P(HEMA-co-EA) as host polymer for flexible dye-sensitized solar cell (DSSC) electrolyte

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Abstract. An electrolyte is the main component of a dye-sensitized solar cell (DSSC) which influences the efficiency of the DSSC. In order to prevent leakage problem and adhesive problem, new solid-state polymer electrolyte proposed rather than using a liquid electrolyte. For this research, new copolymers using 2-hydroxyethyl methacrylate (HEMA) and Ethyl Acrylate (EA) monomers are randomly copolymerized via UV-cure polymerization method with different ratio of each monomer (10,30,50,70,90) towards development as a solid-state electrolyte in flexible DSSC. In this study, the best ratio of the copolymer HEMA-co-EA will be the host polymer for electrolyte in DSSC. The most promising characteristics as a host in polymer electrolytes are due to its smooth cross-sectional surface and lowest glass transition temperature. Therefore, a best ratio of p(HEMA-co-EA) will be stirred with sodium iodide (NaI), Tetrahydro folic acid (THF) and iodine crystal for 24 hours to form a homogenous solution of an electrolyte. This p(HEMA-co-EA) will incorporate with different weight ratios of sodium iodide (NaI). This research reported that after 1500 s only three ratios of new host polymer p(HEMA-co-EA) were successfully copolymerized completely. All three ratio will be characterized by physical appearance, FTIR, DSC and XRD. By naked eyes, only 3 ratios of monomer (50HEMA:50EA, 70HEMA:30EA and 90HEMA:10EA) gave brittle structure which proved the copolymerization process completely success. For FTIR, those three ratios show the breakdown of a double bond at the HEMA monomer structure proved the complete copolymerization process. DSC shows that all three ratio shows the glass transition temperature (Tg) and only 50HEMA:50EA gave melting temperature (Tm) at 192.49°C and XRD confirmed the phase structure and crystallinity of three ratios. All these characterizations show that HEMA and EA monomers can be successfully random copolymerize with a three suitable ratio of each monomer and been used as an electrolyte for flexible DSSC.

1. The first section in your paper
As we know, Silicon is non-renewable energy source and will be finished one day. Due to this reason, the fabrication of Silicon solar cell/panel become more expensive nowadays and alternating way to replace silicone sources been studies by many researchers [1]. For the reasons, Professor M. Grätzel in 1991 inverted low manufacturing cost and high efficiency device to capture sunlight and converts the light to energy [2]. The device is known as dye-sensitized solar cell (DSSC) [2]. DSSC is belong to
third generation of solar cells and become attracted due to their simple device fabrication processes in ambient conditions.

A typical DSSC consists of photoelectrode and counter electrode at the back contact of the photovoltaic cell as the catalyst surface deposited onto the thin layer of TCO substrate. There are a few types of transparent conductive oxide glass substrate that are commonly used in DSSC such as indium-doped tin oxide (ITO), fluorine doped tin oxide (FTO), or aluminium-doped zinc oxide (AZO) [3]. So much attention has recently been focused on the fabrication of flexible DSSC, where plastic is used as the substrate ([4],[5],[11]). So far, liquid electrolyte for DSSC electrolyte gave highest 12.3% energy conversion efficiency [6]. However, liquid electrolyte had a few problems such as dye degradation, leakage problem and creates electrode corrosion which limits the commercialization potential of DSSC as well as flexible DSSC. By concerning these problems, new quasi-solid-state polymer electrolyte from acrylic-based are developed to give better adhesive properties and increased the conversion efficiency due to the unique retention and absorption properties hydrophobic hydrogel materials [7]. In order to synthesis quasi-solid electrolyte for DSSC, the modification of host polymer is need. UV-cure preparation method is one of very fast curing process for acrylic-based polymer that lead to lower-energy consumption and high productivity [7]. For this research, the promising ratio of p(HEMA-co-EA) host polymer been discussed.

