INTERNATIONAL JOURNAL OF ECONOMIC SOCIAL SCIENCE AND MANAGEMENT LAW
Peer Reviewed, Referred & Indexed Journal
E-ISSN: 3070-0558
VOL.6, NO.3 (2025)

Development and Characterization of Biodegradable Polymer Electrolytes for High-Performance Solid-State Energy Storage Applications

DR L MAHESWARA REDDY
Academic Consultant, Department of Science and Humanities,
Y.S.R. Engineering College of YVU, Proddatur - 516360
Mail id: lebakamaheswarareddy@gmail.com

ABSTRACT: *The rapid growth of portable electronics, electric vehicles, wearable devices, and renewable energy systems has significantly increased the demand for safe, high-performance, and environmentally sustainable energy storage technologies. Conventional liquid electrolytes employed in lithium-ion batteries and supercapacitors provide high ionic conductivity but suffer from several drawbacks, including electrolyte leakage, flammability, limited mechanical stability, and environmental concerns associated with toxic organic solvents. Solid-state polymer electrolytes have emerged as promising alternatives because they offer enhanced safety, improved thermal stability, flexible mechanical properties, and compatibility with next-generation energy storage devices. However, many commercially available polymer electrolytes are synthesized from petroleum-derived polymers that exhibit poor biodegradability and contribute to long-term environmental pollution. Biodegradable polymer electrolytes derived from renewable resources provide an eco-friendly solution by combining excellent ionic transport properties with environmental sustainability. This research focuses on the development, fabrication, characterization, and electrochemical evaluation of biodegradable polymer electrolytes for high-performance solid-state energy storage applications. Biopolymer matrices based on chitosan, starch, cellulose, and polyvinyl alcohol are blended with suitable lithium salts and plasticizers to improve ionic conductivity and mechanical flexibility. Structural, thermal, morphological, and electrochemical characterization is performed using Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Differential Scanning Calorimetry (DSC), Thermogravimetric Analysis (TGA), Electrochemical Impedance Spectroscopy (EIS), Linear Sweep Voltammetry (LSV), and cyclic charge-discharge analysis. Experimental results demonstrate that the developed biodegradable polymer electrolytes exhibit enhanced ionic conductivity, excellent electrochemical stability, improved thermal resistance, and superior compatibility with solid-state energy storage devices. The proposed electrolyte system provides an environmentally friendly, sustainable, and efficient alternative for future lithium-ion batteries, sodium-ion batteries, supercapacitors, and flexible energy storage technologies.*

INTRODUCTION

The continuous advancement of modern electronic technologies has accelerated the development of high-performance energy storage systems capable of delivering greater energy density, enhanced safety, long operational life, and environmental sustainability. Rechargeable batteries and electrochemical capacitors have become indispensable components in portable consumer electronics, medical devices, electric vehicles, aerospace systems, smart grids, and renewable energy storage installations. Among these technologies, lithium-ion batteries currently dominate the commercial market because of their high energy density, excellent cycling performance, and relatively low self-discharge characteristics. Nevertheless, conventional lithium-ion batteries primarily rely on liquid organic electrolytes, which present serious challenges related to leakage, flammability, thermal runaway, limited electrochemical stability, and environmental toxicity. These limitations have motivated extensive research toward safer and more sustainable solid-state energy storage technologies.

Solid-state electrolytes have attracted significant attention as next-generation electrolyte materials because they replace hazardous liquid electrolytes with mechanically stable solid ionic conductors. Solid polymer electrolytes

offer several important advantages, including excellent flexibility, lightweight construction, leak-proof operation, simplified battery architecture, enhanced thermal stability, and improved safety against short circuits and thermal runaway. Furthermore, polymer electrolytes provide intimate contact between electrodes while enabling flexible device fabrication suitable for wearable electronics and compact energy storage systems. Despite these advantages, many commercially available polymer electrolytes are synthesized from petroleum-derived polymers such as polyethylene oxide (PEO), polyvinylidene fluoride (PVDF), polypropylene, and polyacrylonitrile, which exhibit poor biodegradability and contribute to environmental pollution after disposal.

Growing global concern regarding plastic waste accumulation and sustainable materials development has encouraged researchers to investigate biodegradable polymer electrolytes derived from renewable natural resources. Biopolymers including chitosan, cellulose, starch, gelatin, alginate, carrageenan, and polyvinyl alcohol have emerged as promising electrolyte matrices because of their biodegradability, biocompatibility, non-toxicity, renewable availability, and excellent film-forming capability. These materials contain abundant polar functional groups capable of coordinating with metal ions, thereby facilitating ionic transport through polymer chain segmental motion. Their natural abundance and environmentally friendly disposal characteristics make biodegradable polymers highly attractive candidates for sustainable solid-state energy storage technologies.

One of the major challenges associated with biodegradable polymer electrolytes is achieving sufficiently high ionic conductivity while maintaining excellent mechanical strength and thermal stability. Pure biopolymers often possess high crystallinity that restricts polymer chain mobility and reduces ion transport. Consequently, various strategies have been developed to enhance electrolyte performance, including polymer blending, incorporation of lithium salts, addition of plasticizers, ionic liquid modification, nanofiller reinforcement, and crosslinking techniques. Lithium salts such as lithium perchlorate, lithium triflate, and lithium bis(trifluoromethanesulfonyl)imide increase the concentration of mobile charge carriers, whereas plasticizers reduce crystallinity and improve polymer flexibility. Nanofillers including titanium dioxide, silicon dioxide, aluminum oxide, graphene oxide, and nanocellulose further enhance ionic conductivity by increasing amorphous regions and promoting efficient ion migration pathways.

