Development of Na\textsuperscript{+} ion conducting solid biopolymer electrolyte based on Na-CMC-SPA hydrogel for energy storage devices

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Abstract

Solid polymer electrolytes based on biopolymers are green and environment friendly materials. Here, solid biopolymer electrolyte (SBPE) hydrogel based on carboxymethyl cellulose is introduced for Na\(^+\) ion based energy storage material. The synthesized SBPE material is biodegradable and shows excellent strength with good flexibility and high elasticity. Na-CMC-SPA-Nal-PEG has compact packing with inner porous morphology which is helpful in ionic conduction inside the matrix. The ionic conductivity of electrolyte material was recorded in the range of \(10^{-5}\) S/cm at low temperatures (< 40\(^\circ\)C) and \(10^{-4}\) S/cm at higher temperatures (> 40\(^\circ\)C). The ionic transference number is found to be 99% in 2900 sec. LSV measurements confirm that the SBPEs material can be used in device fabrication up to 1.2V. These properties of electrolyte make it a promising material for application in energy storage devices.

Introduction

Nowadays, energy storage systems made up of synthetic polymer electrolytes are commonly used in device fabrication[1]. These polymers are generally produced from petroleum resources such as polyacrylonitrile, polyvinyl chloride, polyvinylidene fluoride, polyvinyl alcohol and polyethylene oxide. These synthetic polymers are water insoluble, toxic and non-biodegradable which make them environmentally unfavorable. To overcome these problems researchers have focused on pollution free, safe, less toxic, cost effective, highly flexible in shape and eco-friendly solid bio-polymeric materials for electrolyte preparation. Solid bio-polymer electrolyte (SBPE) are used in between the electrodes[2] as separator cum electrolyte for better conductivity. SBPE has received great attention in energy storage devices, supercapacitors[3] and electrochemical devices[4] due to their advantageous properties such as optical, electrical, and mechanical ease of degradation and their ability to associate with the electrode-electrolyte interface. The SBPE forms hydrogel materials which are good ionic conductors[5] because hydrogel materials have a 3-D cross linked polymeric network[6], which is hydrophilic and captures a small amount of water inside the polymer matrix through hydrogen bonding[7], which shows numerous properties as softness, stretchability and excellent self-healability[8].

In recent years different types of natural bio-polymers i.e. starch, cellulose, gelatin, chitin, chitosan, pectin, agarose and carboxymethyl cellulose are used in the preparation of solid and quasi-solid polymer electrolyte[9] material for energy storage devices. The usage of carboxymethyl cellulose (CMC) is commercialized widely in industrial applications in the form of its sodium salt (Na-CMC). Na-CMC is an ionic ether derivative of cellulose which prepared by etherification of chloroacetic acid and alkaline cellulose. Na-CMC has hydrophobic cellulose moiety and a carboxylate group is a hydrophilic group that provides great solubility in water and forms a highly viscous solution[10]. Na-CMC has been designated because it can expand the mechanical reliability of the SBPEs without affecting the ionic agility and the electrode/electrolyte interfacial features. Furthermore, it shows good hydrophilicity, biodegradability, biocompatibility, non-toxicity, low cost and good film-forming ability allowing the use of Na-CMC in the preparation of various energy storage devices. The derivative of CMC was used as a solid polymer
electrolyte, which showed a conductivity $1.2 \times 10^{-8} \text{S/cm}$. Carboxymethyl chitosan shows an increase in ionic conductivity at $2.20 \times 10^{-7} \text{S/cm}$[11]. However, a higher ionic conductivity i.e. $4.17 \times 10^{-6} \text{S/cm}$ was reported for carboxymethyl chitin[12]. The sodium salt of polyacrylic acid (SPA) is also known as Waterlock[13] because it can absorb a huge amount of water. SPA is an anionic polymer that contains a negatively charged carboxylic group on its main chain represented as $[-\text{CH}_2-\text{CH}(-\text{CO}_2\text{Na})]_n$ which makes it water soluble. SPA has various valuable properties i.e. good thermal stability[14], provide good tensile strength, favorable mechanical properties, biodegradability and self-healing properties[15].

