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Simple, convenient, low-cost, and solventless greener way to pH-responsive polymeric hydrogels: Synthesis and characterization

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ABSTRACT: Utilization of hydrogels in a simple, low-cost, solventless. and greener approach toward the pH-responsive hydrogels which comprise of citric acid (CA) with varying glycol unit viz., ethylene glycol (EG), diethylene glycol (DEG), and triethylene glycol (TEG) were prepared along with methacrylic acid (MAA). The formations of pre-polymer and hydrogels were confirmed using ^{13}C-NMR and FT-IR spectral techniques. Thermal studies (TGA, DTA, and DSC) and morphology (SEM) of various hydrogels have been investigated. Swelling studies of hydrogels at different pH ranging from 4.0 to 10.0 have also been performed. The results of swelling studies imply that the percentage of swelling is comparatively higher at neutral pH than acidic and alkaline pH. The reciprocal relationship was identified among thermal stability and swelling behavior of hydrogels while increasing the chain length from EG to TEG. © 2015 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 41921.

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INTRODUCTION

Hydrogels are three-dimensional networks of hydrophilic polymers that are cross-linked either chemically via covalent bonds or physically by ionic, Van der Waals, hydrophobic, or hydrogen bond interactions.[1] The hydrogels can take great amounts of water while maintaining their structure, which is similar to soft tissue. Hydrogels show the ability to uptake solvent due to the presence of certain functional groups on the polymer chains, which are often sensitive to the conditions of the surrounding environment. Such environment-sensitive hydrogels are also called "smart" or "intelligent hydrogels". Hydrogels are sensitive to environmental parameters such as pH,[2] temperature,[3] solvent composition, ionic concentration,[4] and electric fields. These properties make hydrogels an ideal class of materials for medical applications such as drug delivery,[5] scaffolds for cell or tissue culture,[6,7] soft contact lenses,[8] and implants.[9] Other practical applications include the immobilization of enzymes, food processing technology, electrophoresis, and phase transfer catalysis.[10,11]

pH-sensitive hydrogels are obtained when acidic or basic functional groups are present on the polymer backbone.[12] The water retention of these materials is due to the presence of –OH, –COOH, –$CONH_2$, –CONH, or –SO_3H along with the polymer chains.[13] pH-sensitive hydrogels can be divided into anionic and cationic depending on the nature of pendant groups in the networks, which show sudden or gradual changes in their dynamic and equilibrium swelling behavior as a result of pH changes. Anionic gels often contain carboxylic or sulfonic acid. Cationic hydrogels usually contain pendant group such as amines and amides. Citric acid (CA) is a renewable resource based multifunctional, readily available and inexpensive monomer. It is nutritionally harmless in nature because of nontoxic metabolic products of the body (Krebs or citric acid cycle) in all living cells that use oxygen as a part of cellular respiration. It is also versatile reactive functional monomer that can participate in hydrogen bonding interaction within a polyester network.[14,15] Ethylene glycol (EG) was chosen as a difunctional monomer to improve the properties of hydrogels because of its flexibility and biocompatibility.[16] Methacrylic acid (MAA) was also used to develop pH-sensitive hydrogels.[17] pH-responsive hydrogels based on MAA have also been used in biochemical and biomedical applications such as biosensors, membranes, molecular imprinting, drug delivery devices, etc. Ethylene glycol and methacrylic acid are biocompatible monomers with excellent biocompatibility and no-toxicity; they are often blended or compounded with other monomers or polymers to be used in

Table I. Physical Parameter of Series of Polymeric Hydrogels of Various Diol

S. No.	Sample	Composition (mole)					Description
		MAA	CA	EG	DEG	TEG	
1	MACE	0.025	0.025	0.025	—	—	White glassy gel, insoluble in water
2	MAC1E4	0.025	0.010	0.040	—	—	White glassy gel, insoluble in water
3	MAC2E3	0.025	0.020	0.030	—	—	White glassy gel, insoluble in water
4	MAC3E2	0.025	0.030	0.020	—	—	White glassy gel, insoluble in water
5	MACD	0.025	0.025	—	0.025	—	White glassy gel, insoluble in water
6	MAC1D4	0.025	0.010	—	0.040	—	White glassy gel, insoluble in water
7	MAC2D3	0.025	0.020	—	0.030	—	White glassy gel, insoluble in water
8	MAC3D2	0.025	0.030	—	0.020	—	White glassy gel, insoluble in water
9	MACT	0.025	0.025	—	—	0.025	White glassy gel, insoluble in water
10	MAC1T4	0.025	0.010	—	—	0.040	White glassy gel, insoluble in water
11	MAC2T3	0.025	0.020	—	—	0.030	White glassy gel, insoluble in water
12	MAC3T2	0.025	0.030	—	—	0.020	White glassy gel, insoluble in water

the field of drug-controlled release systems.[18–21] In recent years, solvent-free reaction has drawn a considerable attention and popularity.[22] Functionalization performed under solvent-free conditions has greater improvement in the designing of green process with many applications.

Hence, the present investigation aimed to satisfy the increased swelling equilibrium, stimuli responsiveness of the hydrogel based on citric acid/MAA/various diols (EG, DEG, TEG). The synthesized hydrogels were also characterized and confirmed the formation using various instrumentation techniques viz. ^{13}C-NMR, FT-IR, TGA-DTA, DSC, and SEM.

EXPERIMENTAL

Materials

Anhydrous citric acid (CA) was obtained from Sigma Aldrich (India). Ethylene glycol, diethylene glycol, and triethylene glycol were obtained from Merck (India). The monomer methacrylic acid was purchased from Sigma Aldrich Chemical Company (Bangalore, India). Before use, MAA was vacuum distilled at 54°C/25 mmHg to remove the inhibitor hydroquinone. Demineralized water was used for polymerizations and the preparation of the buffer solutions.

