

Enhancing Bio-Battery Performance through a Multi-Ion Electrolyte System of *Moringa oleifera*, NH_4Cl , and *Eichhornia crassipes* in a Sugarcane Bagasse Matrix

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Abstract

The global energy crisis due to dependence on fossil fuels and increasing carbon emissions is encouraging the development of alternative energy based on local resources, one of which is biomass bio-batteries from organic waste. This study aims to analyze and optimize the performance of bagasse-based bio-batteries with a multi-ion electrolyte system consisting of moringa leaf powder (*Moringa oleifera*), ammonium chloride (NH_4Cl), and water hyacinth powder (*Eichhornia crassipes*). The research was carried out in laboratory experiments through variations in electrolyte composition and the use of aluminum, copper, and zinc anodes with graphite cathodes. The parameters measured include voltage, current, and impedance using a digital multimeter and the YR1035+ Battery Impedance Tester. The results showed optimal conditions in the composition of 6 g moringa leaf powder, 3 g NH_4Cl , and 3 g water hyacinth powder with a voltage of 0.921 V, a current of 4.81 mA, and a minimum impedance of 3.02 Ω . The addition of NH_4Cl improves ion mobility and lowers internal resistance, while water hyacinth powder helps maintain electrolyte stability and ion diffusion. Electrode variations indicate metals with a higher oxidation tendency result in better electrical performance. This biomass-based multi-ion electrolyte system has been proven to improve ionic conductivity, lower internal resistance, and produce more stable electrical output, potentially developing as an alternative energy source that is environmentally friendly and sustainable for the future.

Keywords: Bio-batteries, bagasse, multi-ion electrolyte, ionic conductivity, alternative energy.

INTRODUCTION

The global energy sector in the 21st century remains heavily dependent on fossil fuels, which account for approximately 80% of the world's energy supply. The extensive use of fossil fuels generates approximately 36–37 gigatons of CO_2 emissions annually. These emissions have contributed to an increase in global temperatures of approximately 1.2 °C above pre-industrial levels (IEA, 2023). This situation not only exacerbates climate change but also highlights the long-term unsustainability of the current energy system. In Indonesia, approximately 85–90% of

national energy consumption continues to rely on fossil-based sources, while the share of renewable energy remains below 15% (KESDM, 2023). Amid rising energy demand and the limited availability of domestic energy reserves, the development and deployment of clean energy technologies have become increasingly critical. Such efforts are aligned with the national policy framework aimed at achieving the Net Zero Emissions target by 2060 (IEA, 2022).

One promising innovation that has attracted considerable attention is the bio-battery, an electrochemical system that utilizes biological materials, biomass, or

redox-active biomolecules as the primary components of redox reactions (e.g., within the electrodes or electrolyte) for electricity generation and energy storage (Liedel, 2020). The operating principle of a bio-battery is based on the conversion of chemical energy into electrical energy through oxidation reactions at the anode and reduction reactions at the cathode, employing naturally derived biological materials as the electrolyte medium (Yu et al., 2019). Unlike conventional batteries, such as lithium-ion (Li-ion), nickel-cadmium (Ni-Cd), and lead-acid (Pb-acid) batteries, bio-batteries offer several advantages, including high biodegradability, low toxicity, cost-effective production, and the potential for environmentally friendly recycling.

Despite their numerous advantages, the development of bio-batteries continues to face significant challenges, particularly with respect to low ionic conductivity and limited electrochemical stability. Various studies have sought to address these limitations by utilizing biological resources, either through the application of natural electrolytes or the incorporation of biomass as a matrix in electrochemical processes (Mita et al., 2025). Liquid electrolytes derived from fruits and plant-based materials have been reported to generate relatively high initial voltages; however, their performance tends to be unstable due to chemical degradation and restricted ion mobility (Hasrolita et al., 2025; Anjarsari et al., 2024; Yanti et al., 2024). In contrast, porous solid biomass materials, such as cellulose and agricultural waste, can enhance electrolyte retention and mechanical stability, although their electrical performance remains limited by the low concentration of electrochemically active ions (Ji & Kim, 2023; Liedel, 2020). Alternative approaches employing biopolymers, including starch, pectin, and lignocellulosic composites, have also demonstrated promising sustainability

characteristics; nevertheless, their ionic conductivity remains insufficient for long-term practical applications (Huang et al., 2025). Although these approaches have demonstrated promising improvements in specific aspects of bio-battery performance, most studies have focused on optimizing individual electrolyte components rather than developing an integrated electrolyte system. Consequently, the combined utilization of a porous lignocellulosic matrix, multi-ion natural electrolytes, and an ionic conductivity enhancer to simultaneously improve ionic conductivity, electrolyte retention, and electrochemical stability remains insufficiently explored.

These limitations indicate that enhancing bio-battery performance cannot be achieved solely by substituting a single material component; rather, it requires the development of electrolyte systems capable of simultaneously integrating structural support and efficient ion transport. In this context, porous lignocellulosic matrix-based electrolytes represent a promising approach, as cellulose networks containing abundant hydroxyl functional groups can facilitate electrolyte retention while providing more organized ion diffusion pathways within semi-solid systems (N. Wang et al., 2022). Among the available lignocellulosic resources, sugarcane bagasse has emerged as a particularly attractive biopolymer host due to its porous microstructure, which can improve mechanical stability and maintain charge transport continuity without significantly increasing the viscosity of the electrolyte system. Therefore, sugarcane bagasse is expected to function not only as a structural support but also as an effective electrolyte-host matrix that facilitates continuous ion transport, thereby providing a stable foundation for integrating additional electrolyte

components within the bio-battery system.

To enhance electrochemical functionality, the integration of multi-ion electrolyte sources is essential for increasing charge carrier density without compromising system stability. *Moringa oleifera* leaves and *Eichhornia crassipes* (water hyacinth) offer considerable potential as complementary electrolyte sources, providing a diverse combination of mineral ions and redox-active organic compounds that can support more adaptive charge-transfer mechanisms compared with single-biomass electrolytes (Divya et al., 2024). Further enhancement can be achieved through the incorporation of ammonium chloride (NH_4Cl) as an ionic conductivity enhancer, which increases the concentration of free ions and reduces internal resistance. Consequently, both ion transport dynamics and electrochemical potential stability can be improved simultaneously, leading to enhanced overall bio-battery performance (Mejenom et al., 2025). These complementary functions suggest that combining sugarcane bagasse, *Moringa oleifera*, *Eichhornia crassipes*, and NH_4Cl within a single electrolyte system may provide synergistic improvements in electrolyte retention, ion transport, ionic conductivity, and electrochemical stability compared with the use of individual materials.

