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ORIGINAL PAPER

Synthesis and characterization of citric acid-based pH-sensitive biopolymeric hydrogels

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Abstract Biocompatible hydrogels based on citric acid (CA) with varying glycol unit, viz., ethylene glycol (EG), diethylene glycol and triethylene glycol were prepared along with acrylic acid. The formations of various hydrogels were confirmed using spectral techniques such as FT-IR and ^{1}H NMR. Thermal stability (thermogravimetric analysis, DTA and differential scanning calorimetry) and morphology (SEM) of the synthesized hydrogels were investigated. Swelling studies of hydrogels at various pH values ranging from 4.0 to 10.0 were also investigated. The results of swelling studies show that the percentage of swelling is comparatively higher at higher pH than lower pH. Swelling equilibrium for various hydrogels was also found. Increased composition of CA in hydrogels at different pH values of 4.0, 6.0, 7.4, 8.0 and 10.0 enhanced the swelling equilibrium.

Keywords Hydrogels · Swelling studies · Swelling equilibrium · pH sensitive · Spectral techniques

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Introduction

Hydrogels are hydrophilic, weakly cross-linked polymeric biomaterials which can absorb and retain large amounts of water and biological fluids [1–3]. The success of hydrogels originates from their well-known biocompatibility, mainly due to their high water content and soft nature. They are often sensitive to environmental conditions and can show reversible swelling behavior with changes in the external conditions, such as in the pH, temperature, and electrical stimulus [3, 4]. The presence of hydrophilic groups, high polymer chain flexibility, and the availability of a large free volume between polymer chains enhances the swelling capacity of hydrogels [5]. Due to their hydrophilic and biocompatible nature, a variety of hydrogels have been synthesized from different polymers used for drug delivery, immobilization of enzymes, dewatering of protein solutions, solute separation, baby diapers, soil for agriculture and horticulture, water-blocking tapes, absorbent pads, and numerous other applications [6–12].

pH-sensitive hydrogels are obtained when acidic or basic functional groups are present on the polymer backbone [13]. The water retention of these materials is due to the presence of hydrophilic functional groups, such as –OH, –COOH, $–CONH_2$, –CONH, or $–SO_3H$, along the polymer chains [14]. 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. When the pH value of the surrounding medium rises above its pK_a, the ionized structure will provide increased electrostatic repulsion between $–COO^-$ leading to a high mean free radius of the polymer backbone. Under these conditions, hydrogels are capable of taking up large amounts of water and forming a very loose structure. In contrast, cationic hydrogels usually contain pendant group such as amines. As pH values become lower than pK_b, the amine group changes from NH_2 to NH_3^+, resulting in increased hydrophilicity, strong electrostatic repulsion, and high swelling ratio.

Citric acid (CA) is a renewable resource-based substance, mainly manufactured by fermentation of carbohydrate, viz., starch or glucose. CA was chosen as a poly functional monomer because it is a nontoxic metabolic product of the body (Krebs or citric acid cycle) in all living cells that use oxygen as part of cellular respiration, readily available, and inexpensive. It is also a versatile reactive functional monomer that can participate in hydrogen bonding interaction within a polyester network [15]. Ethylene glycol (EG) was chosen as a difunctional monomer to improve the properties of hydrogels because of its flexibility and biocompatibility [16].

Acrylic acid (AA)-based polymeric hydrogels were also used to develop pH-sensitive hydrogels [17]. AA-based materials offer vast potential for biomedical applications, because gels formed from AA can be formulated at varying concentrations. They can be easily fabricated in a wide array of sizes and shapes. Other materials can be incorporated into the AA prior to gel formation. Many investigations have shown that AA interactions exert strong influence on the swelling behavior of hydrogels and there is a great potential for their application in pharmaceutical preparations, particularly in site-specific drug delivery systems [18].

Numerous works have been contributed by Peppas et al. [19–23] on environmentally and physiologically pH-responsive hydrogels for biochemical and biomedical applications such as biosensors, membranes, molecular imprinting, drug delivery devices. Based on the careful analysis of literature on biopolymeric hydrogels, the present investigation was aimed to focus on the preparation of citric acid-based biopolymeric hydrogels with various diols (EG, DEG, TEG) and acrylic acid of different mole ratios. The percentage of swelling at various pH values followed by swelling equilibrium has also been investigated. The synthesized hydrogels were characterized fully using various instrumentation techniques, viz., FT-IR, NMR, TGA, differential scanning calorimetry (DSC) and SEM.

Experimental

Materials and methods

Anhydrous citric acid (CA) was purchased from S.D. Fine Chemicals (Mumbai, India). Ethylene glycol, diethylene glycol and triethylene glycol were purchased from Merk (India). The monomer acrylic acid was purchased from Sigma-Aldrich Chemical Company (Bangalore, India), and it was vacuum distilled at 54 °C/25 mmHg to remove inhibitor hydroquinone. Demineralized water was used for polymerizations and the preparation of the buffer solutions.

