying the mass of each component to determine the optimum condition. The first stage involved varying the mass of guava leaves (1-5 g), followed by the addition of CaCl_2 (0.5-2.5 g) under optimum conditions, and finally the variation of banana leaf mass (1-5 g). In addition, aluminum, copper, and zinc were used as anode materials, with graphite as the cathode. The parameters analyzed included voltage, current, and impedance. The results show that the optimum condition was achieved at 3 g of guava leaves, 1 g of CaCl_2 , and 2 g of banana leaves, using aluminum as the anode. Under these conditions, a voltage of 0.871 V, a current of 2.19 mA, and a minimum impedance of 3.29 Ω were obtained. The multi-ion electrolyte system significantly enhanced ionic conductivity, reduced internal resistance, and produced more stable electrical performance compared to a single-electrolyte system. The duck eggshell matrix also improved ion distribution and system stability. Therefore, this bio-battery demonstrates strong potential as an environmentally friendly and sustainable alternative energy source.

Keywords: Bio-battery, multi-ion electrolyte, biomaterials, ionic conductivity, alternative energy.

INTRODUCTION

Global energy demand continues to rise, necessitating the development of safer and more sustainable alternative energy sources (Sher et al., 2021). This issue has become increasingly critical as reliance on conventional batteries, such as lithium-ion and alkaline systems, poses significant environmental challenges due to the presence of heavy metals and toxic compounds that are difficult to degrade (Mishra et al., 2025). Battery waste has the potential to

contaminate soil and water resources, thereby adversely affecting human health and ecosystems (J. Zhang et al., 2024). One promising approach to addressing these challenges is the utilization of bio-batteries.

Bio-batteries are energy storage devices that utilize biodegradable biological materials and do not generate hazardous waste (Lee et al., 2021). This technology not only reduces the reliance on toxic chemical substances but also promotes the utilization of renewable resources, thereby representing a crucial

strategy in the transition toward sustainable energy systems (Jaiswal et al., 2022).

The utilization of organic materials containing natural electrolytes-including organic acids, minerals, metal ions, and phenolic compounds-demonstrates significant potential as a substitute for conventional chemical electrolytes (Yaman Uzunoglu & Yuksel, 2025). These compounds play a crucial role in facilitating ion transport mechanisms, which constitute the core of electrochemical reactions in bio-batteries (Dong et al., 2024).

Various types of leaves are known to contain high concentrations of minerals and ions, thereby enhancing ion mobility and the rate of electron transfer (Chand et al., 2024). Such leaf-based biomaterials represent effective natural electrolyte candidates and are highly relevant for the development of environmentally friendly energy technologies (Thongsai et al., 2024).

Previous bio-battery studies have utilized a wide range of biomaterials as electrolytes and supporting matrices to enhance the performance of environmentally friendly energy devices (Liedel, 2020). From the electrolyte perspective, several studies have explored liquid biomaterials derived from fruit and vegetable extracts, such as bilimbi (Tiyak et al., 2024), noni (Yanti and Rahman, 2024), tomato, lime (Mita et al., 2025), and cucumber (2025), due to their organic acid content and naturally occurring ions that can facilitate electrochemical processes. In terms of supporting matrices, numerous studies have employed porous biomaterials such as cassava pulp (Anjarsari et al., 2024), rice crust, activated carbon, and eggshells to improve mechanical stability, maintain ion distribution, and reinforce the structure of solid electrolytes (Rahman et al., 2024). Although these approaches have demonstrated promising results,

most studies remain focused on single biomaterial sources or simple combinations. Consequently, the synergistic potential arising from the integration of multiple biomaterials within bio-battery systems has not yet been fully explored (Karlilar Pata et al., 2025).

Guava leaves and banana leaves are two biomaterials that exhibit significant potential as natural electrolytes (Huynh et al., 2025). Banana leaves are rich in potassium, magnesium, and organic compounds that facilitate ion mobility (Pantoja et al., 2024). The combination of these two types of leaves is expected to generate a complementary synergistic effect, enabling the formation of a more stable and conductive electrolyte system. This synergy has the potential to enhance voltage output, current generation, and the operational stability of bio-batteries (Srivastava et al., 2025).

The optimization of leaf-based electrolytes can be enhanced through the addition of calcium chloride (CaCl_2), a strong electrolyte salt that readily ionizes to produce high concentrations of Ca^{2+} and Cl^- ions (Li et al., 2024). The presence of CaCl_2 enriches the ionic density within the system, increases ionic conductivity, and helps maintain electrolyte stability during electrochemical processes (Huamani et al., 2024). The integration of CaCl_2 with guava leaf and banana leaf extracts is expected to facilitate ion transport and improve electron transfer efficiency, thereby enhancing the overall performance of bio-batteries (Nundwe et al., 2023).

The performance of such systems can be further maximized through the use of duck eggshells as a supporting matrix (Venkategowda et al., 2025). Duck eggshells are primarily composed of calcium carbonate (CaCO_3) and possess a porous structure capable of effectively absorbing and retaining electrolytes

(Kiryakova & Kolchakova, 2023). These properties not only enhance mechanical stability but also help maintain uniform ion distribution, thereby enabling more consistent and efficient electrochemical reactions (Chatterjee et al., 2024). In addition to their technical advantages, the utilization of organic waste such as eggshells aligns with circular economy principles by increasing the value of previously underutilized materials (Miyamoto et al., 2021).

Such an integrative approach remains relatively underexplored in previous studies. Existing research has predominantly focused on the utilization of fruits, fruit peels, or plant gels as natural electrolytes (Suriana et al., 2025). In contrast, the combination of two types of leaves along with their integration with CaCl_2 and a duck eggshell matrix has not been extensively investigated in a systematic manner, despite the potential of these three components to produce a more stable, conductive, and innovative electrolyte system. This research gap highlights the need for the development of novel formulations capable of delivering enhanced performance in bio-battery systems.

Although previous studies have demonstrated promising advancements in the development of bio-batteries, most investigations have primarily focused on single biomaterial sources or relatively simple combinations. Consequently, the synergistic potential arising from the integration of multiple biomaterials within a single bio-battery system remains insufficiently explored.

Therefore, this study proposes an innovative hybrid bio-battery system by integrating guava leaf extract, banana leaf extract, and CaCl_2 within a duck eggshell matrix. This combination is expected to enhance ionic conductivity as well as the overall electrochemical performance of the system. This study aims to determine the optimal composition of the hybrid

electrolyte system in order to achieve maximum voltage output, current generation, and operational stability.