To address these challenges, this study proposes a hybrid bio-battery design that integrates a porous lignocellulosic matrix derived from sugarcane bagasse with a multi-ion natural electrolyte obtained from *Moringa oleifera* leaves and *Eichhornia crassipes* (water hyacinth), supplemented with NH_4Cl as an ionic conductivity enhancer. Porous lignocellulose is a naturally occurring biomass structure composed of cellulose, hemicellulose,

and lignin, and is enriched with hydroxyl ($-\text{OH}$) functional groups. These polar functional groups exhibit a strong affinity for water molecules and ionic species, thereby facilitating electrolyte absorption and retention. In addition, the porous architecture and abundant hydroxyl groups enable sugarcane bagasse to serve as an effective electrolyte-host matrix by providing stable ion diffusion pathways within the bio-battery system (Huang et al., 2025). The combination of *Moringa oleifera* and *Eichhornia crassipes* introduces a broader spectrum of ionic species and redox-active compounds, thereby promoting more efficient charge-transfer processes. Meanwhile, the incorporation of NH_4Cl increases the concentration of mobile charge carriers and reduces internal resistance.

The synergistic integration of these three components represents a comprehensive strategy for balancing structural stability and electrochemical performance while simultaneously enhancing ion mobility and voltage stability throughout the bio-battery system. The novelty of this study lies in integrating sugarcane bagasse as a porous lignocellulosic matrix with multi-ion natural electrolytes derived from *Moringa oleifera* and *Eichhornia crassipes*, supplemented with NH_4Cl as an ionic conductivity enhancer, into a hybrid bio-battery system. Unlike previous studies that mainly optimized individual electrolyte components, this study employs a sequential optimization strategy to determine the optimum electrolyte composition for enhancing bio-battery performance. Therefore, this study aims to develop and evaluate the proposed hybrid bio-battery by investigating the effects of electrolyte composition and electrode configuration on voltage output, current output, and internal impedance to identify the optimum bio-battery configuration.

MATERIALS AND METHODS

The electrolyte materials used in this study consisted of a sugarcane bagasse matrix and a multi-ion electrolyte system comprising *Moringa oleifera* leaf powder (PT Mustika Family Nusantara, Situbondo, Jawa Timur, Indonesia), ammonium chloride (NH_4Cl) technical grade (Chemical Supply, Tangerang Selatan, Indonesia), and *eichhornia crassipes* (water hyacinth) powder (PT Mustika Family Nusantara, Situbondo, Jawa Timur, Indonesia). Sugarcane bagasse was collected from local sugarcane juice seller as a waste by-product of the sugarcane extraction process. The collected sugarcane bagasse was thoroughly dried and subsequently ground into a fine powder using a blender. The resulting bagasse powder was then sieved through a 14-mesh screen to obtain relatively uniform particles for use as the solid-electrolyte matrix.

The electrodes employed in this study consisted of an anode and a cathode. The anode material was varied using aluminum, copper, and zinc, while graphite was used as the cathode material. The variation in anode materials was intended to evaluate the influence of metal type on the electrochemical performance of the bio-battery. All electrodes were cut into dimensions of 3 cm $\times$ 4 cm to ensure compatibility and consistency within the battery cell configuration.

The solid electrolyte was prepared by dispersing *Moringa oleifera* leaf powder at varying masses of 2, 4, 6, 8, and 10 g into a beaker, followed by the addition of distilled water at a fixed volume of 20 mL. The mixture was stirred using a magnetic stirrer for 10 min to ensure uniform ion distribution throughout the solution. Subsequently, 2 g of sugarcane bagasse powder was added to the mixture and continuously stirred until a homogeneous solid-

electrolyte paste was formed. The mixture is then assembled into a bio-battery cell and performance parameters such as current strength, voltage, and impedance are measured. The optimization of electrolyte composition was performed sequentially rather than simultaneously to minimize the influence of interactions among multiple variables. In the first stage, the mass of *Moringa oleifera* leaf powder was optimized while maintaining the sugarcane bagasse matrix and distilled water volume constant. This approach enabled the individual contribution of *Moringa oleifera* to ionic transport and electrochemical performance to be evaluated before introducing additional electrolyte components.

After obtaining the optimum composition of *Moringa oleifera* leaf powder, ammonium chloride (NH_4Cl) was added to the electrolyte system at varying masses of 1, 2, 3, 4, and 5 g. The mixture was subsequently stirred using a magnetic stirrer until a homogeneous electrolyte was obtained. Then current, voltage, and impedance measurements are performed. This procedure was carried out to assess the effect of NH_4Cl incorporation on ionic conductivity and the electrical performance of the bio-battery. During this optimization stage, the optimum mass of *Moringa oleifera* leaf powder determined in the previous stage was maintained constant. Therefore, any changes in voltage, current, and impedance could be attributed primarily to the incorporation of NH_4Cl , allowing its contribution to ionic conductivity enhancement to be evaluated independently.

Once the optimum compositions of *Moringa oleifera* powder and NH_4Cl had been established, *eichhornia crassipes* (water hyacinth) powder was introduced at varying masses of 1, 2, 3, 4, and 5 g. This step was undertaken to investigate the effect of integrating multiple ion sources on the maximum voltage, current

output and impedance of the sugarcane bagasse matrix-based bio-battery. The sequential optimization of these electrolyte components was intended to identify the most effective composition for enhancing ion transport and overall electrochemical performance. Likewise, the optimum compositions of *Moringa oleifera* leaf powder and NH_4Cl obtained from the previous stages were retained during the optimization of *Eichhornia crassipes*. This strategy ensured that the electrochemical response observed in the final stage predominantly reflected the contribution of the additional natural ion source rather than simultaneous changes in multiple experimental variables.

In each stage, the bio-battery is assembled by applying the electrolyte evenly on a 3 cm $\times$ 4 cm graphite electrode sheet. Next, an anode electrode sheet of aluminum, copper, or zinc of the same size is placed on top of the solid electrolyte layer and then clamped using clammer on both sides to ensure the stability of mechanical and electrochemical contact between the layers. The electrolyte paste was uniformly distributed over the entire electrode surface before assembly to ensure consistent electrode–electrolyte contact and minimize variations in interfacial resistance among experimental samples.