Synthesis of pre-polymer CE

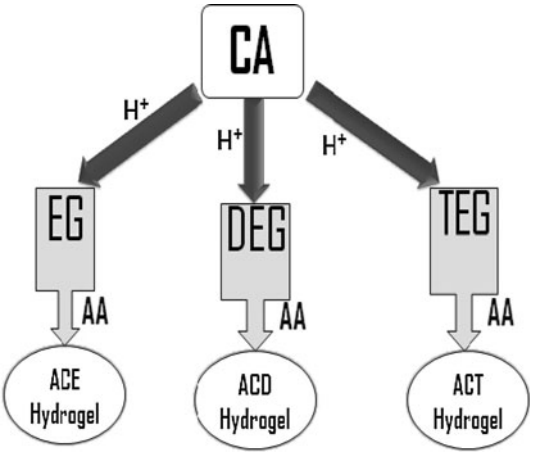
Citric acid (0.025 mol–4.8 g) dissolved in 1 % solution of hydrochloric acid was taken in a round bottomed flask fitted with a mechanical stirrer and nitrogen inlet. Ethylene glycol (0.025 mol–1.41 ml) was added dropwise using a dropping funnel. The content was stirred for 1 h at 140 °C in a nitrogen atmosphere. The completion of the reaction was observed by the formation of a white colored sticky gel-like compound. Diethylene glycol and triethylene glycol were added instead of ethylene glycol to a different reaction vessel with citric acid for the synthesis of CD and CT prepolymers, respectively, using the same procedure described above.

Synthesis of polymeric hydrogel ACE

Acrylic acid (0.025 mol–1.71 ml) was added to pre-polyester CE at 140 °C with constant stirring for 2 h in a nitrogen atmosphere. The formation of glassy gel implies the completion of the reaction. The resultant gel was immersed in distilled water for 24 h to remove the unreacted monomers. Then the gel was allowed to dry in an oven at lukewarm condition for 24 h. The synthesis procedure was repeated with ethylene glycol replaced by diethylene glycol and triethylene glycol, respectively. The polymer hydrogel of diethylene glycol and triethylene glycol are named ACD and ACT, respectively. The descriptions of EG-, DEG- and TEG-based hydrogels are presented in Table 1. The synthetic pathway of ACE, ACD and ACT hydrogels are shown in Scheme. 1.

Table 1 Physical parameter polymeric hydrogels based on EG, DEG and TEG

S. no	Sample	Composition (mol)					Color, appearance and solubility
		AA	CA	EG	DEG	TEG	
1	ACE	0.025	0.025	0.025	–	–	White glassy gel, insoluble in water
2	AC1E4	0.025	0.010	0.040	–	–	White glassy gel, insoluble in water
3	AC2E3	0.025	0.020	0.030	–	–	White glassy gel, insoluble in water
4	AC3E2	0.025	0.030	0.020	–	–	White glassy gel, insoluble in water
5	AC4E1	0.025	0.040	0.010	–	–	No gel formation, soluble in water
6	ACD	0.025	0.025	–	0.025	–	White glassy gel, insoluble in water
7	AC1D4	0.025	0.010	–	0.040	–	White glassy gel, insoluble in water
8	AC2D3	0.025	0.020	–	0.030	–	White glassy gel, insoluble in water
9	AC3D2	0.025	0.030	–	0.020	–	White glassy gel, insoluble in water
10	AC4D1	0.025	0.040	–	0.010	–	No gel formation, soluble in water
11	ACT	0.025	0.025	–	–	0.025	White glassy gel, insoluble in water
12	AC1T4	0.025	0.010	–	–	0.040	White glassy gel, insoluble in water
13	AC2T3	0.025	0.020	–	–	0.030	White glassy gel, insoluble in water
14	AC3T2	0.025	0.030	–	–	0.020	White glassy gel, insoluble in water
15	AC4T1	0.025	0.040	–	–	0.010	No gel formation, soluble in water



Scheme 1 The synthetic pathway of ACE, ACD and ACT hydrogels

FT-IR studies

FT-IR studies of the powdered specimens were recorded on a FTIR-8400 S, Shimadzu spectrophotometer. Prior to analysis, KBr pellets were prepared by mixing 1:10 of sample:KBr (w/w) followed by uniaxial pressing of the powders under vacuum. Spectra were recorded between 4,400 and 450 cm^{-1} at 2 cm^{-1} resolution.

Proton NMR studies

Pre-polyesters was dissolved in D_2O in a 5-mm outside-diameter tube and analyzed by ^{1}H-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 referenced relative to tetramethylsilane (TMS, 0.00 ppm) as the internal standard.

Swelling studies

The quantity of water imbibed by a material is an important property, as it greatly contributes to biocompatibility of the end used material and decides if the material may be used for biomedical purposes. The dried gel swelling experiments were performed in phosphate buffer solutions (PBS) of various pH values 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 same procedure was conducted for solutions with different pH values (4.0–10.0), which were adjusted using aqueous HCl and NaOH solution. 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

$$S = \frac{W_t - W_d}{W_d} \tag{1}$$

$$S_{eq}\,\% = \frac{W_{eq} - W_d}{W_d} \times 100 \tag{2}$$

where W_d, W_t and W_{eq} are the weights of the sample in the 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 is called equilibrium swelling (S_{eq} %).

Scanning electron microscopy

Scanning electron micrographs of the dried samples were carried out using Hitachi, Model: S-3400. To determine the conducting impact, the samples were gold-sputter coated to render them electrically conductive. The scanning was synchronized with a microscopic beam to maintain the small size over a large distance relative to the specimen. The resulting images had a great depth of the field. A remarkable three-dimensional appearance with high resolution was obtained in the polymer hydrogels.

Thermal analysis

Differential scanning calorimetry using a Q20 DSC differential scanning calorimeter (TA Instruments) and thermogravimetric 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 800 °C at a heating rate of 10 °C min^{-1}, under a N_2 atmosphere.

Results and discussion

Table 1 summarizes the physical parameters EG-, DEG- and TEG-based polymeric hydrogels. The composition in moles and concerned inferences have also been presented in Table 1.