MATERIALS AND METHODS

The materials used in this study included guava leaves, CaCl_2 (Chenmocal Supply, South Tangerang, Indonesia) and banana leaves.

The preparation of the solid electrolyte began with a material pre-treatment stage. Fresh guava leaves were first washed with clean water to remove adhering impurities, then cut into small pieces and homogenized using a blender to obtain guava leaf extract. This extract served as the primary electrolyte source in the bio-battery system. Subsequently, the guava leaf extract was weighed at varying masses of 1 g, 2 g, 3 g, 4 g, and 5 g, then transferred into a beaker and homogenized using a magnetic stirrer for approximately 10 minutes to ensure uniform ion distribution.

Duck egg shells used as the supporting matrix were prepared by first washing them under running water to remove adhering impurities and residual membranes, followed by drying under sunlight until completely dry. The dried eggshells were then ground using a mortar into a fine powder and sieved through a 100-mesh sieve to obtain a uniform particle size. The duck eggshell powder was subsequently added gradually into the guava leaf extract solution until a homogeneous solid electrolyte paste was formed. The porous structure of the duck eggshell powder matrix plays a crucial role in absorbing and retaining the electrolyte, thereby enhancing the overall stability of the system.

The variation in the mass of guava leaf extract was conducted to determine the optimum composition that yields the maximum current and voltage output in the bio-battery system. After identifying

the optimum composition, calcium chloride (CaCl_2) was added with mass variations of 0.5 g, 1 g, 1.5 g, 2 g, and 2.5 g. The addition of CaCl_2 aimed to increase the ionic concentration within the system, thereby enhancing ionic conductivity and improving the electrochemical performance of the bio-battery.

Subsequently, at the optimum composition of guava leaf extract and CaCl_2 , banana leaf extract was introduced. The banana leaves were prepared by washing with clean water, cutting into small pieces, then blending and filtering to obtain the extract. The banana leaf extract was then added with mass variations of 1 g, 2 g, 3 g, 4 g, and 5 g to form a multi-ion electrolyte system. This variation was carried out to determine the most optimal electrolyte combination for generating maximum current and voltage output in the bio-battery system.

The bio-battery was assembled by uniformly applying a solid electrolyte onto the surface of a graphite sheet serving as the cathode, with dimensions of 3 cm $\times$ 4 cm. Subsequently, an aluminum sheet of identical dimensions was used as the anode and placed on top of the solid electrolyte layer based on a duck eggshell matrix containing guava leaf extract, banana leaf extract, and calcium chloride (CaCl_2). Both electrodes

were then configured into a single bio-battery cell and secured using transparent adhesive tape to maintain structural stability. The total mass of the electrodes coated with the electrolyte was measured to be approximately 5 g. The terminals of the anode and cathode were connected to a multimeter (Sanwa CD800A) using cables and alligator clips for voltage and current measurements, while the internal resistance was measured using a Battery Impedance Tester YR1035+.

All experiments were conducted at room temperature ($\pm 25^\circ\text{C}$) under ambient conditions. Each measurement was performed in triplicate to ensure the reproducibility and reliability of the data. The obtained data were analyzed using descriptive statistical methods, including mean value calculation and graphical representation, to evaluate the performance of the bio-battery system.

RESULTS AND DISCUSSION

The fabricated bio-battery was developed using guava leaf extract as the electrolyte ion source, with duck eggshell powder serving as a solid supporting matrix within the system. The mass of guava leaves was varied at 1 g, 2 g, 3 g, 4 g, and 5 g. The parameters evaluated included voltage (V), current (mA), and impedance (Ω), as presented in Table 4.1 and Figure 4.1.

Table 4.1. Relationship between the variation of guava leaves and voltage (V), current (mA), and impedance (Ω).

Variation of Guava Leaves (g)	Voltage (V)	Current (mA)	Impedance (Ω)
1	0.566	0.18	91.3
2	0.596	0.23	45.5
3	0.680	0.58	30.2
4	0.566	0.27	42.8
5	0.524	0.23	88.8

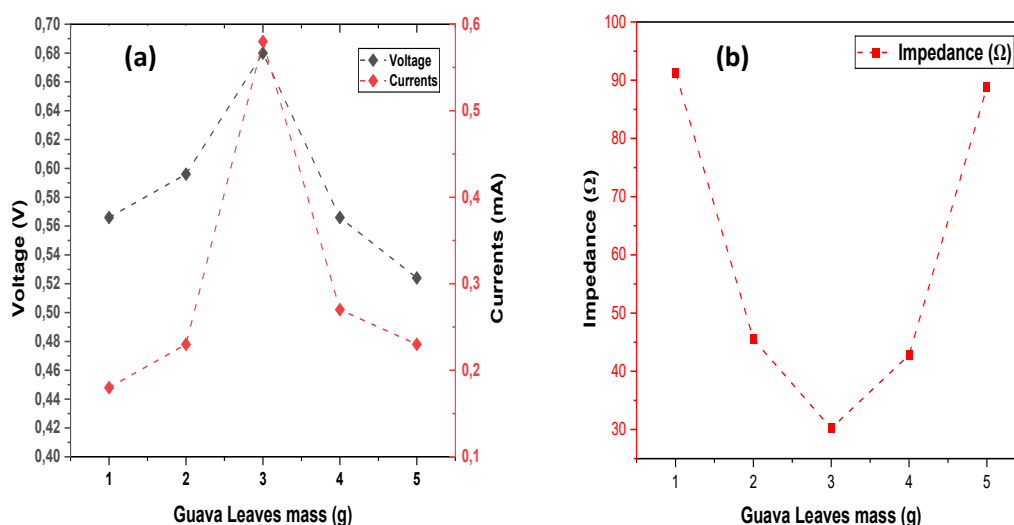


Figure 4.1. Relationship between the mass of guava leaves and (a) voltage (V) and current (mA), and (b) impedance (Ω) of the biobattery.

Table 4.1 and Figure 4.1 present the measured voltage, current, and impedance of the bio-battery with varying masses of guava leaves as the ion source in an electrolyte system based on a duck eggshell powder matrix. The mass variation was conducted to evaluate the effect of biomass quantity on the electrical performance of the bio-battery.