The total mass of the electrolyte was measured using a digital balance and

maintained at approximately 4 g to ensure sample uniformity across all experimental variations. The cathode and anode terminals of the assembled bio-battery were connected to the positive and negative terminals of a digital multimeter (Sanwa CD800A) using connecting wires and alligator clips for the measurement of voltage and current output generated by the bio-battery system. The internal resistance of the bio-battery was evaluated using a Battery Impedance Tester (YR1035+). The optimum electrolyte composition was determined based on the combination of the highest voltage output, highest current output, and lowest internal impedance, as these parameters collectively represent the electrochemical performance, charge-transfer efficiency, and ionic conductivity of the bio-battery system.

RESULTS AND DISCUSSION

At the initial stage of the study, the effect of varying the mass of *Moringa oleifera* leaf powder as the primary electrolyte source in a sugarcane bagasse matrix-based bio-battery system was investigated. The evaluated parameters included current, voltage, and impedance, which served as indicators of the system's electrochemical performance, as presented in Table 4.1.

Table 4.1 Relationship between *Moringa oleifera* Leaf Powder Mass and Current (mA), Voltage (V), and Impedance (Ω)

Moringa Leaf Powder Mass (gr)	Current (mA)	Voltage (V)	Impedance (Ω)
2	0,67	0,584	42,5
4	0,92	0,667	33,6
6	1,47	0,706	28,6
8	0,80	0,634	44,2
10	0,41	0,578	49,4

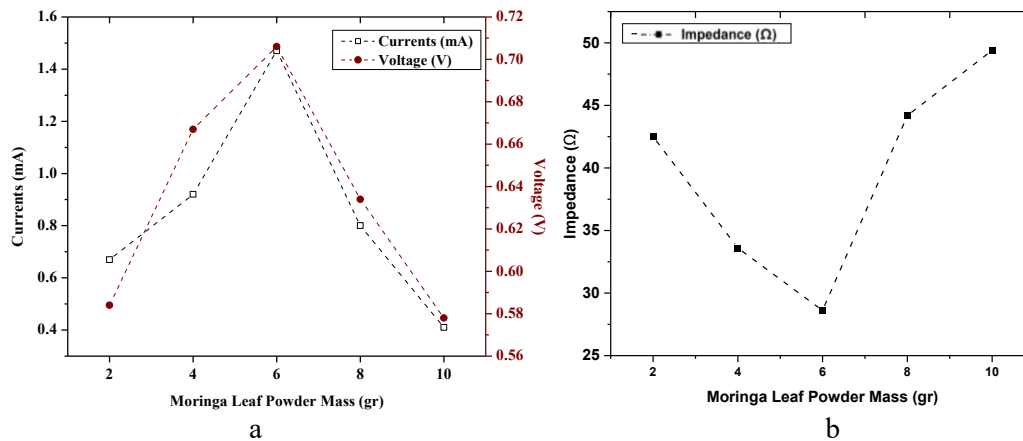


Figure 4.1. Relationship between *Moringa oleifera* Leaf Powder Mass and (a) Voltage (V) and Current (mA), and (b) Impedance (Ω) of the Bio-Battery System

Table 4.1 and Figure 4.1 present the measured current and voltage outputs of the biomass-based bio-battery utilizing *Moringa oleifera* leaf powder as a natural electrolyte source. Five different masses of *Moringa oleifera* powder were investigated, namely 2, 4, 6, 8, and 10 g.

The results indicate a considerable increase in current output with increasing *Moringa oleifera* powder mass during the initial stage of the experiment. The current increased from 0.67 mA at a mass of 2 g to 0.92 mA at 4 g, reaching a maximum value of 1.47 mA at 6 g. However, further increases in the mass of *Moringa oleifera* powder to 8 g and 10 g resulted in a decrease in current output to 0.80 mA and 0.41 mA, respectively.

A comparable trend was observed in the voltage measurements. The voltage increased from 0.584 V at 2 g of *Moringa oleifera* powder to 0.667 V at 4 g, reaching a peak value of 0.706 V at 6 g. Further increases in powder mass resulted in a gradual decline in voltage to 0.634 V and 0.578 V at 8 g and 10 g, respectively. The concurrent maxima observed in both current and voltage outputs suggest that 6 g represents the optimum *Moringa oleifera* powder loading for this bio-battery system, providing the most favorable conditions for electrochemical charge transport and energy generation.

To further elucidate this phenomenon, impedance measurements were conducted as an indicator of the electrolyte system's conductivity. The results show that the initial impedance value was relatively high, reaching 42.5 Ω at a *Moringa oleifera* powder mass of 2 g. This value subsequently decreased to 33.6 Ω at 4 g and reached a minimum of 28.6 Ω at 6 g. The reduction in impedance indicates an improvement in electrolyte conductivity with increasing *Moringa oleifera* powder content. However, beyond the optimum mass, impedance increased again to 44.2 Ω at 8 g and 49.4 Ω at 10 g, suggesting a decline in system conductivity.

This pattern indicates that increasing the mass of *Moringa oleifera* leaf powder contributes to an enhanced concentration of free ions within the electrolyte system up to an optimum condition. *Moringa oleifera* leaves are known to contain various mineral ions such as potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), as well as organic compounds including flavonoids and organic acids that may function as proton donors (Divya et al., 2024). These ionic species act as charge carriers within the bio-battery system; therefore, an increase in their concentration enhances the system's ability to conduct electrical current.

However, when the amount of *Moringa oleifera* leaf powder exceeds the optimum condition, further increases in ion concentration lead to a decrease in conductivity. This phenomenon can be explained by fundamental electrochemical principles, in which excessively high ion concentrations reduce the average interionic distance, thereby intensifying electrostatic interactions between ions. Such interactions may promote the formation of ion pairs that are no longer freely mobile, consequently reducing the number of effective charge carriers contributing to charge transport (Francelanord & Grossman, 2018).

In addition, increasing the mass of *Moringa oleifera* leaf powder may induce changes in the physical structure of the electrolyte matrix, particularly a reduction in porosity due to the accumulation of biomass particles. This decrease in porosity can hinder ion diffusion pathways within the sugarcane bagasse matrix, which is composed of a porous lignocellulosic structure (Lopic'ic et al., 2016). As a consequence, ion mobility is reduced, leading to an increase in impedance and a corresponding decrease in both current and voltage output.

