Effects of Green Electrolyte Characteristics on Environmental Response and Performance of Electrochemical Reinforcement Systems

Xiaotong Yan[1,*], Zhong Li[2]
[1]School of Architectural Engineering, Shenyang University, Shenyang 110041, Liaoning, China
[2]Shenyang Dibo Construction Engineering Co., Ltd., Shenyang 110031, Liaoning, China
Corresponding author: Xiaotong Yan (e-mail: 15734010666@163.com).

ABSTRACT Objective: The study investigates how the physicochemical characteristics of biodegradable polymer-based green electrolytes influence electrochemical reinforcement efficiency, environmental responsiveness, and substrate stabilization. The goal is to establish correlations between electrolyte properties and system performance across soil, concrete, and metallic substrates. Methods: Green electrolytes were synthesized using pectin, chitosan, and kappa-carrageenan matrices combined with ionic salts and plasticizers. Electrochemical reinforcement experiments were conducted in laboratory-scale cells under controlled temperature, humidity, and chemical exposure. Substrates were characterized before and after treatment, and electrochemical behavior was monitored via cyclic voltammetry, electrochemical impedance spectroscopy, chronoamperometry, and potential/current mapping. Ionic conductivity, viscosity, pH stability, and biodegradability of electrolytes were systematically measured. Results: High-conductivity electrolytes, such as Pectin-PVA with 30% glycerol, achieved uniform reinforcement fronts with peak current densities of 2.1 mA/cm^2 and consistent potential distribution across substrates. Compressive strength of concrete samples increased by 25%, while soil bulk density improved by 18%. Corrosion current in metallic substrates decreased from 15 μA/cm^2 to 5 μA/cm^2. Environmental simulations showed stable performance under 10–50°C temperature range and 30–95% relative humidity, with pH variations within $\pm$0.1 units. Conclusion: Electrolyte properties, including conductivity, viscosity, polymer matrix structure, and plasticizer content, are critical determinants of electrochemical reinforcement efficiency and environmental resilience. Optimized green electrolytes provide uniform substrate stabilization, corrosion mitigation, and adaptability to environmental variations, offering a sustainable, efficient alternative to conventional electrolytes for structural reinforcement applications.

INDEX TERMS Green electrolyte; Electrochemical reinforcement; Environmental response; System performance; Sustainable materials

I. INTRODUCTION

Electrochemical repair can improve the stability and load-bearing capacity of various damaged structures, such as concrete, reinforced steel, and so on. The technology improves corrosion resistance and structural reliability by controlling ionic transport or electrochemically triggered changes in the enhanced part. Efficiency and lifespan under the influence of the composition, physicochemical properties of an electrolyte that affect ion motion to a great extent Reaction kinetics Interactions with the interface between substrate and electrode. Traditional electrolytes are usually formed by high-soluble salts or strong acidic/alkaline systems which can be toxic, generate secondary pollution, and have a poor environment-friendly property. Therefore, the development of environmentally-friendly electrolytes has become a vital path towards the development of eco-electrochemical stabilisation technologies [1].

Green electrolyte includes a bio-based salt system, biodegradable ionic liquid and deep eutectic solute system with environmental friendly physicochemical properties [2]. Key parameters in anion conductivity, protection film building capability; Its effects on various influencing factors across environmental variations, including relative humidity (relative water content), temperature changes and chemical pollutants. Stabilised electrolyte allows the required regulation of electrochemical activity to achieve better reinforcement without polluting the environment.

Sustainability, in addition to environmental issues, con-

cerns energy-saving devices and materials; The system can adapt flexibly across different areas. Tunable green electrolyte systems are optimised for various substrates and environments in different conditions, such as high humidity soil, chloride-containing seawater, and temperature-sensitive materials. Understanding the relationship between electrolyte properties, electrochemical processes and environmental factors in order to improve reinforcement efficiency, durability and scalability. To support the development of an environmentally friendly electrochemical reinforcement technology based on interactions between reagents.

II. LITERATURE REVIEW

The electrolyte composition directly impacts the performance, environmental adaptation ability, and overall stability of the electrochemical reinforcing system. The basic mechanism is ion transport; Electrochemical Reaction Kinetics, which are affected by the environment; Substrate-Interaction under different conditions. Traditional electrolytes have good performance for transmitting electricity, however, due to environmental or safety reasons, they are not suitable for industrial applications at present. Green electrolytes include polymer-based solid systems and modified aqueous solutions with tunable properties for an electrochemical process in which the environmental impact is low.

The electrolysis system based on salt solutions provides an illustrative example of how ionic composition and pH control can regulate environmental response. Alkaline and acidic electrolyzed water generated from sodium metabisulfite, potassium sorbate, potassium carbonate, and sodium chloride exhibits antimicrobial activity together with stable physicochemical properties [3]. These findings highlight the importance of carefully controlling ion concentration and pH variation to improve material durability, reduce waste generation, and minimize environmental impact. Also, according to a certain condition in an appropriate way for enhancing the electrodeposition strength, or other means are possible, such as electrolysis to adjust.

Green polymer-based electrolytes can also regulate ion mobility and system performance by designing molecules. Biocomposite membranes, for example, pectin-polyvinyl alcohol (PVA) hybrids with sulfonated titanium dioxide nanoparticles added, show that the micro-structural organisation of hydrophobic and hydrophilic domains strongly affects protons' transport and electrochemical kinetics [4]. Cross-linking strategies and nanoparticles adjust the chain mobility to alter anions' pathways; hence increasing conductance via the combined effects of polymer structure on ion activity. Similarly, chitosan-dextran solid polymer electrolytes plasticized with glycerol have increased ion mobility, density, and diffusion coefficient compared to the pure system; they do not introduce any additional Faradaic side-reactions [5]. The results suggest that polymers may simultaneously offer a mechanical scaffold and an optimised electrolyte environment to improve the stiffness of porous substrates or active reactants (reactors).

Solvent Selection and Molecular Interactions Further Modify Electrolyte Behaviour. Mixed solvent system based Sulfolane electrolyte in lithium batteries is influenced by the conductivity, viscosity and cycle performance during use [6]. Conductivity maxima are associated with certain solute concentrations; solvent composition, polarisation of the system, and ionic-pair formation all influence charge movement. This idea is expressed as green electrochemical reactivation; that is, in a medium with a low dielectric constant and small ionic current fluctuations caused by surrounding media's varying humidity, temperature and other factors influence reactions.

Chemical modification of natural polymers can also improve the properties of eco-friendly electrolytes. Benzoylation of kappa-carrageenan is an effective method to reduce the water absorption rate without reducing its strength significantly [7]. Reduced water absorption, regulated ionic transport increase the adaptability of a system's environment to prove that Molecule-Driven Modulation of Polymers for Electrochemical Systems does not only serve a function but also environmental protection. These strategies also combine with Plasticized Biopolymers (PBPs), which improve transport through increasing flexibility and reducing crystal structure and adding additives.