Although acrylic-based monomer had been used mainly in biomedical application[8] such in vivo use[9] and biomedical industry such as intraocular lenses, corneal prosthesis and contact lenses in ophthalmology [10] etc., these acrylic-based monomers also gained attention for solar cell application [11-15] from other researchers. Example of acrylic-based monomer that had potential in solar cell application especially as host polymer of DSSC’s electrolyte are hydroxyethyl methacrylate (HEMA) [16-20], poly(methyl methacrylate (PMMA) [13, 20-25], hydroxyethyl acrylate(HEA) [26], Ethyl acrylate (EA) [25], butyl acrylate (BA) [13], Glycidyl methacrylate(GMA) [27], poly-acrylic acid (PAA) [13, 28] poly(glycidyl acrylate) (PGA) [29], Methyl acrylate (PMA) [30, 31] and many more. Acrylic monomers had proposed in this research since its stability against UV radiation. Acrylate, methacrylate, acrylonitrile and many more are examples of acrylic monomers types. Among all these types of acrylic monomers, methacrylate monomer is a versatile monomer group. Methacrylate monomers mostly used to produce copolymers because of its very reactive double bond and easily to polymerize with other type of acrylic monomers [32].

To the best of our knowledge, there is no report on poly(2-hydroxyethyl methacrylate-co-ethyl acrylate p(HEMA-co-EA) since the morphology image (applied for biomedical application) reported by Diego, Olmedilla [33] shows porosity structure which expected give larger surface area and increase the adhesive properties for electron transfer if been use as electrolyte for flexible DSSC.

2. Methodology

2.1. Materials

2-hydroxyethyl methacrylate (HEMA) (brand Aldrich, clear liquid form) density 1073 g/mL at 25 degree-lit. Ethyl Acrylate (EA) density 0.918g/cm3 at 25 degree liquid colourless. 2, 2-dimethoxy-2-phenylacetophenone (DMPA) (99%) with density 1.1 ± 0.1 g/cm were purchased from Aldrich. Tetrahydrofuran (THF) was obtained by J.T. Baker. All materials used without purification.

2.2. Preparation of host polymer p(HEMA-co-EA) with different ratio of each monomer

(x) wt.% of HEMA and (100-x) wt.% EA monomer were mixed in five different ratios (where x+10, 30, 50, 70 and 90) in beaker. Then, photo-initiator (0.016g DMPA) added into the 1g copolymer (HEMA-co-EA) [32, 34, 35]. The difference of copolymerization ratio of the two monomers cannot be too small because there is no significant effect to the polymer chain. The mixture was stirred at 40°C with 80 rpm until the solution became clear for a few seconds. The clear solution poured onto Teflon mould and exposed to UV light with the presence of nitrogen gas about 1500 s. Figure 1 shows the chemical structure for copolymer p(HEMA-co-EA).
2.3. Characterization of host polymer p(HEMA-co-EA)
In order to identify the most potential copolymer ratio to be used as host polymer electrolytes, Fourier-transform infrared spectroscopy (FTIR), Differential Scanning Calorimetry (DSC) and X-ray Diffraction (XRD) were carried out.

2.3.1. Fourier-transform infrared spectroscopy (FTIR) Perkin Elmer Frontier FTIR spectrometer with attenuated Total Reflectance (ATR) accessory was used to record FTIR spectra in 4000-450 cm\(^{-1}\) range for the sample. ATR suitable used for solid sample.

2.3.2. Thermal analysis. Thermal measurement in this research using differential scanning calorimetry (DSC Q20, TA Instrument) at gas flow rate 30ml/min from 10°C to 230°C. DSC measures the heat flow, temperature and phase transitions in materials as plotted graph of time and temperature. Besides, DSC used to characterize thermal transitions of materials and provide useful informations about melting point, glass transition temperature, crystallinity, heat capacity and thermal stability [36].

2.3.3. X-ray Diffraction (XRD) XRD is a versatile, non-destructive technique for identification of various crystalline forms (phase) of compound samples. Modern computer-controlled diffractometer system uses automatic routines to measure, record and interpret the unique diffractogram produced by individual constituents in even highly complex mixture. XRD spectra (brand Malvern Panalytical, model Empyrean) data was recorded at wavelength 5-100° (2θ).