Purification of pre-polyester

Pre-polyester CE, CD and CT were purified by evaporation of solvent, and the residual mixture was dissolved in ethyl acetate. The solution was washed three times with a saturated solution of sodium bicarbonate. The aqueous solution was washed twice with ethyl acetate and then adjusted to pH 2 by the dropwise addition of concentrated HCl. The precipitate obtained was extracted with three portions of ethyl acetate. The organic phase was dried with magnesium sulfate, filtered and the solvent evaporated. The residues were washed with acetone to get purified pre-polyester(s) CE, CD and CT.

Spectral studies of polymeric hydrogels

The synthesized polymer hydrogels ACE, ACD and ACT were characterized by FT-IR spectroscopy as shown in Fig. 1. CE ester showed a strong absorption band at around 1,734.01 cm^{-1} [24], which is characteristic absorption of C=O stretching vibrations, and C–O stretching was observed at 1,195.87 cm^{-1} of ester groups indicating the formation of polyesters. The spectra clearly marked broad stretching at 3,433 cm^{-1} suggesting the presence of hydrogen-bonded hydroxyl group. The peaks centered at around 2,937.59 cm^{-1} exhibiting methylene (–CH_2–) stretching contributed by diol. Similar to our observation, Yang et al. [25] observed for citric acid and 1, 8 octane diol-based systems.

In the FT-IR spectra of CD ester, the absorption peaks at 2,927.94 and 1,448.54 cm^{-1} showed the stretching and bending vibration of the –CH_2– group, respectively. The broad peak around 3,437 cm^{-1} indicated the presence of hydrogen-bonded –OH group. An absorption band due to C=O stretching of ester was observed at 1,729.29 cm^{-1} as well as signals of the C–O–C stretching at 1,111.11, 1,037 cm^{-1}, indicating the formation of ester. The FT-IR spectra of CT ester revealed the characteristic stretching vibrating band of hydrogen-bonded alcohol OH around 3,437.15 cm^{-1}; the C=O stretching vibration of the ester group also appeared at 1,726.29 cm^{-1} as well as signals of the C–O–C stretching at 1,109.07 cm and 1,035.77 cm^{-1}. An absorption with weak shoulder peak at around 2,927.94 cm^{-1} and peak at 1,446 cm^{-1},which correspond to the aliphatic –CH_2– stretching and bending bands, respectively, were revealed. The new absorption band

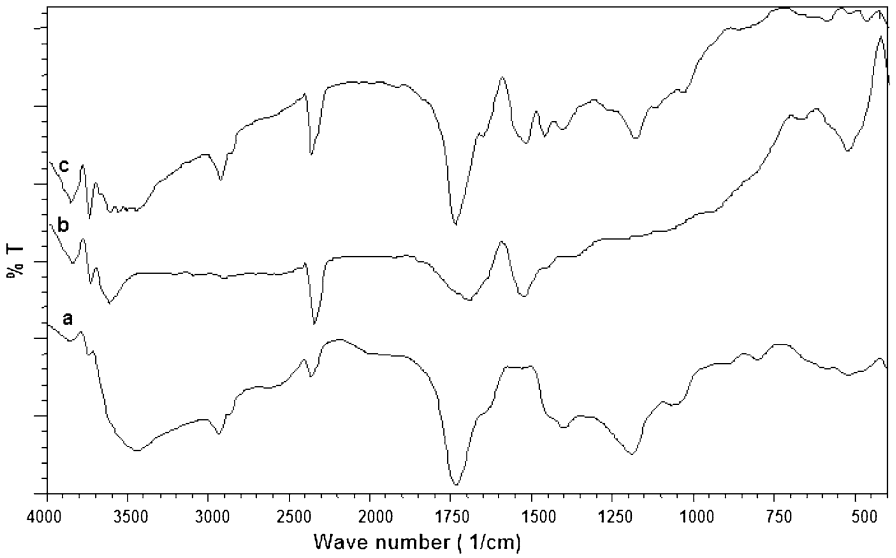


Fig. 1 Comparative FT-IR spectra of *a* ACE, *b* ACD and *c* ACT

appeared at 1,529.55 cm^{-1} attributable to COO^- stretching in all the ACE, ACD and ACT hydrogels. The results of spectroscopy confirmed the formation of various polyesters and incorporation of AA in polyester network in the citric acid-based hydrogels. Similar stretching vibrations at 1,542 and 1,567 cm^{-1} were observed by Kim and Peppas [26] and Sadeghi and Heidari [27] for their poly (methacrylic acid-g-ethylene glycol) hydrogels and methacrylic acid and gelatin-based hydrogels, respectively. An almost similar observation has been reported by Panic and coworkers [28] at 1,552 cm^{-1} for the poly (methacrylic acid)-based hydrogels.

The resonance of pre-polyester networks was confirmed by analyzing the chemical shift of ^1H NMR peaks with respect to tetra methyl silane (TMS). Figure 2a represents the ^1H NMR spectrum of citric acid and the concerned esters. ^1H NMR spectra are also shown in Fig. 2b–d. From Fig. 2b–d, it was clear that the disappearance of signal at 11 ppm indicated the complete utilization of citric acid transformed into the corresponding ester. Thus, both diol and acid participated in the reaction. As shown in Fig. 2b, the multiple peaks located between 2.699 and 2.964 ppm and 4.059–4.302 ppm correspond to the protons in the $–CH_2–$ group and alcoholic –OH group from citric acid. The peak at around 3.509–3.656 ppm could be due to the proton signal of $–OCH_2CH_2–$ from ethylene glycol. Similarly, in Fig. 2c, the multiple peaks located between 2.707 and 2.989 ppm and 4.164–4.339 ppm correspond to the protons in the $–CH_2–$ group and alcoholic –OH group from citric acid. The peak at around 3.514–3.516 ppm could be due to the proton signal of $–OCH_2CH_2–$ from diethylene glycol. The results are in good agreement with literature [24]. The peak around 4.7 ppm was attributed to solvent D_2O [29].