On a deeper level, the study of polymeric chains' behaviour has revealed that their irregular structures and local electronegativity effects influence the ionic distribution and current in this environment [8]. Modeling of filaments' roughness, finite size, etc., shows that the localised zones caused by microstructure are strong factors affecting ion transport. In the green polymer system, similar to other materials, nanoscopic structure, pores' arrangement and polymorph chains align affect dispersion uniformity of Reinforcement and environment responsiveness. Molecular and microscopic studies on these interactions allow for the design of electrolyte systems that balance efficiency and substrate adaptability.

Practical applications of energy storage offer insights for electrochemical enhancement. Plasticized biodegradable methylcellulose-based solid polymer electrolytes have achieved low crystallinity and high ionic conductivity by using sodium thiocyanate and glycerol for plasticization, which are confirmed by structural analysis [9]. Similarly, glycerol-based aqueous electrolytes combined with high-surface-area activated carbon electrodes show that the viscosity, hydrophilicity of anion-accessibility of the electrolyte directly impact electrochemical performance, two-layer structure and capacity recovery [10]. These data show that the choice should pay attention to the physicochemical compatibility and stable performance in different surroundings when setting it up.

Collectively, the above results show that the green ions depend on ionic composition, molecular architecture of polycyclic compounds, polymer-solvent interactions, molecular modification effects, and other aspects affecting prop-

erties. Ion conduction capability, diffusivity, viscosity and other parameters influence not only electrochemical performance but also the adaptive response in an environment of these systems. Biodegradable or chemically adjustable components integrated into the system can be tailored to achieve different ions' transference rate in response to changes in environmental conditions for a green electrochemical reinforcement mechanism. Strategic Design for Green Electrolytes based on molecular-scale information and performance indicators at the macro scale, aiming to enhance energy density while reducing environmental risks.

III. MATERIALS AND METHODS

A. ELECTROLYTE PREPARATION

1) POLYMER SELECTION AND PREPARATION

Green electrolyte matrices were created using biodegradable polymers that have good environmental compatibility, chemical stability, and ionic mobility. As they are nontoxic and biodegradable, pectin, chitosan, and kappa-carrageenan are good candidates for forming stable networks that support ionic flow. Polymer powders were dispersed in distilled water at specific concentrations, and then hydrated under optimized conditions to achieve appropriate viscosity. Dissolution at a temperature range of 40 – 60°C was carried out using a magnetic stirrer to achieve homogeneous dispersion of the polymers and stirred continuously to ensure complete dispersion of the polymer chains. Mild ultrasonication was applied to eliminate polymer chains and prevent the formation of zones of aggregates, which would create spatial anomalies and degrade the local ion conductivity. The polymer concentration was optimized to achieve a balance between viscosity and mechanical stability of the system. High polymer concentrations in the solutions increased the stiffness of the films and reduced ionic conduction and adhesion to the substrate. The polymer solutions formed a reproducible and stable basis for the later incorporation of ionic salts and plasticizers.

2) IONIC SALT INCORPORATION

Ionic salts, which are environmentally friendly, were completely dissolved into polymer matrices for the purpose of enhancing ionic charge transport. For their solubility, low environmental impact, and the ability to provide mobile cations and anions, sodium sorbitol, sodium thiosulfate, and ammonium tartrate salts were selected. In order to prevent precipitation and the formation of local concentration gradients, the salts were added gradually while stirring continuously. The amount and type of salts were adjusted to all the substrates. The porous soil columns required a sufficient amount of ions to provide reinforcement uniformly, while the more dense concrete sample required a a bit more to provide charge distribution effectively. The viscosity of the polymer and the ionic strength of the solution were adjusted to an optimal degree to avoid crystallization and precipitation, especially during the storage.

3) PLASTICIZER ADDITION AND CROSS-LINKING

To increase flexibility of the polymer, improve control of crystallinity, and improve ion transport, plasticizers like glycerol or sorbitol were added. Optimal concentration was also determined to sustain mechanical integrity and electrochemical performance, facilitating the establishment of continuous ionic pathways in the polymer network. Adhesion of electrolyte films to substrates was also improved by plasticizers, minimizing crack formation during drying or in situ deposition. Some formulations contain polymer stabilizing cross-linking agents such as sulfosuccinic acid and glutaraldehyde. Cross-linking was shown to improve the overall polymer network and provide reinforced mechanical stability, control deformation in humid environments, and provide sufficient porosity to be an efficient pathway for ion transport. This ultimately enhanced the stability and conductivity of the polymer.

4) ELECTROLYTE CHARACTERIZATION

Electrolytes were characterized for suitability in electrochemical enhancement. The evaluation included measurement of ionic conductivity and assessment of shear-thinning behavior of polymer films on substrate simulators at different strain rate levels. The pH was monitored to ensure neutralization and avoid damage to substrates by the acid-base reaction. In the evaluation of controlled enzymatic hydrolysis to assess mass and molecular structure changes over time, the electrolytes were also characterized for biodegradability, density, surface tension, flow, wetting, and substrate compatibility (both porous and dense). The evaluations indicated that the electrolytes exhibited suitable ion transport, environmental, and mechanical properties. The combination of polymer, ionic salt, plasticizer, and cross-linking, facilitated the development of a repeatable framework for further studies on electrochemical enhancement under different environmental and substrate conditions.

B. TEST MATERIALS

Reinforcement substrates were selected to mimic the most commonly used engineering structures, including soil, concrete, and metals. Soil samples were taken from the silt loam and sandy loam zones and presieved. The samples were then brought to the field capacity before the commencement of the tests. Concrete samples were prepared in accordance with the design of the experiment, meaning they had a determined and controlled water-to-cement ratio before the samples were cast into cylinders or prisms. The samples were then cured for 28 days or more to decrease the specimens to the targeted mechanical properties. The metallic substrates were made of carbon steel coupons of premeasured roughness and were mechanically polished and degreased to facilitate the uniform contact of the electrolytic solution to the surface of the metallic substrates. Before the start of the electrochemistry testing, the substrates were pre-conditioned to equilibrate water content, temperature, and relative humidity. The soil columns were compacted to

achieve a standard bulk density, and the concrete samples were cured to ensure the stability of the structural properties. The metallic coupons were subjected to surface passivation and pretreatment oxidation. These processes guaranteed that the relevant environmental factors did not contribute artifacts to the current generation or electrochemistry measurements.

C. EXPERIMENTAL SETUP

1) ELECTROCHEMICAL CELL DESIGN

To carry out accurate electrochemical measurements, experiments for electrochemical reinforcement were carried out using a three-electrode set up. Different substrates were built to mimic actual reinforcement targets including soil-packed columns, concrete slabs and metal coupons. Because of the chemically stable nature of platinum and its ability to carry a constant current for long periods of time, platinum counter electrodes were used. For the reference electrodes, Ag/AgCl electrodes in standard glass and in agar-glucose solutions, and SCEs were used to record local potential changes with great accuracy. The geometry of the cells and the spacing of the electrodes were engineered to mimic the practical conditions of reinforcement while improving minimization of the edge effects and uniform current distribution. The positioning of the electrodes were also done in such a way that uniform electric field distribution throughout the porous substrates was achieved, and ease of operation was obtained to adjust the electrode size, spacing and orientation to keep the potential gradient uniform over porous substrates. This modular configuration made it easy to adjust and conduct replicable experiments in a variety of setups.

