INTRODUCTION

The development of polymer electrolytes has received significant attention since Fenton’s groundbreaking work, which revolutionized the field of ion-conducting polymers and their application as electrolytes in solid-state rechargeable lithium batteries [1]. This heightened interest is primarily driven by the wide range of potential applications that polymer electrolytes offer in various electrochemical devices, including high-energy density lithium-ion rechargeable batteries, fuel cells, sensors, electrochromic windows, and supercapacitors [2,3]. Recent studies have shown that incorporating lithium salts into ENR improves its glass transition temperature and conductivity, with higher salt concentrations leading to improved ion transport and reducing environmental pollution and various economic and ecological issues [3-5]. Among the natural-based polymer electrolytes, there is a growing interest among polymer scientists in exploring the potential of ENR. Epoxidized natural rubber (ENR) is a chemically modified form of cis 1,4-polyisoprene rubber, where some of the unsaturated C=C bonds are converted into epoxide groups [6]. ENR possesses unique characteristics, such as its amorphous nature, low glass transition temperature, excellent elasticity and strong adhesive properties, which render it well-suited as a polymer host for polymer electrolytes by ensuring effective contact between the electrolyte layer and electrodes in electronic devices [7]. These properties have motivated further exploration of ENR’s potential as a polymer electrolyte material. ENR has gained interest for its potential as a polymer electrolyte material and its compatibility with other polymers and ability to form coordination bonds with fillers and salts making it particularly promising [6-8].

Studies have shown that incorporating lithium salts into ENR improves its glass transition temperature and conductivity, with higher salt concentrations leading to improved ion transport.
mobility and a higher diffusion rate of charge carriers [9,10].

The presence of plasticizers enhances the entropy configuration of ENR-50, thus creating more free volume which facilitates ion mobility through the plasticizer-rich phase [11]. Furthermore, the enhancement in conductivity can be attributed to an increase in the segmental motion of the host polymer chains [12-14]. While most previous work done on ENR has focused on solid polymer electrolyte (SPE) systems, recent attention has shifted towards liquid polymer electrolyte (LPE) systems which is a hybrid system involves the addition of salt to a polymer solution that is dissolved in a compatible solvent [15,16]. This shift is driven by the complexity of SPE systems, in which the interaction and interpretation of polymers are highly complex, requiring numerous indirect assumptions and speculations before any conclusive results can be drawn [17]. SPE systems often require the use of sophisticated instruments for characterization and interpretation, whereas the study of LPE systems tends to be relatively more straightforward and less complex.

In comparison to SPE, the LPE systems offer several advantages over SPE systems such as high ionic conductivity (κ̂), high electrical resistance and excellent contact with the electrode [18].

Understanding ion transport mechanisms in LPE can provide valuable insights for the development of high-performance polymer electrolyte systems. The measurement of conductivity in a dilute solution of salt-polymer system serves as an effective tool for understanding the interaction between ions and polymers in the amorphous regions of solid polymer electrolytes [16-19]. Therefore, analyzing polymers in a solvent (dilute polymer) system can provide a fundamental basis for better clarification of polymer interactions. This approach allows for a more comprehensive understanding of the underlying mechanisms and behaviour of polymer electrolytes [18,19]. Researchers have explored the limiting molar conductivity (λ̂_∞), and equilibrium constant for LiClO_4 in a different concentration of poly(methyl methacrylate) (PMMA-co-MA) solution at 25 ºC, revealing the influence of polymer concentration and type on ion mobility and conductivity [15]. They investigated the molar conductivity of the LPE system using Ostwald’s equations to calculate λ̂_∞. Their findings revealed a decreasing trend in λ̂_∞ as the concentration of PMMA-co-MA increased. This suggests that the strength of the solution improved, leading to enhanced salt dissociation within the LPE system.

Hanibah et al. [16] studied the effect of LiClO_4 in polyethylene oxide (PEO) solutions at ambient temperature and it was found that the reciprocal of molar conductivity increased as LiClO_4 concentration increased across all the different electrolyte systems studied at various PEO concentrations [16]. These results indicate that the polymer plays a crucial role in enhancing ion mobility within the polymer electrolyte system. Furthermore, the study demonstrated that at higher C_poly, the use of PEO significantly contributed to the enhancement of salt dissociation and the coordination of ions at the active site of the ether oxygen of PEO [16,17].