Methods

Pre-polyesters were dissolved in DMSO in a 5-mm outside-diameter tube and analyzed by ^{13}C-NMR using a Bruker AVANCE III 500 MHz (AV 500). The chemical shifts for the ^{1}H-NMR spectra were recorded in parts per million (ppm) and tetramethylsilane (TMS, 0.00 ppm) as the internal standard. FT-IR studies of the hydrogel samples were recorded on a FTIR-8400 S, Shimadzu spectrophotometer. Spectra were recorded between 4000 and 400 cm^{-1} at 4 cm^{-1} resolution. Scanning electron micrographs of the dried samples were performed using Hitachi, Model: S-3400. Differential Scanning Calorimetry (DSC) using a Q20 DSC Differential Scanning Calorimeter (TA Instruments) and Thermo gravimetric Analysis (TGA) using an SDT Q 600 Simultaneous DSC–TGA (TA Instruments) were used to characterize the thermal properties of different polymeric hydrogels. The glass transition temperatures of the hydrogels were determined by differential scanning calorimetry. Both TGA and DSC curves were recorded in the temperature range of ambient to 500°C at a heating rate of 10°C min^{-1}, under N_2 atmosphere.

Preparation of Buffer Solution (pH = 4.0, 6.0, 7.4, 8.0, and 10.0)

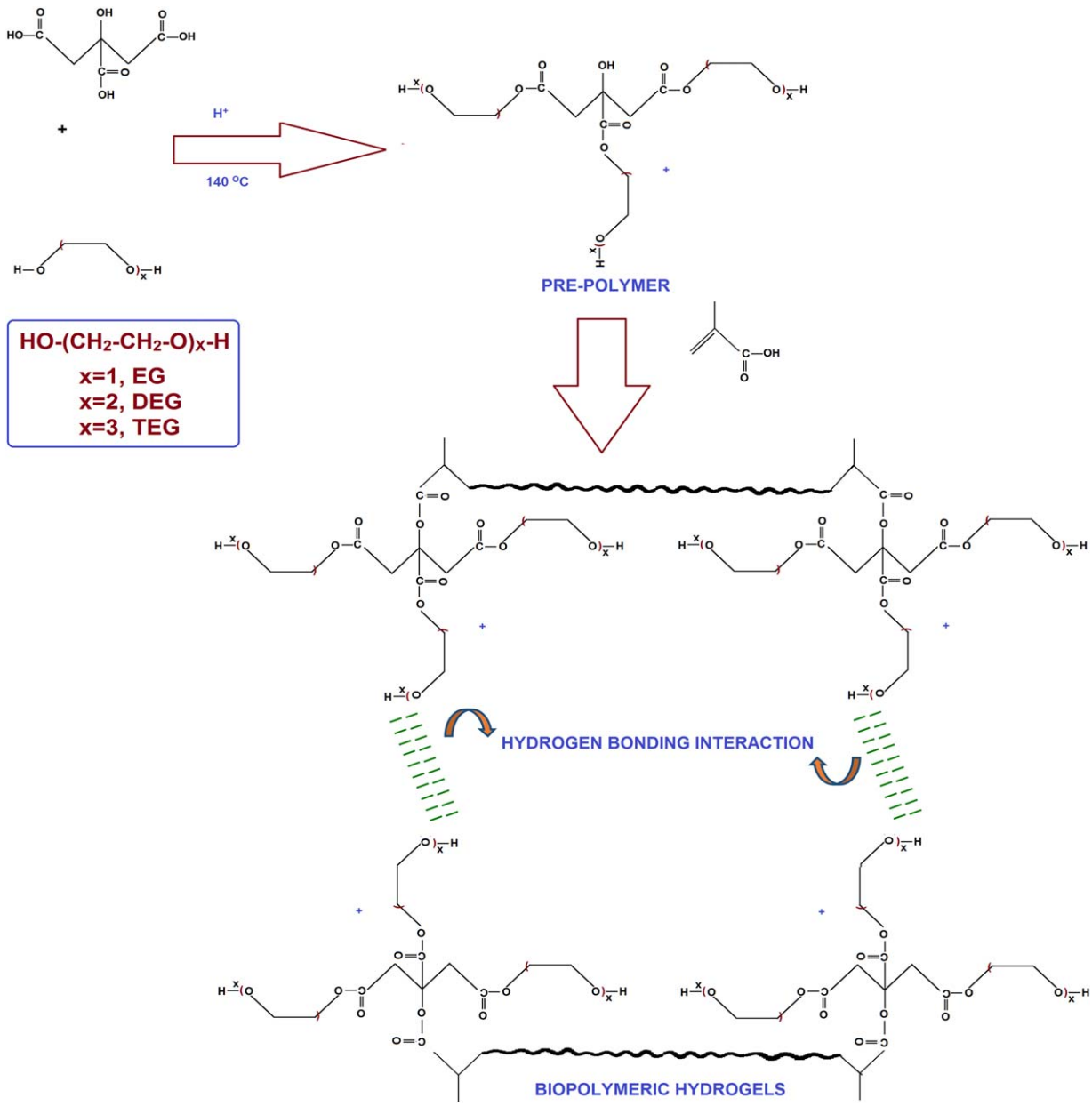
A 0.2*M* phosphate buffer solution was prepared by the following procedure: 39 mL of dihydrogen sodium phosphate was mixed with 61 mL of disodium hydrogen phosphate in a 200-mL distilled water using standard flask. The nominal pH of the solution is 6.8. pH value of the phosphate buffer solution was adjusted by using aqueous diluted HCl and diluted NaOH solution.