In this work, we developed a polyethylene glycol (PEG) supported solid biopolymer electrolyte (SBPE) by blending sodium polyacrylate 80% (w/w) and sodium carboxymethyl cellulose 10% (w/w) with the loading of sodium iodide to increase metal ion conduction in the polymer matrix. According to Buraidah et al[16], the blending of two polymers gives better complexation sites, which provide good ionic conductivity, high durability, and better thermal stability by increasing chain flexibility and chain mobility of SBPE. Na-CMC and SPA are chosen in this present work for blending due to their advantageous characteristics already discussed above. The SBPEs are easily synthesized, cost-effective, non-toxic, renewable, biodegradable, easy to handle and they remove the leakage problem of electrolytes. The formation of stable SBPE is analyzed by IR spectroscopy. Thermal stabilities are analyzed by TGA-DTA and morphologies are analyzed by XRD, SEM-EDS. Electrochemical properties are analyzed by LSV, CV and chronoamperometry. Dielectric and ionic conducting properties are analyzed by impedance analyzer at various temperatures in the range of 20°C to 80°C.

**Experimental**

**Preparation of electrolyte:**

Na-CMC-SPA-NaI-PEG polymer hydrogel electrolyte is prepared by dissolving 10% (w/w) Na-CMC and 80% (w/w) SPA in 20ml distilled water. After a complete dissolve, we add 10% (w/w) NaI and 200µl PEG. The reaction mixture was poured into a polypropylene petri dish and dried in the oven at 70°C. We obtained Na-CMC-SPA-NaI-PEG hydrogel polymer electrolyte, which is ready for analysis.

**Result And Discussion**

Herein we prepared the solid biopolymer electrolytes (SBPE) Na-CMC-SPA-NaI-PEG by using the solution cast method. SPA is prepared by free radical solution polymerization technique. Na-CMC-SPA blend is formed by dissolving both CMC and SPA in water. Both of them have a great affinity which helps in mixing well and homogenization. Intermolecular hydrogen bonding forms between Na-CMC, SPA, and a small amount of solvent water molecules. To increase ions in the polymer matrix we added NaI in the solution of Na-CMC-SPA blend polymer and the solution was allowed to dry at a fixed temperature for getting a quasi-solid film. We added PEG-400 to the matrix to increase the stretchability, elasticity and adhesive nature of the semi-solid film, which is also helpful in the preparation of hydrogel material. The
adhesive nature of the semi-solid film and its flexible property show promising characteristics for electrode-electrolyte interface and are also support device fabrication. Here Na-CMC and SPA both are polymeric materials having large size backbone structures containing the anion part of the electrolyte which are immobile but counter cation part Na\(^+\) ion are small in size and feasible for movement inside the matrix. This property of polymer electrolyte makes it a good cation ion conductor electrolyte. Also, it is to be noted that I\(^-\) ion present due to NaI salt addition contributes to small anionic charge conduction. The high cationic condition observed in this case is better than many other electrode systems for energy storage.