3. Results and discussions

3.1. Physical
As shown in Figure 2, the colour of the different ratio changed after exposed under UV-light in 1500s. The 90HEMA:10EA sample shows the faster brittle structure with the most yellow in colour. However, the 10HEMA:90EA and 30HEMA:70EA samples were in gel state, white in colour and became agglomerated even after more than 1500 s. This is due to the incomplete copolymerization process even after 1500 s. Differ with 50HEMA:50EA, the copolymer became stronger and can be broke out after 1500 s and seen in white colour. By increasing the HEMA ratio, the copolymer become more darker yellow and more brittle after 1500 s. The physical characterization was done on the copolymer since the copolymer containing EA more 50 wt.% are poor in mechanical properties become gel-like (Figure 2, (a) and (b)) below, hence they are not suitable use for preparation of solid polymer electrolyte.
3.2. FTIR

Figure 3 shows full FTIR spectra of HEMA, EA monomers, and HEMA-co-EA copolymers with different ratios.

As shown in Figure 4, the intensity peak at wave number 3400 cm\(^{-1}\) become decrease as the ratio of HEMA increase. The FTIR spectra of HEMA monomer shows strong broad peak absorption at wavelength ~3400 cm\(^{-1}\) but no absorption peak shown for EA monomer. This is due to the present of OH stretching in HEMA structure. For pure HEMA, the broad peak (-OH) present at 3422 cm\(^{-1}\) and shifted to lower wavenumber after copolymer with EA monomer. Then, it shows that OH (alcohols phenols) group remain the properties of HEMA even after copolymer p(HEMA-co-EA) formed. C-H stretching vibration of ethene (O-C\(_2\)H\(_5\)) and methylene (C-CH\(_3\)) group show peaks at 2800 to 3000 cm\(^{-1}\) peaks region. Similar observation reported by Venkatesan, Liu [38].

The double bond for HEMA and EA monomer presented in Figure 5 can be seen at wavelength ~1638 cm\(^{-1}\). After copolymerized both monomers with different ratio, the peak at 1638 cm\(^{-1}\) disappeared.
for all 3 sample (50HEMA:50EA), (70HEMA:30EA) and (90HEMA:10EA) which that free-
radical reaction under UV light was well performed since the C=C stretching vibration peak with the intensity of absorption weak to medium around 1,600–1,680 cm$^{-1}$ of all monomers demolished after successfully copolymerized [13, 32, 37]. Carbonyl group (C=O) and ether group (C-O-C) gave strong absorption peaks at 1720 cm$^{-1}$ and 1158 cm$^{-1}$ respectively in Figure 5 and Figure 6 respectively. The peaks are shifted to the lower wavenumbers due to the interaction between monomer HEMA and EA [32].

![Graph Transmission against Wavelength](image)

Figure 5. FTIR spectra for wavelength 2200 to 1500 cm$^{-1}$.

Peaks located at 1298 cm$^{-1}$, 1640 cm$^{-1}$ and 1320 cm$^{-1}$ based to vinyl group =CH deformation/wagging [39]. Medium C-H bend (alkane) at peak ~1370 to 1453 cm$^{-1}$. Then the strong absorption peak at 1162,1186,1141,1141 and 1150 cm$^{-1}$ for HEMA, EA, 50HEMA:50EA and both 70HEMA:30EA, 90HEMA:10EA respectively indicates C-O stretching. Significantly, as shown in Figure 6, there is a medium peak at 750 cm$^{-1}$ for three different ratio of copolymer p(HEMA-co-EA) but none peak presented for EA and HEMA monomer. This is due to the present of C-H bending group after the dissappears of C=C (double) because of the copolymerization process between two monomers. Peak spectra show the absorption peak at 664 cm$^{-1}$ for EA monomer and 653 cm$^{-1}$ for HEMA monomer. Since the ratio of monomer HEMA is more than ratio monomer EA in p(HEMA-co-EA), the FTIR spectra more likely follow the FTIR of the HEMA. Moreover, C-H bond present due to the break bond at C-CH$_2$ group showed by demolished of 939cm$^{-1}$ peaks proves the successful copolymerization process [32].