Swelling experiments of dried hydrogels were performed in phosphate buffer solutions (PBS) of various pH ranging from 4.0 to 10.0. Swollen gels were removed from the swelling medium at regular time intervals and dried superficially with filter paper, weighed, and placed in the same bath. The measurement was continued until constant weight was reached for each sample. The swelling equilibrium was monitored gravimetrically for 24 h. The pH values were precisely checked with a pH meter (Systronics 3300, India), known amounts of the dried hydrogel were immersed in solutions of different pH, and the swelling degree and equilibrium swelling were calculated with eqs. (1) and (2).

$$S\% = \frac{W_t - W_d}{W_d} \times 100 \quad (1)$$

$$S_{eq}\% = \frac{W_{eq} - W_d}{W_d} \times 100 \quad (2)$$

W_d, W_t, and W_{eq} are the weights of the sample in dried state, swollen state at time "*t*", and swollen at equilibrium, respectively. The values of S % increased with time but reached constant value. This value of swelling was called equilibrium swelling (S_{eq} %).



Scheme 1. Synthetic pathway of citric acid–based polymeric hydrogels. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Synthesis of Polymeric Hydrogel MACE, MACD, and MACT

Citric acid (0.025 mol) was taken in a round-bottomed flask fitted with a mechanical stirrer and nitrogen inlet. Ethylene glycol (0.025 mol) and 1% solution of hydrochloric acid was added drop wise using a dropping funnel. The content was stirred for 1 h at 140°C in a nitrogen atmosphere. The completion of the reaction was observed by the formation of a white colored sticky gel-like compound (CE). Methacrylic acid (0.025 mol) was added to pre-polyester CE at 140°C with constant stirring for 2 h in the nitrogen atmosphere. The formation of shiny gel implied the completion of the reaction.[15,22] The resultant hydrogels were immersed in distilled water for 2 days intermittently refreshed for every 6 h to complete removal of the unreacted monomer. The sample was dried at 25°C at a hot air oven (mild condition) for 24 h. The dried hydrogels were reserved in air-tight container for further use. The synthesis procedure was repeated with EG replaced by DEG and TEG, respectively. The polymer hydrogel of diethylene glycol and triethylene glycol was named as MACD and MACT, respectively. The description of hydrogels is presented in Table I. The general mechanism of the formation of polymeric hydrogel is given in Scheme 1.

RESULTS AND DISCUSSION

Spectral Studies of Hydrogels

^{13}C-NMR Spectral Studies of Pre-Polyesters CE, CD, and CT. The use of nuclear magnetic resonance (NMR) spectroscopy for the characterization of polymers has seen enormous growth in

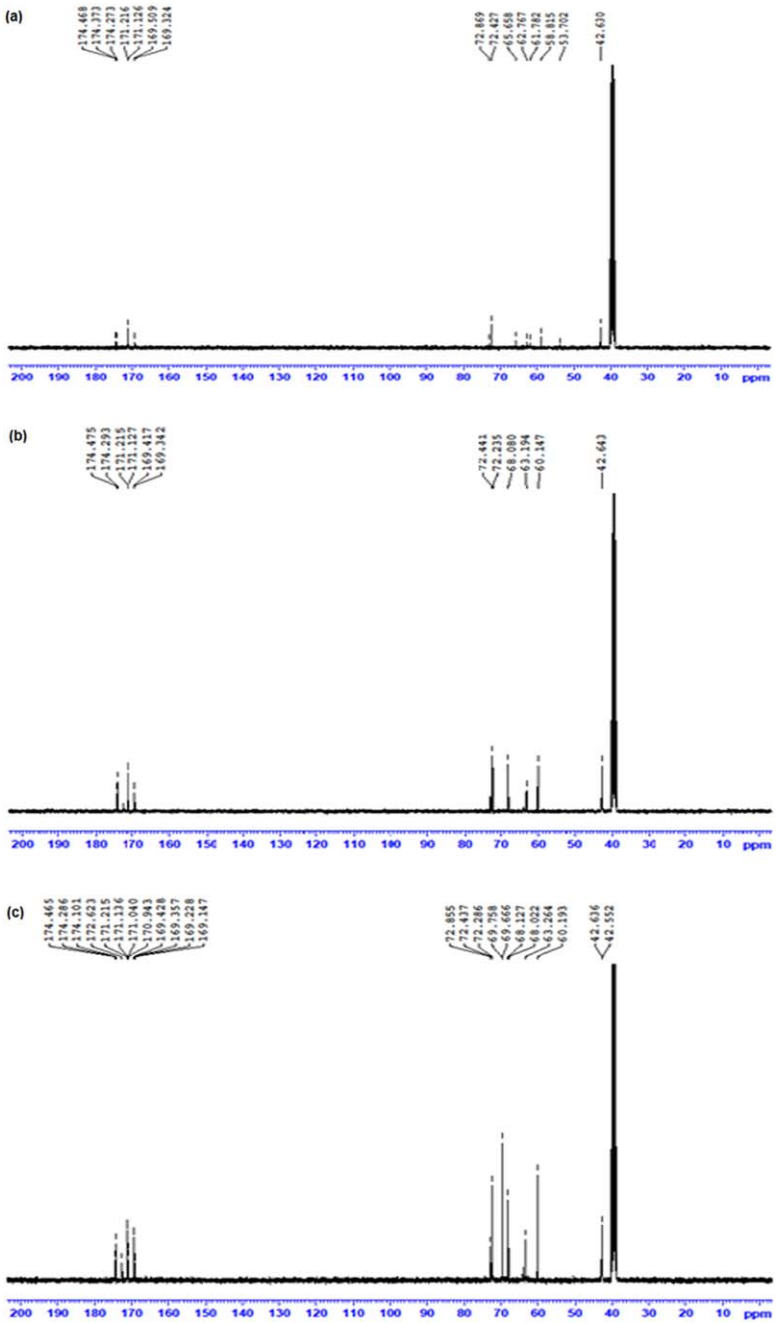


Figure 1. Comparative ^{13}C-NMR spectra of pre-polyester (a) CE (b) CD (c) CT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