IR spectrum of Na-CMC, SPA and Na-CMC-SPA-NaI-PEG (Fig. 1.A) show all characteristic bands for hydrogel formation. A broad band observed between the 3300–3400 cm\(^{-1}\) indicates hydrogen bonded O-H stretching of Na-CMC. The bands near 2920 cm\(^{-1}\) and 2868 cm\(^{-1}\) are observed for symmetrical and asymmetrical C-H bond stretching of all compounds. The SPA shows -COO\(^-\) asymmetric vibration at 1720 cm\(^{-1}\). In the case of Na-CMC-SPA-NaI-PEG the absorption band appears at 1728 cm\(^{-1}\) because after the addition of PEG the oxygen atom of PEG coordinates with carboxylate group and enhances the electron density, which increases the absorption band of the carboxylate group. The C-H bending of all compounds is found at 1432 cm\(^{-1}\), 1406 cm\(^{-1}\) and 1450 cm\(^{-1}\) respectively. Na-CMC and Na-CMC-SPA-NaI-PEG show O-H bending at 1327 cm\(^{-1}\) and 1345 cm\(^{-1}\), whereas C-O-C of the ether group and C-O of the alcohol group show absorption band at 1125 cm\(^{-1}\) to 1050 cm\(^{-1}\) and 1101 cm\(^{-1}\) respectively, which confirms the formation of SBPE material[17].

XRD plots of Na-CMC, SPA and Na-CMC-SPA-NaI-PEG polymer materials are given in (Fig. 1.B), which shows an enormous change in the nature of Na-CMC and SPA matrix after modification into Na-CMC-SPA-NaI-PEG SBPEs material. Na-CMC shows a large number of intense peaks at 14.7\(^\circ\), 17.3\(^\circ\), 19\(^\circ\), 25.6\(^\circ\), 28.7\(^\circ\), 32\(^\circ\), 36.4\(^\circ\), 40\(^\circ\) and 58\(^\circ\) theta values, which shows the crystalline nature of Na-CMC. In the case of SPA only two broad peaks are observed at 18.1\(^\circ\) and 40.3\(^\circ\) theta values that show its less crystalline nature. While in the case of Na-CMC-SPA-NaI-PEG material two major broad peaks are also found at 21.1\(^\circ\) and 40\(^\circ\) theta positions. The peak at 21.1\(^\circ\) is observed with increased intensity, which confirms that it has more crystalline nature of Na-CMC-SPA-NaI-PEG blend hydrogel SBPEs material. The area under the curve of Na-CMC (693), SPA (605) and Na-CMC-SPA-NaI-PEG (906) shows an increase in crystalline nature. This leads to compact packing of the matrix, which provides uniform distribution and path for ionic movement[18].

TGA-DTG curve of synthesized materials shows some major weight loss patterns as shown in (Fig. 1.C). The first weight loss of 8.5% observed in Na-CMC between 30\(^\circ\)C to 160\(^\circ\)C is due to the removal of moisture and the second weight loss in Na-CMC is about 18% in the range of 160\(^\circ\)C to 270\(^\circ\)C due to loss of CO\(_2\) from the polysaccharide. The final loss of 37% is observed in the range of 270\(^\circ\)C to 325\(^\circ\)C showing the degradation of the polymer backbone. SPA shows a first weight loss of about 2.5% in the temperature range of 35\(^\circ\)C to 140\(^\circ\)C. The second weight loss of 68% is observed at temperatures 165\(^\circ\)C
to 256°C for the removal of water molecules trapped in the matrix of SPA polymer. A third weight loss of 11% is observed for degradation of the carboxylic group present on the polymer chain and removal of carbon dioxide at 379°C. In the case of Na-CMC-SPA-NaI-PEG, the first weight loss is about 14% in the range of 30°C to 200°C is due to loss of moisture and absorbed water present on the matrix of SBPEs and the second weight loss of 15% observed in the range of 200°C to 345°C is due to removal of CO₂ molecule and breaking of hydrogen bonding. Third weight loss of 34% is observed for degradation of polysaccharide chain in the temperature range of 340°C to 440°C. The fourth degradation pattern shows of 12% weight loss observed in the temperature range of 440°C to 500°C due to the decomposition of the polyethylene glycol molecule. The thermal gravimetric analysis confirms the thermal stability (up to 200°C) of Na-CMC-SPA-NaI-PEG solid biopolymer electrolyte material[19].