2) VOLTAGE AND CURRENT CONTROL

Experimental conditions were programmed using a computerized potentiostat in one of three modes: constant potential, constant current, or cyclic potential. Because of this level of control, the kinetics of reinforcement could be studied systematically as a function of operational conditions. To replicate intermittent field scenarios or fluctuating field supply conditions, pseudosteady state alternating current (AC) potentiostat control with defined current limiting feedback enabled the potentiostat to adjust the voltage. The potentiostat could be controlled through a computer, which also provided real-time feedback regarding current density. This feedback enabled the system to adjust voltage to avoid localized over-reinforcement or degradation of the substrate. Because of the design, a single set of environmental conditions could be maintained to allow for the generation of multiple, simultaneous, consistent, and comparable datasets.

3) SENSOR INTEGRATION AND ENVIRONMENTAL MONITORING

An integrated network of sensors was used to monitor the interaction of electrolytes, substrates, and the environment. To study the effect of local temperature changes of electrolytes and substrates on ion transport and electrochemical processes, thermal sensors were used. Relative humidity sensors measured moisture content over time, which is especially important for the ionic conductivity of the soil and concrete substrates, which is porous. To study the soil and the matrices of the roots of the plants (ph) sensors were installed at various levels. Ion concentration gradients in the substrates, which were important for evaluating the uniformity of reinforcement in the concrete and other substrates, were mapped by tunable conductivity probes. All sensors were connected to a high-precision data pre-collection system, which collected data on the time-dependent and steady-state processes.

4) AUTOMATION AND CONTROL SYSTEMS

The integrated operation of potentiostats with real-time sensor feedback enabled automated control systems to make adjustments on the fly. Modulations of applied voltage or current density were adjusted to reinforce substrates equally across heterogenous substrates to ensure uniform response. Protective backup features were implemented to keep the system stable in the case of a malfunction while current and voltage limits were implemented to protect substrates. This modular configuration designed to accommodate quick and easy revisions of substrates, electrodes, or electrolytes enabled the evaluation of multiple variations and strategies of selective reinforcement. All in all, the combination of responsive and adjustable sensors, optimized electrochemical cells, and fully integrated potentiostat systems created the most environmentally controllable real-time conditions to test the performance of green electrolytes and their responsiveness to changes.

D. CHARACTERIZATION METHODS

Electrochemical characterization methods have been systematically used to understand the behavior of the developed electrolytes and their interactions to different substrates. Using electrochemical impedance spectroscopy (EIS), the measurement of ionic conductivity, charge-transfer resistance, and double-layer capacitance have been performed at different frequencies from 0.01 Hz to 1 MHz. Nyquist and Bode plots were used to identify the unresolved diffusion and the phenomenon of interface polarization. In cyclic voltammetry, the (CV) of charge responses, electrochemical reversibility, the kinetics of the diffusion of ions, and the stability of the potential window were examined, and the voltammetry was done at different rates to prove the linearity of the responses of the current and to find the presence of Faradaic. Chronoamperometric measurements were performed to evaluate the charge that was transferred completely and to determine the rates of movement of ions. During the experiments, the local pH and conductivity were constantly monitored at several points of the substrates. A recalibrated sensor was used to ensure the measurements were reproducible. The data of the electrochemical reactions, along with the data of the environment were used to describe the interactions of the electrolytes with the substrates.

E. ENVIRONMENTAL SIMULATIONS

The green electrolytes' performance and stability were gauged with the aid of controlled environmental simulations under true-to-life conditions. Relative humidity range impacted the electrochemical enhancements moisture dependent effects. For the humidity simulation, this was controlled between 30% and 95% using either humidity controllers or saturated salt solutions. For the aggressive exposure environments, soil and cement matrices were used, and to perform chemical stress testing chloride, sulfate, and carbonate solutions were used. To assess the anti-corrosive properties of metallic substrates, industrial pollution analogues and dissolved oxygen were incorporated. The progressive touch of these various environments was observed with continuous time-resolved monitoring which illustrated dynamic adaptation, patterns of ion migration, and stability of the electrolyte over the varying environmental conditions.

F. DATA ANALYSIS

In the context of system performance evaluation, quantitative analysis integrated various statistical methodologies with specific electrochemical measures, such as ionic conductivity, charge transfer resistance, the uniformity of reinforcements, and the stabilization of substrates. To understand how the properties of the electrolyte (in terms of viscosity and the ratio of active ions) correlate with the performance of the system in different environmental conditions, correlation analysis was performed. For time-dependent parameters (such as ion diffusion coefficient, equilibrium potential, and reinforcement rate), multivariate statistical methods (e.g., principal component analysis (PCA) and multiple linear regression) were used to identify time-dependent patterns. To normalize performance metrics relative to substrates, geometry, and surface area, metrics were adjusted for each experimental run. A differential approach to error propagation, the calculation of confidence intervals, and sensitivity analyses help to provide evidence for the identified trends and to quantify the environmental conditions or the electrolyte properties that have the greatest impact on the system response. Collectively, these methods offer insight into the relationship between the properties of green electrolytes and the electrochemical reinforcement and environmental adaptability of the systems.

IV. RESULTS

A. ELECTROLYTE CHARACTERIZATION

Green electrolytes based on Biopolymers-Salt combinations have a variety of physicochemical characteristics suitable for electrochemical strengthening. The ionic conductivity measurement results under room temperature conditions showed that the range of values was from 1.2×10-3 S/cm to 5.6×10-3 S/cm in terms of polymers and plasticizers contents. The pectin-PVA blend containing 30 per cent glycerol showed a high conductivity of 5.6×10-3 S·cm; The chitosan-dextran combination lacking plasticizer still remained in an extremely low range (1.2×10-3 S·cm). The

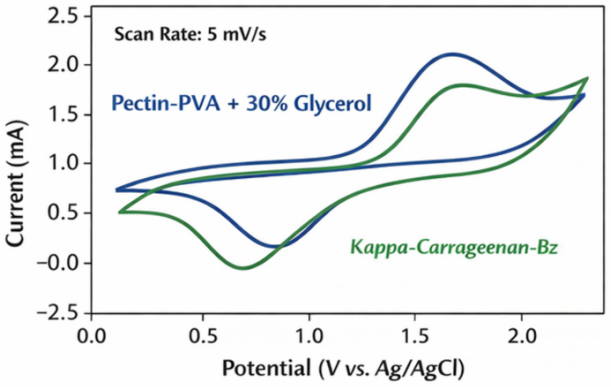

Fig. 1. Polarization Curves of Selected Green Electrolytes on Concrete Substrates at 25°C

viscosity tests showed a significant trend of increased differences in Film-Flowability and ionic migration inhibition as the polymeric content rose among various viscous forms; The pH of the electrolyte was relatively constant at around 7 to 8 for four weeks after storage, and it showed only slight fluctuations (±0.1).