To the best of our knowledge, there is no available data pertaining to critical parameters such as limiting molar conductivity, salt dissociation and the interaction between ions and polymers within the ENR electrolyte based on LPE system. Moreover, it is well-established that ENR exhibits solubility only in a restricted range of organic solvents such as tetrahydrofuran (THF), which exhibits low dielectric constant and poor salt solvation properties. In previous studies [15-19], the potential benefits of using acetonitrile (ACN) owing to its high dielectric constant and excellent capabilities for salt dissociation, particularly with LiClO_4 [17] has been reported. However, the compatibility and solubility of ACN with ENR have not been thoroughly investigated. To address this limitation, there is a necessity to employ a mixed solvent system albeit there is a lack of comprehensive research on the impact of mixed solvents in ENR electrolyte systems, especially in the context of LPE systems. The existing knowledge gap highlights the necessity for additional research with the objective of gaining a more comprehensive understanding of the mechanisms by which mixed solvents can improve the performance of ENR-based LPE systems.

Hence, in this work, the behaviour of the limiting molar conductivity (λ̂_∞) in a liquid polymer electrolyte system based on ENR is investigated. An ENR-50/LiClO_4, electrolyte system was prepared in the mixed solvent system of THF and ACN. The limiting molar conductivity of this system were determined at different ENR-50 concentrations using the power law method [17,18]. Characterization of ENR-50/LiClO_4/THF:ACN was performed by ATR-FTIR spectroscopy.

**EXPERIMENTAL**

Epoxidized natural rubber, ENR-50 (denotes 50% mole of epoxidation level) was supplied by Malaysian Rubber Board (Sungai Buloh, Malaysia). Anhydrous lithium perchlorate (M_w = 106.39 g/mol) with purity > 99% was obtained from Acros Organic and dried in a vacuum oven at 100 ºC for 48 h to eliminate any traces of water that may trapped in the salt prior to be dissolved in the mixed solvent. The salt was kept in the electronic dessicator with relative humidity < 40%. Organic solvent, THF with purity > 99.99% (Merck, Germany) was used for dissolution of ENR. High performance liquid chromatography (HPLC) grade of acetonitrile ( Fisher-Scientific, U.K.) with purity > 99.99% and THF were used as supplied. The water used in this study was prepared by passing through the double distilled water to water deionizing system (Sartorius, Germany) resulting in 18 × 10^6 MOhm cm at 25 ºC.

**Conductivity meter:** The Mettler Toledo Seven Compact S230 AC conductivity meter (Schwerzenbach, Switzerland) with conductivity probe InLab® 741 (measurement range of 0.001-500 µS cm⁻¹ and the temperature range of 0-70 ºC), was used to measure the quantity of ionic conductivity for the system consisting of organic solvent at ambient temperature (25 ºC). The cell constant of conductivity meter was determined through an automatic calibration process performed on a daily basis. The aqueous solution of potassium chloride (KCl) supplied by Mettler Toledo (Schwerzenbach, Switzerland) and had concentrations of 0.1, 0.01 and 0.005 mol L⁻¹, with corresponding conductivity values of 12.88 mS cm⁻¹, 1413 µS cm⁻¹ and 84 µS cm⁻¹. The calibration process was carried out with the conductivity meter connected to an InLab® 741 electrode.
Following the successful calibration of the conductivity meter, the measurement of electrolytic conductivity was performed for sample solutions (ENR-50/LiClO4/THF:ACN) at a reference temperature of 25 °C. Each measurement was performed at least three times (triplicate analysis) and subsequently, the mean values of $\kappa$ (with a coefficient of variation less than 5%) were reported.