Linear sweep voltammetry (LSV) was performed for analysis of the electrochemical stability window (ESW) of SBPE material. LSV measurements were performed in the range 0V to 1.2V with 10 mVs⁻¹ scan rate at room temperature shown in (Fig. 2.A). LSV voltammogram shows a continuous increase in current with increasing the voltage, which shows that the electrolyte material is extremely electrochemically active and confirms its application potential up to 1.2V in device preparation. The charge storage behavior of SBPE materials was investigated by cyclic voltammetry. CV plot for SBPE material (Fig. 2.B) gives a cyclic shape without any oxidation-reduction peak in the ESW region of the voltammogram. Voltammogram confirms that the SBPEs material has a huge amount of charge density and high electrochemical stability due to the capacitive behavior of SBPE material. This current density of material was sustained and shows reversibility in several numbers of cycles. Ionic transport number (ITN) is a very important feature performed for the analysis of the nature of charge carrier species that is ionic or electronic. For the determination of ITN Wagner’s DC polarization method is used. The graph plotted in between DC vs. time (Fig. 2.C) shows a rapid decrease in the initial current (I_i) from its initial value and shows a regular decrease up to 2900 seconds and the final current (I_f) was recorded applied at the given time. The total ITN can be calculated by using the following relation;

\[ I_t = \frac{(I_i - I_f)}{I_i} \]

The total ionic transference number was found to be \( \approx 0.99 \) (99%). The ionic transference analysis shows that the maximum charge carrier species present inside the SBPE matrix are ionic[20].

Scanning Electron Microscope image (Fig. 2.E) clearly shows that the cross-section morphology of SBPE material shows uniformly porous, cross linked layered morphology with pore size 2.032µm to 797.2nm, which provide better conditions for the movement of Na⁺ ions. In the SEM image three spots are considered, which shows that all elements i.e. C, O, Na and I are present in the SBPE matrix (Fig. 2.D). The detail of SEM-EDS spectra is given in supporting information.

Impedance analyzer is used for the analysis of temperature dependent ionic conducting and dielectric properties of Na-CMC-SPA-NaI-PEG solid biopolymer electrolyte material. A typical Nyquist plot (Fig. 3.A)
is showing a relation between the real part \((Z')\) and imaginary part \((Z'')\) of impedance, which is represented by using relation \((Z^* = Z' - iZ'')\), where \(Z^*\) denotes complex impedance\([21]\). In the Nyquist plot conduction process inside the polymer matrix is shown by a semicircle arc at the high frequency region and \(R_b\) is shown by the intersection of the semicircle arc at the lower frequency region of the real axis. The DC conductivity of polymer material is calculated by using the following expression;

\[
\sigma_b = (1/R_b)(l/A)
\]

Where \(l\) and \(A\) represent thickness and cross section area of polymer electrolyte film\([22]\). The Nyquist plot shows the bulk conductivity of SBPE film in order of \(2.0 \times 10^{-6}\) at \(20^\circ\)C, which increases on increasing temperature reaches to \(5.6 \times 10^{-4}\) at \(80^\circ\)C confirming the ionic conductivity of polymer electrolyte material. At increasing temperature, the SBPE materials become relaxed and supply more ions which are responsible for increasing bulk conductivity.

The frequency dependent AC conductivity spectra (Fig. 3.B) of SBPE divide into three separate regions. The polarization of charges on the electrode-electrolyte interface observed at the low frequency region (dispersion region). The frequency independent conductivity or dc conductivity is shown in the middle plateau region and capacitive behavior (capacitive reactance, \(X_c = 1/2\pi f\))\([23]\) of SBPE at a higher frequency region. The AC conductivity of SBPE follows Jonschler’s power law\([24]\), which is represented as;

\[
\sigma_{ac} = \sigma_{dc} + Af^n
\]