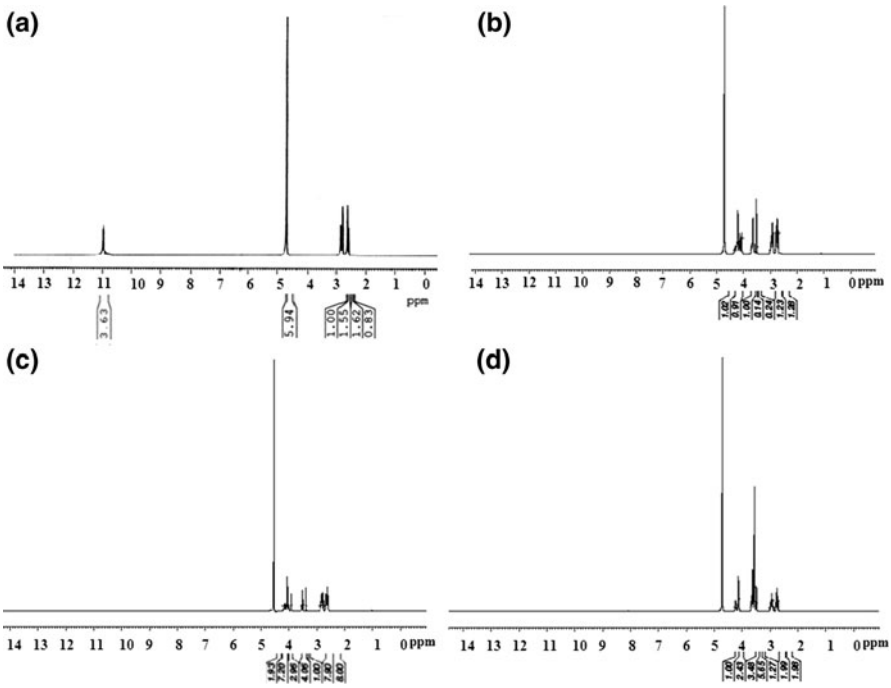


Fig. 2 ^{1}H NMR spectra of **a** Citric acid, **b** CE pre-polyester, **c** CD pre-polyester and **d** CT pre-polyester

As can be seen, Fig. 2d represents the ^{1}H NMR spectrum of CT pre-polyester. The multiple peaks located between 2.699 and 2.998 ppm and 4.132–4.238 ppm correspond to the protons in the $–CH_2–$ group and alcoholic –OH group from citric acid. The peak at around 3.473–3.672 ppm could be due to the proton signal of $–OCH_2CH_2–$ from triethylene glycol.

Swelling studies of polymeric hydrogels

Figures 3, 4 and 5 show the dynamic swelling expressed as the variation of the swelling percentage as a function of the time of immersion of ACE, ACD and ACT hydrogels in phosphate buffer solutions(PBS) at different pH values in the range of pH 4.0–10.0, respectively. It is clearly observed that dry sample exhibits rapid absorption of the solution after immersion. Together with the weight gain of the sample, noticeable increase in the volume of the sample was also observed.

As shown in Fig. 3, the swelling (*S*) values for ACE hydrogel were strongly influenced by changes in the pH of the swelling medium. The ACE 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 1.70, 1.80, 2.85, 3.60 and 5.00, respectively. S values of the same gel after 6 h were found to be 2.30, 5.07, 9.92, 10.00, 13.28, respectively. It clearly indicated that *S* of ACE hydrogel increases with respect to time and the swelling was strongly

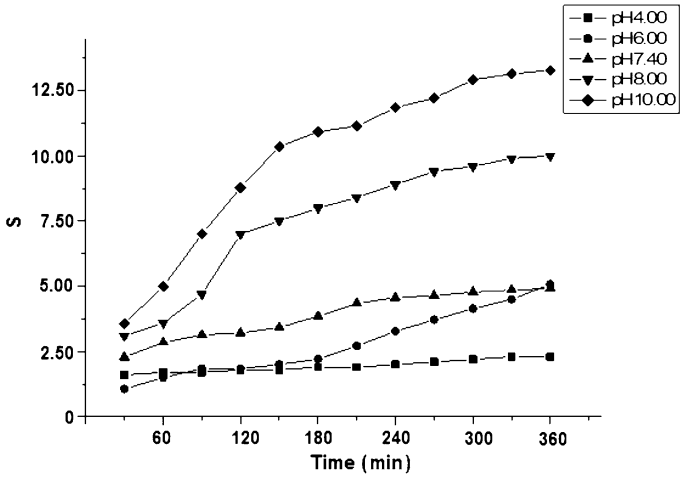


Fig. 3 The swelling percentage of ACE-based hydrogels at different pH

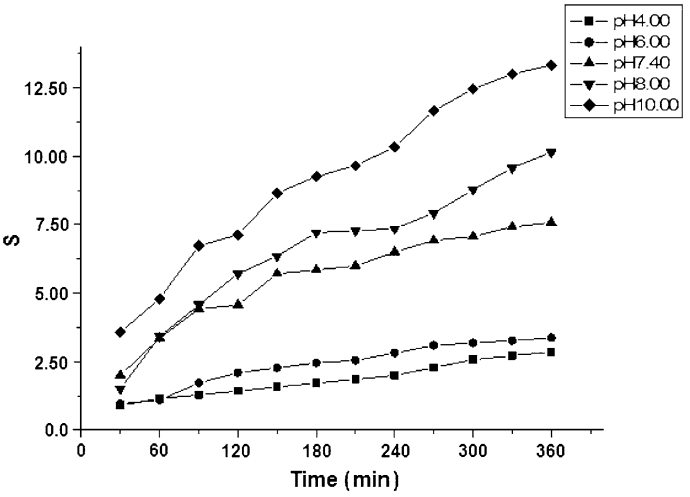


Fig. 4 The swelling percentage of ACD-based hydrogels at different pH

dependent on pH. It is obvious that swelling % of ACE was significantly higher at higher pH, compared to a lower pH value.