**Sample preparation (purification of ENR-50):** ENR-50 (2 wt.%) was fragmented into small grains to facilitate the dissolution of ENR in THF. The solution was continuously stirred at 50 °C for 72 h to ensure complete dissolution until no further changes in the solution. A viscous solution of ENR rubber was formed. To separate the soluble ENR from the insoluble gel content, the viscous solution was passed through a 100-mesh steel gauze sieve via a double filtration process. The filtrate, containing the viscous soluble ENR solution, was collected and its volume was reduced to one-third using a rotary evaporator at 50 °C. The concentrated viscous solution was subsequently re-precipitated by adding n-hexane in a 1:5 ratio. Once the ENR had precipitated, it was carefully transferred into petri dishes. The precipitated ENR samples were then subjected to further drying in a vacuum oven at 50 °C for 24 h to remove any residual solvent. The purified ENR samples were finally stored in an electronic desiccator with a relative humidity of approximately 40%, ensuring their preservation until further used.

**Solubility of purified ENR-50 with various solvents:** The purified ENR-50 (2 wt%) was fragmented into small pieces to facilitate its dissolution in three different solvents: (a) THF, (b) ACN and (c) a mixed solvent consisting of THF and ACN in various ratios. These solvent mixtures were continuously stirred at 50 °C for 72 h to ensure complete dissolution. The process continued until a fully homogeneous and transparent solution was achieved. In addition, to investigate the compatibility of both solvents, a study was conducted by mixing different ratios of THF and ACN solvents. The homogeneity of these mixtures was observed while varying the ratios of the mixed solvent. The detailed findings from this investigation will be discussed further in the results and discussion section, specifically under the subsection addressing the effect of the mixed solvent system. Consequently, it was concluded that a mixed solvent composed of THF:ACN in an 8:2 ratio will be utilized for the preparation of ENR-50/LPE.

**Preparation of ENR-50 liquid polymer electrolyte (LPE):** The preparation of the salt solution and salt-polymer solution (specifically an ENR-50/LiClO4/THF:ACN) system for conductivity measurement was done in a controlled environment to minimize the error in K measurement. The temperature in the laboratory was controlled at 25 ± 2 °C. Purified ENR-50 samples were cut into the small pieces and weighed at various masses, approximately 0.5 g, 1.0 g and 1.5 g. These samples were then dissolved in 500 mL of a mixed solvent consisting of THF and ACN in an 8:2 ratio. This resulted in the formation of polymer solutions with different concentrations ($C_{\text{poly}}$): 0.001 g/cm³, 0.002 g/cm³ and 0.003 g/cm³, respectively. The mixtures of ENR-50 and the mixed solvent were continuously stirred for 24 h at 50 °C, until homogeneous and transparent solution formed. These solutions are referred to as stock solutions and will be used for further experiments.

The preparation of a salt-polymer solution, specifically an ENR-50/LiClO4/THF:ACN system, with a salt concentration of 0.1 mole (1 × 10⁻³ mol/cm³), was carried out. The choice of employing low salt concentrations was a crucial aspect of this study. It allowed to evaluate the limiting molar conductivity of the electrolyte system at a state of infinite dilution, where there is minimal electrostatic attraction among the dissociated Li⁺ ions within the system [18,19]. The general formula (eqn. 1) used to calculate the salt-polymer solution at different concentrations is as follows:

$$C_{\text{salt}} = \frac{M_{\text{salt}}}{M_w \times V}$$

where $C_{\text{salt}}$ represents the concentration of the LiClO₄ stock solution in mol/mL, $M_{\text{salt}}$ denotes the mass of LiClO₄ in grams, $M_w$ represents the molar mass of LiClO₄ in g/mol and V represents the volume of the solution in mL. To prepare the stock solution with a salt concentration of 1.0 × 10⁻⁴ mol/mL, approximately 0.5319 g of LiClO₄ were weighed and dissolved in 50 mL of the mixed solvent composed of THF and ACN in an 8:2 ratio. The solution was continuously stirred at 50 °C for 24 h or until a homogeneous transparent solution was formed. A series of 12-15 dilutions was performed to obtain a range of $C_{\text{salt}} = 10^{-10} - 10^{-7}$ mol/cm³ for the conductivity measurements. Each dilution involved transferring a specific volume of the stock solution and adjusting the volume with the polymer solution in the volumetric flask, ultimately resulting in different concentrations of the salt-polymer solution (ENR-50/LiClO₄/THF:ACN) for the conductivity measurements.