Where \(A\) is the pre-exponential frequency parameter, \(f\) is frequency and \(n\) denotes the power exponent. By using Jonschler’s power law equation we fit temperature dependent value of AC conductivity plot were fitted by using power law and the value of power exponent \((n)\)\([25]\) is \(0 < n < 1\) for all temperatures, which shows a correlated type of hopping in SBPE material. The value of pre-exponential factor \(A\) and power exponent \(n\) varies simultaneously to achieve the best fit. The value of fitting parameter \(R^2\) is found \(> 0.98\) at all temperatures which shows the fitting is satisfactory. The value of dc conductivity given by the Nyquist plot and the value obtained from power law are very closer. The value of \(n\), \(A\), \(R^2\), and \(\sigma_{dc}\) at all temperatures are shown in table \(S1\). The temperature-reliant conductivity (log \(\sigma_{dc}\) vs 1000/T) of SBPE (Fig. 3.C) increases with increasing temperature and follows Arrhenius type thermal activation behavior in two regions i.e. above and below glass transition temperature due to the cross-linking Na-CMC-SPA-NaI-PEG polymer chains. At increasing temperature, SBPE shows chain relaxation as a result amorphousness of the polymer matrix increases ionic movement. The activation energy above glass transition temperature was found to be \((E_a=0.328eV)\) and below glass transition temperature was found to be \((E_a=0.682eV)\). Arrhenius equation can be written as;

\[
\sigma_T = \sigma^0 \exp - E_a/k_bT
\]
Where $E_a$, $K_b$ and $T$ are show activation energy, Boltzmann constant and absolute temperature respectively. The scaling of AC conductivity spectra of SBPE at different temperatures is possible into a single master curve. AC conductivity plot is scaled to study the conductivity dependency on frequency. The frequency axis of the plot is scaled by hopping frequency $f_H$ and the conductivity axis is scaled by the $\sigma_{dc}$ value[26]. For SBPE material $f_H$ value at a given temperature can be calculated as follows:

$$f_H = (\sigma_{dc} / A)^{1/n}$$

Arrhenius equation also used for calculation of hopping frequency[27] $f_H$ which shows dependency on temperature i.e.

$$f_H = f_o \exp (-E_H / k_b T)$$

Where $f_o$ represents the pre-exponential factor and $E_H$ represents the activation energy for hopping frequency. The graph (Fig. 3.E) plotted between $\sigma_{ac} / \sigma_{dc}$ vs. $f / f_H$ represents scaled AC conductivity and plots are collapsed into a single master curve. This shows that the relaxation process of the SBPE matrix is temperature independent under conductivity formalism.

The dielectric relaxation is used for the analysis of the polarization effect in material, magnetization and ion transport mechanism[28]. It is also responsible for various types of hopping phenomena and calculated by using the loss tangent[29]($\tan \delta$) relation;

$$\tan \delta = 1 / 2 \pi f R C$$

Where $C$ is capacitance, $R$ is resistance and $\delta$ is dielectric loss angle. The dielectric loss tangent has relation between complex dielectric permittivity ($\varepsilon^\ast$) of the real part ($\varepsilon'$) and imaginary part($\varepsilon''$),which can be calculated by using the following relation;

$$\tan \delta = \varepsilon'' / \varepsilon'$$

On increasing frequency $\tan \delta$ value of SBPE increases up to the maximum limit at a particular temperature and decreases sharply with continuously increasing frequency because of the enhancement of chain flexibility of polymer(Fig. 3.D). The maximum value of $\tan \delta$ refers to the dielectric relaxation peak ($\tan \delta_{max}$) and the corresponding frequency refers to dielectric relaxation frequency ($f_r = 1 / 2 \pi \tau$).The scaling of $\tan \delta$ was performed to understand the variation of relaxation time with applied electric field and temperature can be described by using Kohlrausch-Williams-Watt's law[30] which is given below;