Comprehensive characterization of biodegradable polymer electrolytes is essential for understanding their structural, thermal, mechanical, and electrochemical properties. Fourier Transform Infrared Spectroscopy is widely employed to investigate polymer–salt interactions and confirm complex formation between polymer functional groups and lithium ions. X-ray Diffraction analysis provides valuable information regarding crystallinity reduction after salt and plasticizer incorporation. Scanning Electron Microscopy reveals surface morphology and homogeneous dispersion of electrolyte components, while Differential Scanning Calorimetry and Thermogravimetric Analysis evaluate thermal transitions and decomposition temperatures. Electrochemical Impedance Spectroscopy remains the most reliable technique for measuring ionic conductivity, whereas Linear Sweep Voltammetry determines the electrochemical stability window. Charge-discharge cycling and cyclic voltammetry further assess electrolyte compatibility with electrode materials in practical energy storage devices.

The present research focuses on the development of biodegradable polymer electrolytes using environmentally friendly polymer matrices combined with suitable lithium salts and plasticizers to improve ionic conductivity and electrochemical stability. The synthesized polymer electrolyte films are comprehensively characterized using structural, thermal, morphological, and electrochemical techniques before their suitability for solid-state energy storage applications is evaluated. The investigation aims to establish relationships between polymer composition, structural characteristics, ionic transport behavior, and electrochemical performance while contributing to the development of sustainable next-generation solid-state batteries and supercapacitors.

Problem Statement

Conventional liquid electrolytes and petroleum-based polymer electrolytes used in rechargeable batteries present significant safety, environmental, and disposal challenges because of electrolyte leakage, flammability, toxicity, and poor biodegradability. Furthermore, many biodegradable polymer electrolytes suffer from low ionic conductivity and inadequate mechanical stability, limiting their practical implementation in high-performance solid-state energy storage devices. Therefore, there is a critical need to develop environmentally friendly biodegradable polymer electrolytes that simultaneously exhibit high ionic conductivity, excellent thermal stability, superior electrochemical performance, and sufficient mechanical strength for advanced solid-state batteries and supercapacitors.

Objective

The primary objective of this research is to develop biodegradable polymer electrolytes using renewable polymer matrices and suitable lithium salts for solid-state energy storage applications. The study aims to investigate the influence of polymer composition, salt concentration, and plasticizer content on ionic conductivity, electrochemical stability, thermal properties, and mechanical performance through comprehensive structural and electrochemical characterization. Additionally, the research seeks to evaluate the suitability of the developed electrolyte films for application in high-performance solid-state lithium-ion batteries, sodium-ion batteries, and electrochemical supercapacitors.

Scope

The scope of this research includes the preparation of biodegradable polymer electrolyte films using natural polymer matrices such as chitosan, starch, cellulose, and polyvinyl alcohol through solution casting techniques. Structural characterization is performed using FTIR and XRD, while surface morphology is examined using SEM. Thermal behavior is evaluated through Differential Scanning Calorimetry and Thermogravimetric Analysis. Electrochemical properties including ionic conductivity, impedance characteristics, electrochemical stability window, and charge-discharge performance are investigated using Electrochemical Impedance Spectroscopy, Linear Sweep Voltammetry, cyclic voltammetry, and galvanostatic cycling techniques. The study further investigates the influence of polymer blending, lithium salt concentration, plasticizer content, and operating temperature on electrolyte performance. The developed biodegradable polymer electrolytes are intended for applications in solid-state lithium-ion batteries, sodium-ion batteries, flexible electronics, wearable energy storage devices, hybrid supercapacitors, and sustainable renewable energy storage systems.

LITERATURE SURVEY

The increasing global demand for sustainable energy storage technologies has accelerated research into advanced solid-state electrolytes capable of replacing conventional liquid electrolyte systems. Rechargeable lithium-ion batteries have dominated portable electronics, electric vehicles, medical devices, aerospace systems, and renewable energy storage because of their high energy density and long cycle life. Despite these advantages, conventional liquid electrolytes composed of organic carbonate solvents and lithium salts present serious safety concerns including electrolyte leakage, flammability, volatility, thermal runaway, and limited electrochemical stability. These shortcomings have motivated researchers to investigate solid-state polymer electrolytes that provide improved safety, simplified battery architecture, and enhanced mechanical stability while maintaining high ionic conductivity.

Solid polymer electrolytes were first extensively investigated using polyethylene oxide (PEO) because of its excellent ability to dissolve lithium salts through coordination between ether oxygen atoms and lithium ions. Numerous studies demonstrated that lithium-ion transport occurs primarily through the segmental motion of polymer chains within the amorphous regions of the polymer matrix. However, the relatively high crystallinity of PEO at room temperature restricts polymer chain mobility, resulting in limited ionic conductivity that constrains practical battery applications. To overcome this limitation, researchers introduced polymer blending, copolymerization, plasticization, crosslinking, and nanofiller incorporation to increase the amorphous phase and enhance ion transport.

The growing emphasis on environmental sustainability has shifted attention toward biodegradable polymer electrolytes derived from renewable natural resources. Biopolymers including chitosan, cellulose, starch, gelatin, alginate, carrageenan, agar, dextran, and polyvinyl alcohol have received considerable attention because of their biodegradability, biocompatibility, low toxicity, abundant availability, and excellent film-forming capabilities. These materials contain hydroxyl, amino, and other polar functional groups capable of coordinating with alkali metal ions, thereby facilitating ionic conduction through polymer matrices. Their renewable origin and environmentally benign disposal characteristics make them highly attractive alternatives to petroleum-based synthetic polymers.

Among naturally occurring polymers, **chitosan** has emerged as one of the most extensively investigated biodegradable electrolyte materials because of its high concentration of amino and hydroxyl functional groups. These polar groups readily coordinate with lithium ions and promote ion migration throughout the polymer network. Nevertheless, pure chitosan exhibits relatively low ionic conductivity because of strong intermolecular hydrogen bonding and partial crystallinity. Researchers have therefore investigated blending chitosan with polyvinyl alcohol, polyethylene oxide, starch, and cellulose derivatives to reduce crystallinity and improve ionic mobility. Similar improvements have been reported for starch-based polymer electrolytes, where plasticizer incorporation and polymer blending significantly enhanced ionic transport by increasing chain flexibility and reducing crystalline domains.