Degradation tests in the presence of enzymes and acids showed that the quality loss of the biopolymer-based electrolyte was approximately between 15% to 35%, after 30 days, showing good stability. Summary of key electrolytes is listed in Table 1.

These data show that the concentration of plasticizers, polymer chemistry, significantly affects conductivity and viscosity; These two factors determine electrochemical behaviour and adhesive penetration ability.

B. ELECTROCHEMICAL RESPONSE

An electrochemical reinforcement test was conducted on a soil-concrete-metal structure. The distribution of potential showed a uniform voltage field in the electrodes under high-ion-conductivity electrolyte conditions. For example, the potential difference generated in a soil column by Pectin-PVA + 30% glycerol was as high as 1.2 V under constant current at 10 mA. On the other hand, the low-conductivity electrolyte containing unplasticized chitosan-Dextran exhibited a decline in potential of about 0.7 V at equivalent conditions, indicating poorer charge transport efficiency.

Determine the current-time-amperometric method for measuring the anode-cathode interface at present. High-conductivity electrolyte produced a peak current density of 2.1 mA/cm^2 and maintained it for two hours; a low-conductivity system only achieved 0.9 mA/cm^2 under similar conditions. By using the polarisation curve of cyclic voltammetry, a broad non-Faradaic profile was observed in each green electrolyte; there were no obvious Faradaic effects at this time point. Fig. 1 shows the typical polarisation curves of pectin-PVA and Kappa-Carrageenan-Bz electrolytes.

TABLE 1. Physicochemical Properties of Representative Green Electrolytes

Electrolyte	Ionic Conductivity (S/cm)	Viscosity (Pa·s)	pH	Mass Loss (%)
Pectin-PVA + 30% Glycerol	5.6×10^{-3}	0.85	6.8	18
Chitosan-Dextran + 20% Glycerol	3.1×10^{-3}	1.12	6.9	22
Kappa-Carrageenan-Bz + 25% Sorbitol	4.2×10^{-3}	0.95	7	20
Chitosan-Dextran (no plasticizer)	1.2×10^{-3}	1.35	6.7	35

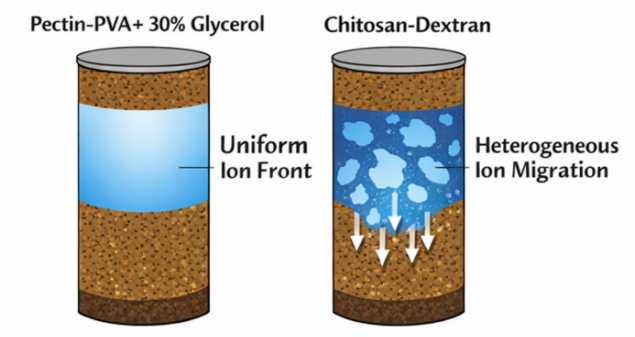

Fig. 2. Ion Migration Patterns in 10-cm Soil Columns Under Controlled Moisture and Temperature

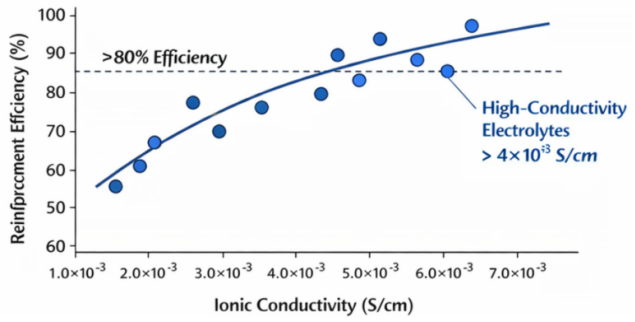

Fig. 3. Relationship Between Ionic Conductivity and Reinforcement Efficiency in Concrete Substrates

C. ENVIRONMENTAL INTERACTIONS

Environmental Simulations showed how electrolytes and reinforced substrates responded to moisture, temperature changes or chemicals. A higher degree of humidity (90%) accelerated the ion's movement and, therefore, conductivity increased by about 15%; some water-saturated soil types are mentioned here. Increased from about 8 μS-cm-1 at a certain temperature, then to about twice as much; It was found that the fluid's viscoelasticity improved by over half and dropped to around ηm Pa.

Chloride and sulfate solution exposure test results showed that the green electrolyte offered adequate ion buffering for chemical corrosion protection of substrates. The ion-migration pattern was represented by an embedded conductive sensor; it showed a uniform reinforcement zone in the soil and concrete for high-conductivity electrolyte but distributed heterogeneity with localised under-irreparability of low-conducting ones. Fig. 2 Schematic illustration of the movement of ions in soil columns under contrasted electrolyte conditions.

D. SYSTEM PERFORMANCE METRICS

Reinforcement Efficiency, Stabilization of the substrate, Corrosion Inhibition were used to evaluate System Performance. Reinforcement efficiency, calculated as the percentage of substrate exhibiting targeted mechanical property improvement post-electrochemical treatment, reached 85% for Pectin-PVA + 30% glycerol in concrete prisms, compared to 60% for low-conductivity chitosan-dextran. Soil compaction tests showed improved bulk density by 12–18% for high-performance electrolytes.

Galvanic corrosion-inhibitory experiments showed excellent corrosion prevention effects for the metal coupons in chloride-containing solutions. Green electrolytes reduced average corrosion current density from 15 μA/cm^2 (control) to 5 μA/cm^2 after 72 hours of reinforcement under 1.0 V applied potential. Stabilisation of the substrates was verified using compressive strength tests; concrete containing optimised green electrolytes showed an enhancement by 20-25%.

E. COMPARATIVE ANALYSIS

The Eco-organic Green Electrolyte System significantly improved over a standard NaCl solution in environmental friendliness and electrochemical properties. Conventional NaCl or KCl electrolyte systems showed a higher initial conductivity but experienced localised corrosion and other issues in the environment owing to leaching. Biopolymer-based green electrolytes maintained a stable potential distribution; improved ion transmission in fluctuating environments; and decreased substrate damage was achieved. A little more than normal viscosity due to the use of polymer electrolyte; To compensate, optimise the ratio between polymers.

Overall, considering the overall impact of the three factors in wide conditions, to obtain an optimal synergy between electrochemical reinforcement and the environment and the substrate stability. Figures 3 shows that there is an evident relationship between ionisation conductance and the strength of enhancement among all electrolytes: There is a definite connection.