Based on the obtained data, it is evident that increasing the mass of guava leaves from 1 g to 3 g results in a significant enhancement in both current and voltage. The current increased from 0.18 mA at 1 g to 0.23 mA at 2 g, reaching a maximum value of 0.58 mA at 3 g. A similar trend was observed for the voltage, which increased from 0.566 V to 0.596 V and peaked at 0.680 V at a mass of 3 g.

This phenomenon is closely associated with changes in ion concentration and mobility within the system. Guava leaves contain various minerals, such as potassium, calcium, and magnesium, as well as organic compounds including flavonoids and tannins, which can ionize in an aqueous medium (El-Feky & AbdelRahman, 2025). At the initial stage of mass addition, the number of charge-carrying

ions increases, leading to higher ionic density within the system and more effective conduction pathways. This condition reduces ohmic resistance and enhances the current, in accordance with the fundamental relationship between current, voltage, and resistance (Arisesa et al., 2024).

However, at higher mass levels, a decline in performance may occur due to the increased viscosity and density of the electrolyte medium, which hinder ion mobility. Interactions among ions also become more dominant, potentially leading to the formation of ion pairs or aggregates that reduce the number of free ions available for conduction (Kang et al., 2022). This condition results in increased internal resistance and a decrease in ionic conduction efficiency. A similar phenomenon has been reported in various bio-electrochemical systems, where an optimum electrolyte concentration exists prior to performance degradation caused by limited ion mobility (Kim et al., 2024).

Impedance analysis further clarifies this relationship. The impedance value, initially 91.3 Ω at 1 g, decreased significantly to 45.5 Ω at 2 g and reached its lowest value of 30.2 Ω at 3 g. This

reduction indicates a decrease in internal resistance, allowing more efficient charge transfer. However, at a mass of 4 g, the impedance increased again to $42.8\ \Omega$ and rose more substantially at 5 g to $88.8\ \Omega$. This increase in internal resistance is consistent with the observed decline in current, indicating that the overall system resistance rises when the mass of guava leaves exceeds the optimum condition.

Figure 4.1 also indicates that when the ion concentration becomes excessively high, the system no longer exhibits an increase in conductivity. The reduced distance between ions enhances electrostatic interactions and promotes the formation of ion pairs, thereby decreasing the effective mobility of charge carriers (Ma et al., 2019). In addition, an excess of electrolyte within the matrix can lead to non-uniform distribution and increased diffusion resistance. The combined effect of these factors contributes to the observed increase in impedance and the decline in current at masses of 4 g and 5 g.

of the Grotthuss mechanism decreases due to the reduced ratio of water molecules to ions ($R < 10$), leading to disruption of the hydrogen-bond network and decreased proton mobility.

Furthermore, increased ionic concentration strengthens interionic interactions and promotes the formation of heterogeneous structures and stronger ionic correlations, as described in the liquid structure model by Abu-Lebdeh, ultimately resulting in increased internal resistance of the system (Bi & Salanne, 2024). The phenomenon of increased ionic conductivity resulting from the use of single-ion electrolytes has also been widely reported in various biopolymer-based electrolyte systems. A study conducted by (Ahmad & Isa, 2015) demonstrated that the incorporation of NH_4Cl as a single-ion source in a carboxymethyl cellulose (CMC) system significantly enhances ionic conductivity. In that study, the conductivity increased

A similar phenomenon has been widely reported across various electrolyte systems, where ionic conductivity exhibits a non-linear dependence on concentration. At low to moderate concentrations, an increase in the number of free ions leads to enhanced conductivity; however, beyond an optimum point, conductivity tends to decrease due to the dominance of interionic interactions and ion-pair formation. The results of this study are consistent with findings reported in acid-based electrolyte systems by (Al-Salih & Abu-Lebdeh, 2024), which indicate that ionic conductivity is strongly influenced by the degree of dissociation and proton transport mechanisms in aqueous media. At low concentrations, strong acids such as HCl and HNO_3 are nearly fully dissociated, generating a high concentration of protons and enhancing conductivity through proton transfer, i.e., rapid proton migration via the hydrogen-bond network of water. However, at higher concentrations, the effectiveness progressively with increasing salt concentration, reaching an optimum at approximately 16 wt.% with a conductivity value of $1.43 \times 10^{-3}\ \text{S cm}^{-1}$. This improvement is attributed to the increased number of NH_4^+ and Cl^- ions acting as charge carriers, as well as enhanced ion mobility within the polymer matrix. Moreover, the increase.

In conductivity is associated with the expansion of the amorphous phase, which facilitates ion transport within the electrolyte structure. However, when the salt concentration exceeds the optimum level, ionic conductivity decreases. This decline is primarily due to stronger interionic interactions that promote ion pairing, thereby reducing the number of free ions available for charge transport. In addition, higher salt concentrations increase the viscosity of the system, which ultimately hinders ion mobility. However, when the concentration is increased beyond this point, the

conductivity decreases. This decline is solvated phases, as well as intensified interionic interactions that hinder ion conductivity. A similar phenomenon has also been observed in weak acid systems such as $\text{H}_3\text{PO}_4/\text{H}_2\text{O}$, although the maximum conductivity is significantly lower, at approximately 255 mS cm^{-1} . This indicates that the degree of acid dissociation plays a crucial role in determining the electrical conductivity of the solution.

The performance of the bio-battery is strongly influenced by the balance between the number of available ions and their ability to move freely within the system. A mass of 3 g represents the most optimal condition, as it yields the highest current, the lowest impedance,

attributed to the formation of hydrated or movement. As a result, ion mobility is reduced, leading to a decrease in and the maximum voltage.

These results confirm that controlling the electrolyte composition is a critical aspect in the design of guava leaf-based bio-batteries, as it determines the efficiency of charge transport and the stability of the electrical output.

To enhance the current and voltage of the bio-battery, calcium chloride (CaCl_2) was added to the banana leaf-based electrolyte system at its optimum composition. Calcium chloride was selected as an additional ionic source due to its ability to improve the ionic conductivity of the solid electrolyte system.

Table 4.2. Relationship between CaCl_2 variation and guava leaves at the optimum mass with respect to voltage (V), current (mA), and impedance (Ω).