recent years. C^{13} NMR spectra of CE is depicted in Figure 1(a). The methylene group is from citrate in the interval of 42.630 ppm. The quaternary carbon atom appeared in 72.1427, 72.86 ppm (OH group attached to the C–OH contributed by citric acid). CE exhibited signals between 61.782 and 65.658 ppm assigned to a C atom of –CO–O–CH_2–CH_2– present in the polyester network.[23] The chemical shift of the ester and acid carbonyl was observed at 169.324, 169.504, 171.126, 171.273, and 171.373 ppm. CD pre-polyester [Figure 1(b)] showed the methylene group from citrate was observed in the interval of 42.643 ppm. The quaternary carbon atom appeared at 72.235 and 72.441 ppm (OH group attached to the C–OH contributed by citric acid). CD exhibit signals between 60.147 and 68.080 ppm assigned to a C atom of –CO–O–CH_2–CH_2– present in the polyester network. The peak of carbonyl atom of ester and acid was observed at 169.342, 169.417, 171.127, 171.215, 171.293, and 171.475 ppm, respectively. The structural characterization of the pre-polyester CT was accomplished by ^{13}C spectroscopy [Figure 1(c)]. Methylene group of citrate was observed in the range of 42.630 ppm. The quaternary carbon atom appeared at 72.235 and 72. 441 ppm (OH group attached to the C–OH contributed by citric acid). CT exhibited signals

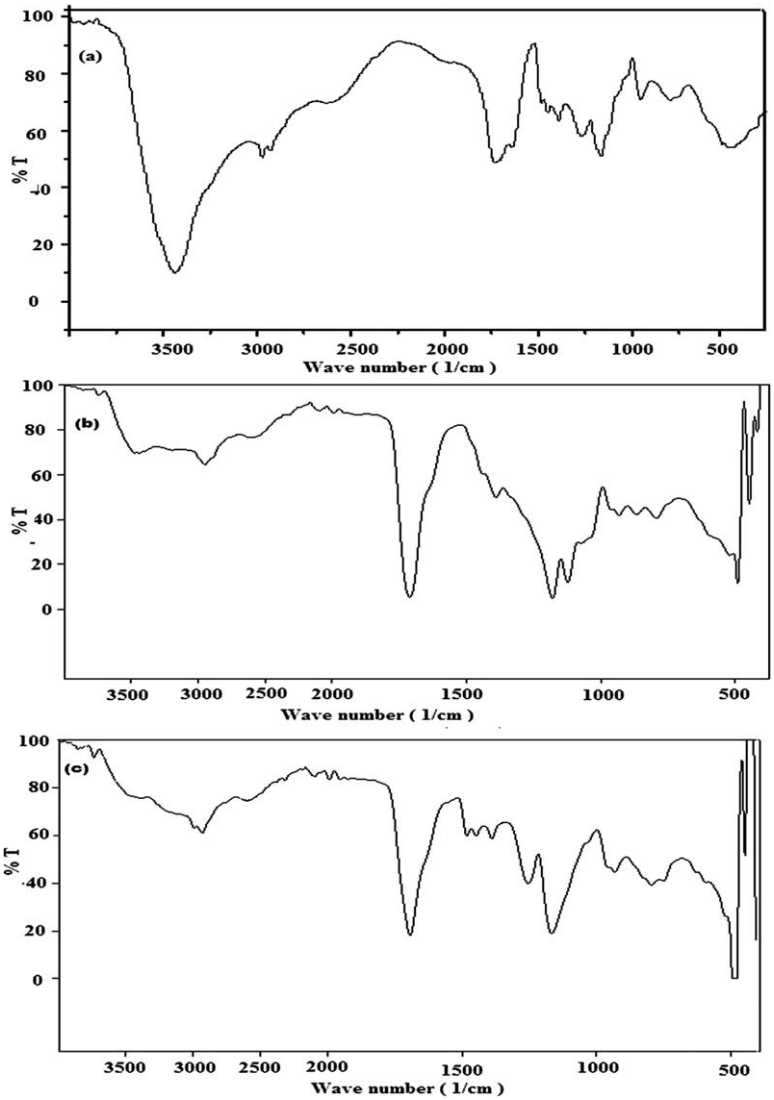


Figure 2. Comparative FT-IR spectra of (a) MACE (b) MACD (c) MACT.

between 61.782 and 65.638 ppm assigned to a C atom of –CO–O–CH_2–CH_2– present in the polyester network. The peak of carbonyl atom (ester and acid) was observed at 169.3324, 169.504, 171.126, 171.273, and 171.373 ppm, respectively.

FTIR Spectral Studies of Polymeric Hydrogels

Infrared spectroscopy was performed to confirm the chemical structure and nature of bonding formed in the hydrogel. The FTIR spectra of the MACE is shown in Figure 2(a), the most distinct peak 1719 cm^{-1}, which can be ascribed to the band C═O stretching.[24] The C–O stretching vibration observed at 1166.91 and 1269.64 cm^{-1}.[25] It is clearly indicated the formation of ester by utilization of citric acid unit involved reaction with diol units. The –CH_3, –CH_2, and –C–H symmetric stretching vibration occur at 2907.41 and 2926.60 cm^{-1}. Similar to our observation, in addition, there is also a distinct broad absorption band observed at 3438.00 cm^{-1} can be attributed to the hydrogen bonded hydroxyl groups.[16] According to Yang *et al.*[26], hydrogen bonded hydroxyl group can contribute to improve hydrophilicity, biocompatibility, and mechanical properties. The new absorption peaks observed at 1449.86 cm^{-1}, assigned to stretching vibration of –COO^-.[27]