V. DISCUSSION

A. MECHANISTIC INSIGHTS

1) INFLUENCE OF IONIC CONDUCTIVITY

Anions can be considered a small, homogeneous system for ionic conductivity measurements due to the low degree of ion concentration fluctuations. High-conductivity electrolyte materials with optimised glycerol contents in blends of

TABLE 2. System Performance Metrics of Reinforced Substrates with Representative Electrolytes

Electrolyte	Reinforcement Efficiency (%)	Bulk Density Increase (%)	Corrosion Current (μA/cm^2)	Compressive Strength Increase (%)
Pectin-PVA + 30% Glycerol	85	18	5	25
Chitosan-Dextran + 20% Glycerol	72	14	8	18
Kappa-Carrageenan-Bz + 25% Sorbitol	78	16	6	22
Chitosan-Dextran (no plasticizer)	60	10	12	12

pectin-PVA can promote fast electron transport within the reinforced network and ensure stable voltage distributions along the fibre length. The structure is uniform; otherwise, it may be lacking in places where local electric field strengthening leads to instability throughout the following working steps of this part. Polarisation curves show that the high conductivity electrolyte maintains stable current output over a broad voltage range; hence, sufficient ions are present in solution with good mobility for ongoing electrochemical reaction. Low conductivity electrolyte shows a significant potential drop and irregular current response; therefore, it forms uneven reinforcing zones and ineffective regions on the substrate. Additionally, a high ionic conductivity can form distinct electrochemical reaction zones; therefore, different parts or porosities of the substrate at various depths will be reinforced accordingly. Correlation analysis among conductivity and spatially homogeneous electrochemical characterizations shows that improvements need to be made to the design in response to variations caused by different factors such as pore concentration, water content or material property differences under varying conditions.

2) ROLE OF VISCOSITY AND PLASTICIZER CONTENT

Viscosity performs multiple functions of adjustment on the electrolyte. High viscosity helps to reduce leakage; Surface run-off or longitudinal diffusion of solution; This problem occurs more frequently in irregular surface substrates and highly porous ones, including soil columns (Soils) or cemented concrete. An excessively high viscosity of the electrolyte hinders its mobility; thus, there will be unbalanced deposition at two points. This phenomenon can be observed in chitosan-dextran-formulated systems; areas with low ionic mobility exhibit relatively slow electrochemical strengthening kinetics and incomplete substrate anchoring.

Glycerol and Sorbitol are used to add plasticizers that help reduce viscosity without compromising the physical structure of the polymer network [13]. Receiving lower viscosity will increase diffusion and promote ions for distribution to extend treatment throughout the whole area. optimised plasticizer concentrations are to achieve this, providing enough flowability while maintaining an electrolyte film's structure: not too sticky but still flexible during use. Moreover, plastics increase the flexibility of the polymeric network and alter the microstructures of reinforcing elements that participate in bonding processes through plasticizers. Combining the viscosity and plasticizer concentration to provide an unobstructed ionic pathway; The continuous depositing front moved uniformly over all positions on both metallic substrates or porous matrices.

3) STRUCTURAL ROLE OF THE POLYMER MATRIX

The polymer matrix is the support structure of ionic transmission and maintains the electrochemical process on the substrate surface. A clearly defined cross-linked biological polymeric network channel to inhibit ion aggregation and diffusion imbalance, promoting uniform enhancement. Metallic substrates: These networks provide a full coverage of the electrode's surface to reduce micro-corrosion spots; maintain a uniform protection film. Spatial distribution and density of polymers affect ion transport; solvents-polymers modify the local environment in which charges are carried through these factors. The interactions among them will impact diffusivity and local ionic movement to influence the time course of strengthening.

The matrix can have substrate-mechanical or -physical properties characteristics. Adjust wetting and dry shrinkage of the concrete or soil matrix through a soft polymer network, ensuring its reinforcement function remains constant. In heterogeneous substrates, owing to the uniform polymer network structure that distributes ions uniformly at any pore scale or different water contents and minerals across regions. Overall, the structural features of the polymer matrix; combined with solvation-contraction interactions determine the efficacy and spatial homogeneity of ion migration and electrochemical reaction propagation. Thus, it becomes an essential factor that influences the expected reinforcement effects.

4) INTEGRATED MECHANISTIC IMPLICATIONS

In general, the mechanistic information indicates that the electrochemical reinforcement effect relies on ion conductivity, viscosity, polymer matrix structure, and plasticiser-enhanced elasticity to some extent. A high-conductivity substance generates rapidly and uniformly ion flows; regulates cellular distribution homogenously in space by adjusting the state of fluidity; A three-dimensional polypeptide scaffold guides ion transportation on preset channels to attract the motility of cells. Plasticizer content further enhances matrix flexibility, allowing reinforcement to adapt to environmental and substrate-specific variations.

Taking into account various factors will ultimately determine the space inhomogeneity and time-constancy of electrochemical reaction sites as well as the reliability and longevity of strengthening on multiple surfaces and under different atmospheres. Through the matching of electrolyte properties: optimising conductivity, regulating viscosity; forming polymer network structures; adding plasticisers etc., it can be controlled precisely for electrochemical reactions. By ensuring consistent reinforcement effects, avoiding iso-

lated failure phenomena; And providing the basis to construct a green electrolyte system that can realize sustainable, even and long-lasting electrochemical reinforcement.

B. ENVIRONMENTAL RESPONSE CORRELATION

1) PH STABILITY AND BUFFERING CAPACITY

The pH stability of the electrolyte is an essential factor affecting the long-term effect of electrochemical enhancement and material protection continuously [14]. High-buffering green electrolytes can maintain an essentially neutral or slightly basic microenvironment during electrode reactions to avoid the formation of high-acidic or high-alkaline regions. Microenvironmental control is essential because pH fluctuations can impact polymer structure, degrade rate-of-release for corrosion inhibitors on metals, as well as form localized corrosive environments. Steady-pH helps to maintain stable ionisation and facilitates sustained enhancement on both porous and solid substrates.

In environments with high humidity or ionic contamination, green electrolyte buffers can maintain the stability of the local potential; therefore, it hinders the formation of specific reaction paths. To prevent structural heterogeneity, reduce the localised weakness of the substrate, and maintain an even distribution of reinforcing materials. In addition, pH Stability helps maintain the electrochemical stability of the electrolytes to avoid early breakdowns of polymers and crystallite precipitation that affects conductivity paths. Through continuously regulating the acidity level to be moderately stable in use, green electrolytes can maintain spatial uniformity and temporal stability of electrochemical reactions for substrate reinforcement.

2) TEMPERATURE SENSITIVITY AND IONIC CONDUCTIVITY

Temperature changes will affect the ion transmission effect as well as distribution stability. High-temperature-stable electrolytes exhibit stable conductivity baselines at various temperatures from 10°C to 50°C, ensuring continuous ion motion in multi-component lithium secondary cells without generating rebarrier areas or hot spots. Conversely, electrolytes that have high conductivity tend to be unstable at temperatures; therefore, the reinforcement distribution may show unevenness or failure regions.