![Graph Transmission against Wavelength](image)

Figure 6. FTIR spectra at wavelength 1500 to 450 cm$^{-1}$. 
3.3. Thermal analysis (DSC)

DSC curves of copolymer HEMA-co-EA with different ratio were shown in Figure 7. Tg is defined as the temperature at which the polymer experiences the transition from rubbery to rigid states [40]. The free volume created by continuous segmental motion of polymer chain will increase the ionic conductivity of polymer. The amorphous properties help the migration of ion and facilitates the movement of ions [41]. Among three sample, 50HEMA:50EA shows the lowest Tg value which is 45.8 ºC. While Tg value for 70HEMA:30EA is 53.9 ºC and 90HEMA:10EA gives 57.8 ºC value of Tg. The value of Tg were calculated as midpoint at gradient as marked (•) in Figure 7. Nature of amorphous polymer gave lower Tg value. Low Tg caused the polymer chains to produce faster segmental motion and bond rotations. So that increased the ionic mobility in polymer electrolyte. A more disordered arrangement of polymer matrix gave more amorphous region of polymer matrix. The disorder will influence the flexibility of polymer backbone then increases the mobility of charge carriers [37]. With the increasing HEMA monomer ration in p(HEMA-co-EA), the Tg value of copolymer become increased. The nature of amorphous polymer will be confirmed by XRD. Higher melting point and higher heat of fusion indicates higher crystallinity. The melting point only exist for 50HEMA:50EA at temperature 192.49 ºC. This shows that 50HEMA:50EA have semi-crystalline structure that effected when the presence of heat flow since it has lowest Tg value and the only shows the melting temperature point marked as X in Figure 7.

![Graph Heat Flow against Temperature](image)

**Figure 7.** DSC curves for p(HEMA-co-EA) by different ratio of each monomer.

3.4. XRD

The XRD patterns of p(HEMA-co-EA) were recorded in the angle range of 20 (5° < 20 < 100°) and shown in Figure 8. For amorphous polymer, the XRD peaks will be broad and polymer with crystalline region will have sharp XRD peaks [42]. No peak observed at 50°–80° part of the spectra for any of the samples. Only two significant broad peaks (around 20: 7° and around 18-20°) were observed in the all three samples which is a strong indication that the samples are amorphous. Shanti, Bella [13] reported that the synthesized copolymer is a amorphous type since the broad hump shown at short range order. If the crystallites of the copolymer are very small, the peaks of the XRD pattern will broaden, resulting larger FWHM. However, all samples gave small FWHM which is less than 1° (20). Results of 90HEMA:10EA and 50HEMA:50EA showed semi-crystalline morphology since both ratio shows two sharp peaks with small FWHM as listed in Table 1.
Figure 8. XRD spectra

![XRD spectra](image)

Figure 9. XRD spectra for two specific range 2θ (a) Range 5° to 13° (b) Range 25° to 35°.

Using Debye-Scherrer equation (2), the average crystalline size of p(HEMA-co-EA) can be calculated:

\[
D = \frac{(k \lambda)}{(\beta \cos \theta)} \quad (1)
\]

where λ is the X-ray wavelength (1.5418 Å), K is the Scherrer constant with value from 0.9 to 1 (shape factor), β is the width of the XRD peak at half height and θ is the Bragg angle. Using equation (2) and considering the dominant peaks, the average crystalline size was calculated and tabulated in Table 1. FWHM data was recorded from XRD (brand Malvern Panalytical, model Empyrean) report. Two small peaks were observed at 28.7° (2θ) and 29.5° (2θ) which suggest that both 50HEMA:50EA and 90HEMA:10EA start to form crystalline structure [38]. The Tg values point up the weakening of the intra and intermolecular forces between chains as a result of copolymerization process [43]. For this research, the Tg value increase as the ration of HEMA increased in p(HEMA-co-EA). This explained the inter and intermolecular chain of the copolymer that synthesized. The crystalline size of p(HEMA-co-EA) at 42° peak position was not been calculate since the change in the peak intensity was insignificant. So, the 50HEMA:50EA and 90HEMA:10EA can be grouped in semi crystalline structure with the presence of broad peak and small intense peak.
Table 1. Calculated crystalline size for significant small FWHM peaks.