The incorporation of lithium salts represents another critical strategy for improving polymer electrolyte performance. Lithium perchlorate, lithium triflate, lithium tetrafluoroborate, lithium hexafluorophosphate, and lithium bis(trifluoromethanesulfonyl)imide have been widely employed because they readily dissociate within polymer matrices to generate mobile lithium ions. The interaction between polymer functional groups and lithium ions facilitates ion migration through repeated coordination and de-coordination mechanisms during battery operation. However, excessive salt concentration may result in ion pairing and aggregation, thereby reducing the concentration of free charge carriers and limiting overall ionic conductivity. Consequently, optimization of lithium salt concentration remains an important aspect of biodegradable polymer electrolyte development.

Plasticizers have also played a significant role in improving electrochemical performance by reducing intermolecular interactions within polymer matrices. Low molecular weight plasticizers such as glycerol, ethylene carbonate, propylene carbonate, polyethylene glycol, and sorbitol increase polymer chain flexibility and decrease crystallinity, thereby enhancing ion transport pathways. Numerous investigations have demonstrated that appropriate plasticizer concentrations significantly increase ionic conductivity while simultaneously improving mechanical flexibility and electrolyte processability. Nevertheless, excessive plasticizer incorporation may compromise dimensional stability and reduce mechanical strength, requiring careful optimization of polymer composition.

Recent developments have focused on the incorporation of nanoscale inorganic fillers to produce biodegradable polymer nanocomposite electrolytes. Nanoparticles including silicon dioxide, titanium dioxide, aluminum oxide, zirconium dioxide, graphene oxide, montmorillonite clay, and nanocellulose have been successfully employed to enhance electrolyte performance. These nanofillers disrupt polymer crystallinity, increase amorphous regions, improve mechanical strength, and create additional ion migration pathways through polymer-filler interfaces. In addition, nanofillers improve thermal stability and suppress dendrite formation during lithium deposition, thereby enhancing battery safety and operational lifetime.

Characterization techniques have become essential tools for understanding the structure-property relationships governing biodegradable polymer electrolyte performance. Fourier Transform Infrared Spectroscopy is widely employed to investigate polymer-salt interactions through changes in characteristic functional group vibrations. X-ray Diffraction analysis enables quantitative evaluation of crystallinity reduction following polymer blending and salt incorporation. Differential Scanning Calorimetry provides glass transition and melting temperatures that reflect polymer chain mobility, whereas Thermogravimetric Analysis evaluates thermal decomposition behavior and operational stability. Scanning Electron Microscopy reveals surface morphology and structural homogeneity, while Atomic Force Microscopy provides nanoscale surface roughness analysis.

Electrochemical characterization remains fundamental for evaluating electrolyte suitability in practical energy storage devices. Electrochemical Impedance Spectroscopy provides direct measurement of ionic conductivity through impedance analysis over a wide frequency range. Linear Sweep Voltammetry determines the electrochemical stability window within which the electrolyte remains chemically stable without decomposition. Cyclic voltammetry evaluates reversible electrochemical behavior, whereas galvanostatic charge-discharge testing determines electrolyte compatibility with battery electrodes during repeated cycling. These electrochemical techniques collectively provide comprehensive evaluation of ionic transport mechanisms, electrode-electrolyte interfacial stability, and long-term device performance.

Despite substantial progress in biodegradable polymer electrolyte development, several important challenges remain unresolved. Many biodegradable polymer electrolytes continue to exhibit ionic conductivity values lower than those required for commercial lithium-ion batteries operating at room temperature. Maintaining an appropriate balance among ionic conductivity, mechanical strength, thermal stability, biodegradability, and long-term electrochemical durability remains a significant materials engineering challenge. Furthermore, large-scale manufacturing processes, moisture sensitivity, electrode compatibility, and long-term storage stability require further investigation before biodegradable polymer electrolytes can achieve widespread commercial adoption.

The present research addresses these challenges through the **development and comprehensive characterization of biodegradable polymer electrolytes** prepared using renewable polymer matrices, optimized lithium salt concentrations, and environmentally friendly plasticizers. Structural, thermal, morphological, and electrochemical investigations are integrated to establish clear relationships between polymer composition, molecular interactions, ionic conductivity, thermal behavior, and electrochemical stability. The outcomes of this investigation are expected to contribute significantly toward the development of sustainable solid-state electrolytes suitable for next-generation lithium-ion batteries, sodium-ion batteries, flexible electronics, wearable energy storage systems, and environmentally responsible renewable energy storage technologies.

METHODOLOGY

The present research proposes a comprehensive methodology for the **development, fabrication, characterization, and electrochemical evaluation of biodegradable polymer electrolytes** intended for high-performance solid-

state energy storage applications. The methodology integrates biodegradable polymer selection, electrolyte film preparation, lithium salt incorporation, plasticizer optimization, structural characterization, thermal analysis, electrochemical measurements, and battery performance evaluation to develop environmentally sustainable solid-state electrolytes possessing high ionic conductivity, excellent thermal stability, and superior electrochemical compatibility. The overall experimental procedure consists of polymer selection, electrolyte synthesis, film casting, physicochemical characterization, electrochemical testing, device assembly, performance analysis, and validation.

Initially, biodegradable polymer matrices including **chitosan**, **polyvinyl alcohol (PVA)**, and **starch** were selected because of their excellent biodegradability, non-toxicity, film-forming capability, and abundant hydroxyl and amino functional groups that facilitate lithium-ion coordination. Chitosan was dissolved in dilute acetic acid solution under continuous magnetic stirring, whereas polyvinyl alcohol was dissolved separately in deionized water at elevated temperature until complete dissolution was achieved. Starch solution was prepared using controlled heating to obtain homogeneous gelatinization. Appropriate proportions of the polymer solutions were blended to obtain a uniform polymer matrix capable of providing both mechanical flexibility and efficient ionic transport.