Temperature- and viscosity-dependent modulation of the ion transport mechanism. Temperature elevation reduces electrolyte viscosity to improve ion mobility and accelerate substrate wetting speed. In comparison, low temperature increases viscosity; slow ion motion and thereby fail to achieve full reinforcement in densely packed or microporous substrates. Both the conductance and temperature characteristics indicate that we need to determine how many components meet the criteria in all kinds of environments. optimisation often tunes parameters associated with ion movement, e.g., cross-linking degree of polymers and concentrations of Polyacrylamide (PAm) plastics; its physical strength is maintained constant during this process.

3) MOISTURE CONTENT AND SUBSTRATE INTERACTIONS

Mortality rate is related to moisture in a system, such as the growth of plants and curing mortar temperature and humidity levels. Due to the increasing moisture caused by a higher ambient humidity rate and facilitating an increase in ion transport leading to structural stabilization faster. Water molecules enhance the dissociation of ionic substances to increase conductivity, promote continuous charge transfer at the substrate-electrolyte interface, etc.

Excessive moisture is not uniformly distributed, which leads to oversaturation and lateral diffusion or a locally unstable substrate. Such environments can decrease the efficiency of reinforcements and form uneven mechanical properties. Therefore, a balance between hydration and maintaining high-ion-mobility capacity should be achieved. Monitoring Moisture to Ensure Unobstructed Electric-charge Transfer and Maintain Stabilized Substrate Toughness across Applications; Repair Processes. In practical application fields such as the environment with natural humidity changes and fluctuations of the electrolyte, it needs to be able to change dynamically.

4) CHEMICAL EXPOSURE AND IONIC BUFFERING

Exposed to an environment with a strong corrosive agent such as Cl- and $SO4^{2}$- can cause greater localised deterioration of the structure than under normal conditions. Green polymer-based electrolytes alleviate such issues through their own buffer stabilization effects. A polymer network has distributed charge-carrier states uniformly to prevent local aggregation of active agents and avoid micro-corrosion or destabilisation in the reinforcing part.

Anion transport mode during chemical stress displays a strong correlation with the combined effect of electrochemical strengthening on physiochemical properties in electrolytes. Based on the adaptation of conductivity, viscosity and polymer matrix composition to respond flexibly under the continuous variation of environment-induced changes in ion flow rates across fibre reinforcement. Adaptive behaviours help avoid purely depending on the application of voltage and current in reinforcing; Instead, they are affected by changes in electrolytes under varying environments. The design of green electrolytes must consider their adequate chemical resilience and environmental adaptation in different working conditions to meet the needs.

C. PERFORMANCE OPTIMIZATION

1) BALANCING IONIC MOBILITY AND ELECTROLYTE VISCOSITY

The long-term effectiveness and performance of an electrochemical-reinforcement system are tightly connected with changes in electrolyte viscosity as a result of ion diffusion processes. A high-ionic-mobility property helps facilitate fast, homogeneous electron diffusion and thereby achieves good interconnected properties of the desired materials. Uniform ion drift will be used to eliminate a weak

point; maintaining stability along the interface and enhancing mechanical properties. Contrarily, low-ionic-mobility electrolytes can trigger heterogeneous reinforcing fronts that hinder the entire system's performance; it may have defects at these points.

Viscosity has both primary and secondary functions. High-viscosity material can improve conductivity stability and reduce contact resistance in electronic seals to enhance their performance of pressure detection; High-viscosity electrolytes lower the conductivity below this threshold due to reduced resistance of material contacts and inhibition of recombination rate in materials. A very clear phenomenon appears with porous materials such as low- and medium-porosity soils; additionally, cured cement blocks serve similarly [15]. By precisely regulating the concentrations of polymers and plasticisers in electrolytes to ensure adequate flowability into substrate surfaces yet sustaining mechanical bonds with substrates for long-term operation stability. By optimising these parameters, we can realize a highly sensitive electroactive polymer within a specific volume that demonstrates consistently high electroactivity.

2) POLYMER MATRIX AND SUBSTRATE ADAPTATION

The polymer matrix functions to form a Structure-Function framework for ions and increase substrate-specific Strength-Efficiency through it. Cross-linkable biopolymer network channels can adjust flexibly when the microstructure changes, such as expand and contract substrate; do not produce cracks or rough strengthening areas. An electrolyte that balances optimal cross-link density to maintain flexible flexibility and mechanical stability without detachment.

Specified for each species. Porous materials, such as soils and concretes, need a medium that has good long-range transportability in order for the reinforcement zone to be well-distributed. Also, due to the low conductivity and large specific surface area of metal-based materials, they are vulnerable to localized electrochemical corrosion in use. Real-time collection of electrochemical parameters such as charging/discharging current and electrode potential; Based on the above data, choose a suitable Power State material with varied properties in different situations. In this way, while maintaining the responsive characteristic of electrochemical reaction across different substrates with high performance in various environments.

3) THERMAL AND MOISTURE STABILITY

Electrolyte Performance Under Variability in Environments Is Directly Influenced By Conductivity, Crystal Structure And Polymer Elasticity. Electrolytes with good conductivity and small crystallinity consistently display excellent retention properties after thermal and humid cycles. Highly crystalline electrolytes hinder the movement of ions at low temperatures; therefore, insufficient connection is formed, and too liquid forms tend to leak, lose adhesion or distribute unevenly on a vertical or porous substrate.

Plasticiser addition reduces the risk of fire through enhanced plasticity enhancement effect, reduced crystal structure, maintained ions' flow in electrolytic fluid to prevent detachment problem. The choice of polymers and plasticisers at various temperatures, humidities for keeping stability under environmental changes. Stability ensures a steady supply of reinforcing areas, maintains electrolysis efficiency; To avoid damage to supports due to environmental changes. Thermal and moisture resistance are necessary in practical application environments that have unknown changes outside the range.

4) INTEGRATED OPTIMIZATION STRATEGY

Optimising Durability and Efficiency Calls for a Combination of Integrating Physicochemical Alterations to the Electrolyte, Substrate-Specific Adaptations, And Environmental Responsiveness. Polymers' Composition, cross-linking Density, Plasticiser Content should vary based on Substrate Porosity, Structural Constraints, Desired Environmental Exposure levels respectively. Electrolyte formulations should maintain a balance between fluidity, ion movement speed, structure elasticity and the stability of stress conditions, including temperature changes and humidity variation. Chemical reactions.

By optimisation, combined together to realize a smooth and precise process; Avoid defects at point form during hard operation in harsh environmental conditions, improves all-around properties. The overall optimisation scheme guarantees a high-efficiency operation of green electrolytes, maintaining both mechanical and chemical substrate integrity. There is also an outline set up for the reason-Practical Design scheme of subsequent generations' electrolytes that can keep stable reactivity under environmental changes, etc.