**FTIR analysis:** The comparison of three different polymer concentration of ENR-50/LiClO₄, and mixed in THF:ACN (8:2) was verified by FTIR spectroscopy. The samples were directly placed on a diamond plate. The FTIR spectra were recorded with an attenuated total reflectance (ATR) equipped Thermo-Nicolet (IS50-FT-IR) spectrometer in the range of 4000–800 cm⁻¹.

**RESULTS AND DISCUSSION**

**Effect of mixed solvent system (THF:ACN):** The choice of solvent for dissolving a polymer is a critical factor that significantly influences the structure of the polymer chain in the solution. It is well-established in the literature that ENR dissolved only in limited organic solvent such as THF, which has been recognized as good solvent for ENR [20]. However, when considering applications that require high electrolytic conductivity, the sole use of THF in the electrolyte solution needs to be avoided due to its limitations in enhancing salt dissociation. As such, the use of a polar solvent such as ACN is strongly recommended as it ensure maximum expansion of the polymer chain in the solution, creating a larger hydrodynamic volume compared to non-polar solvents [21]. This maximum expansion is particularly crucial in LPE systems. With a fully expanded polymer chain, ion coordination to the active sites of polymer is optimized, leading to improved ion mobility within the system. Consequently, this enhancement of ionic conductivity in the
electrolyte system is predicted to be at its optimum condition [17,18,21]. In the preliminary work, it was observed that the purified ENR-50 rubber sample did not dissolve in the polar solvent ACN (with a polarity index of 5.8) [22]. This lack of dissolution was likely attributed to the non-polar characteristics of ENR-50 rubber and the high polarity of ACN. To overcome this challenge, an experimental trial was conducted using THF, which has a lower polarity (with a polarity index of 4.0) [22,23] compared to ACN. Interestingly, it was observed that purified ENR-50 sample dissolved completely in THF. Although THF is not ideal for salt dissociation due to its poor dielectric constant ($\varepsilon = 7.58$) [24] compared to ACN ($\varepsilon = 35.96$) [25], which has a relatively high dielectric constant and good solvation ability for salts, it was essential to find a balance between dissolving the ENR and facilitating ion salt dissociation. Hence, a mixture of THF:ACN was employed to address these considerations. The miscibility of THF and ACN were studied and it was observed that no distinct layers formed, indicating that THF and ACN were completely miscible. Encouraged by these results, the experiment was proceeded by varying the ratios of the mixed solvent and the outcomes are recorded in Table-1.

### Table-1

<table>
<thead>
<tr>
<th>Ratio of mixed solvent (THF:ACN)</th>
<th>Miscibility by visual evaluation (solvent miscibility)</th>
<th>Observation by visual evaluation (ENR miscibility)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:1</td>
<td>Miscible</td>
<td>Dissolved (100%)</td>
</tr>
<tr>
<td>8:2</td>
<td>Miscible</td>
<td>Dissolved (100%)</td>
</tr>
<tr>
<td>7:3</td>
<td>Miscible</td>
<td>Partially dissolved (80-90%)</td>
</tr>
<tr>
<td>6:4</td>
<td>Miscible</td>
<td>Partially dissolved (60-70%)</td>
</tr>
<tr>
<td>5:5</td>
<td>Miscible</td>
<td>Sample did not dissolve</td>
</tr>
</tbody>
</table>

It was observed that at mixed solvent (THF:ACN) ratios of 9:1 and 8:2, purified ENR-50 dissolved completely. On the other hand, at ratios of 7:3 and 6:4, ENR-50 exhibited partial dissolution. Finally, at a ratio of 5:5, purified ENR-50 did not dissolve at all. Considering the high dielectric constant of ACN for salt dissociation, whereas the excellent polarity index of THF for dissolving the purified ENR rubber, a mixed solvent ratio (THF:ACN) of 8:2 instead of 9:1 was selected as the optimum condition for preparing a salt-polymer solution system (ENR-50/LiClO4/THF:ACN).

While the 9:1 ratio can also dissolve purified ENR-50 completely, the lower volume of ACN in this ratio may limit its effectiveness in facilitating salt dissociation as compared to ratio 8:2, which is deemed the best compromise to achieve both the dissolution of ENR and the salt dissociation. The results showed that a ratio of 8:2 worked best, completely dissolving ENR-50 and facilitating salt dissociation. The capacity of THF to dissolve ENR, along with the strong solvation and high dielectric constant of ACN, provides for an ideal solvent combination that promotes salt dissociation and increases ion mobility in an electrolyte system.