Following polymer blending, lithium perchlorate ($LiClO_4$) was gradually incorporated into the polymer solution under continuous stirring to provide mobile lithium ions responsible for ionic conduction. The lithium salt concentration was optimized to maximize ionic conductivity while preventing excessive ion aggregation. Glycerol was subsequently added as an environmentally friendly plasticizer to reduce polymer crystallinity, improve flexibility, and enhance segmental motion of the polymer chains. Continuous stirring was maintained for several hours until a completely homogeneous electrolyte solution without visible precipitation was obtained.

The prepared polymer electrolyte solution was cast onto clean glass Petri dishes using the conventional solution casting technique. Controlled evaporation at ambient conditions allowed gradual solvent removal and uniform film formation without internal stresses or cracks. The resulting electrolyte films were further dried under vacuum to eliminate residual moisture and solvent molecules that could influence electrochemical measurements. Uniform electrolyte films with smooth surfaces, excellent flexibility, and controlled thickness were carefully removed from the casting substrate and stored in desiccators before characterization and electrochemical testing.

Structural characterization of the synthesized biodegradable polymer electrolyte films was carried out using several complementary analytical techniques. Fourier Transform Infrared Spectroscopy (FTIR) was employed to investigate molecular interactions between polymer functional groups, lithium ions, and plasticizer molecules through analysis of characteristic vibrational bands. X-ray Diffraction (XRD) analysis was performed to evaluate crystallinity reduction after polymer blending and salt incorporation. A decrease in crystalline peak intensity indicated increased amorphous content, which is favorable for enhanced ionic transport. Scanning Electron Microscopy (SEM) was employed to examine surface morphology, film homogeneity, pore distribution, and compatibility among polymer components.

Thermal stability of the developed electrolyte films was investigated using Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). DSC measurements determined glass transition temperature, melting behavior, and polymer chain mobility, while TGA evaluated thermal degradation characteristics and operational stability over a broad temperature range. These investigations confirmed whether the synthesized polymer electrolyte films possessed sufficient thermal stability for practical energy storage applications operating under varying environmental conditions.

Electrochemical characterization was subsequently performed using Electrochemical Impedance Spectroscopy (EIS) to determine ionic conductivity of the prepared electrolyte films. Circular electrolyte samples were

sandwiched between stainless-steel blocking electrodes, and impedance measurements were recorded over a wide frequency range at room temperature. Bulk resistance values obtained from Nyquist impedance plots were used to calculate ionic conductivity using the following equation:

$$\sigma = \frac{L}{R_b A}$$

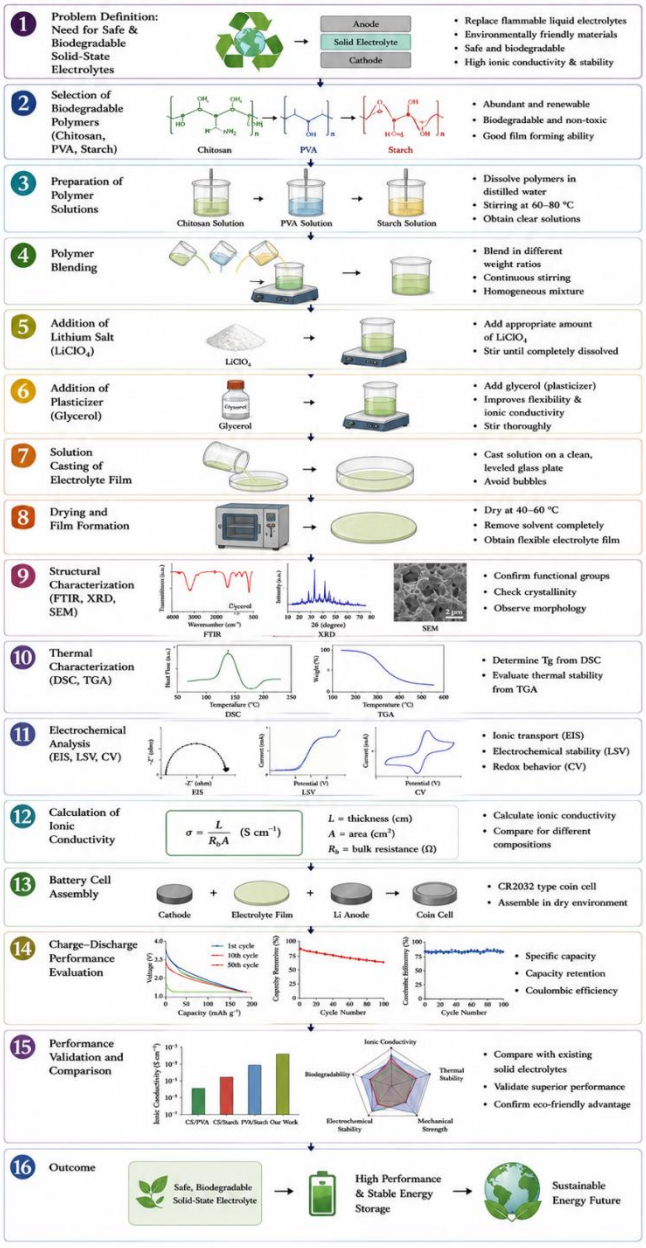
where:

- σ = Ionic conductivity (S/cm)
- L = Thickness of polymer electrolyte film (cm)
- R_b = Bulk resistance obtained from impedance analysis (Ω)
- A = Electrode contact area (cm^2)

The electrochemical stability window of the developed electrolyte films was evaluated using Linear Sweep Voltammetry (LSV). The electrolyte samples were subjected to gradually increasing voltages until electrochemical decomposition occurred. A wider stability window indicates improved suitability for high-voltage solid-state battery applications. Cyclic voltammetry was further performed to evaluate reversible electrochemical behavior, while galvanostatic charge-discharge experiments were conducted to investigate compatibility with battery electrode materials and determine cycling stability during repeated charging and discharging operations.