The phenomenon of increased ionic conductivity resulting from the use of single-salt electrolytes has been widely reported in biopolymer electrolyte systems. For instance, Ahmad & Isa, (2015) demonstrated that the incorporation of NH_4Cl into a carboxymethyl cellulose (CMC) system significantly enhanced ionic conductivity. The conductivity increased progressively with increasing salt concentration from 4 wt.% and reached an optimum value at 16 wt.% NH_4Cl , yielding a maximum conductivity of $1.43 \times 10^{-3} \text{ S cm}^{-1}$. This improvement was attributed to the increased availability of free NH_4^+ and Cl^- ions as charge carriers, as well as enhanced ion mobility within

the polymer matrix, which was further facilitated by the formation of an amorphous phase that allowed more facile ion transport.

However, beyond the optimum concentration, ionic conductivity decreased due to intensified interionic interactions that promoted ion pairing, thereby reducing the number of free ions available for charge transport. In addition, the increased system viscosity further restricted ion mobility, resulting in diminished overall conductivity.

Similar findings were reported by Aziz et al, (2022), who demonstrated that the incorporation of NH_4Cl into a poly(vinyl alcohol)–methyl cellulose (PVA–MC) blend matrix significantly enhanced ionic conductivity. The conductivity increased progressively with increasing NH_4Cl concentration from approximately 10 wt.% and reached an optimum value at 30 wt.%, yielding a maximum conductivity of $1.99 \times 10^{-3} \text{ S cm}^{-1}$. This improvement was attributed to the higher degree of salt dissociation, which increased the concentration of free ions acting as charge carriers, as well as the high mobility of protons (H^+) that facilitated charge transport throughout the system.

However, when the salt concentration exceeded the optimum level, ionic conductivity tended to decrease due to an increase in system viscosity and the formation of ion aggregates, which restricted ion mobility within the polymer matrix. These findings suggest that the incorporation of chemical ions into electrolyte systems is governed by an optimum concentration threshold, beyond which further ion addition no longer enhances conductivity and may instead impair ionic transport. This behavior is consistent with the results of the present study, where excessive NH_4Cl content led to increased ionic interactions and reduced electrochemical performance despite the higher concentration of ionic species.

A similar enhancement in ionic conductivity within biopolymer electrolyte systems was reported by Sohaimy & Isa, (2020), who demonstrated that the incorporation of ammonium carbonate (AC) into a carboxymethyl cellulose (CMC) matrix significantly improved both the structural properties and ionic conductivity of the polymer electrolyte. The conductivity increased progressively with AC concentration from 1 wt.% and reached an optimum value at 7 wt.%, achieving a conductivity of $7.71 \times 10^{-6} \text{ S cm}^{-1}$ at 303 K. This enhancement was attributed to an increased concentration of free H^+ ions, higher ion mobility and diffusion coefficients, and the predominance of the amorphous phase, which facilitated ion transport within the polymer matrix.

Furthermore, FTIR analysis revealed interactions between COO^- functional groups and protons, supporting the charge transport process within the electrolyte. The reported ionic transference number ($t_{\text{ion}} \approx 0.98$) indicated that the conduction mechanism was predominantly governed by ionic species, particularly protons. However, when the AC concentration exceeded 7

wt.%, the conductivity decreased due to an imbalance between ion concentration and ion mobility, accompanied by an increase in the internal resistance of the system. Therefore, an optimum electrolyte concentration exists at which maximum conductivity can be achieved through a balance among free-ion concentration, ion mobility, and the amorphous structure of the polymer matrix.

Based on the results of this study, it can be concluded that a *Moringa oleifera* leaf powder mass of 6 g represents the optimum condition for achieving the best bio-battery performance. At this composition, the concentration of available ions is sufficient to enhance electrolyte conductivity while maintaining efficient ion mobility. Consequently, maximum current and voltage outputs, together with minimum impedance, were obtained under this condition. However, at higher powder masses, interionic interactions and diffusion limitations become increasingly dominant, leading to reduced ion mobility and a subsequent decline in the overall electrochemical performance of the system.

Table 4.2 Effect of NH_4Cl Mass and Optimum *Moringa oleifera* Leaf Powder Content on Current (mA), Voltage (V), and Impedance (Ω)

NH_4Cl Mass (gr)	Current (mA)	Voltage (V)	Impedance (Ω)
1	2,15	0,672	3,18
2	3,15	0,727	2,82
3	3,62	0,812	2,03
4	1,63	0,628	2,07
5	0,53	0,622	2,16

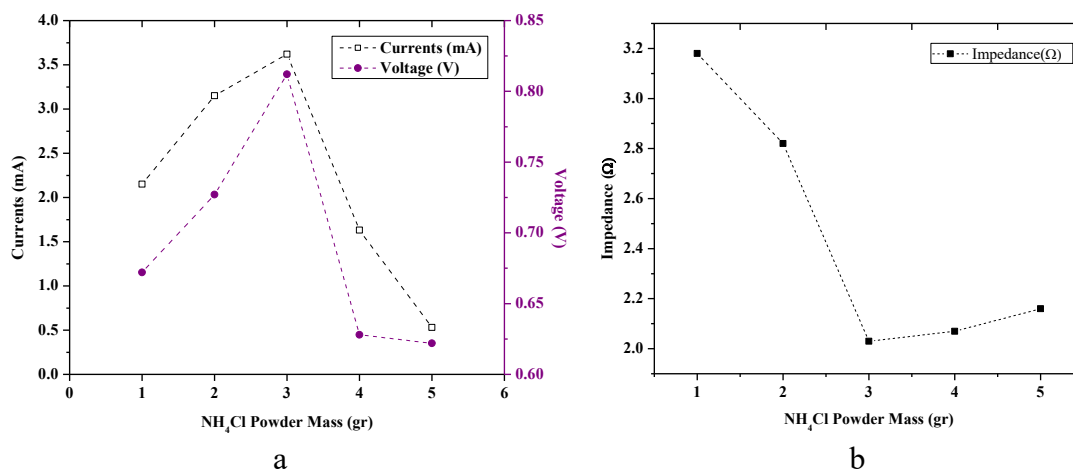


Figure 4.2. Effect of NH_4Cl Mass and Optimum *Moringa oleifera* Leaf Powder Content on (a) Voltage (V) and Current (mA), and (b) Impedance (Ω) of the Bio-Battery

Table 4.2 and Figure 4.2 present the measured current and voltage outputs of the bio-battery following the incorporation of NH_4Cl into the electrolyte system composed of *Moringa oleifera* leaf powder and a sugarcane bagasse matrix. Five different NH_4Cl masses were investigated, namely 1, 2, 3, 4, and 5 g.

The measurement results indicate that the current output increased with increasing NH_4Cl mass during the initial stage of the experiment. The current increased from 2.15 mA at an NH_4Cl mass of 1 g to 3.15 mA at 2 g, reaching a maximum value of 3.62 mA at 3 g. However, further increases in NH_4Cl mass to 4 g and 5 g resulted in a pronounced decline in current output, decreasing to 1.63 mA and 0.53 mA, respectively.