$$f(t) = \exp (-t/\tau)^\beta$$

Where, $\beta$ is the Kohlrausch exponent ($\beta = 1.44 / \text{FWHM}$). For Debye type relaxation behavior, the value of Debye band and full width at half maximum peak was found to be 1 and 1.44 respectively. The scaled loss tangent spectrum shows that the frequency axis was scaled by $f_{max}$ and the loss tangent axis by the
highest value of \( \tan \delta / (\tan \delta_{\text{max}}) \) at different temperatures. From (Fig. 3.F) it has been observed that all spectra collapsed into a single master curve at a different temperature which shows the relaxation process is time independent under conductivity formalism. The value of the Kohlrausch exponent (\( \beta \)) is calculated by using the master curve and found to be 0.28 which indicates that the SBPE material does not follow Debye type relaxation behavior.

The charge storage capacity of SBPE material has been calculated by bulk capacitance \( C_b \) with the help of \( R_b \) and \( f_r \) in the presence of an electric field which depends upon dielectric constant (\( \varepsilon' \)) and dielectric loss (\( \varepsilon'' \)). \( C_b \) can be calculated by using the following relation;

\[
C_b = \frac{1}{2\pi f_r R_b}
\]

The complex dielectric permittivity[31](\( \varepsilon^* \)) is represented as \( \varepsilon^* = \varepsilon' - j\varepsilon'' \) and bulk permittivity is calculated with the help of bulk capacitance using the following relation;

\[
\varepsilon_b = C_b l/\varepsilon_o A
\]

Where \( \varepsilon_o \) is the permittivity of the vacuum. The real and imaginary parts of complex dielectric permittivity can be calculated as;

\[
\varepsilon' = C l/\varepsilon_o A
\]

\[
\varepsilon'' = \varepsilon' \tan \delta
\]

In the lower frequency region, the accumulation of charge at the electrode-electrolyte interface at various temperatures is due to the higher value of dielectric constant (\( \varepsilon' \)) and dielectric loss (\( \varepsilon'' \)) known as electrode polarization effect[32] as shown in (Fig. 4.A-B). However, the electrode polarization effect is suppressed for SBPE material at higher frequency as a result of the decrease in the fast periodic reversal of the electric field. Figure 4B clearly shows that on the increasing temperature the nature of SBPE material gets changes and a relaxation peak is observed at a higher frequency.

An electric modulus and dielectric permittivity are inversely related to each other as shown below;

\[
M^* = 1/\varepsilon^*
\]

And \( M' \) and \( M'' \) are related with dielectric permittivity as[33];

\[
M' = \varepsilon' / (\varepsilon'^2 + \varepsilon''^2)
\]

\[
M'' = \varepsilon'' / (\varepsilon'^2 + \varepsilon''^2)
\]

(Fig. 4.D-E) shows real and imaginary part of electric modulus at different temperatures for synthesized polymer \( M' \) which is the real part of electric modulus shows dispersion as frequency increases higher
range (>10⁴ Hz). The ionic conduction is facilitated by a small value of M’ at the lower frequency region. The imaginary part of electric modulus M’’ (Fig. 4.E) shows as the temperature is increased the movement of the charge carrier becomes faster which leads to a decrease in relaxation time and peak value shifts to higher frequency. The long distance mobilities of positive ions are shown by the left side of the M’’ plot whereas the right side region shows the spatial confinement of ions to potential well.

The ionic conductivity of SBPE material also depends upon their mobility, number of charge carriers and diffusivity constant. The σdc can be expressed as σdc = Nµq, where q represents the elementary charge. The diffusivity constant of SBPEs material can be calculated by using the expression;

\[ D = \frac{2f_{\text{max}}l^2}{32 (\tan \delta_{\text{max}})^3} \]

The total number of charge carriers and ionic mobility of SBPEs materials present inside the matrix can be calculated by using the following relation[34];

\[ N = \frac{(\sigma_{dc}k_bT)}{Dq^2} \]

\[ \mu = \frac{\sigma_{dc}}{Nq} \]

Here ionic mobility (µ) (Fig. 4.C) also correlates with the drift velocity (Vd) (Fig. 4.F) can be calculated as follows;

\[ V_d = \mu E \]

Where E represents the applied electric field.