The FTIR transmittance spectra of MACD hydrogels has shown in Figure 2(b). The spectra showed strong bands at 1711 and 1122, 1072 cm^{-1}, were attributed to C═O and C–O–C stretching, respectively. Similarly, a broad band around 3000–3500 cm^{-1}, which clearly marks the presence of hydrogen-bonded hydroxyl group. The peak at 2950.49 cm^{-1} corresponds to stretching vibration of methylene group of polymer backbone. In addition, the absorption peaks at 1449.10 cm^{-1} assigned to the stretching of COO^- appeared in the spectrum of MACD hydrogels. The spectral characteristics of MACT hydrogels is presented in Figure 2(c), revealed the C═O stretching vibration of ester carbonyl groups appeared at 1710 cm^{-1} and the stretching vibration of C–O observed at 1165.64 and 1253.47 cm^{-1}. In addition, the characteristics absorption band of COO^- observed at 1447.55 cm^{-1}. A broad absorption band of –OH in the range of 3400 to 3700 cm^{-1} appeared. An absorption band with a weak shoulder peak around

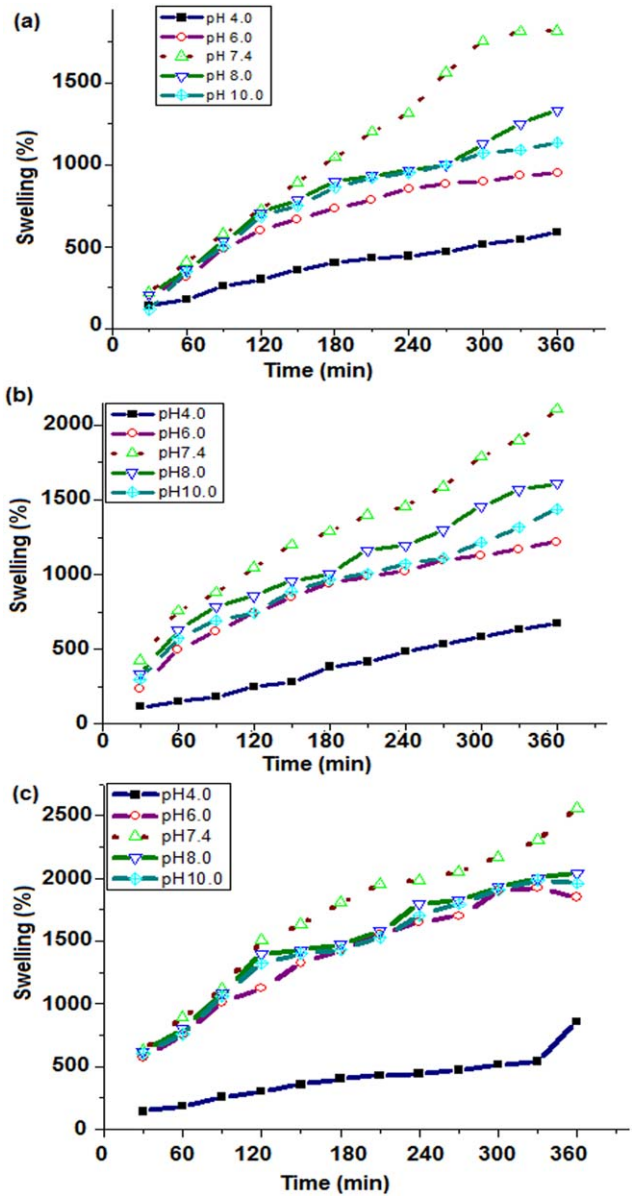


Figure 3. The swelling percentage of hydrogels at different pH with respect to time (a) MACE, (b) MACD, and (c) MACT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

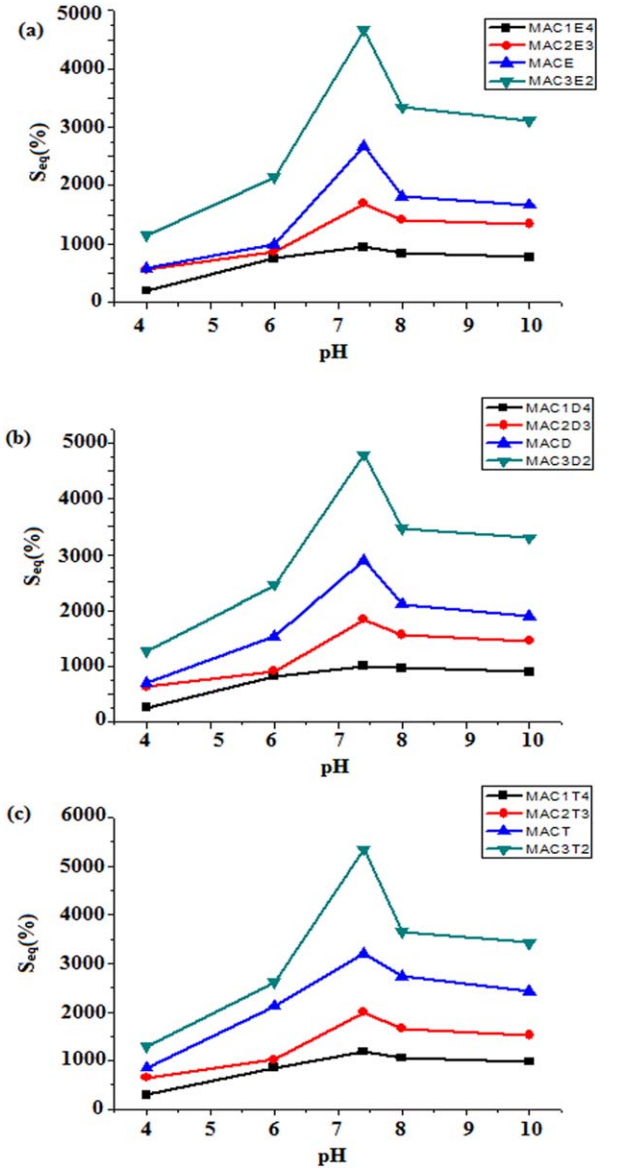


Figure 4. The swelling equilibrium (a) EG based hydrogels, (b) DEG based hydrogels, and (c) TEG based hydrogels at different pH (4.0–10.0). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

2930.84 cm^{-1} which correspond to the C–H stretching vibration. MACE, MACD, and MACT hydrogels exhibited COO^- stretching at 1449.80, 1449.10, and 1447.52, respectively. An almost similar observation has been reported by Fu and coworkers[28] at 1442 cm^{-1} for their environment-friendly carboxymethyl cellulose (CMC) hydrogels.