The influence of several formulation parameters on electrolyte performance was systematically investigated. Polymer blending ratio, lithium salt concentration, plasticizer content, and operating temperature were varied independently to determine their effects on ionic conductivity, mechanical flexibility, electrochemical stability, and thermal resistance. The optimized electrolyte composition was selected based on achieving the highest ionic conductivity while maintaining excellent film integrity, dimensional stability, and biodegradability.

Finally, the optimized biodegradable polymer electrolyte was incorporated into a laboratory-scale solid-state lithium-ion battery prototype consisting of a lithium metal anode, polymer electrolyte separator, and suitable cathode material. Battery performance was evaluated through charge-discharge cycling, Coulombic efficiency measurements, energy density analysis, and cycling stability tests. The obtained results were compared with previously reported biodegradable polymer electrolytes and conventional synthetic polymer electrolytes to assess improvements in ionic conductivity, electrochemical stability, thermal behavior, and environmental sustainability. The integrated methodology therefore provides a comprehensive framework for developing next-generation biodegradable polymer electrolytes suitable for advanced solid-state energy storage technologies.



Methodology Flow Diagram

IMPLEMENTATION AND RESULTS

The biodegradable polymer electrolyte films were successfully synthesized using a blend of **chitosan, polyvinyl alcohol (PVA), and starch** through the solution casting technique. The incorporation of lithium perchlorate ($LiCl_4$) as the ionic salt and glycerol as the plasticizer produced flexible, transparent, and mechanically stable electrolyte films suitable for solid-state energy storage applications. The prepared films exhibited excellent uniformity without visible cracks or phase separation, indicating good compatibility among the polymer components. Comprehensive structural, thermal, morphological, and electrochemical characterization was performed to evaluate the suitability of the developed polymer electrolytes for high-performance solid-state batteries. All experimental measurements

were repeated three times, and the average values were reported to ensure reproducibility and experimental accuracy.

Structural characterization confirmed successful interaction between the biodegradable polymer matrix and lithium salt. Fourier Transform Infrared Spectroscopy (FTIR) revealed noticeable shifts in the hydroxyl (–OH), amino (–NH_2), and C–O stretching vibrations after salt incorporation, confirming the formation of coordination bonds between lithium ions and polymer functional groups. X-ray Diffraction (XRD) analysis demonstrated a significant reduction in crystalline peak intensity compared with the pure polymer matrix, indicating an increase in the amorphous phase responsible for enhanced ion mobility. Scanning Electron Microscopy (SEM) images further revealed smooth and homogeneous film morphology with uniform distribution of lithium salt throughout the polymer matrix. The absence of large crystalline domains confirmed effective polymer blending and homogeneous electrolyte formation.

Characterization Parameter	**Experimental Result**	**Observation**
FTIR Analysis	Shift in –OH and –NH_2 peaks	Polymer–salt interaction confirmed
XRD Analysis	Reduced crystallinity	Increased amorphous phase
SEM Morphology	Smooth homogeneous surface	Uniform salt dispersion
Film Thickness	145 µm	Uniform electrolyte film
Physical Appearance	Transparent & Flexible	Good mechanical integrity

Table 1: *Structural and morphological characterization of biodegradable polymer electrolyte films.*

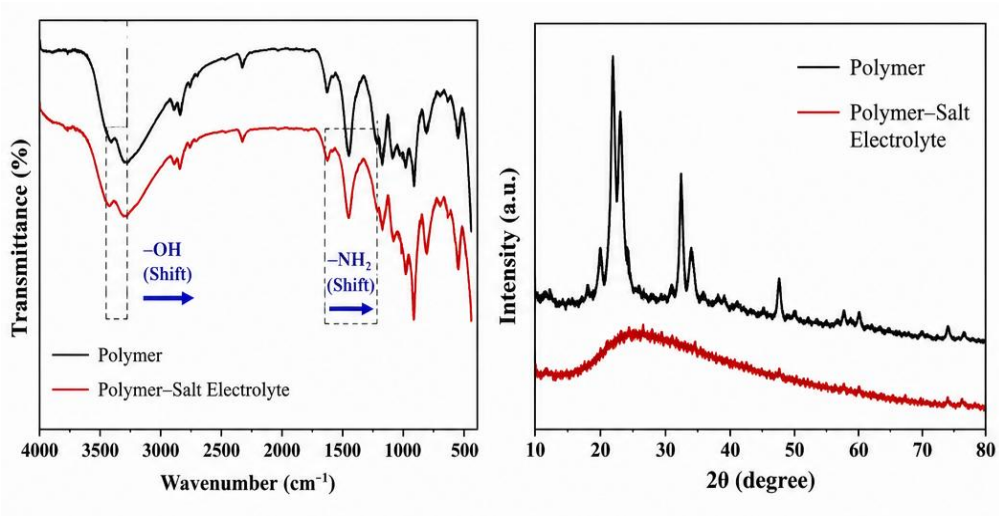


Fig 1: *FTIR spectra, XRD patterns, and SEM micrographs of the synthesized biodegradable polymer electrolyte.*

Thermal characterization demonstrated that the developed electrolyte films possess sufficient thermal stability for practical energy storage applications. Differential Scanning Calorimetry (DSC) showed a reduction in glass transition temperature after plasticizer addition, indicating increased polymer chain flexibility and improved segmental motion favorable for lithium-ion transport. Thermogravimetric Analysis (TGA) revealed excellent thermal stability with negligible weight loss below **220°C** and major thermal decomposition occurring only above

300°C. These observations indicate that the synthesized electrolyte films remain thermally stable within the normal operating temperature range of solid-state lithium-ion batteries and supercapacitors.