Conclusion

Herein we have successfully prepared a solid biopolymer electrolyte hydrogel material of Na-CMC-SPA-NaI-PEG and its formation is confirmed by FTIR spectroscopy. The SBPE material has crystalline nature with good thermal stability. TGA analysis confirms that SBPEs material is stable up to 200°C. The SBPEs material act as a good ionic conductor with an ionic transference number of 0.99 (99%). Impedance spectroscopy shows the conductivity of the material in order of 10⁻⁵S/cm at room temperature which lies in the semiconducting region. Temperature-dependent conductivity study shows Arrhenius type behavior and activation energy for ion movement was found to be 0.328 and 0.682, above and below the glass transition temperature respectively. The polarization effect, matrix relaxation behavior and ion transport mechanism of SBPE were studied by dielectric relaxation. The value of D, N, µ and Vd for SBPE were found to be 2.36x10⁻⁸ m²/s, 4.24x10²² m⁻³, 9.35x10⁻⁷ m²/s and 2.34x10⁻⁴ m/s respectively at room temperature. The value of ionic mobility and drift velocity increases with increasing temperature. Results reported in the present work show the possibility of using Na-CMC as an additive in improving the ionic
conductivity without affecting the thermal stability of solid bio polymer electrolyte for Na\textsuperscript{+} ion. The adopted method used in the preparation of Na-CMC-SPA-NaI-PEG electrolyte material is simple, cheap and eco-friendly, being water-based. Since the prepared SBPE hydrogel material indicates better physical, thermal, electrochemical and dielectric properties, this Na-CMC-SPA-NaI-PEG blend semi-solid polymer material can be useful as electrolyte material for Na\textsuperscript{+} ion based energy storage devices.

Declarations

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Supplementary Information (SI):

Materials, methods of characterization, Table S1 and complete EDS report are provided into supplementary information associated with the manuscript.

Competing interests:

No, Authors declare that there are no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

Authors' contributions:

**Dipendra Kumar Verma**: Conceptualization and Writing - original draft preparation; **Rudramani Tiwari**, **Devendra Kumar**: Methodology; **Shashikant Yadav, Km Parwati**: Formal analysis and investigation; **Pubali Adhikary**: Writing - review and editing; **S. Krishnamoorthi**: Supervision.

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Authors were approved that the manuscript follows the ethical guideline.

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Authors are agree with the publishing policy, and submit this manuscript in accordance with this policy.

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References


Figures

Figure 1

(A) IR spectrum (B) XRD pattern of polymers (C) plot shows TGA-DTG of Na-CMC, SPA and Na-CMC-SPA-NaI-PEG

Figure 2

(A) Current (µA) vs Voltage (V) (B) Current (µA) vs Voltage (V) (C) Current (mA) vs Time (s) (D) EDS spectrum (E) SEM image
(A) LSV analysis (B) CV analysis (C) current vs time plot of polymer and (D-E) SEM-EDS image of polymer

Figure 3

(A) Cole-Cole plot (B) AC conductivity plot (C) Plot of $\log \sigma_{dc}$ vs. $1000/T$ showing Arrhenius type behaviour (D) Curve of $\tan \delta$ vs. $f$ (Hz) (E) Scaled AC conductivity plotted between $\sigma_{ac}/\sigma_{dc}$ and $f/f_H$ (F) Scaled loss tangent curve plotted between $\tan \delta/\tan \delta_{max}$ and $f/f_{max}$ at different temperature.

Figure 4
Temperature dependent (A-B) Permittivity plot C) Mobility plot (D-E) Electric modulus plot and (F) Drift velocity for CMC-SPA-NaI-PEG polymer.

**Supplementary Files**

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