At a low pH, complexation occurred, resulting in lowering the swelling rate and swelling. Complex formation results from the formation of temporary physical cross-links due to hydrogen bonding with the AA in the polymer network. This hydrogen-bonded complex causes the polymer network to be less hydrophilic, introducing polymer functionalized by weak acid group such as acrylic acid or weakly basic groups such as amines. Swelling of hydrogels sharply charges in the vicinity of their pK_a and pK_b values [30]. It is well known that CA is a triprotic acid

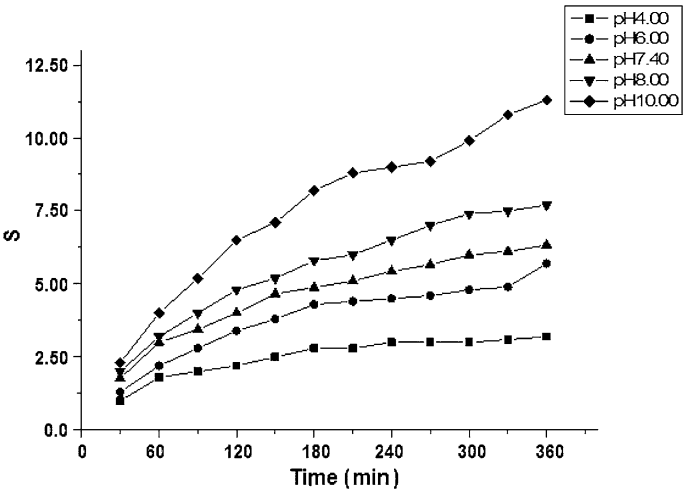


Fig. 5 The swelling percentage of ACT-based hydrogels at different pH

with dissociation constant $pKa_1 = 2.94$, $pKa_2 = 4.14$, $pKa_3 = 5.82$ [31] and acrylic acid dissociation constant $pK_a = 4.65$. Ionization of the carboxylic acid in CA and AA 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.

A similar tendency was observed for both ACD and ACT hydrogels in solutions of different pH ranges from 4.0 to 10.0 as shown in Figs. 4 and 5. The *S* value for ACD hydrogel increased from 2.85 to 13.30 as the pH increased from pH 4.0 to 10.0 after 6 h. Figure 5 illustrates the swelling behavior of ACT hydrogel; it was observed that after 6 h at pH 4.0 and pH 10.0, *S* values were 3.20–11.30. As far as swelling results are concerned, it can be concluded that the swelling behavior of synthesized hydrogels mainly depends on the pH of the swelling medium.

As the pH increases, the carboxylic acid groups can ionize, and complexation does not occur resulting in increased swelling. This might be due to ionic repulsion of carboxylic groups. Similar to our observation, Young et al. [32] and Brannon et al. [33] have investigated the increased swelling behavior of the pH-sensitive hydrogels.

Equilibrium swelling studies of polymeric hydrogels

Equilibrium swelling studies were performed on a gel equilibrated in a buffer with pH value ranging from 4.0 to 10.0 at room temperature. At each of the pH values, the equilibrium swelling S_{eq} % was determined according to Eq. (2). It was observed that the time taken to achieve swelling equilibrium of the hydrogel varied with different pH values of 4.0–10.0. Panduranga rao et al. [34] have reported that the swelling equilibrium at pH 9.0 was found to be 580.00 %, based on the

interpretation that PEG was one of the ingredients in the hydrogels. Similarly, Jafari and Hamid [35] found a maximum of 850.00 % at pH 7.0 for PAA-based complex hydrogels.

Table 2 give the experimental results of swelling equilibrium as a function of various pH values for series of EG-, DEG- and TEG-based hydrogels of varying concentrations of CA. The series of four different EG-based hydrogels (AC1E4, AC2E3, AC3E2 and ACE) by varying CA and EG mol ratio showed equilibrium swelling for all samples exhibiting maxima at higher pH than lower pH. The S_{eq} % value of AC2E3 hydrogel at pH 4.0, 6.0, 7.4, 8.0 and 10.0 were 185.00, 716.00, 642.00, 757.00 and 1,100.00 %, respectively. On comparing these values with AC3E2 hydrogels, S_{eq} % values were found to be 400.00, 1,150.00, 1,327.00, 1,230.00 and 2,011 % at pH 4.0, 6.0, 7.4, 8.0 and 10.0, respectively. It can be seen from the literature [34, 35] and our observations that the addition of CA was found to have increased swelling equilibrium. Furthermore, it indicated clearly S_{eq} % of hydrogels was strongly dependent on pH. The hydrogels swelled at high pH region due to ionic repulsion of carboxyl group and showed less swelling at low pH because of protonation of carboxyl group. In the series of (AC1E4, AC2E3, AC3E2 and ACE) hydrogels, as the pH of the swelling medium increased the gels began to swell. The S_{eq} % values at pH 10.0 observed in the range of 600.00–2,011.00 % and all these hydrogels showed less S_{eq} % at low pH 4.0 in the range of 100.00–400.00 %.