Variation of CaCl_2 (g)	Voltage (V)	Current (mA)	Impedance (Ω)
0.5	0.651	1.88	02.45
1.0	0.864	2.11	02.25
1.5	0.761	1.98	09.11
2.0	0.678	1.72	09.45
2.5	0.654	1.68	09.55

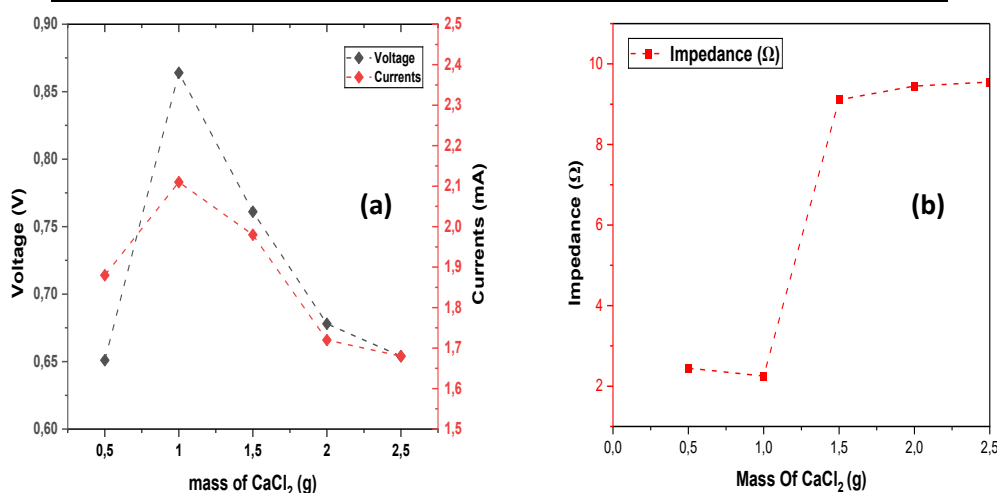


Figure 4.2. Relationship between CaCl_2 mass and the optimum composition of guava leaves with (a) voltage (V) and current (mA), and (b) impedance (Ω) of the biobattery.

Table 4.2 and Figure 4.2 show that the measurement data indicate that variations in CaCl_2 mass have a direct influence on the electrical characteristics

of the system under the optimum mass condition of guava leaves. When the mass of CaCl_2 was increased from 0.5 g to 1.0 g, the current increased from 1.88

mA to 2.11 mA, reaching its highest value at 1.0 g. Beyond this point, the current decreased to 1.98 mA at 1.5 g, followed by further declines to 1.72 mA at 2.0 g and 1.68 mA at 2.5 g. A similar trend was observed for voltage. The voltage increased from 0.651 V at 0.5 g to a maximum of 0.864 V at 1.0 g, then decreased to 0.761 V at 1.5 g, 0.678 V at 2.0 g, and 0.654 V at 2.5 g. This trend indicates that the addition of CaCl_2 is only effective up to an optimum threshold, beyond which system performance begins to decline.

Impedance analysis further clarifies this relationship. The impedance value, initially $22.45 \, \Omega$ at 0.5 g, slightly decreased to $22.25 \, \Omega$ at 1.0 g, representing the lowest value in the system. This reduction indicates relatively low internal resistance, allowing more efficient ion transport. However, when the mass of CaCl_2 was increased to 1.5 g, the impedance rose significantly to $29.11 \, \Omega$ and continued to increase to $29.45 \, \Omega$ at 2.0 g and $29.55 \, \Omega$ at 2.5 g. This increase in internal resistance is consistent with the observed decline in current, indicating that the overall system resistance increases when the ion concentration exceeds the optimum condition.

From an electrochemical perspective, the initial improvement in performance can be attributed to the increase in the number of free ions in the solution resulting from the dissociation of CaCl_2 into Ca^{2+} and Cl^- . Within the 0.5–1.0 g mass range, this increase in ion concentration accelerates charge transport mechanisms within the electrolyte, thereby reducing internal resistance and enhancing current up to the optimum condition. At this stage, ion distribution remains relatively homogeneous, and interionic interactions are not yet significant, resulting in high ion mobility and improved system conductivity.

In contrast, at higher concentrations, the system begins to exhibit a decline in performance. An increase in CaCl_2 mass beyond 1.0 g leads to higher ion density, resulting in stronger electrostatic interactions among ions, particularly those involving divalent Ca^{2+} species (Zhang et al., 2020). This promotes ion pairing or aggregation, thereby reducing the number of free ions available for charge conduction (Kang et al., 2022). In addition, higher concentrations may increase the viscosity of the electrolyte medium, which in turn decreases ion diffusion coefficients and increases electrical resistance (Vincent et al., 2021). This phenomenon is reflected in the increase in impedance and the decrease in current observed at 1.5–2.5 g, indicating that the system has exceeded its optimum condition and that ion transport efficiency has declined.

This phenomenon is consistent with the reported effect of plasticizer type, as demonstrated by Samsudin and Isa (2016) through the use of ethylene carbonate (EC) in a carboxymethyl cellulose (CMC)- NH_4Br -based electrolyte system. In the absence of a plasticizer, the maximum conductivity achieved was $1.12 \times 10^{-4} \, \text{S cm}^{-1}$ at 25 wt.% NH_4Br composition. After the addition of EC, the conductivity increased significantly to $3.31 \times 10^{-3} \, \text{S cm}^{-1}$. This enhancement is attributed to the role of EC in promoting salt dissociation and accelerating the protonation process, thereby increasing both the number and mobility of H^+ ions within the polymer matrix. In addition, the system exhibited a conductivity-temperature relationship following the Arrhenius equation, indicating that ion transport is governed by activation energy. However, excessive addition of plasticizer may lead to a decrease in conductivity due to disruption of ion transport pathways within the polymer matrix. This phenomenon is consistent with the study by (Yang et al., 2021) on

dual-salt electrolytes in high-nickel cathode lithium-ion batteries, which demonstrated that variations in the ratio of two lithium salts, LiPF_6 and LiDFP , significantly influence impedance and the electrochemical performance of the cell. Area-specific impedance (ASI) measurements revealed that all dual-salt systems exhibited a much smaller increase in impedance compared to the single-salt baseline (Gen2) up to 99 cycles. The compositions of 1.1 M + 0.1 M and 1.0 M + 0.2 M showed the best performance, with impedance increases of only about 30% relative to the baseline system, indicating these as optimum compositions.