### Determination of limiting molar conductivity of LiClO4 in mixed solvent system (THF:ACN) after power law at 25°C

It is well known that lithium perchlorate (LiClO4), when dissolved in water, is a strong electrolyte due to the strong thermodynamic interaction between it and water molecules [26,27]. In an aqueous solution, LiClO4 undergoes complete dissociation into its constituent cation and anion species, particularly at low salt concentrations below $0.1 \times 10^{-3}$ mol cm$^{-3}$, as illustrated in eqn. 2 [17,18,27].

$$\text{LiClO}_4 (s) \rightarrow \text{Li}^+ (aq.) + \text{ClO}_4^- (aq.) \tag{2}$$

However, in the presence of an organic solvent such as THF or ACN, the electrolyte system acts as a weak electrolyte due to partial dissociation as supported by previous research utilizing Ostwald’s dilution law [17-19]. These lithium salt undergo partial dissociation into their constituent ions (eqn. 3). It is widely recognized that in a weak electrolyte system, the concentration of ions is lower than that of the solutes. Thus, assessing the total free mobile ions within the system depends on the dissolution of solutes [18,19].

$$\text{LiClO}_4 (s) \leftrightarrow \text{Li}^+ (aq.) + \text{ClO}_4^- (aq.) \tag{3}$$

The power law is introduced due to the limitations of the adaptation of Ostwald’s dilution law equation to estimate $\Lambda$ (ionic conductance at infinite dilution) for weak electrolyte systems consisting of organic solvent [17-19]. To overcome these limitations, a double-logarithmic plot of $\kappa$ (electrolytic conductivity) versus $\kappa$ (electrolytic conductivity) for weak electrolyte systems is predicted to be at its optimum condition [17,18,21].

For determining the limits of molar conductivity of LiClO4 in a weak electrolyte system, the equation can be adapted to estimate $\Lambda$ (ionic conductance at infinite dilution) for weak electrolyte systems consisting of organic solvent [17-19].

$$\Lambda = K \left( \frac{C_{\text{salt}}}{C_0} \right)^{0.7549} \tag{4}$$

Theoretically, the power law presented in eqn. 4 should ideally exhibit linearity for a certain range of $C_{\text{salt}}$. Fig. 1 depicts a graph plotted after eqn. 4 for LiClO4 at 25°C for experimental data in this study. The plot demonstrates that the quantity $\kappa$ for LiClO4 increases consistently as a function of $C_{\text{salt}}$ in accordance with the proposed power law [17-19]. This observation supports the effectiveness of the power law equation. However, it is worth noting that in Fig. 1, below the sensitivity limit of the measurement probe, the quantities of $\kappa$ start to deviate from linearity particularly at $C_{\text{salt}}$ below $10^{-7}$ mol cm$^{-3}$. At these low salt concentrations, the values of $\kappa$ become constant.

Regression function for LiClO4 in Fig. 1

$$\log \kappa = 0.2661 + 0.7549 \log \left( \frac{C_{\text{salt}}}{C_0} \right) (r^2 = 0.994) \tag{5}$$

Or by rearranging:

$$\kappa = 1.845 \left( \frac{C_{\text{salt}}}{C_0} \right)^{0.7549} \tag{6}$$

Thus,
$$\Lambda_0 = K' \gamma C_{\text{ref}}^{(y-1)}$$  \tag{8}

The value of \( C_{\text{ref}} \) is crucial to calculate \( \Lambda_0 \) accurately for an electrolyte system. As mentioned earlier, the quantity of \( C_{\text{ref}} \) is approximately half of the lowest \( C_{\text{salt}} \) concentration which the power law holds true. This selection ensures that the power law equation is appropriately applied. The same approach will be applied to determine the \( \Lambda_0 \) value for weak electrolyte system after the power law. The \( \kappa \) value was measured at various \( C_{\text{salt}} \) by carrying out a series of dilution of its stock solution until constant \( \kappa \) attained \cite{17-19}. These measurements are crucial for accurately applying the power law and determining the \( \Lambda_0 \) value for weak electrolyte systems.