From the Table 2 the swelling of CA- and DEG-based hydrogels (AC1D4, AC2D3, AC3D2 and ACD) were observed between pH 4.0 and 10.0. At pH 10.0, the amount of absorbed water in the polymer network was larger than that of pH 4.0 at the same time. At pH 10.0, the S_{eq} % ranged from 750.00 to 1,828.00 %, and $\underline{S}_{eq}$ % was about 138.00–357.00 % for the series of DEG-based hydrogels at pH 4.0. As seen from Table 2, the value of S_{eq} % CA- and TEG-based hydrogels (AC1T4,

Table 2 S_{eq} % values of polymeric hydrogels based on EG, DEG and TEG

S. no	Sample code	pH				
		4	6	7.4	8	10
1	ACE	260.00	368.00	1,000.00	1,020.00	1,450.00
2	AC1E4	100.00	428.00	283.33	500.00	600.00
3	AC2E3	185.00	716.00	642.00	757.00	1,100.00
4	AC3E2	400.00	1,150.00	1,327.00	1,230.00	2011.00
5	ACD	357.00	640.00	671.00	890.00	1,633.00
6	AC1D4	138.00	100.00	290.00	355.00	750.00
7	AC2D3	109.00	160.00	490.90	670.00	1,207.00
8	AC3D2	200.00	466.00	1,100.00	1,260.00	1,828.00
9	ACT	433.00	741.00	788.00	930.00	1,975.00
10	AC1T4	110.00	209.00	450.00	552.00	1,118.00
11	AC2T3	146.00	654.00	516.00	636.00	1,718.00
12	AC3T2	383.00	150.00	800.00	972.00	2,192.00

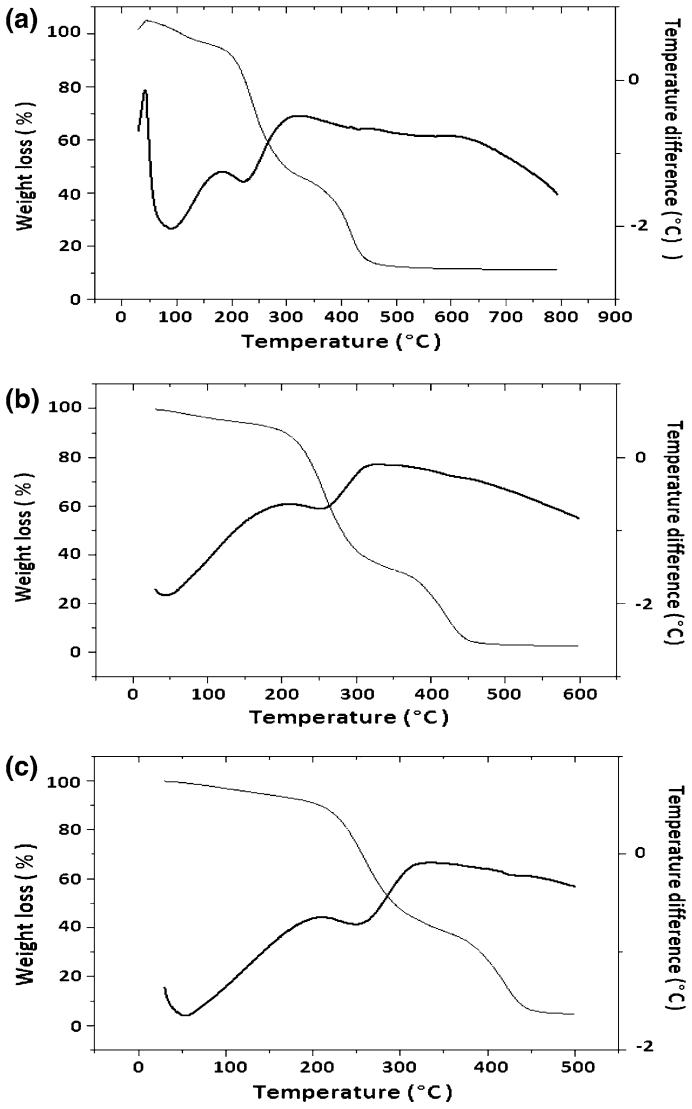


Fig. 6 TGA-DTA curve of **a** ACE, **b** ACD and **c** ACT

AC2T3, AC3T2 and ACT) exhibited a range of S_{eq} % of about 1,118.00–2,192.00 % at pH 10.0. S_{eq} % range was about 110.00–433.00 % at pH 4.0. The systems AC4E1, AC4D1 and AC4T1 were soluble in water due to increase in the mole ratio of CA to diol (0.04:0.01), which increases the more hydrophilic nature of polymeric hydrogel.

As seen from Table 2, the values S_{eq} % of various hydrogels increased gradually with the incorporation of the ionizable CA [31] and AA. The S_{eq} % value increased on increasing the molar proportion of CA in the polymer network. Hence, the ionization of all carboxylic groups in acid increases the S_{eq} % of hydrogels in the

basic media than acidic media. This type of pH-sensitive hydrogels exhibited good swelling ability to uptake metal ions and dyes from aqueous solutions [36].