A similar trend was observed for the voltage output. The voltage increased from 0.672 V at an NH_4Cl mass of 1 g to 0.727 V at 2 g, reaching a maximum value of 0.812 V at 3 g. Beyond this optimum point, the voltage decreased to 0.628 V at 4 g and 0.622 V at 5 g. These results indicate that an optimum NH_4Cl content of 3 g exists, at which both current and voltage outputs attained their maximum values.

To gain further insight into this behavior, impedance measurements were

performed as an indicator of electrolyte conductivity. The results revealed that the impedance decreased from 3.18 Ω at an NH_4Cl mass of 1 g to 2.82 Ω at 2 g, reaching a minimum value of 2.03 Ω at 3 g NH_4Cl . This reduction in impedance indicates an enhancement in system conductivity resulting from the addition of the strong electrolyte. However, beyond the optimum point, the impedance increased to 2.07 Ω at 4 g and 2.16 Ω at 5 g, suggesting a decline in the conductivity of the electrolyte system.

This trend indicates that increasing the NH_4Cl content directly contributes to a higher concentration of free ions within the electrolyte system up to an optimum condition. NH_4Cl is a strong electrolyte that readily dissociates in the electrolyte medium into NH_4^+ and Cl^- ions. The presence of these ions increases the density of charge carriers within the system, thereby enhancing its electrical conductivity and improving its ability to transport electric current.

From an electrochemical perspective, the initial enhancement in conductivity can be attributed to the addition of NH_4Cl , which increases the concentration of charge carriers within the electrolyte system. NH_4Cl dissociates into NH_4^+ and Cl^- ions, where NH_4^+ ions possess a relatively small ionic size and high ionic mobility, enabling them to

migrate more rapidly through the electrolyte medium. Meanwhile, Cl^- ions contribute to charge balance and the electrochemical stability of the system (Mejenom et al., 2025). These conditions facilitate more efficient ion transport, as evidenced by the increase in current and voltage outputs accompanied by a reduction in impedance.

However, when the NH_4Cl concentration exceeds the optimum level, the increasing ion concentration leads to a decline in conductivity due to several interconnected factors. First, ion pairing between NH_4^+ and Cl^- ions reduces the number of free ions available for effective charge transport. Second, the emergence of an ionic crowding effect, resulting from the reduced distance between ions at high concentrations, intensifies electrostatic interactions and restricts ion mobility. Third, the increased viscosity of the electrolyte system limits ion diffusion within the medium, thereby reducing the efficiency of charge transport (Robin, 2024). Collectively, these effects contribute to the observed decrease in conductivity despite the higher concentration of ionic species.

This phenomenon is consistent with the fundamental theory of electrolyte conductivity, which states that conductivity increases with increasing ion concentration until an optimum point is reached, after which it decreases due to excessive interionic interactions. The observed trend is also in agreement with previous studies. For example, Zainuddin & Samsudin, (2017) investigated a carboxymethyl cellulose (CMC)– NH_4Br –polyethylene glycol (PEG) electrolyte system. Initially, the CMC– NH_4Br system exhibited an ionic conductivity of approximately $1.12 \times 10^{-4} \text{ S cm}^{-1}$ at an optimum NH_4Br concentration of 25 wt.%. The incorporation of PEG as a plasticizer significantly enhanced the conductivity, reaching a maximum value of $2.48 \times 10^{-3} \text{ S cm}^{-1}$ at an optimum

PEG concentration of approximately 8 wt.%.

This improvement was attributed to increased polymer chain flexibility, greater free volume within the polymer matrix, and an enhanced degree of salt dissociation, all of which promoted the generation and mobility of charge carriers, particularly protons (H^+). However, when the PEG concentration exceeded the optimum level, the conductivity tended to decrease due to ion accumulation and disruption of ion transport pathways within the polymer matrix. These findings further support the existence of an optimum ion concentration required to achieve maximum ionic conductivity and electrochemical performance.

Consistent with these findings, Isa & Samsudin, (2017) also reported that the incorporation of NH_4Br into a carboxymethyl cellulose (CMC) matrix enhanced ionic conductivity, reaching an optimum value at an NH_4Br concentration of approximately 25 wt.% with conductivity on the order of $\sim 10^{-4} \text{ S cm}^{-1}$. The subsequent addition of plasticizers such as polyethylene glycol (PEG), glycerol, and ethylene carbonate (EC) further improved the conductivity to the order of $\sim 10^{-3} \text{ S cm}^{-1}$. This enhancement was attributed to the ability of the plasticizers to increase polymer chain flexibility and ion mobility through the expansion of free volume within the polymer matrix.

However, the study also demonstrated that plasticizer concentrations exceeding the optimum level resulted in a decline in conductivity due to dilution effects and a reduction in effective ionic interactions. Consequently, ion transport within the electrolyte system became less efficient, leading to a decrease in overall ionic conductivity. These observations reinforce the concept that electrolyte performance is governed by an optimal balance between ion concentration,

polymer matrix structure, and ion transport dynamics.

Similar findings regarding the role of plasticizers were reported by Samsudin & Isa, (2016) through the incorporation of ethylene carbonate (EC) into a carboxymethyl cellulose (CMC)–NH₄Br electrolyte system. In the absence of a plasticizer, a maximum ionic conductivity of $1.12 \times 10^{-4} \text{ S cm}^{-1}$ was achieved at a composition of 25 wt.% NH₄Br. Following the addition of EC, the conductivity increased significantly, reaching a maximum value of $3.31 \times 10^{-3} \text{ S cm}^{-1}$. This enhancement was attributed to the ability of EC to promote salt dissociation and facilitate protonation processes, thereby increasing both the concentration and mobility of H⁺ ions within the polymer matrix.

Furthermore, the system exhibited conductivity behavior that followed an Arrhenius-type temperature dependence, indicating that the ion transport mechanism was governed by activation energy. Nevertheless, as observed in other plasticized electrolyte systems, excessive plasticizer content may lead to a reduction in conductivity due to disruption of ion conduction pathways within the polymer matrix. These findings further emphasize that electrolyte performance depends not only on the concentration of ionic species but also on the optimization of matrix composition and ion transport pathways.