Swelling Studies of Polymeric Hydrogels

As shown in Figure 3(a), the swelling S % values for MACE hydrogel were strongly influenced by changes in the pH of the swelling medium. The MACE hydrogel showed S % after 1 h in an immersion medium at pH 4.0, 6.0, 7.4, 8.0, and 10.0 of about 180.00, 316.00, 405.00, 356.00 and 575.00%, respectively. S % values of the same gel after 6 h were found to be 585.00, 950.00, 1815.00, 1330.00, and 1133.00%, respectively. It is clearly indicated that S % of MACE hydrogel increased with respect to time and the swelling was strongly dependent on pH. It is obvious that swelling % of MACE was significantly higher at neutral pH, compared with lower and higher pH value.[22]

Swelling of hydrogels sharply charges in the vicinity of their pK_a and pK_b values.[29] It is well known that CA is a triprotic acid with dissociation constant $pKa_1 = 2.94$, $pKa_2 = 4.14$, $pKa_3 = 5.82$,[30] and methacrylic acid dissociation constant $pK_a = 4.66$. Ionization of the carboxylic acid in CA and MAA was observed only when the pH of the swelling medium crossed above the pK_a value of the concerned hydrogel, which facilitated a more hydrophilic polymer network and contributed to increased water absorption. As the pH value of the medium increased from 4 to 7.4, a greater number of COOH groups

Table II. S_{eq} % Values of Methacrylic Acid–Based Citric Acid Containing Polymeric Hydrogels of Various Diol

S. No.	Sample code	pH				
		4	6	7.4	8	10
1	MAC1E4	200.00	757.00	950.00	840.00	780.00
2	MAC2E3	560.00	869.00	1700.00	1420.00	1350.00
3	MACE	587.00	994.50	2676.20	1816.00	1675.00
4	MAC3E2	1160.00	2150.00	4673.00	3340.00	3120.00
5	MAC1D4	254.30	821.48	1003.25	963.38	896.32
6	MAC2D3	625.31	913.56	1836.89	1563.20	1452.74
7	MACD	695.00	1530.00	2890.00	2105.10	1895.00
8	MAC3D2	1269.87	2456.32	4800.23	3465.00	3298.00
9	MAC1T4	296.30	856.32	1189.36	1058.97	983.21
10	MAC2T3	650.14	1023.54	1993.21	1658.97	1524.78
11	MACT	862.00	2125.00	3195.00	2733.00	2425.00
12	MAC3T2	1300.32	2621.00	5356.00	3653.24	3425.86

were deprotonated to form $–COO^-$, which causes an electrostatic repulsion of resulted increased swelling markedly in the network of the hydrogels.[31,32] Hence, the swelling capacity was shooting up to the maximum extent. A similar tendency was observed for both MACD and MACT hydrogels. However, as the pH value further increased at alkaline pH, the swelling capacity of the hydrogel dropped sharply. It might be indebted the fact that osmotic pressure of external solution was higher at higher pH. In addition to basic medium, the screening effects of the counter ions (Na^+) shielded the charge of $–COO^-$ and made repulsive electrostatic interactions become weak, thus swelling capacity decreased continuously.[33]

Equilibrium Swelling Studies of Polymeric Hydrogels

The swelling equilibrium S_{eq} % was plotted as a function of pH shown in Figure 4; it was observed that the time taken to achieve swelling equilibrium for the hydrogel has been varied with different pH 4.0–10.0. The S_{eq} % value of MAC2E3 hydrogel at pH 4.0, 6.0, 7.4, 8.0, and 10.0 was 560.00, 869.00, 1700.00, 1420.00, and 1350.00%, respectively, by comparing these values with MAC3E2 hydrogels S_{eq} % values were found to have 1160.00, 2150.00, 4673.00, 3340.00, and 3120.00 at pH 4.0, 6.0, 7.4, 8.0, and 10.0, respectively.

It was obvious that the water up take was higher for hydrogels in solution of pH > 4 than that of hydrogels in lower pH. Thus, pKa value of CA and MAA in the range of 4.0–5.0. The hydrogel has involved in significant swelling when pH of swelling medium crosses its pKa. They do not swell significantly at lower pH.[34] Similar to our observation, Baril and co-workers observed that the pH of the swelling medium was above 5, swelling ratio and swelling equilibrium was increased due to the ionization of the carboxylic acid groups of poly(methyl methacrylate) in the gel occurred and lead to ionic repulsion, which resulted in enhanced hydrophilic nature of polymer network and contributed to higher water absorption.[35] The swelling equilibrium at 7.0 was found to have 1480%. Similar swelling behavior has been studied in our study with increasing value. The S_{eq} (%) at 7.4 was found at 2676.20 for MACE system. These results clearly indicated that the contribution of citric acid units toward the swelling behavior. Kim *et al.*[36] also observed increased swelling for poly(MAA)-g(EG)–based hydrogels as an oral drug delivery carrier and observed the network exhibited pH-responsive swelling behavior and carboxylic groups of MAA became ionized at pH values higher than pKa value of polymer (pH > 5).[37]

It is clear that hydrogels of DEG and TEG [Figure 4(b,c)] with increasing composition of CA unit enhances the swelling behavior at various buffer solutions. Percentage of swelling equilibrium of series of hydrogels is summarized in Table II. In general, triethylene glycol–based hydrogels have shown increased swelling than DEG and EG–based hydrogels. The swelling of hydrogels at different pH is influenced by chain length of glycol [$HO–(CH_2–CH_2–O)_n$-H, ($n = 1$, 2, and 3 for EG, DEG, and TEG, respectively)] component. By introducing increasing chain length ethylene oxide ($CH_2–CH_2–O$) portion from EG to TEG in the hydrogel swelling was increased. The superiority in swelling of TEG-based hydrogels might be due to the following factors (i) The TEG unit contribution in the hydrogels marks balanced chain flexibility effect, which connected hydrogels more hydrophilic. (ii) Large number of water molecule binding to TEG through hydrogen bonding due to increase ratio between the length of the ethylene oxide unit able to form hydrogen bond make hydrophilic nature at the pendant level. Similar to our observation, Dobic *et al.*[38,39] have also observed improved swelling for poly(2-hydroxyethyl methacrylate/itaconic acid/poly(ethylene glycol) dimethacrylate) hydrogels of increased chain length of glycol unit.