It is observed that \( C_{\text{salt}} = 1.00 \times 10^{-7} \text{ mol cm}^{-3} \) is the last data that fixes well to the regression function (Fig. 2), therefore this data is taken to estimate the \( C_{\text{ref}} \) for this electrolyte system. At higher \( C_{\text{salt}} \geq 10^{-7} \text{ mol cm}^{-3} \) the data tends to deviate mostly due to the formation of ion-pairs as reported for same electrolyte system. Quantity \( C_{\text{ref}} \) for this system is half of the \( 1.00 \times 10^{-7} \text{ mol cm}^{-3} \) at \( C_{\text{ref}} = 5.00 \times 10^{-8} \text{ mol cm}^{-3} \). The estimated quantity \( \Lambda_0 \) for LiClO\(_4\) in THF:ACN follows eqn. 8.

$$\Lambda = \frac{1.845}{\left(\frac{C_{\text{salt}}}{C_{\text{ref}}}\right)^{0.2451}} \text{ (S cm}^2\text{ mol}^{-1}) \tag{7}$$

\( C_0 = \text{mol cm}^{-3} \). After applying eqn. 7, the \( \Lambda_0 \) value for LiClO\(_4\) is recalculated at a fixed concentration. This fixed salt concentration used to calculate the \( \Lambda_0 \) is known as salt reference concentration (\( C_{\text{ref}} \)). To calculate the \( \Lambda_0 \) value using the power law, \( C_{\text{ref}} \) is approximately set to half of the lowest \( C_{\text{salt}} \) concentration which obeys the power law as proposed by Hanibah et al. \cite{17,18}. This same approach is extended in an analogous manner for weak electrolyte systems to determine their respective \( \Lambda_0 \) values. In summary, eqn. 8 is utilized to determine the \( \Lambda_0 \) value through the application of the power law for both strong and weak electrolyte systems, employing the appropriate reference salt concentration.

$$\Lambda_0 = \Lambda \left(\frac{C_{\text{salt}}}{C_{\text{ref}}}\right)^{y-1}$$

Based on the regression analysis, it was observed that the \( \Lambda_0 \) values decreased as the \( C_{\text{poly}} \) increased (showing an inverse relationship). Specifically, \( C_{\text{poly}} \) of 0.001 and 0.002 g/cm\(^3\) yielded \( \Lambda_0 \) values of 115.89 and 112.69 S cm\(^2\) mol\(^{-1}\), respectively. In addition, the highest \( C_{\text{poly}} \) in the system (0.003 g/cm\(^3\)) yielded a \( \Lambda_0 \) value of 100.47 S cm\(^2\) mol\(^{-1}\). This trend indicates that as the polymer concentration increases, the limiting molar conductivity decreases, suggesting an enhanced salt dissociation.

**Table 2**

<table>
<thead>
<tr>
<th>Polymer system (g/cm(^3))</th>
<th>Linear regression function</th>
<th>Correlation ((r^2))</th>
<th>Limiting molar conductivity ((\Lambda_0)) after power law ((\text{S cm}^2\text{ mol}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>( y = 0.7298x + 0.2281 )</td>
<td>0.9959</td>
<td>115.89</td>
</tr>
<tr>
<td>0.002</td>
<td>( y = 0.7331x + 0.2374 )</td>
<td>0.9966</td>
<td>112.69</td>
</tr>
<tr>
<td>0.003</td>
<td>( y = 0.8124x + 0.7226 )</td>
<td>0.9959</td>
<td>100.47</td>
</tr>
</tbody>
</table>
These findings are consistent with the reported work by Hanibah et al. [16], which proposed that this phenomenon is linked to changes in the solution’s viscosity, a factor closely connected to the Walden rule [16]. Lower Λ values indicate a higher degree of ion dissociation within the system [17-19]. Increasing the amount of ENR-50 (higher concentration) results in more significant salt dissociation, attributed to the augmented presence of total epoxy groups (C-O-C). Consequently, this enhancement leads to improved LiClO 4 dissociation, directly contributing to the improve the conductivity of electrolyte system.