In the context of the biomass-based bio-battery system, interactions between NH₄⁺ and Cl[−] ions and the naturally occurring ions derived from *Moringa oleifera* leaf powder also play a crucial role. The electrolyte functions as a multi-ion system, in which ions originating from NH₄Cl interact with naturally occurring ionic species such as K⁺ and Ca²⁺. These interactions may enhance conductivity through synergistic effects; however, at elevated concentrations, they can also increase the

complexity of ionic interactions, thereby restricting ion mobility. Furthermore, the sugarcane bagasse matrix serves as a solid supporting medium that influences ion distribution throughout the electrolyte system. Its porous structure facilitates efficient ion diffusion under optimum conditions; however, excessive electrolyte loading may lead to pore saturation, which obstructs ion diffusion pathways and limits charge transport.

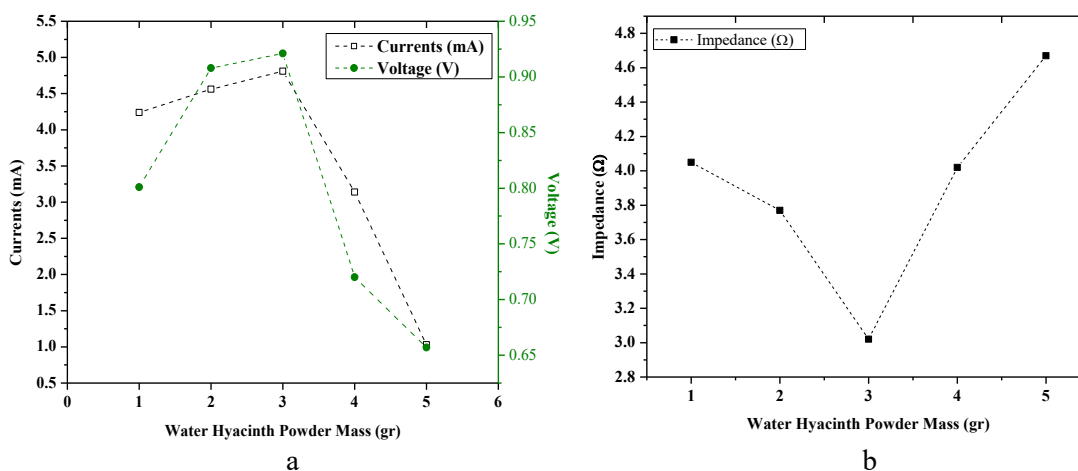
Based on the findings of this study, the addition of 3 g NH₄Cl was identified as the optimum condition for enhancing bio-battery performance. At this composition, a favorable balance between free-ion concentration and ion mobility was achieved, resulting in maximum current and voltage outputs together with minimum impedance. Beyond this optimum concentration, interionic interactions and diffusion limitations became increasingly dominant, leading to a deterioration in the overall electrochemical performance of the system.

Table 4.3 and Figure 4.3 illustrate the current and voltage characteristics of the bio-battery following the addition of water hyacinth powder to the optimized electrolyte system containing moringa leaf powder and NH₄Cl. Water hyacinth powder was added at varying masses of 1, 2, 3, 4, and 5 g to evaluate its effect on the electrochemical performance of the bio-battery.

The measurement results showed that the current increased markedly during the initial stages of water hyacinth powder addition. The current was recorded at 4.24 mA for a mass of 1 g, increased to 4.56 mA at 2 g, and reached a maximum value of 4.81 mA at 3 g. However, when the mass of water hyacinth powder was further increased to 4 g and 5 g, the current decreased significantly to 3.14 mA and 1.03 mA, respectively.

Table 4.3 Effect of Eichhornia crassipes (Water Hyacinth) Powder Mass at the Optimum Moringa oleifera Leaf Powder and NH_4Cl Composition on Current (mA), Voltage (V), and Impedance (Ω)

Water Hyacinth			
Powder Mass (gr)	Current (mA)	Voltage (V)	Impedance (Ω)
1	4,24	0,801	4,05
2	4,56	0,908	3,77
3	4,81	0,921	3,02
4	3,14	0,720	4,02
5	1,03	0,657	4,67

Figure 4.3 Effect of water hyacinth powder mass, at the optimum NH_4Cl and moringa leaf powder masses, on the (a) voltage (V) and current (mA), and (b) impedance (Ω) of the bio-battery.

A similar trend was observed for the voltage values. The voltage increased from 0.801 V at a water hyacinth powder mass of 1 g to 0.908 V at 2 g and reached a maximum value of 0.921 V at 3 g. Beyond this optimum point, the voltage decreased to 0.720 V at 4 g and further declined to 0.657 V at 5 g. These results indicate the existence of an optimum water hyacinth powder mass of 3 g, at which both the current and voltage attained their maximum values.

To gain a deeper understanding of these changes, impedance measurements were conducted as an indicator of the electrolyte system's conductivity. The results showed that the impedance decreased from 4.05 Ω at a water hyacinth powder mass of 1 g to 3.77 Ω at 2 g and reached its minimum value of 3.02 Ω at 3 g. This reduction in

impedance indicates an improvement in the conductivity of the system with increasing water hyacinth powder mass. However, beyond the optimum point, the impedance increased to 4.02 Ω at 4 g and further to 4.67 Ω at 5 g, indicating a decline in the conductivity of the electrolyte system.

This trend indicates that the addition of water hyacinth contributes to the enhancement of electrolyte conductivity up to an optimum condition. Water hyacinth (*Eichhornia crassipes*) is known to contain various mineral ions, including potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), as well as smaller amounts of iron ions ($\text{Fe}^{2+}/\text{Fe}^{3+}$) and other electrochemically active organic compounds. The presence of these ionic species increases the concentration of charge carriers within the electrolyte

system, thereby enhancing its ability to conduct electric current.

Furthermore, water hyacinth possesses a porous and hygroscopic cellulose structure that is capable of absorbing and retaining water within the system. This characteristic is particularly important in solid-state electrolyte systems, where water serves as a medium for ion transport. Enhanced water retention promotes more stable and continuous ion diffusion pathways, thereby improving ionic mobility within the electrolyte system (Sayago et al., 2020).

However, when the mass of water hyacinth exceeded the optimum condition, the increased biomass content resulted in a decline in conductivity. This phenomenon can be attributed to several mechanisms, including the occurrence of ionic saturation effects due to the higher ion concentration, which reduces the distance between ions, intensifies electrostatic interactions, and consequently decreases ionic mobility. In addition, excessive biomass accumulation may lead to overlapping diffusion pathways, reducing the effective porosity of the sugarcane bagasse matrix and hindering ion transport. Furthermore, the ion distribution becomes less homogeneous, resulting in a lower efficiency of charge transfer within the system (Tang et al., 2024).