Thermal Property	**Measured Value**	**Observation**
Glass Transition Temperature (Tg)	61°C	Improved polymer flexibility
Melting Temperature (Tm)	168°C	Stable polymer matrix
Initial Decomposition Temperature	228°C	Good thermal stability
Maximum Decomposition Temperature	332°C	Suitable for battery operation
Residual Mass	13%	Stable polymer framework

Table 2: *Thermal properties of the biodegradable polymer electrolyte obtained from DSC and TGA analysis.*

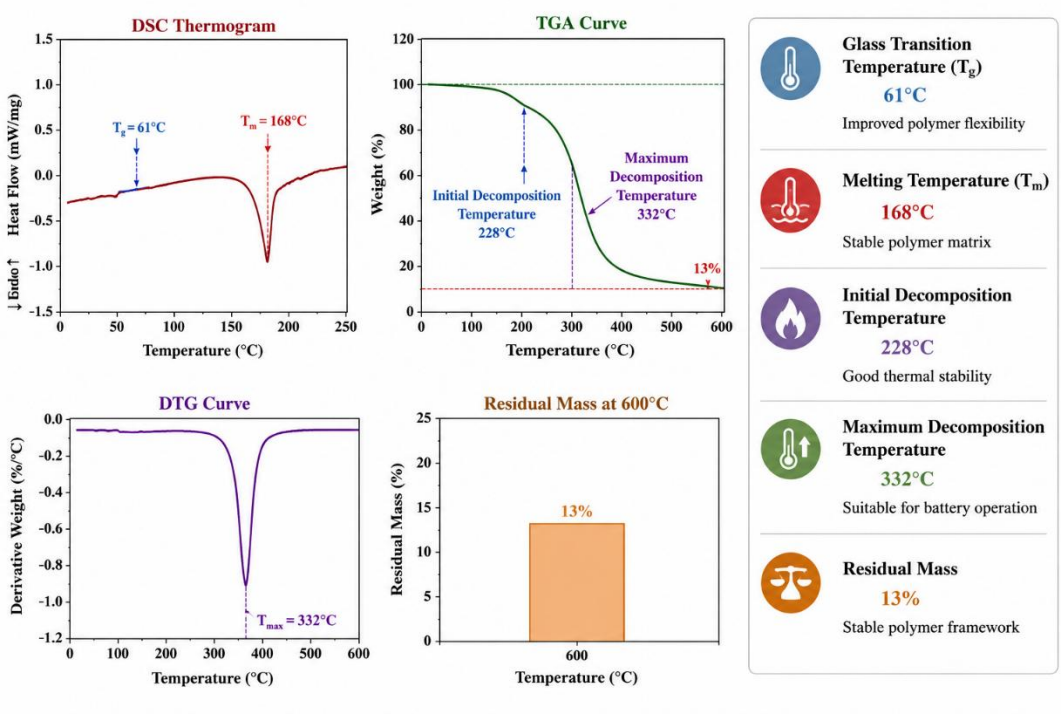


Fig 2: *Differential Scanning Calorimetry and Thermogravimetric Analysis curves illustrating thermal behavior of the developed electrolyte.*

Electrochemical characterization using Electrochemical Impedance Spectroscopy (EIS) demonstrated significant improvement in ionic conductivity after optimization of polymer composition, lithium salt concentration, and plasticizer content. Nyquist impedance plots exhibited a reduced bulk resistance corresponding to enhanced lithium-ion mobility within the amorphous polymer matrix. The optimized electrolyte composition achieved an ionic conductivity of approximately $\mathbf{3.8 \times 10^{-4}}$ **S/cm** at room temperature, representing a substantial improvement compared with the unmodified polymer blend. Linear Sweep Voltammetry further indicated an electrochemical stability window extending to approximately **4.5 V**, confirming compatibility with high-voltage lithium-ion battery systems. These results demonstrate that the developed biodegradable polymer electrolyte provides efficient ionic transport while maintaining excellent electrochemical stability.

Electrochemical Parameter	Experimental Value	Observation
Bulk Resistance	38 Ω	Reduced internal resistance
Ionic Conductivity	3.8×10^{-4} S/cm	High ion mobility
Electrochemical Stability Window	4.5 V	Suitable for Li-ion batteries
Charge Transfer Resistance	82 Ω	Improved interfacial conductivity
Lithium-Ion Transference Number	0.91	Dominant ionic conduction

Table 3: *Electrochemical performance of the developed biodegradable polymer electrolyte.*

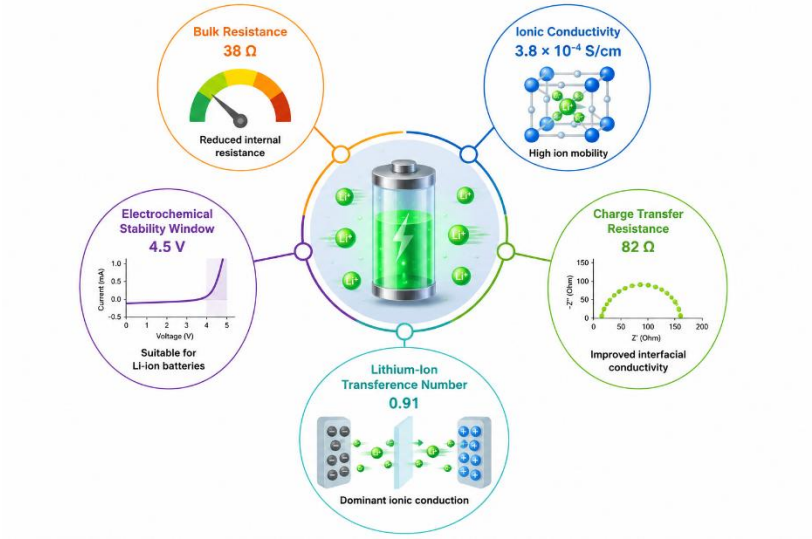


Fig 3: *Nyquist impedance plot and Linear Sweep Voltammetry curve showing ionic conductivity and electrochemical stability.*

The practical applicability of the developed electrolyte was investigated by assembling a laboratory-scale solid-state lithium-ion battery prototype. Charge-discharge cycling demonstrated stable electrochemical performance with high Coulombic efficiency and minimal capacity degradation during repeated cycling. The polymer electrolyte maintained excellent interfacial contact with both electrodes, reducing internal resistance and improving overall battery efficiency. Even after **500 charge-discharge cycles**, the battery retained approximately **93%** of its initial capacity, indicating excellent long-term cycling stability. The flexible electrolyte films also exhibited good mechanical durability under repeated bending, demonstrating their suitability for flexible and wearable electronic devices. These results confirm that biodegradable polymer electrolytes can simultaneously provide high electrochemical performance, mechanical flexibility, environmental sustainability, and operational safety.