This improvement is attributed to the synergistic effect of both salts in forming a more stable electrode-electrolyte interfacial layer and facilitating Li^+ transport, thereby reducing charge transfer resistance. However, a higher fraction of LiDFP leads to performance degradation at high current rates due to reduced bulk ionic conductivity. This indicates that increasing salt concentration does not always result in overall performance enhancement of the system. The phenomenon of increased ionic conductivity in electrolyte systems has also been reported in studies based on lithium perchlorate (LiClO_4) in a mixed solvent of propylene carbonate (PC) and 1,2-dimethoxyethane (DME), which demonstrate that binary electrolyte systems can enhance Li^+ ion mobility and improve ion transport efficiency in solution. In these studies, conductivity initially increases with the addition of salt concentration, where the number of free Li^+ and ClO_4^- ions rises, thereby increasing the contribution of charge carriers within the system. In addition, variations in solvent composition significantly affect ionic performance, where an increased fraction of DME, which has a lower viscosity (~ 0.46 cP)

compared to PC (~ 2.40 cP), reduces ion transport resistance and enhances overall ion mobility.

However, this system exhibits a maximum behavior, where conductivity increases with composition up to an optimum at approximately 70-75% DME, and then decreases at higher DME fractions due to a reduction in the dielectric constant of the mixture and enhanced ion-pair formation. In addition, from a concentration perspective, the highest molar conductivity is observed at low salt concentration, around 0.1 M LiClO_4 , whereas at higher concentrations such as 1.0 M and 2.0 M, conductivity decreases due to stronger ion-ion interactions and the formation of ion associations that hinder ion mobility.

Furthermore, the optimum composition of this electrolyte system lies in the range of 60-70% DME, indicating a balance between low viscosity and a sufficiently high dielectric constant to effectively sustain ion dissociation. Under these conditions, the system exhibits higher ion mobility, a more homogeneous ion distribution, and minimized ion-pair formation that could otherwise reduce conductivity.

In contrast, at excessively high DME fractions or elevated salt concentrations, enhanced electrostatic interactions among ions lead to ion aggregation and a reduction in the number of free ions contributing to conductivity. This behavior demonstrates that optimum conductivity is achieved when a balance is maintained between the concentration of free ions and maximum ion mobility, resulting in more efficient and stable ion transport within the binary electrolyte system.

In addition, the solid matrix within the system also plays a crucial role in determining ion distribution. The matrix structure enables optimal ion diffusion under certain conditions; however, at high electrolyte concentrations, an excess of ions may lead to blockage of diffusion pathways and increase the internal resistance of the system (Zheng et al., 2025).

To enhance the current and voltage of the bio-battery system, variations in

banana leaf mass were introduced into a system that had previously utilized a combination of guava leaf electrolyte and CaCl_2 at optimum conditions. This addition aimed to evaluate the extent to which ions derived from banana leaves could further strengthen the pre-formed electrolyte system through a multi-ion synergistic effect. The influence of banana leaf mass variation on the electrical performance of the bio-battery is presented in Table 4.3 and Figure 4.3.

Table 4.3. Relationship between guava leaves, CaCl_2 , and banana leaves under optimum conditions with respect to voltage (V), current (mA), and impedance (Ω).

Banana Leaf Variation (g)	Voltage (V)	Current (mA)	Impedance (Ω)
1	0.790	1.80	9.24
2	0.871	2.19	3.29
3	0.784	1.57	8.21
4	0.778	1.36	10.33
5	0.720	1.27	15.47

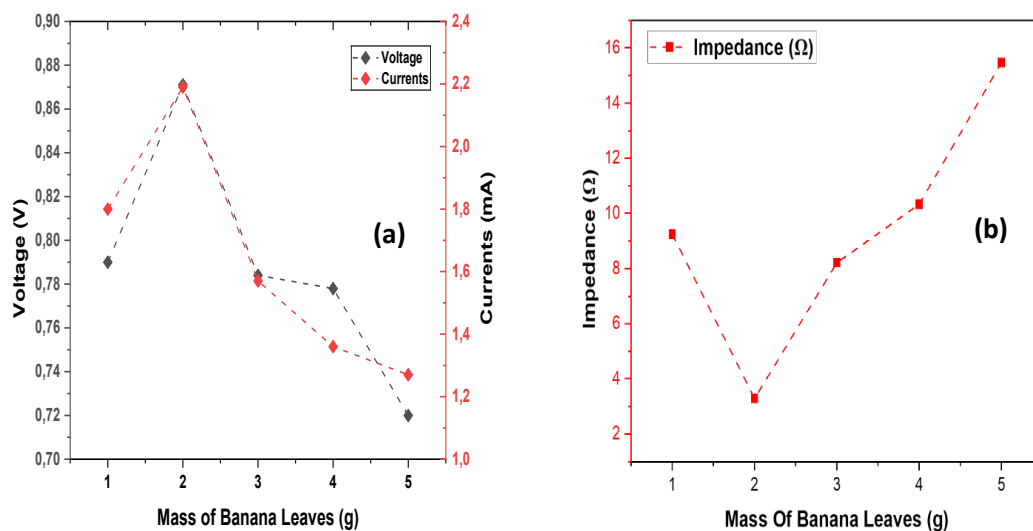


Figure 4.3 Relationship between banana leaf mass and the optimum composition of guava leaves and CaCl_2 with (a) voltage (V) and current (mA), and (b) impedance (Ω) of the bio-battery.

Table 4.3 and Figure 4.3 show that the measurement data indicate that variations in banana leaf mass influence the electrical characteristics of the system under optimum conditions. When the mass was increased from 1 g to 2 g, the

current increased from 1.80 mA to 2.19 mA, reaching its highest value at 2 g. Beyond this point, the current decreased to 1.57 mA at 3 g, followed by further reductions to 1.36 mA at 4 g and 1.27 mA at 5 g. A similar trend was observed

for voltage. The voltage increased from 0.790 V at 1 g to a maximum of 0.871 V at 2 g, then decreased to 0.784 V at 3 g, 0.778 V at 4 g, and 0.720 V at 5 g. This trend indicates that increasing banana leaf mass is only effective up to a certain threshold, beyond which system performance declines.

Impedance analysis further clarifies this relationship. The impedance value, which was initially 9.24 Ω at 1 gram, decreased significantly to 3.29 Ω at 2 grams, representing the lowest value in the system. This decrease indicates a reduction in internal resistance, allowing charge transfer to occur more efficiently. However, at a mass of 3 grams, the impedance increased again to 8.21 Ω , and continued to rise to 10.33 Ω at 4 grams, reaching the highest value of 15.47 Ω at 5 grams. This increase in internal resistance is consistent with the observed decrease in current, indicating that the total system resistance increases when the mass of banana leaves exceeds the optimum condition.