| Sample         | Peak position (20) | FWHM (20) | Lambda, λ (nm) | Crystalline size, D (nm) |
|----------------|--------------------|-----------|----------------|------------------------|
| 50HEMA: 50EA   | 9.5400 28.7055 29.5252 | 0.0768 0.1023 0.1279 | 0.15418 0.15418 0.15418 | 108.46 83.75 67.12 |
| 90HEMA: 10EA   | 9.5336 28.7139 29.5181 | 0.1535 0.1535 0.1023 | 0.15418 0.15418 0.15418 | 54.26 55.82 83.96 |

4. Conclusion
HEMA and EA monomers were randomly copolymerized via UV-cure method with five different ratios. However, only three ratios of monomers were successful completely copolymerize randomly under UV-cure method with the present of photo-initiator for 1500 s which are 90HEMA:10EA, 70HEMA:30EA and 50HEMA:50EA. These three ratios were continued for other characterizations method. FTIR spectra shows the disappearance of main peak indicate the break of C=C (double bond) in each monomer confirmed the successful copolymerization of both monomer by UV-cure method. The observation by XRD indicated that 90HEMA:10EA and 50HEMA:50EA were the semi-crystalline copolymer synthesized in this study and DSC confirmed the 50HEMA:50EA has crystalline structure due to the presented melting temperature value. Thus, from this research, both HEMA and EA monomers successfully can be copolymerized by easy UV-cure method and future to be used as host polymer in flexible DSSC’s electrolyte rather than been used in biomedical application.

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References
[1] Iftikhar, H., et al., Progress on Electrolytes Development in Dye-Sensitized Solar Cells. Materials, 2019. 12(12): p. 1998.
[2] O'Regan, B. and M. Grätzel, A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films. Nature, 1991. 353: p. 737.
[3] Su'ait, M.S., M.Y.A. Rahman, and A. Ahmad, Review on polymer electrolyte in dye-sensitized solar cells (DSSCs). Solar Energy, 2015. 115: p. 452-470.
[4] Weerasinghe, H.C., et al., Fabrication of efficient solar cells on plastic substrates using binder-free ball milled titania slurries. Journal of Photochemistry and Photobiology a-Chemistry, 2009. 206(1): p. 64-70.
[5] Bittner, F., T. Oekermann, and M. Wark, Scale-Up of the Electrodeposition of ZnO/Eosin Y Hybrid Thin Films for the Fabrication of Flexible Dye-Sensitized Solar Cell Modules. Materials, 2018. 11(2): p. 232.
[6] Yella, A., et al., Porphyrin-sensitized solar cells with cobalt (II/III)-based redox electrolyte exceed 12 percent efficiency (vol 334, pg 629, 2011). Science, 2011. 334(6060): p. 1203-1203.
[7] Asif, A. and W.F. Shi, UV curable waterborne polyurethane acrylate dispersions based on hyperbranched aliphatic polyester: effect of molecular structure on physical and thermal properties. Polymers for Advanced Technologies, 2004. 15(11): p. 669-675.
[8] Montheard, J.P., M. Chatzopoulos, and D. Chappard, 2- Hydroxyethyl Methacrylate (Hema) - Chemical- Properties and Applications in Biomedical Fields. Journal of Macromolecular Science-Reviews in Macromolecular Chemistry and Physics, 1992. C32(1): p. 1-34.
[9] Kemal, E., K.O. Adesanya, and S. Deb, Phosphate based 2-hydroxyethyl methacrylate hydrogels for biomedical applications. Journal of Materials Chemistry, 2011. 21(7): p. 2237-2245.
[10] Chirila T, H.D., Biomaterials and Regenerative Medicine in Ophthalmology. 2nd ed ed. 2016,
Tang, Z.Y., et al., Preparation of poly(acrylic acid)/gelatin/polyaniline gel-electrolyte and its application in quasi-solid-state dye-sensitized solar cells. Journal of Power Sources, 2012. 203: p. 282-287.