Thermal characterization of polymeric hydrogels

The TG–DTA curves of ACE, ACD and ACT are depicted in Fig. 6a, b, and c, respectively. Two-stage decomposition was observed from TGA of polymeric hydrogels ACE, ACD and ACT. ACE showed the first-stage decomposition between 175 and 285 °C with weight loss 41.63 % due to loss of moisture and initial breakage occurring in the polymer chain. Second-stage decomposition was observed in the temperature range from 350 to 450 °C with 31.2 % weight loss due to breakdown of the polyester network. DTA curves also supported the TGA results for the polymeric hydrogel ACE system.

The thermal stability at 500 °C for ACE, ACD and ACT were found to have 12.44, 4.75 and 4.25 % retaining capacity, supporting that ACE was thermally stable than ACD and ACT systems. Further, for the ACD and ACT the first-stage decomposition was found at 190 and 200 °C with weight loss of 41 and 47 %, respectively. The second-stage weight loss was observed in ACD and ACT at 330 and 337 °C with weight loss of 52 and 47.62 %, respectively. The overlay curve of TGA of ACE, ACD and ACT (Fig. 7) clearly indicated that the thermal stability decreased from ACE to ACT due to increased length of the polymer chain.

DSC thermograms of polymeric hydrogels

Figure 8a–c shows the DSC thermograms of dried polymeric hydrogels, viz., ACE, ACD and ACT, respectively. All scans were obtained for a heating rate of

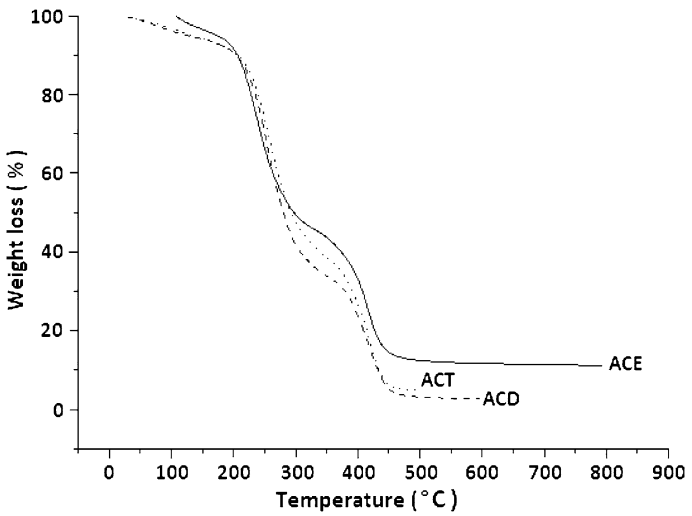


Fig. 7 Overlay TGA curve of ACE, ACD and ACT

10 °C/min. All hydrogels were quenched by dropping the DSC pan containing the samples into the liquid nitrogen and then transferring them into the pre-cooled instrument. From Fig. 8a, b and c, the glass transition temperature of ACE, ACD and ACT was found to be 29, 25 and 28 °C. Further, the DSC thermograms of dry hydrogels of ACE, ACD and ACT show them to be endothermic up to 100 °C. The sample ACE exhibited an important feature of endothermic step with an onset temperature of 100 °C; on the other hand, ACD and ACT were found to have 50 and 45 °C as their onset temperature. The extent of linearity of the glycol group might be the reason behind this jump [37]. Furthermore, the curves in Fig. 8a–c for the hydrogels show a weak and broad exotherm starting at 190 °C, which had also been

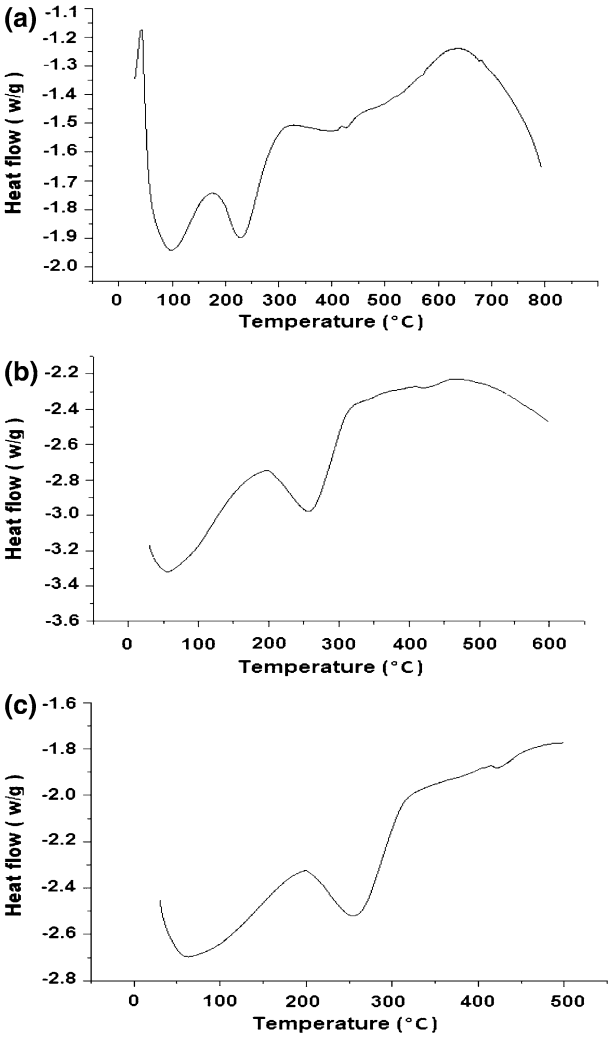


Fig. 8 DSC thermograms of **a** ACE, **b** ACD and **c** ACT

observed by Wilson and Turner [38] as assigned to the crystallization of the hydrogel. The thermal stability from the TGA (Fig. 7) and SEM images (Fig. 9a–c) followed by the swelling behavior of the polymeric hydrogels ACE, ACD and ACT additionally supported the findings in the DSC thermograms.