This pattern indicates that the addition of guava leaves contributes to an increase in electrolyte conductivity up to an optimum condition. Guava leaves are known to contain various mineral ions such as potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), as well as active organic compounds that can be ionized (Ogbonnia et al., 2025b). The presence of these ions increases the number of charge carriers in the electrolyte system, thereby enhancing the system's ability to conduct electric current.

In addition, the porous biomass structure of guava leaves, which is capable of absorbing water, also plays a role in maintaining the moisture content of the electrolyte system. The presence of water within the matrix is essential as an ion transport medium, enabling more stable and continuous ion diffusion conductivity by enhancing the number of free ions and suppressing the formation of immobile ionic aggregates. In contrast,

pathways. This condition enhances ion mobility under certain conditions, particularly at the optimum mass.

However, once the mass of guava leaves exceeds the optimum condition, further increases in biomass lead to a decline in conductivity. This phenomenon can be explained by several key mechanisms. First, ionic saturation occurs, where excessively high ion concentrations intensify electrostatic interactions among ions, thereby hindering their mobility. Second, biomass accumulation reduces the effective porosity of the matrix, resulting in restricted ion diffusion pathways. Third, the ion distribution within the system becomes less homogeneous, which ultimately decreases charge transport efficiency (Tucci et al., 2025).

A similar phenomenon was also reported by (Karpierz et al., 2016), who demonstrated that the formation of a ternary system consisting of ionic liquids, lithium salts, and glymes (triglyme/tetraglyme) can enhance the number of highly mobile free Li^+ ions through the formation of positively charged lithium-glyme solvation complexes. Ionic conductivity increased significantly from 0.61 $mS\ cm^{-1}$ (binary system) to 1.75 $mS\ cm^{-1}$ (1:2 ratio) and reached 3.73 $mS\ cm^{-1}$ (1:5.6 ratio) at 20 $^{\circ}C$, representing approximately a six-fold increase, and up to a sixteen-fold increase at 70 $^{\circ}C$. This enhancement is attributed to reduced viscosity and increased ion dissociation, leading to a higher number of charge carriers. In addition, the lithium transference number increased from 0.04 to 0.23, indicating that Li^+ ions dominate the charge transport mechanism.

Electrolyte composition plays a crucial role in determining the optimum condition, where a salt fraction of $x = 0.10-0.15$ combined with a high glyme ratio (1:5.6) yields maximum low glyme ratios promote ion aggregation and reduce conductivity. Therefore, the combination of a moderate

salt fraction and a high glyme ratio results in optimal ionic performance. The phenomenon of increased ionic conductivity in electrolyte systems has also been reported in a ternary solid polymer electrolyte system based on PVA-CS-FSG doped with NaSCN, which demonstrates that increasing salt concentration significantly enhances both the number of charge carriers and ion mobility within the polymer matrix. In this study, ionic conductivity increased from 1.21×10^{-7} S/cm at 10 wt% NaSCN to a maximum value of 2.64×10^{-6} S/cm at the optimum composition of 40 wt% NaSCN. This improvement is attributed to the increased number of free ions (Na^+ and SCN^-) and a reduction in the degree of polymer crystallinity from approximately 38.5% to 17.2%, resulting in a more amorphous structure that provides more efficient ion transport pathways. In addition, the bulk resistance (R_b) significantly decreased with increasing salt concentration, indicating a higher charge carrier density within the electrolyte system. However, when the salt concentration was further increased to 50 wt%, the conductivity decreased to approximately 2.08×10^{-6} S/cm, which is attributed to ion pairing and ion aggregation that hinder ion mobility. This condition suggests that excessive ion concentration strengthens electrostatic interactions, thereby reducing the efficiency of ion transport. Therefore, the optimum composition was achieved at 40 wt% NaSCN, where a balance between free ion concentration and high ion mobility was obtained. This confirms that maximum conductivity in ternary systems is achieved when the polymer structure is sufficiently amorphous and ion distribution is homogeneous, enabling efficient ion transport.

Thus, the resulting electrolyte system can be classified as a complex multi-ion system, in which interactions between natural ions and additional ions contribute to the enhancement of bio-battery performance. However, when the biomass content becomes excessively high, the complexity of ion interactions increases, which in turn reduces ion mobility and increases internal resistance.

At this stage, an evaluation was conducted on the effect of variations in electrode pairs on the performance of the bio-battery under optimal electrolyte conditions. The electrode combinations employed included graphite-aluminum, graphite-copper, and graphite-zinc, in order to examine differences in electrochemical characteristics in generating current, voltage, and impedance values as indicators of the system's internal resistance.

These variations in electrode pairs influence the oxidation-reduction reactions occurring at the electrode surfaces, thereby affecting charge transfer efficiency. From an electrochemical perspective, cell performance is determined by the potential difference between the anode and cathode, which depends on the standard reduction potentials of each material (Baranowska et al., 2018).

The selection of electrode combinations significantly affects voltage output, current generation, and internal resistance, as reflected in the impedance values. In this study, graphite serves as the cathode, while aluminum, copper, and zinc function as anodes with distinct characteristics, resulting in variations in bio-battery performance. The measurement results are presented in Table 4.4.

Table 4.4. Relationship between electrode variations and guava leaves, CaCl_2 , and banana leaves under optimum conditions with respect to voltage (V), current (mA), and impedance (Ω).

Anode and Cathode Variations	Voltage (V)	Current (mA)	Impedance (Ω)
Graphite-Aluminium	0.871	2.19	3.29
Graphite-Copper	0.148	0.23	1.221
Graphite-Zinc	0.376	0.07	4.54

Table 4.4 shows the effect of electrode pair variations on the voltage, current, and impedance of the bio-battery under optimum electrolyte conditions. The measurement results indicate that the graphite-aluminium pair exhibits the best overall performance, with a voltage of 0.871 V, a current of 2.19 mA, and an impedance of 3.29 Ω . In contrast, the graphite-copper pair shows lower performance, with a voltage of 0.148 V and a current of 0.23 mA, despite having the lowest impedance of 1.221 Ω . Meanwhile, the graphite-zinc pair yields a voltage of 0.376 V, a current of 0.07 mA, and an impedance of 4.54 Ω , indicating intermediate performance but relatively higher internal resistance.