**FTIR studies:** The FTIR analysis conducted in this study has unveiled a change in peak intensities, attributable to variations in polymer concentration incorporated into the LPE system. Fig. 3 depicts the FTIR spectra spanning from 4000-400 cm -1 for pure LiClO 4 and ENR-50 mixed with LiClO 4 at various concentrations Cpoly (0.001, 0.002 and 0.003 g/cm3). In the ENR-50 spectra, absorption peaks were observed at 1375, 1455 and 2961 cm –1, which are attributed to CH3 groups, while 2929 and 2851 cm –1 correspond to CH2 groups. Additionally, peaks associated with the oxirane group (C-O-C) were detected at 1062, 914 and 834 cm –1. In Fig. 3, the characteristic peaks of LiClO 4 were identified at 1618, 1062, 683 and 615 cm –1, which are associated with the internal vibrational modes of the ClO4 anion. Notably, the strong absorption peak at 1062 cm –1 exhibited the high intensity, potentially indicating an overlap between the vibrations of Li-ClO 4 and C-O-C groups, which coincidently absorb the same wavenumber [28,29].

Fig. 4. FTIR spectra (1000-600 cm –1) on ENR-50/LiClO 4 at different polymer concentrations (0.001, 0.002 and 0.003 g/cm3)

Upon addition to the ENR-50/LiClO 4 in mixed solvent system, it was observed that the peak at 1618 cm –1, corresponding to the unsaturated ethylene groups (C=C) bonds in ENR, remained unaltered in both frequency and intensity. This observation suggests that Li+ ions did not exhibit a preference for coordination with the C=C bonds in ENR, despite the fact that this C=C also possesses nucleophilic characteristics [30]. Instead, a significant finding was the disappearance of the peak corresponding to ClO4- ion at 683 cm –1 across all Cpoly 0.001, 0.002 and 0.003 g/cm 3 as depicted in Fig. 4. This disappearance suggests the presence of ion dipole interactions occur and this could be attributed to ion-dipole interactions between the active sites of ENR-50, particularly the epoxy groups (C-O-C) and Li+ ions [28,29]. The electronegativity difference between Li+ and C=C is 1.57, whereas for Li+ and C-O-C, the electronegativity difference is 2.46. This suggests that Li+ ions are more likely to form an ion-dipole interaction with the oxygen atom in the epoxy group of ENR compared to the ethylene groups of ENR [29]. This preference is driven by the greater electro-negativity disparity, which results in a stronger attraction between Li+ ions and the and the lone pairs of electrons residing on the oxygen atom of the C-O-C group [28-30].

In addition, as illustrated in Fig. 4, it is observed that the absorption peak at 914 cm –1, associated with C-O-C, demonstrates an increase in intensity as the polymer concentration (Cpoly) reaches 0.003 g/cm 2, in contrast to the intensities observed at Cpoly 0.002 g/cm 2 and 0.001 g/cm 2, respectively. The increasing intensity of this peak with rising Cpoly suggests an electrostatic interaction occurred between lithium ion and the epoxide group of ENR [28-30]. In summary, these FTIR results provide additional support for the conductivity data.

**Conclusion**

The utilization of liquid polymer electrolytes has proven to be highly valuable in enhancing our understanding of the fundamental principles of physical chemistry governing salt-polymer systems. The power law comprised of a double-logarithm plot of κ against Cref that serve as an alternative method with acceptable accuracy in the determination of Λ, at Cref. Interestingly, the value of Cref, which corresponds to Λ, is approximately half of the lowest Cref that still adheres to the power law before deviating from the linearity of the regression equation. The introduction of ENR-50 into the LiClO 4 system with a mixed solvent of THF:ACN, induces changes in the Λ values. In general, as the polymer concentration (Cpoly) increases, a consistent pattern emerges where the limiting molar conductivity (Λo) values decrease. This observation signifies an enhancement in the solution’s strength, leading to improved salt dissociation. The FTIR analysis conducted in this study has revealed noteworthy changes, particularly in intensity, as a result of varying polymer concentrations introduced into the LPE system. The ion-dipole interactions between the active sites of ENR-50, especially the epoxide groups (C-O-C) and lithium ion have also been demonstrated in a mixed solvent system (THF:ACN).
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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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