The phenomenon of enhanced ionic conductivity in polymer electrolyte systems has also been reported by Atik et al. (2021), who demonstrated that the incorporation of a pyrrolidinium-based ionic liquid functionalized with oligo(ethylene oxide) groups, namely $\text{Pyr}_{11}(\text{2O})_7\text{TFSI}$, into a ternary PEO/LiTFSI electrolyte system significantly improved Li^+ ion mobility through a cation-assisted transport mechanism. Their study revealed a substantial increase in the Li^+ diffusion coefficient from $0.292 \times 10^{-12} \text{ m}^2 \text{ s}^{-1}$ to

$0.578 \times 10^{-12} \text{ m}^2 \text{ s}^{-1}$ at a composition ratio of 20:2:1 when the conventional $\text{Pyr}_{11,4}\text{TFSI}$ cation was replaced by the solvating $\text{Pyr}_{11}(\text{2O})_7\text{TFSI}$ cation. Moreover, the theoretical Li^+ diffusion coefficient increased by up to 3.7 times with increasing oligo(ethylene oxide) chain length. This enhancement was attributed to the formation of solvation complexes between Li^+ ions and the ionic liquid cations, enabling a vehicular transport mechanism in which Li^+ ions are effectively carried by the ionic liquid cations, thereby facilitating more efficient ion transport. This behavior was further reflected by an increase in the lithium transference number (T_{Li^+}) from approximately 0.05 to 0.10 at 40 °C, indicating a greater contribution of Li^+ transport to the overall ionic conduction.

However, electrolyte composition played a critical role in achieving optimal performance, with PEO:LiTFSI:IL ratios of 20:2:1 to 20:2:2 providing the best balance among ionic mobility, amorphous structural stability, and homogeneous ion distribution. Although higher ionic liquid contents, such as a ratio of 20:2:4, increased the ionic conductivity to $6.6 \times 10^{-4} \text{ S cm}^{-1}$ at 40 °C and $1.4 \times 10^{-3} \text{ S cm}^{-1}$ at 60 °C, partial crystallization effects began to emerge, potentially compromising performance at lower temperatures. Therefore, the optimum condition was achieved at moderate ionic liquid concentrations, which enhanced Li^+ mobility by approximately two- to four-fold, doubled the lithium transference number, and maintained the stability of the amorphous phase, resulting in more efficient ion transport and superior electrolyte performance.

It is also consistent with the findings of Hona et al. (2023), the incorporation of additional ions through the formation of a ternary sulfide-glass electrolyte system based on $\text{K}_2\text{S-P}_2\text{S}_5$ with the addition of the complex salt KOTf was shown to increase the

concentration of free K^+ ions and modify the glass network structure, thereby enlarging ion migration pathways within the electrolyte. The study reported a remarkable increase in ionic conductivity from $4.88 \times 10^{-12} \text{ S cm}^{-1}$ at a composition of $x = 0.45$ to $1.06 \times 10^{-7} \text{ S cm}^{-1}$ at the optimum composition of $x = 0.60$ at room temperature. In contrast, other compositions, such as $x = 0.15$ and $x = 0.75$, exhibited substantially lower conductivities of 2.91×10^{-10} and $3.95 \times 10^{-10} \text{ S cm}^{-1}$, respectively. This enhancement was attributed to the increased concentration of K^+ ions as charge carriers and the formation of conductive structural units, such as $P_2S_4^{6-}$ and $P_2S_4^{7-}$, which facilitated ion mobility and reduced ion migration resistance within the glass matrix.

However, electrolyte composition played a crucial role in achieving optimum performance. In the $z(K_2S-2P_2S_5)-yKOTf$ system, the maximum ionic conductivity of $1.06 \times 10^{-7} \text{ S cm}^{-1}$ was obtained at a salt fraction of $y = 0.10$, representing a substantial increase from $7.81 \times 10^{-11} \text{ S cm}^{-1}$ at $y = 0.05$. Nevertheless, the conductivity decreased sharply at higher salt concentrations due to intensified ion-ion interactions, aggregate formation, disruption of the glass network structure, and an increase in activation energy to 1.17 eV at $y = 0.15$. Therefore, the optimum composition was achieved at a ratio of $0.3K_2S-0.6P_2S_5-0.1KOTf$, which provided the best balance among charge carrier concentration, high ionic mobility, and structural homogeneity, resulting in maximum ionic conductivity.

A similar phenomenon was also reported by Karpierz et al. (2016), who demonstrated that the incorporation of additional ions through the formation of a ternary electrolyte system consisting of the ionic liquid 1-butyl-3-methylimidazolium 4,5-dicyano-2-(trifluoromethyl)imidazolate, lithium 4,5-dicyano-2-(trifluoromethyl)imidazolate

salt, and glymes such as triglyme or tetraglyme significantly increased the concentration of highly mobile free lithium ions (Li^+). This enhancement resulted from the formation of positively charged lithium-glyme solvation complexes, which facilitated efficient ion transport within the electrolyte. The study reported a substantial increase in ionic conductivity from 0.61 mS cm^{-1} in the binary system to 1.75 mS cm^{-1} for a lithium 4,5-dicyano-2-(trifluoromethyl)imidazolate:triglyme ratio of 1:2, reaching 3.73 mS cm^{-1} at a ratio of 1:5.6 at 20°C , corresponding to an approximately sixfold increase. At a higher temperature of 70°C , the conductivity enhancement reached nearly sixteen times that of the glyme-free system. This improvement was attributed to the reduction in system viscosity and the increased degree of ionic dissociation, which generated a greater number of free ions available as charge carriers. Furthermore, the lithium transference number increased markedly from approximately 0.04 in the binary system to 0.23 in the electrolyte containing a 1:5.6 triglyme ratio, indicating a stronger contribution of Li^+ ions to the overall charge transport process.

However, electrolyte composition was found to be a critical factor in achieving optimum performance. Systems with salt fractions of approximately $x = 0.10-0.15$ exhibited the most pronounced improvements in both ionic conductivity and lithium transference number, while higher glyme-to-salt ratios, particularly the 1:5.6 triglyme composition, produced the maximum conductivity by increasing the concentration of free lithium ions and suppressing the formation of immobile lithiumbis (4,5-dicyano-2-(trifluoromethyl)imidazolate) polyanion aggregates. In contrast, at low glyme contents or in the absence of glyme, ion aggregation became dominant, leading to

lithium-ion immobilization and reduced conductivity. Therefore, the optimum composition was achieved at an intermediate salt fraction combined with a high glyme ratio, providing the best balance among free-ion concentration, low viscosity, and homogeneous ion distribution.