The differences in performance are closely related to the standard reduction potentials of each electrode, which govern the tendency of redox reactions within the system. Aluminium has a standard reduction potential of -1.66 V, zinc (Zn) -0.76 V, while copper exhibits a value of +0.34 V (Bard & Faulkner, 2001; Haynes, 2016). Metals with more negative reduction potentials are more prone to oxidation and therefore act as anodes, enabling the generation of a higher electron flow in the electrochemical cell.

In the graphite-aluminium electrode pair, aluminium acts as a highly reactive anode, where oxidation occurs intensively, generating a substantial electron flow toward the graphite electrode serving as the cathode. This results in increased current and voltage output. In addition, the relatively low

impedance value indicates that charge transfer within the system proceeds efficiently. In the graphite-zinc electrode pair, zinc also acts as the anode; however, its tendency to undergo oxidation is lower compared to aluminium. Consequently, fewer electrons are generated, resulting in a relatively low measured current. The higher impedance value indicates greater internal resistance, which further limits charge transport efficiency within the system.

In contrast, in the graphite-copper electrode pair, copper has a positive reduction potential and is therefore less prone to oxidation. This condition leads to non-optimal electrochemical reactions, resulting in low voltage and current outputs. Although the impedance value is relatively low, limitations in electron transfer processes still result in poor overall system performance. Overall, these results confirm that differences in electrochemical potentials between electrodes are a key factor in determining the performance of the bio-battery.

CONCLUSION

The biomass-based bio-battery system in this study was successfully developed using a duck eggshell powder matrix combined with guava leaves, calcium chloride (CaCl_2), and banana leaves as electrolyte sources. Variations in the mass of guava leaves exhibited a significant influence on the bio-battery performance, with the optimum condition achieved at 3 g, producing a voltage of

0.680 V, a current of 0.58 mA, and an impedance of 30.2 Ω . Increasing the mass up to the optimum point enhanced the number of free ions and the system's conductivity, whereas excessive mass led to performance deterioration due to limitations in ion mobility. The addition of CaCl_2 also played a crucial role in improving system performance, where the optimum mass of 1 g resulted in a voltage of 0.864 V, a current of 2.11 mA, and an impedance of 22.25 Ω . This improvement is attributed to the presence of Ca^{2+} and Cl^- ions, which enhance electrolyte conductivity; however, at higher concentrations, increased ion-ion interactions reduce ion mobility and elevate internal resistance.

Furthermore, the incorporation of banana leaves as an additional electrolyte component was proven to enhance the bio-battery performance through the synergistic effect of a multi-ion electrolyte system. The optimum mass of 2 g yielded a voltage of 0.871 V, a current of 2.19 mA, and an impedance of 3.29 Ω , whereas higher masses led to ion saturation and increased diffusion resistance. Variations in electrode pairs also exhibited a significant influence on performance, with the graphite-aluminum pair delivering the best results, achieving a voltage of 0.871 V, a current of 2.19 mA, and an impedance of 3.29 Ω . This superior performance is attributed to the higher oxidation tendency of aluminum, which facilitates greater electron flow. In contrast, graphite-zinc and graphite-copper pairs demonstrated lower performance due to differences in standard reduction potentials that affect electron transfer capability.

Overall, the optimization of electrolyte composition and the appropriate selection of electrodes play a critical role in enhancing conductivity, current, and voltage while reducing internal resistance. These findings indicate that biomass-based bio-batteries hold significant potential as

environmentally friendly and sustainable alternative energy sources.

REFERENCES

- Ahmad, N. H. B., & Isa, M. I. N. B. M. (2015). Proton conducting solid polymer electrolytes based carboxymethyl cellulose doped ammonium chloride: ionic conductivity and transport studies. *International Journal of Plastics Technology*, 19(1), 47–55.
- Al-Salih, H., & Abu-Lebdeh, Y. (2024). Investigating the phase diagram-ionic conductivity isotherm relationship in aqueous solutions of common acids: hydrochloric, nitric, sulfuric and phosphoric acid. *Scientific Reports*, 14(1), 7894.
- Arisesa, H., Idrus Sutan Nameh, S. M., Iqbal, F., Wijayanto, Y. N., & Adhi, P. (2024). Characterization of Tropical Leaf Properties Considering Millimeter Wave Wireless. *2024 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*, 405–408.
- Baranowska, M., Suliborska, K., Chrzanowski, W., Kusznierevicz, B., Namieśnik, J., & Bartoszek, A. (2018). The relationship between standard reduction potentials of catechins and biological activities involved in redox control. *Redox Biology*, 17, 355–366.
- Bi, S., & Salanne, M. (2024). Cluster analysis as a tool for quantifying structure-transport properties in simulations of superconcentrated electrolyte. *Chemical Science*, 15(28), 10908–10917.