Morphologies of polymeric hydrogels

Figure 9a–c shows the SEM images of dried ACE, ACD and ACT hydrogels. As shown in Fig. 9a and b, the surface morphology of the concerned hydrogels were extremely smooth, which might be related to the perfect homogeneity among the ingredients. Further, the dried hydrogels shown in Fig. 9a, b exhibited a highly macroporous sponge-like structure, which strongly supported the increased thermal stability of ACE being greater than ACD and ACT. It is worth investigating the swelling behavior of hydrogels with respect to environmental

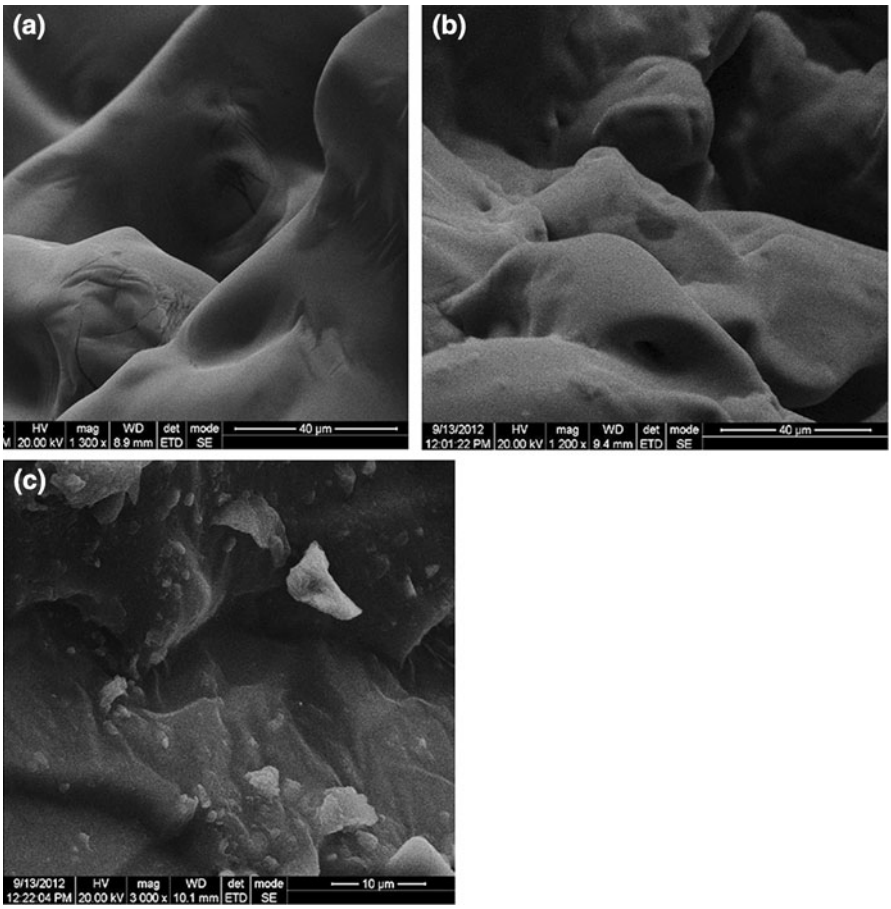


Fig. 9 Scanning electron microscope picture of **a** ACE, **b** ACD and **c** ACT

stimuli, which are very important factors for their applications. It has been established from Fig. 9c that ACT hydrogels exhibited irregularly large pores and channels within the polymer matrix. It encouraged the fluid to easily enter into the gaps, leading to substantially increase of the absorption rate than of ACE and ACD hydrogels.

The swelling equilibrium at pH 4.0, 6.0, 7.4, 8.0 and 10.0 were (in percentage) 433.00, 741.00, 788.00, 930.00 and 1,975.00 % for ACT, 260.00, 368.00,1,000.00,1,020.00 and 1,450.00 % for ACE and 357.00, 640.00, 671.00, 890.00 and 1,633.00 % for ACD hydrogels, respectively. The SEM images Fig. 9a, b, c also well supported the results of swelling equilibrium. Moreover, it is clearly observed from Fig. 9c that the ACT hydrogels had the maximum swelling equilibrium than other hydrogels. The increased swelling equilibrium of ACT might be due to the presence of highly porous and uneven surface to account for the swelling rate at acidic and alkaline medium.

Conclusions

In this study, the biopolymeric pH-responsive citric acid-based hydrogels with varying EG, DEG and TEG were synthesized by condensation polymerization in the presence of acidic medium. Spectral techniques such as FT-IR and ^{1}H NMR supported the formation of various hydrogels.

1. Thermal stability of the hydrogels has been investigated by TGA, DTA and DSC. TGA studies of ACE, ACD and ACT revealed that ACE hydrogels were found to have excellent thermal stability than ACD and ACT hydrogels. The glass transition temperature of ACE, ACD and ACT were found to be 29, 25 and 28 °C, respectively, from DSC analysis. The two-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 increased CA content in all the hydrogels was found to exhibit higher swelling and swelling equilibrium at higher pH.
3. The surface morphologies of hydrogels exhibiting perfect homogeneity among their ingredients and also macroporous sponge-like structure enable the hydrogels to achieve their increased thermal stability and swelling equilibrium.

Hence, synthesized biocompatible pH-sensitive hydrogels may have a great opening for industrial and biological applications such as metal ion removal, cationic dye removal and controlled release of drugs to pH-sensitive parts of human beings.

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