[12] Li, P.J., et al., The application of P(MMA-co- MAA)/PEG polyblend gel electrolyte in quasi-solid state dye-sensitized solar cell at higher temperature. Electrochimica Acta, 2007. 53(2): p. 903-908.

[13] Shanti, R., et al., Poly(methyl methacrylate-co-butyl acrylate-co-acrylicacid): Physico-chemical characterization and targeted dye sensitized solar cell. Materials & Design, 2016. 108: p. 560-569.

[14] Su'aif, M.S., A. Ahmad, and M.Y.A. Rahman, Ionic conductivity studies of 49% poly(methyl methacrylate)- grafted natural rubber-based solid polymer electrolytes. Ionics, 2009. 15(4): p. 497-500.

[15] Imperiya, M., et al., Preparation and Characterization of Polymer Electrolyte of Glycidyl Methacrylate-Methyl Methacrylate-LiClO4 Plasticized with Ethylene Carbonate. International Journal of Polymer Science, 2014.

[16] Xia, K., et al., High efficiency quasi-solid state dye- sensitized solar cells based on a novel mixed-plasticizer modified polymer electrolyte. Electrochimica Acta, 2015. 153: p. 28-32.

[17] Li, Q.H., et al., Quasi-solid-state dye-sensitized solar cells from hydrophobic poly(hydroxyethyl methacrylate/glycerin)/polyaniline gel electrolyte. Materials Chemistry and Physics, 2014. 144(3): p. 287-292.

[18] Dai, Y.H., et al., In Situ Quaternized Gel Electrolyte For Quasi-Solid-State Dye-Sensitized Solar Cell. Advanced Materials, Pts 1-3, 2012. 415-417: p. 1586-1589.

[19] Winther-Jensen, O., et al., In situ Photopolymerization of a Gel Ionic Liquid Electrolyte in the Presence of Iodine and Its Use in Dye Sensitized Solar Cells. Macromolecular Rapid Communications, 2010. 31(5): p.479-483.

[20] [20] Dai, Y.H., et al., Influence of Polymer Gel Electrolyte on the Performance of Dye-Sensitized Solar Cells Analyzed by Electrochemical Impedance Spectroscopy. Acta Physico-Chimica Sinica, 2012. 28(11): p. 2669-2675.

[21] Xu, T.T., et al., Environmental effects on the ionic conductivity of poly(methyl methacrylate) (PMMA)- based quasi-solid-state electrolyte. Ionics, 2018. 24(9): p. 2621-2629.

[22] Ganesan, S., et al., Low-cost tetra ethylene glycol derivatives in polymer blend electrolytes for dye- sensitized solar cells with high photovoltaic conversion efficiencies. Materials Science and Engineering B- Advanced Functional Solid-State Materials, 2018. 229: p. 37-43.

[23] Sandararajan, V., et al., Exploring the effect of novel N - butyl-6-methylquinolinium bis(trifluoromethylsulfonil)imide ionic liquid addition topoly(methyl methacrylate-co-methacrylic) acid electrolyte system as employed in gel-state dye sensitized solar cells. Electrochimica Acta, 2017. 240: p. 361-370.

[24] Mohan, K., et al., A highly stable and efficient quasi solid state dye sensitized solar cell based on Polymethyl methacrylate (PMMA)/Carbon black (CB) polymer gel electrolyte with improved open circuit voltage. Electrochimica Acta, 2017. 247: p. 216-228.

[25] Seidlalir, Z., et al., High-Performance Gel-Type Dye- Sensitized Solar Cells Using Poly (methyl methacrylate- co-ethylacrylate)-Based Polymer Gel Electrolyte with Superior Enduring Stability. Journal of the Electrochemical Society, 2015. 162(14): p. H922-H928.

[26] Li, Q.H., et al., Enhanced photovoltaic performances of quasi-solid-state dye-sensitized solar cells using a novel conducting gel electrolyte. Journal of Power Sources, 2014. 248: p. 923-930.