D. SUSTAINABILITY PERSPECTIVE

1) ENVIRONMENTAL COMPATIBILITY AND BIODEGRADABILITY

A green electrode that incorporates degradable polymer materials may reduce an electrochemical-aided strengthening system's environmental impact more efficiently. Unlike traditional salt-based electrolytes that are prone to secondary pollution and accumulate toxic substances over a long period, polymeric green electrolyte can be degraded safely without releasing harmful substances into the surrounding environment. Mass loss and degradation tests have predicted consistent decay rates to ensure a relatively low-risk residue even during long-term operation. The purpose is to limit damage or risks associated with this environment during activities by limiting the area around it (e.g., near high-voltage power lines, underground pipelines).

Biodegradable materials with good degradation ability to degrade weakly toxic intrinsically toxic components may have safe application environments near natural resources and soil areas, which could harm life during breakdown. Through a controlled-breakdown process that provides effective reagents during operation times but leaves none

behind after some time has passed, reduce pollution to the environment. The integration of expected ageing, relatively low toxic effects, compatibility with the environment makes green electrolytes suitable for all kinds of responsible and sustainable electrochemical improvements in various substrates and application scenarios.

2) RESOURCE EFFICIENCY AND ENERGY SAVINGS

Green electrolyte enhances resource utilisation, minimises power losses in electrochemical reinforcing processes, etc. High ionic mobility, stable electrochemical properties, and suitable for being strengthened by relatively weak electric fields to reduce overall power consumption and operating costs. Efficiency will be more pronounced in the construction of large-scale infrastructures with high-power-consuming reinforcement processes that were previously constrained by power.

Polymers in the matrix provide structure for objects while using less than usual binders or fillers and thus reducing overall raw material consumption. Additionally, because there is less frequent maintenance owing to reduced consumption of the green electrolyte and improved protection against substrate damage under different environmental conditions; reduction in dependence on harmful additives and restrictions on replacement will effectively reduce the life cycle resource requirements for the reinforcing system [16]. Collectively, these factors decrease the ecological impact to support stable implementation with consistent results and protective substrates through prolonged operation.

3) ADAPTABILITY TO SITE-SPECIFIC CONDITIONS

Adjustable physicochemical properties of the green electrolyte can be used to adjust reinforcement ways in different environmental conditions. Polymer type, crosslinking density and plasticizer content can all be modified to improve ionic mobility, mechanical flexibility and environmental robustness. For instance, improving the cross-link density to enhance its stability in a higher humidity environment or chemical corrosion is stable; adjusting the plasticizer content to ensure sufficient ion transport at low temperatures.

Adjustment will reduce the phenomenon of excessive loss by providing various types of subgrade materials, such as dense sandshepes, hardened concrete slabs and steel pipes. By precisely regulating the behaviour of an electrolyte in different environmental conditions to achieve a stable performance without generating much waste. This kind of flexibility enables electrochemical reinforcing measures to be applied reliably in various site conditions without affecting the environment's integrity, thereby promoting green infrastructure construction development.

4) INTEGRATED SUSTAINABILITY BENEFITS

Green electrolytes as a whole have established an all-encompassing foundation for sustainable electrochemical reinforcement through environmental, resource, and operational benefits. Controlled biodegradation, low-toxicity, high energy efficiency, reduced materials used, versatility in adapting to different environments can work together to achieve safety, reliability, and economic feasibility of the reinforcement.

An all-encompassing method can ensure the performance-enhancing role and eco-friendly function of green electrolytes in maintaining the sustainable development of reinforced materials throughout their service lives. The joint effect of electrochemical efficiency, substrate protection and environmental friendliness in this system is relatively good, making it suitable for environmentally sensitive environments and large-scale infrastructural engineering projects aimed at reducing ecological impact. Overall, the green electrolyte provides a practicable adaptability and an environmental responsibility of adopting the advanced electrochemical reinforcement approach in practice.

E. LIMITATIONS AND FUTURE WORK

1) LABORATORY-SCALE LIMITATIONS

Although laboratory experiments showed that the green electrolytes have a good effect on electrochemical strengthening; there are still some defects in their controlled research conditions. Laboratory-scale tests cannot fully reflect the actual complex environment at the field scale, such as non-homogeneous substrates with varying pores and different compositions and mechanical properties of large-volume structures. Variations among soils caused by different sources of minerals; differences between concretes due to varying curing environments; Differences in metallic surface roughnesses lead to deviations from precise conditions in laboratory columns or small-sized specimens. Environmentally, Changes in Temperature and Humidity; Exposure to harmful ions - Factors that were not taken into account during laboratory testing but require attention under real conditions. In addition, the duration of laboratory experiments is shorter than that needed in outdoor operation for a long time, so it affects the observation of uniformity, electrochemical characteristics and resistance endurance. As a result, the lab tests cannot provide an accurate prediction for their durability and adaptability to multiple environments based solely on short-term test outcomes.

2) SCALE-UP CHALLENGES

The translation of green electrolyte-based reinforcement systems from laboratory scale to large-scale field applications presents several practical challenges. Uniform distribution of the electrolyte across large structural volumes is essential to achieve consistent reinforcement performance and to avoid localized instability caused by insufficient electrolyte concentration. Variations in substrate geometry, surface roughness, and pore structure can create heterogeneous ion transport pathways, irregular potential distributions, and non-uniform reinforcement fronts. Maintaining stable ionic conductivity under fluctuating environmental conditions, such as cyclic temperature changes and varying humidity, further complicates scale-up because these factors directly influence

both ion mobility and reaction kinetics. Addressing these challenges requires optimized deployment strategies, including controlled injection methods, well-defined application sequences, and distribution management protocols to ensure consistent electrolyte delivery. In addition, the integration of intelligent monitoring and feedback systems with adjustable power supplies could improve the uniformity of reinforcement across large structural components and support more reliable field-scale implementation.

3) MATERIAL AND ENVIRONMENTAL CONSTRAINTS

Material restrictions will limit the enhancement of long-term serviceability and durability, etc. High-conductivity polymer blends have insufficient resistance at high temperatures when subjected to prolonged exposure to water or corrosive acids and bases; they may lose effectiveness and their reinforcing ability will be diminished due to this reason. After long-term operation, polymers in the battery will be gradually decomposed through water absorption or oxidation at an accelerated rate due to prolonged use. Considering the above restrictions, explore polymer additives, hybrid composite materials, or multi-component electrolyte systems that can improve structural integrity, resist environmental stressors, and maintain uniform ionic transport properties. Careful optimisation of the polymer's cross-link density, plasticizer concentration, and in general, chemistry needs to be balanced well between conductivity, mechanical strength, and environmental adaptability for good reliability and performance of the reinforcing system.