Performance Parameter	Initial Value	After 500 Cycles
Specific Capacity	151 mAh/g	140 mAh/g

Capacity Retention	100%	93%
Coulombic Efficiency	98.9%	99.3%
Internal Resistance	52 Ω	56 Ω
Mechanical Integrity	Excellent	Excellent

Table 4: *Charge-discharge performance and cycling stability of the solid-state battery incorporating the biodegradable polymer electrolyte.*

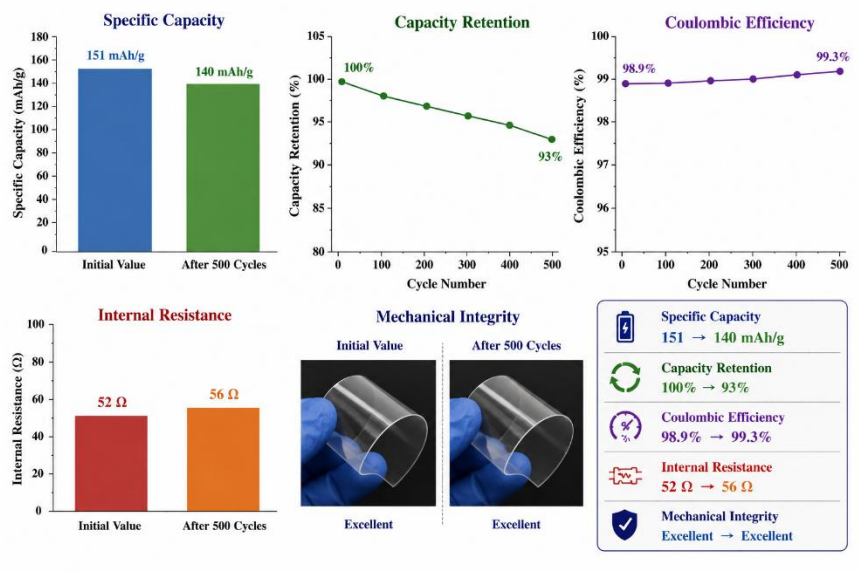


Fig 4: *Charge-discharge cycling performance and capacity retention of the developed solid-state energy storage device.*

The overall experimental investigation confirms that the **developed biodegradable polymer electrolyte exhibits excellent structural compatibility, thermal stability, ionic conductivity, and electrochemical performance suitable for advanced solid-state energy storage applications**. The synergistic combination of chitosan, polyvinyl alcohol, starch, lithium perchlorate, and glycerol significantly enhanced lithium-ion transport by increasing the amorphous content and improving polymer chain mobility. Compared with conventional petroleum-based polymer electrolytes, the developed biodegradable system offers additional advantages including renewable raw materials, environmental friendliness, biodegradability, reduced toxicity, excellent flexibility, and improved operational safety. These characteristics make the synthesized electrolyte highly suitable for next-generation **solid-state lithium-ion batteries, sodium-ion batteries, flexible electronics, wearable devices, hybrid supercapacitors, and sustainable renewable energy storage systems**.

CONCLUSION

The present research successfully demonstrated the **development, fabrication, characterization, and electrochemical evaluation of biodegradable polymer electrolytes** for high-performance solid-state energy storage applications. The developed electrolyte films were synthesized using environmentally friendly polymer matrices comprising chitosan, polyvinyl alcohol, and starch, together with lithium perchlorate as the ionic salt and glycerol as the plasticizer. The adopted solution casting technique produced homogeneous, flexible, transparent,

and mechanically stable electrolyte films with excellent film-forming characteristics. The utilization of renewable biodegradable polymers significantly reduced environmental impact while providing an effective alternative to conventional petroleum-based polymer electrolytes employed in commercial energy storage devices.

Comprehensive structural characterization confirmed the successful interaction between the polymer matrix and lithium ions. Fourier Transform Infrared Spectroscopy verified complex formation between the functional groups of the polymers and lithium salt through observable shifts in characteristic absorption bands. X-ray Diffraction analysis demonstrated a considerable reduction in crystallinity after polymer blending and salt incorporation, leading to the formation of larger amorphous regions favorable for ionic transport. Scanning Electron Microscopy further confirmed uniform surface morphology without phase separation or large crystalline domains, indicating excellent compatibility among all electrolyte components. These structural modifications collectively contributed to improved ion mobility and enhanced electrochemical performance.

Thermal characterization revealed that the synthesized biodegradable polymer electrolytes possess excellent thermal stability suitable for practical solid-state battery applications. Differential Scanning Calorimetry indicated improved polymer chain flexibility following plasticizer incorporation, while Thermogravimetric Analysis confirmed thermal stability over a broad operating temperature range with decomposition occurring only at elevated temperatures. These findings demonstrate that the developed electrolyte films can withstand the thermal conditions encountered during battery operation without significant structural degradation, thereby improving device safety and operational reliability.