- Chand, P., Ambwani, S., Singh, B. R., Ambwani, T. K., & Dubey, A. (2024). Exploring the Antioxidant Potential of Fagopyrum esculentum Moench (Common Buckwheat) Leaf Extract. *Journal of Advances in Biology & Biotechnology*, 27(11), 1243–1251.
- Chatterjee, D., Naik, K. G., Vishnugopi, B. S., & Mukherjee, P. P. (2024). Electrodeposition Stability Landscape for Solid–Solid Interfaces. *Advanced Science*, 11(6).
- Dong, H., Wang, L., Zhang, F., Li, H., Zhao, X., Wei, W., Kang, Y., Yan, C., Sang, Y., Liu, H., & Wang, S. (2024). Green proton reservoirs of PANI for disposable high-performance zinc-ion batteries. *Nano Energy*, 128(1), 109768.
- El-Feky, A. M., & AbdelRahman, M. A. E. (2025). Harvest time and soil-plant relationship effects on phytochemical constituency and biological activities of psidium guajava L. leaves. *Scientific Reports*, 15(1), 25907.
- Huamani, A. L., Laucirica, G., Allegretto, J. A., Toimil-Molares, M. E., Picco, A. S., Ceolín, M. R., Passos, A. R., Azzaroni, O., Mamisollé, W. A., & Rafti, M. (2024). Calcium chloride as an ionic response modulator in metal–organic framework-modified nanochannels (MOF@SSNs): enhancing ionic current saturation and selectivity. *Inorganic Chemistry Frontiers*, 11(24), 8627–8639.
- Huynh, H. D., Nargotra, P., Wang, H.-M. D., Shieh, C.-J., Liu, Y.-C., & Kuo, C.-H. (2025). Bioactive Compounds from Guava Leaves (Psidium guajava L.): Characterization, Biological Activity, Synergistic Effects, and Technological Applications. *Molecules*, 30(6), 1278.
- Jaiswal, K. K., Chowdhury, C. R., Yadav, D., Verma, R., Dutta, S., Jaiswal, K. S., SangmeshB, & Karuppasamy, K. S. K. (2022). Renewable and sustainable clean energy development and impact on social, economic, and environmental health. *Energy Nexus*, 7(1), 100118.
- Kang, P., Wu, L., Chen, D., Su, Y., Zhu, Y., Lan, J., Yang, X., & Sui, G. (2022). Dynamical Ion Association and Transport Properties in PEO–LiTFSI Electrolytes: Effect of Salt Concentration. *The Journal of Physical Chemistry B*, 126(24), 4531–4542.
- Karlilar Pata, S., Pata, U. K., & Wang, Q. (2025). Ecological power of energy storage, clean fuel innovation, and energy-related research and development technologies. *Renewable Energy*, 241(1), 122377.
- Kiryakova, D., & Kolchakova, G. (2023). Preparation And Characterization Of Eggshells Powders Reated With Hydrochloric Acid And Sodium Hydroxide. *Advanced Engineering Letters*, 2(3), 81–87.
- Lee, M. H., Lee, J., Jung, S., Kang, D., Park, M. S., Cha, G. D., Cho, K. W., Song, J., Moon, S., Yun, Y. S., Kim, S. J., Lim, Y. W., Kim, D., & Kang, K. (2021). A Biodegradable Secondary Battery and its Biodegradation Mechanism for Eco-Friendly Energy-Storage Systems. *Advanced Materials*, 33(10).
- Liedel, C. (2020). Sustainable Battery Materials from Biomass. *ChemSusChem*, 13(9), 2110–2141.
- Ma, J., Li, K., Li, Z., Qiu, Y., Si, W., Ge, Y., Sha, J., Liu, L., Xie, X., Yi, H., Ni, Z., Li, D., & Chen, Y. (2019). Drastically Reduced Ion Mobility in a Nanopore Due to Enhanced

- Pairing and Collisions between Dehydrated Ions. *Journal of the American Chemical Society*, 141(10), 4264–4272.
- Mishra, P., Apte, S., & Dhok, V. (2025). Assessing the environmental impact and risks associated with uncontrolled disposal of end-of-life lithium-ion batteries on soil. *MethodsX*, 15, 103576.
- Miyamoto, M., Kitada, A., Adachi, K., Fukami, K., & Murase, K. (2021). Lead Electrodeposition from Highly Concentrated Calcium Chloride Aqueous Solutions. *Journal of MMIJ*, 137(11), 103–109.
- Nundwe, V., Makokha, A. B., & Mwasiagi, J. I. (2023). Effect of electrolyte additives derived from natural plant extracts - Hibiscus Sabdariffa & Bidens Pilosa, on electrochemical performance of a lead-acid battery. *Cleaner Engineering and Technology*, 17(1), 100705.
- Pantoja, F., Beszédes, S., Gyulavári, T., Illés, E., Kozma, G., & László, Z. (2024). Ammonium ion removal from aqueous solutions in the presence of organic compounds, using biochar from banana leaves. Competitive isotherm models. *Heliyon*, 10(10), e31495.
- Sher, F., Curnick, O., & Azizan, M. T. (2021). Sustainable Conversion of Renewable Energy Sources. *Sustainability*, 13(5), 2940.
- Srivastava, V., Sharma, R., & Vaish, R. (2025). Experimental learning on plant-leaf anatomy through electrical conductivity: a multidisciplinary educational inquiry into bio-batteries. *Physics Education*, 60(1), 015017.
- Suriana, I. W., Antari, I. A. D. G., Ariastina, W. G., & Setiawan, I. N. (2025). Journal Review: Potential of Orange Peel, Fruit, and Vegetable Waste as an Environmentally Friendly Electrolyte Source for Bio-Batteries. *Journal La Lifesci*, 6(4), 327–339.
- Thongsai, N., Jirawanichakun, N., Jorn-am, T., Supchocksoonthorn, P., & Paoprasert, P. (2024). Hydroquinone-mediated, bio-renewable corn starch electrolyte assembled with corn leaf-derived activated carbon for a high-performance, sustainable supercapacitor. *Biomass and Bioenergy*, 182(1), 107095.
- Tiyak, S. A., Dui Yanto Rahman, & Rita Sulistyowati. (2024). Pembuatan Bio-Baterai Berbahan Dasar Sari Belimbing Wuluh dan NaCl sebagai Sumber Ion serta Onggok Singkong Sebagai Matriks. *Jurnal Penelitian Fisika Dan Terapannya (JUPITER)*, 6(1), 1–10.
- Tucci, M., Aulenta, F., Corneliussen, M. M., Rosa, L. F. M., Picioreanu, C., & Marzocchi, U. (2025). Differential ion transport and biomass charges create strong electric fields in anammox granules. *Water Research*, 281, 123663.
- Venkategowda, T., S, P., & P R, A. (2025). Mechanical Properties of Duck Eggshell Powder Reinforced Epoxy Composites - A Study on Effect of Reinforcement. *Engineering and Technology Journal*, 10(05).
- Vincent, I., Lee, E.-C., & Kim, H.-M. (2021). Comprehensive impedance investigation of low-cost anion exchange membrane electrolysis for large-scale hydrogen production. *Scientific Reports*, 11(1), 293.
- Yaman Uzunoglu, G., & Yuksel, R. (2025). Toward Green and Sustainable Zinc-Ion Batteries: The Potential of Natural Solvent-Based

Electrolytes. *Small*, 21(6).

Zhang, Y., Zhang, L., Lv, T., Chu, P. K., & Huo, K. (2020). Two-Dimensional Transition Metal Chalcogenides for Alkali Metal Ions Storage. *ChemSusChem*, 13(6), 1114–1154.

Zheng, Z., Cheng, W., Li, X., Sun, J.,

Wang, W., Liu, S., Zhao, D., & Yu, H. (2025). Bio-based supramolecular dual-network gel electrolytes with synergistic mechanical robustness and ionic conductivity for high-performance flexible Zn-ion batteries. *Energy Storage Materials*, 82(1), 104563.