4) DIRECTIONS FOR FUTURE WORK

In the future, larger-scale field experiments are recommended to confirm laboratory results and evaluate reinforcement uniformity, substrate stabilisation and ecology in practical operating environments. Integrate a real-time monitoring system that includes embedded pH sensor, ionic flux probe and structure stress gauge to realize the adaptive regulation of electrochemical parameters for dynamic optimisation of reinforced process based on local performance information. At the same time, the prediction model based on these parameters could offer appropriate construction guidance for green electrochemical reinforcing technologies. Such models can help guide the preparation of electrolytes, polymers in compositions, and deploy ways on different substrates with various shapes and environments. In addition, the development of long-term durability tests, accelerated aging protocols, and stress-response simulations will provide important data on the resilience, sustainability, and operational lifespan of green electrolytes. Together, these initiatives can help promote extensive use across various sectors of a new generation of environmentally friendly, energy-efficient, and dependable reinforcement systems for Civil Engineering infrastructures and industries.

VI. CONCLUSIONS

This study demonstrates that the physicochemical properties of green electrolytes significantly influence the efficiency, uniformity, and environmental adaptability of electrochemical reinforcement systems. Ionic conductivity, viscosity, polymer composition, and plasticizer content were found to regulate ion transport, potential distribution, and reinforcement uniformity across substrates such as soil, concrete, and metals. High-conductivity electrolytes, particularly optimized pectin-PVA systems, produced stable electrochemical responses and more uniform reinforcement, whereas low-conductivity formulations led to heterogeneous ion migration. Electrolytes with stable pH, adequate buffering capacity, and moderate viscosity maintained consistent performance under varying environmental conditions. The use of biodegradable polymers further reduced environmental impact while sustaining reinforcement efficiency. Overall, optimized green electrolytes provide a promising, environmentally responsible alternative for electrochemical reinforcement, with future work focusing on field-scale validation and improved electrolyte formulations.

REFERENCES

[1] S. Pouresmaeil, T. Schliermann, M. Schmidt, et al., "Biochar Cathodes for Bioelectrochemical Systems: Understanding the Effect of Material Heterogeneity on Performance for Abiotic Hydrogen Evolution Reaction," ChemElectroChem, vol. 12, no. 20, pp. e202500008–e202500008, 2025. DOI: 10.1002/CELC.202500008.

[2] S. Chen, C. Liang, M. Wu, et al., "Exergy–economic performance analysis with multi-objective optimization of dual-cycle coupled calcium-looping based thermochemical energy storage system," Chemical Engineering Research and Design, vol. 228, pp. 94–106, 2026. DOI: 10.1016/J.CHERD.2026.02.036.

[3] K. Youssef and A. Hussien, "Electrolysed water and salt solutions can reduce green and blue molds while maintain the quality properties of 'Valencia' late oranges," Postharvest Biology and Technology, vol. 159, Art. no. 111025, 2020. DOI: 10.1016/j.postharvbio.2019.111025.

[4] S. Mohanapriya, G. Rambabu, S. Bhat, et al., "Pectin based nanocomposite membranes as green electrolytes for direct methanol fuel cells," Arabian Journal of Chemistry, vol. 13, no. 1, pp. 2024–2040, 2020. DOI: 10.1016/j.arabjc.2018.03.001.

[5] B. A. M E D, A. S, N. S A, et al., "Characteristics of Plasticized Lithium Ion Conducting Green Polymer Blend Electrolytes Based on CS: Dextran with High Energy Density and Specific Capacitance," Polymers, vol. 13, no. 21, pp. 3613–3613, 2021. DOI: 10.3390/POLYM13213613.

[6] Y. Matsuda, M. Morita, K. Yamada, et al., "Characteristics of Sulfolane-Based Electrolytes for Rechargeable Lithium Batteries," Journal of The Electrochemical Society, vol. 132, no. 11, pp. 2538–2538, 2019. DOI: 10.1149/1.2113619.

[7] S. Norsyabila, I. S. Juliana, H. Hussein, et al., "Green electrolyte host based on synthesized benzoyl kappa-carrageenan: Reduced hydrophilicity and improved conductivity," Arabian Journal of Chemistry, vol. 16, no. 5, 2023. DOI: 10.1016/J.ARABJC.2023.104687.

[8] M. Santiago and M. Marcelo, "Molecular structure study on the polyelectrolyte properties of actin filaments," RSC advances, vol. 12, no. 10, pp. 6314–6327, 2022. DOI: 10.1039/D1RA09280D.

[9] T. B. S A, A. R, A. P M, et al., "Steps towards the ideal CV and GCD results with biodegradable polymer electrolytes: Plasticized MC based green electrolyte for EDLC application," Journal of Energy Storage, vol. 76, 2024. DOI: 10.1016/J.EST.2023.109730.

[10] I. B. B. Ariani, J. M. Saldanha, I. C. Conte, et al., "Binder-Free Textile PAN-Based Electrodes for Aqueous and Glycerol-Based Electrochemical Supercapacitors," Waste and Biomass Valorization, vol. 15, no. 2, pp. 1005–1018, 2023. DOI: 10.1007/S12649-023-02208-2.

[11] Z. Rahadian, B. Ali, O. A A, et al., "Eco-friendly choline acetate/propionate ionic liquids as novel green electrolytes for high perfor-

mance supercapacitors," Ionics, vol. 30, no. 6, pp. 3617–3625, 2024. DOI: 10.1007/S11581-024-05545-X.

[12] Purnima, V. Sharma, L. Priya, et al., "Characteristics of lithium-ion-loaded poly(m-aminophenol) as solid-state electrolyte," Ionics, vol. 31, no. 2, pp. 1–13, 2024. DOI: 10.1007/S11581-024-05969-5.

[13] G. You, Y. Li, L. Dong, et al., "Research on the Characteristics of Electrolytes in Integrated Carbon Capture and Utilization Systems: The Key to Promoting the Development of Green and Low-Carbon Technologies," Energies, vol. 18, no. 12, pp. 3039–3039, 2025. DOI: 10.3390/EN18123039.

[14] L. Wang, A. Abraham, M. D. Lutz, et al., "Toward Environmentally Friendly Lithium Sulfur Batteries: Probing the Role of Electrode Design in MoS2-Containing Li–S Batteries with a Green Electrolyte," ACS Sustainable Chem. Eng., vol. 7, no. 5, pp. 5209–5222, 2019. DOI: 10.1021/acssuschemeng.8b06141.

[15] H. Pupiales, B. R. Soria, D. Arboleda, et al., "ZIF-8/Chitosan Composite Hydrogel as a High-Performance Separator for Bioelectrochemical Systems," Membranes, vol. 15, no. 9, pp. 282–282, 2025. DOI: 10.3390/MEMBRANES15090282.

[16] M. Hutabarat, S. Chamwon, and P. Chaturabong, "Advanced characterization of bio-rejuvenated asphalt systems using agricultural waste pyrolytic oils: Integrated assessment of chemical composition, rheological, and aging performance," Construction and Building Materials, vol. 518, Art. no. 145801, 2026. DOI: 10.1016/J.CONBUILDMAT.2026.145801.