In this study, the resulting electrolyte system can be classified as a complex multi-ion system, comprising naturally occurring ions from moringa leaves, highly dissociative ions supplied by NH_4Cl , and additional ionic species contributed by water hyacinth. The interaction among these three components generates a synergistic effect that enhances the overall conductivity of the electrolyte system. In this context, water hyacinth functions not only as an additional source of ions but also as a structural stabilizer of the electrolyte matrix, helping to maintain moisture retention and preserve continuous ion diffusion pathways.

Furthermore, the presence of multiple ionic species with different sizes and valences enables more complex ion-transport mechanisms, such as ionic hopping and inter-site ion exchange, which can enhance the efficiency of charge transfer within the system. However, when the amount of water hyacinth exceeds the optimum level, the complexity of ionic interactions increases excessively, leading to reduced ion mobility and increased internal resistance of the electrolyte system.

Based on the findings of this study, the addition of 3 g of water hyacinth was identified as the optimum condition for enhancing the performance of the bio-battery. At this composition, the system achieved an optimal balance among ion concentration, ionic mobility, and matrix structure, resulting in maximum current and voltage outputs as well as minimum impedance.

At this stage, the effect of different electrode pair combinations on

the performance of the bio-battery was evaluated under the optimum electrolyte conditions. The electrode variations were investigated to examine the differences in the electrochemical characteristics of each electrode material in terms of current generation, voltage output, and impedance, which serves as an indicator of the system's internal resistance. The use of different electrode pairs influences the oxidation–reduction reactions occurring at the electrode surfaces, thereby directly affecting the efficiency of charge transfer within the bio-battery.

From an electrochemical perspective, the performance of a cell is largely determined by the potential difference between the anode and cathode, which depends on the standard reduction potentials of the respective electrode materials. Therefore, the selection of an appropriate electrode combination is a critical factor in determining the magnitude of the generated voltage and the ability of the system to conduct electric current. In addition, the interaction between the electrodes and the electrolyte influences the internal resistance of the cell, which is reflected in the impedance of the system. The measurement results are presented in Table 4.4.

Table 4.4 presents the effect of electrode variation on the voltage, current, and impedance of the bio-battery under optimum electrolyte conditions. The results indicate that the graphite–aluminum electrode pair exhibited the best performance, producing a voltage of 4.81 V, a current of 0.921 mA, and the lowest impedance of 3.02 Ω . The graphite–zinc pair showed moderate performance, with a voltage of 3.56 V, a current of 0.827 mA, and an impedance of 4.21 Ω . In contrast, the graphite–copper pair demonstrated the lowest performance, yielding a voltage of 0.174 V, a current of 0.20 mA, and the highest impedance of 8.18 Ω .

Table 4.4 Effect of different anode–cathode electrode combinations on the performance of the bio-battery under optimum electrolyte conditions.

Electrode Variation at the Optimal Value of the Electrolyte	Current (mA)	Voltage (V)	Impedance (Ω)
Graphite – Aluminium	4,81	0,921	3,02
Graphite – Copper	0,20	0,174	8,18
Graphite – Zinc	3,56	0,827	4,21

The differences in performance are closely related to the standard reduction potentials of the respective electrode materials. Aluminum has a standard reduction potential of -1.66 V, zinc -0.76 V, and copper $+0.34$ V. In general, the more negative the reduction potential of a metal, the more readily it undergoes oxidation and acts as an anode in an electrochemical system (Smajic et al., 2021). In the graphite–aluminum pair, aluminum functions as the anode due to its highly negative reduction potential, making it more susceptible to oxidation. This facilitates a higher electron flow toward the graphite electrode as the cathode, thereby increasing the current and voltage output. In addition, the large potential difference between the electrodes contributes to the high cell voltage (Wang et al., 2017). In the graphite–zinc system, zinc has a less negative reduction potential compared to aluminum, resulting in lower oxidation tendency. Consequently, the current and voltage produced are lower than those of the graphite–aluminum pair (Zhang et al., 2019).

Meanwhile, in the graphite–copper electrode pair, copper has a positive reduction potential and therefore tends to resist oxidation. This results in less effective electrochemical reactions, leading to very low current and voltage outputs. The high impedance observed in this system also indicates a significant internal resistance, which further reduces charge transfer efficiency (Itahara et al., 2024). In contrast, the lower impedance

observed for the graphite–aluminum pair indicates reduced internal resistance and improved conductivity of the system. This condition supports more efficient electron transfer processes, thereby enhancing the overall performance of the bio-battery.

Based on these results, it can be concluded that electrode pairs with a larger difference in standard reduction potentials tend to exhibit better bio-battery performance. In this study, the graphite–aluminum combination was identified as the most optimal electrode pair, as it produced the highest voltage and current as well as the lowest impedance.

CONCLUSION

This study successfully developed a multi-ion bio-battery based on a sugarcane bagasse matrix by integrating *Moringa oleifera* leaf powder, NH_4Cl , and *eichhornia crassipes* (water hyacinth) powder as electrolyte components. The developed system enhanced the performance of the solid electrolyte through improved ionic conductivity and more efficient charge transport. Varying the mass of *Moringa oleifera* leaf powder identified 6 g as the optimum composition, producing a current of 1.47 mA, a voltage of 0.706 V, and an impedance of 28.6 Ω , indicating an optimal balance between ion concentration and ion mobility. The addition of 3 g NH_4Cl to the optimum *Moringa oleifera* composition further

improved the bio-battery performance, increasing the current and voltage to 3.62 mA and 0.812 V, respectively, while reducing the impedance to a minimum value of 2.03 Ω due to the higher concentration of free charge carriers. Furthermore, incorporating 3 g of water hyacinth powder yielded the highest electrochemical performance, generating a current of 4.81 mA, a voltage of 0.921 V, and an impedance of 3.02 Ω . This enhancement can be attributed to the mineral-ion content of water hyacinth and its ability to retain moisture, which facilitated more effective ion transport within the electrolyte matrix. In addition

to electrolyte composition, electrode selection significantly influenced bio-battery performance. Among the tested electrode pairs, the graphite–aluminum configuration exhibited the best performance owing to its larger electrochemical potential difference and lower internal resistance. Overall, the multi-ion approach proposed in this study effectively improved the electrochemical characteristics of the bio-battery and demonstrated considerable potential for further development as an environmentally friendly, sustainable, and biomass-based alternative energy source.

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