Thermal Characterization of Polymeric Hydrogels

Figure 5(a–c) showed the general nature of thermogram of the polymeric hydrogels of equimolar composition, viz., MACE, MACD, and MACT. The summary of the most important thermogravimetric characteristics obtained from the thermograms is listed in Table II. TGA of all hydrogels (MACE, MACD, and MACT) showed weight loss in three distinct stages. It could be

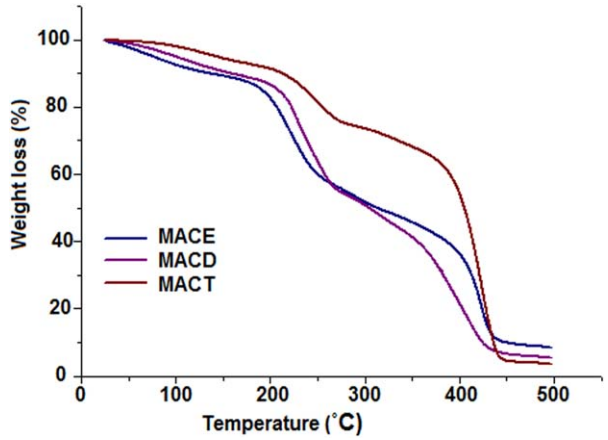


Figure 5. TGA Curve of (a) MACE, (b) MACD, and (c) MACT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

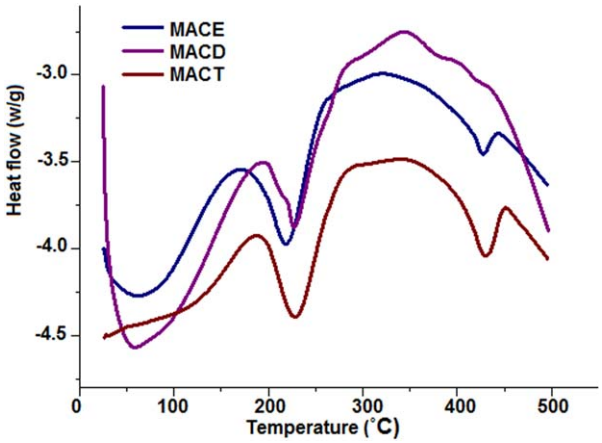


Figure 7. DSC thermograms of (a) MACE, (b) MACD, and (c) MACT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

seen from Figure 5, MACE hydrogel presents three events of degradation. The first stage ranges between 50 and 160°C corresponding to 8% loss in weight. This may correspond to the loss of adsorbed water. The second stage weight loss starts at 180°C and continue up to 275°C with weight loss 29.96% due to decomposition of different structure of polymeric hydrogels and the third stage degradation occurs in the range of 350–450°C, with weight loss 34.00% is due to the carbonization of the polymeric materials. TGA curves of MACD hydrogels are shown in Figure 5(b). The mass loss occurs in three stages: the first one refers to the loss of structural water of the hydrogels (50–140°C) with weight loss of 9%. The second stage decomposition occurs at (140–340°C), with a 33.34% weight loss due to the thermal degradation of the polymeric chains of MACD and the third stage (360–430°C) with corresponding weight loss about 32.00% is due to the carbonization of the polymeric materials. The thermograph of the MACT [Figure 5(c)] shows that within 100°C weight reductions can be due to moisture loss. First stage decomposition has been observed from 50 to 140°C with 10% weight loss. Second stage decomposition started at 200°C and continues up to 330°C with 47.62% weight loss. Third stage decomposition started at 395°C and continues up to 440°C with 35.06% weight loss. The DTA curves of MACE, MACD, and MACT are depicted in Figure 6(a–c), which supported the TGA results of synthesized hydrogels. Table II lists the weight loss of polymeric hydrogels at every 50°C; it clearly illustrates the thermal stability of MACE hydrogel is higher than that of MACD and MACT hydrogels. Thermal stability order of synthesized hydrogels found to have MACE > MACD > MACT.

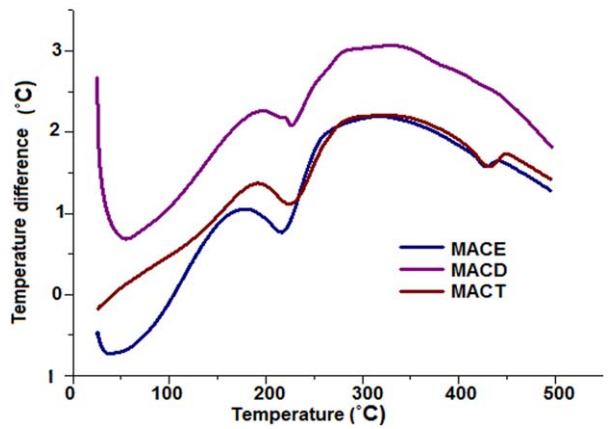


Figure 6. DTA Curve of (a) MACE, (b) MACD, and (c) MACT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