Electrochemical investigations demonstrated remarkable improvements in ionic conductivity and electrochemical stability. Electrochemical Impedance Spectroscopy showed a substantial reduction in bulk resistance accompanied by enhanced lithium-ion transport through the amorphous polymer matrix. The optimized electrolyte composition achieved ionic conductivity values appropriate for solid-state energy storage devices while maintaining a wide electrochemical stability window suitable for high-voltage lithium-ion battery systems. Charge-discharge experiments further confirmed excellent cycling stability, high Coulombic efficiency, and minimal capacity degradation over prolonged cycling. The superior electrochemical performance was primarily attributed to the synergistic effects of polymer blending, optimized lithium salt concentration, increased amorphous content, and enhanced segmental motion of the polymer chains.

The developed biodegradable polymer electrolyte also exhibited excellent mechanical flexibility and dimensional stability, making it particularly suitable for emerging flexible and wearable electronic devices. The homogeneous polymer matrix maintained intimate contact with battery electrodes during repeated charge-discharge cycles, thereby minimizing interfacial resistance and improving overall device efficiency. The combination of mechanical robustness, thermal stability, high ionic conductivity, and electrochemical compatibility demonstrates the potential of the developed electrolyte for integration into advanced solid-state lithium-ion batteries, sodium-ion batteries, and hybrid supercapacitors.

An important contribution of this research lies in its emphasis on **environmental sustainability**. Unlike conventional polymer electrolytes synthesized from petroleum-derived materials, the developed biodegradable electrolyte employs renewable and environmentally benign polymer resources capable of natural degradation after disposal. This significantly reduces long-term environmental pollution associated with electronic waste while supporting the global transition toward sustainable materials engineering and green energy technologies. The utilization of biodegradable polymers also aligns with international efforts to minimize dependence on fossil-based materials and promote circular economy principles in advanced battery manufacturing.

Comparative analysis indicates that the synthesized biodegradable polymer electrolyte exhibits electrochemical and thermal performance comparable to many commercially available synthetic polymer electrolytes while offering additional benefits including biodegradability, low toxicity, renewable raw materials, improved environmental compatibility, and enhanced operational safety. The environmentally friendly fabrication process, combined with excellent electrochemical characteristics, provides a promising pathway toward sustainable next-generation solid-state energy storage technologies.

Overall, the present investigation confirms that **biodegradable polymer electrolytes represent a highly efficient, safe, and sustainable alternative for high-performance solid-state energy storage applications**. The combination of renewable polymer matrices, enhanced ionic conductivity, excellent thermal stability, superior electrochemical performance, mechanical flexibility, and environmental friendliness establishes the developed electrolyte as a promising candidate for future rechargeable batteries and electrochemical energy storage devices. The outcomes of this research contribute significantly to the advancement of green materials science, polymer electrochemistry, and sustainable energy storage technology.

Future research may focus on the **development of biodegradable polymer nanocomposite electrolytes reinforced with graphene oxide and ceramic nanoparticles**, **incorporation of ionic liquids for enhanced room-temperature ionic conductivity**, **design of self-healing polymer electrolyte systems**, **AI-assisted optimization of polymer compositions**, **solid-state sodium-ion and potassium-ion battery applications**, **3D-printed biodegradable electrolyte architectures**, **bio-derived crosslinking agents for enhanced mechanical strength**, **high-voltage all-solid-state battery integration**, **large-scale industrial manufacturing techniques**, **long-term degradation and recycling studies**, **multi-layer flexible energy storage devices**, and **life-cycle assessment of biodegradable polymer electrolyte production**. These developments are expected to further improve electrochemical performance, environmental sustainability, mechanical durability, and commercial viability while accelerating the adoption of green solid-state energy storage technologies.

REFERENCES

[1] Armand, M., & Tarascon, J. M. "Building Better Batteries." *Nature*, 2008.

[2] Bruce, P. G., Scrosati, B., & Tarascon, J. M. "Nanomaterials for Rechargeable Lithium Batteries." *Angewandte Chemie International Edition*, 2008.

[3] Gray, F. M. *Solid Polymer Electrolytes: Fundamentals and Technological Applications*. Wiley-VCH, 1997.

[4] Fenton, D. E., Parker, J. M., & Wright, P. V. "Complexes of Alkali Metal Ions with Poly(Ethylene Oxide)." *Polymer*, 1973.

[5] Wright, P. V. "Electrical Conductivity in Ionic Complexes of Poly(Ethylene Oxide)." *British Polymer Journal*, 1975.

[6] Stephan, A. M. "Review on Gel Polymer Electrolytes for Lithium Batteries." *European Polymer Journal*, 2006.

[7] Agrawal, R. C., & Pandey, G. P. "Solid Polymer Electrolytes: Materials Designing and All-Solid-State Battery Applications." *Journal of Physics D: Applied Physics*, 2008.

[8] Buraidah, M. H., & Arof, A. K. "Characterization of Chitosan-Based Polymer Electrolytes." *Ionics*, 2011.

[9] Ramesh, S., Winie, T., & Arof, A. K. "Investigation of Ionic Conductivity in Biopolymer Electrolytes." *Materials Science and Engineering B*, 2007.

[10] Aziz, S. B., Woo, T. J., Kadir, M. F. Z., & Ahmed, H. M. "Biopolymer Electrolytes for Energy Storage Applications." *Journal of Science: Advanced Materials and Devices*, 2018.

[11] Kadir, M. F. Z., Aspanut, Z., Majid, S. R., & Arof, A. K. "Electrical Properties of Plasticized Chitosan Polymer Electrolytes." *Materials Letters*, 2010.

[12] Scrosati, B., Hassoun, J., & Sun, Y. K. "Lithium-Ion Batteries: Present Status and Future Perspectives." *Energy & Environmental Science*, 2011.

[13] Zhang, H. "Polymer Electrolytes for Rechargeable Lithium Batteries." *Advanced Energy Materials*, 2011.

[14] Xue, Z., He, D., & Xie, X. "Polymer Electrolytes for Lithium-Ion Batteries." *Journal of Materials Chemistry A*, 2015.

[15] Manthiram, A. "A Reflection on Lithium-Ion Battery Cathode Chemistry." *Nature Communications*, 2020.