[27] Bella, F., M. Imperiya, and A. Ahmad, Photochemically produced quasi-linear copolymers for stable and efficient electrolytes in dye-sensitized solar cells. Journal of Photochemistry and Photobiology a- Chemistry, 2014. 289: p. 73-80.

[28] Yuan, S.S., et al., Multifunctional graphene incorporated conducting gel electrolytes in enhancing
photovoltaic performances of quasi-solid-state dye-sensitized solar cells. Journal of Power Sources, 2014. 260: p. 225-232.

[29] Rokesh, K., A. Sambandam, and K. Jothivnkatadhalam, Polymer Electrolytes in Dye Sensitized Solar Cells. Vol. 4. 2015. 262-271.

[30] Azmar, A., M.D. Rozana, and T. Winie, Characterization of PMA-TPAI and PVAc-TPAI solid polymer electrolytes and application in dye-sensitized solar cell. Journal of Applied Polymer Science, 2018. 135(47).

[31] Winie, T., A. Azmar, and M.D. Rozana, Ionic liquid effect for efficiency improvement in poly(methyl acrylate)/poly(vinyl acetate)-based dye-sensitized solar cells. High Performance Polymers, 2018. 30(8): p. 937-948.

[32] Dzulkurnain, N.A., et al., Characterization of Random Methacrylate Copolymers Synthesized Using Free-Radical Bulk Polymerization Method. International Journal of Electrochemical Science, 2015. 10(1): p. 84-92.

[33] Diegolo, R.B., et al., Acrylic scaffolds with interconnected spherical pores and controlled hydrophilicity for tissue engineering. Journal of Materials Science: Materials in Medicine, 2005. 16(8): p. 693-698.

[34] Imperiaka, M., et al., A UV-prepared linear polymer electrolyte membrane for dye-sensitized solar cells. Physica B-Condensed Matter, 2014. 450: p. 151-154.

[35] Imperiaka, M., et al., Photo-polymerization of methacrylate-based polymer electrolyte for dye-sensitized solar cell. Journal of Polymer Engineering, 2014. 34(8): p. 695-702.

[36] Rayung, M., et al., Characteristics of  ionically conducting jatropha oil-based polyurethane acrylate gel electrolyte doped with potassium iodide. Materials Chemistry and Physics, 2019. 222: p. 110-117.

[37] Chang, S., et al., Synthesis of a novel alkaline-developable photosensitive copolymer based on MMA, MAA, SM, and 2-HEMA-grafted GMA copolymer for an innovative photo-imageable dry-peelable temporary protective plastisol. Journal of Polymer Research, 2013. 20(4).

[38] Venkatesan, S., et al., Highly efficient quasi-solid-state dye-sensitized solar cells using polyethylene oxide (PEO) and poly(methyl methacrylate) (PMMA)-based printable electrolytes. Journal of Materials Chemistry A, 2018. 6(21): p. 10085-10094.

[39] Qin, H. and M.J. Panzer, Chemically Cross-Linked Poly(2-hydroxyethyl methacrylate)-Supported Deep Eutectic Solvent Gel Electrolytes for Eco-Friendly Supercapacitors. Chemelectrochem, 2017. 4(10): p. 2556-2562.

[40] Callister, W.D., Jr., Materials science and engineering: an introduction. 4th ed. ed. 1997, New York: John Wiley & Sons.

[41] [41] Johan, M.R., et al., Effects of Al2O3 nanofiller and EC plasticizer on the ionic conductivity enhancement of solid PEO–LiCF3SO3 solid polymer electrolyte. Solid State Ionics, 2011. 196(1): p. 41-47.

[42] Yang, J.M., et al., Two step modification of poly(vinyl alcohol) by UV radiation with 2-hydroxy ethyl methacrylate and sol-gel process for the application of polymer electrolyte membrane. Journal of Membrane Science, 2009. 341(1-2): p. 186-194.

[43] Fares, M. and A. Othman, Smart pH-sensitive Alternating Copolymers of (Methylacrylamide-Hydroxyethylmethacrylate); Kinetic and Physical Properties. Journal of Macromolecular Science®, 2010. Part A: Pure and Applied Chemistry: p. 61-70.