DSC Thermograms of Polymeric Hydrogels

Figure 7(a–c) showed the DSC thermograms of dried polymeric hydrogels viz., MACE, MACD, and MACT, respectively. The glass transition temperature of MACE, MACD, and MACT was found to be at 27.5, 28.5, and 28.5°C.[15] Furthermore, the DSC thermograms of dry hydrogels of MACE, MACD, and MACT addressed as endothermic up to 100°C. The MACE sample exhibited a significant feature of endothermic step with an onset temperature of 90°C, on the other hand, MACD and MACT were found to have 118 and 120°C as their onset temperature. The extent of linearity of glycol group might be the reason behind this jump.[40] Furthermore, the curves in Figure 7(a–c) for the hydrogels show a weak and broad exotherm starting at 190°C, which had also been observed by Wilson and Turner as assigned to the crystallization of the hydrogel.[41] The thermal stability from the thermogravimetric analysis [Figure 5(a–c)] and SEM images Figure 7(a–c) followed by the swelling behavior of the polymeric hydrogels MACE, MACD, and MACT additionally supported the findings in the DSC thermograms.

Morphologies of Polymeric Hydrogels

Scanning electron microscopy (SEM) technique is useful to reveal hydrogels structure**.** Figure 8(a–c) shows the SEM image of dried MACE, MACD, and MACT hydrogels. Figure 8(a) shows SEM micrograph of the polymeric hydrogels MACE obtained from the fracture and has a porous structure. MACD hydrogels exhibited mostly circular and elliptical pores, which may result in swelling at various buffer solutions. Moreover, it is clearly observed from Figure 8(c) that the MACT hydrogels had the maximum swelling equilibrium than other hydrogels. The increased swelling equilibrium of MACT might be due to

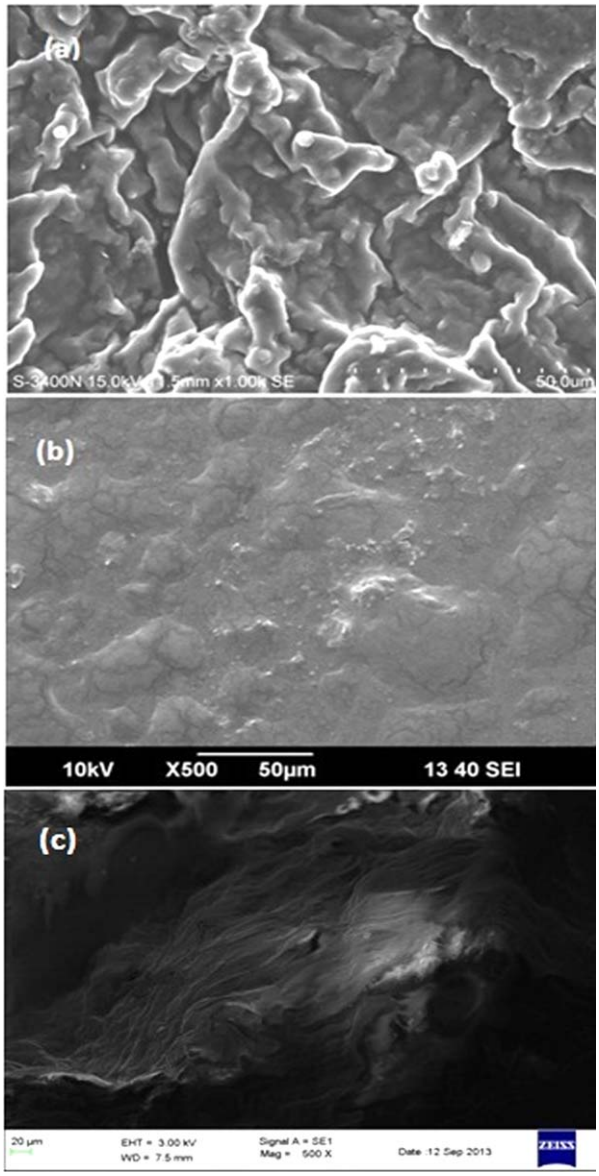


Figure 8. Scanning electron microscope picture of (a) MACE, (b) MACD, and (c) MACT. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the presence of highly sponge-like surface morphology with uneven surface tunes the swelling at acidic and alkaline medium. However, the presence of uneven cavities of MACT made facilitated hydrogel has less thermal stability than the other hydrogel MACE and MACD [Figure 5(a–c)].

CONCLUSIONS

In this study, the polymeric pH-responsive citric acid–based hydrogels with varying glycol units with methacrylic acid were synthesized by condensation polymerization in the presence of acidic medium. The ^{13}C-NMR and FTIR spectral analysis supported the formation of pre-polymer and polymer hydrogels, respectively.

1. Thermal stability of the hydrogels has been investigated by TGA, DTA, and DSC. The thermogravimetric analysis studies of MACE, MACD, and MACT revealed that MACE hydrogels found to have excellent thermal stability than MACD and MACT hydrogels. The glass transition temperature of MACE, MACD, and MACT was found to have at 27.5, 28.5, and 28.5°C, respectively, from DSC analysis. The three-stage decomposition was also supported by DTA in addition to TGA analysis for all the synthesized hydrogels.
2. Swelling behaviors of hydrogels were also studied between pH 4.0 and 10.0 in phosphate buffer solution. The influence of CA content in all the hydrogels was found to exhibit higher swelling and swelling equilibrium at neutral than acid and alkaline medium.
3. The surface morphologies of hydrogels exhibited perfect homogeneity among their constituents and also macroporous sponge like structure enable the hydrogels for their increased thermal stability and swelling equilibrium.

Moreover, citric acid is low-cost and eco-friendly material used in the synthesis of hydrogels, which may be substitute for petroleum-based monomer in near future. The results clearly suggested that the hydrogels could also be an excellent candidate for polymeric drug delivery system. Hence, the synthesized pH-sensitive hydrogels may have a pronounced opening for industrial and biological applications (metal ion removal, cationic dye removal, and controlled release of drugs to pH-sensitive parts of human being).

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