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Photo-induced synthesis, characterization and swelling behavior of poly(2-hydroxyethyl methacrylate) grafted carboxymethyl chitosan

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ABSTRACT

In the present study, carboxymethyl chitosan was prepared and characterized. Photo-induced graft copolymerization of 2-hydroxyethyl methacrylate (HEMA) onto carboxymethyl chitosan (CMCs) was then carried out under nitrogen atmosphere in aqueous solution using 2,2-dimethoxy-2-phenyl acetophenone (PI) as photo-initiator. Grafting process was confirmed and the produced copolymers were characterized with aid of elemental analysis, FTIR, 2D-X ray diffraction, differential scanning calorimetry (DSC) and scanning electron microscopy (SEM). The effects of HEMA and PI concentrations and the reaction time on the grafting yield were investigated by determining the grafting percentage and grafting efficiency. Under the applied experimental conditions, the optimum grafting conditions were obtained at: CMCs = 0.2 g, HEMA = 0.615 mol/L, PI = 0.0078 mol/L and reaction time = 90 min. The synthesized copolymers revealed a self-ability to form physically crosslinked hydrogels. The hydrogel nature of the copolymers was investigated by studying the solubility profiles and the cyclic swelling–deswelling behavior of copolymers with different grafting extents. These investigations of the photo-synthesized graft copolymers showed that they can be tailored and exploited as promising carriers for drug delivery purposes.

1. Introduction

Chitosan (Cs) is a biodegradable and non-toxic cationic biopolymer obtained through the alkaline *N*-deacetylation of chitin (Hirano, Seino, Akiyama, & Nonaka, 1990; Majeti & Kumar, 2000). Carboxymethyl chitosan (CMCs) is one of Cs derivatives that showed numerous superior characteristics such as low toxicity, biocompatibility and good ability to form films, fibres and hydrogels (Muzzarelli, 1988). For this reason, CMCs has been widely utilized in many biomedical fields (Chen, Du, Tian, & Sun, 2005; El-Sherbiny, Abdel-Bary, & Harding, 2010; Liu, Jiao, & Zhang, 2007). A considerable number of studies have focused recently on chemical modification of Cs and CMC to enhance their characteristics and consequently expand their potential applications in several fields (El-Sherbiny, 2009; El-Sherbiny et al., 2010; Heras, Rodriguez, Ramos, & Agullo, 2001; Sridhari & Dutta, 2000). Among various approaches for chemical modifications, the graft copolymerization is one of the most attractive techniques due to its ability to introduce desired characteristics via judicious selection of side chain type. In spite of the substantial body of research focused on grafting synthetic polymers onto Cs (El-Sherbiny, McGill, & Smyth, 2009; Jenkins & Hudson, 2002; Li, Liu, & Fang, 2003; Liu, Liu, Zhang, & Deng, 2002), relatively few recently reported studies have investigated graft copolymerization onto CMCs backbone (El-Sherbiny, 2009; El-Sherbiny, in press; El-Sherbiny et al., 2010; Joshi & Sinha, 2006a, 2006b, 2007; Sabaa, Mohamed, Mohamed, Khalil, & Abd El Latif, 2010; Sun, Xu, Liu, Xue, & Xie, 2003). A wide range of initiator systems can be utilized to initiate graft copolymerization onto Cs and CMCs. For instance, ammonium persulfate (APS), potassium persulfate (KPS) and ceric ammonium nitrate (CAN) have been used. Photo-induced graft copolymerization of vinyl monomers onto polymer backbones has many advantages as compared to other methods of grafting by free radical polymerization. For instance, this grafting technique showed a controlled generation of radical sites on polymer backbones in addition to attaining higher grafting efficiencies (John, Pillai, & Ajayaghosh, 1993). In a previous study (El-Sherbiny, 2009), we reported the photo-induced synthesis and characterization of a new CMCs graft copolymer with N-acryloyl glycine (NAGly). The study revealed the ability of this grafting technique to improve the overall physicochemical characteristics of CMCs towards more prospective applications.

Poly(2-hydroxyethyl methacrylate) (pHEMA) has been widely investigated as a biomaterial candidate with various potential

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applications including soft-tissue replacement, contact lenses and vascular prostheses (Filmon, Grizon, Basle, & Chappard, 2002; Montheard, Chatzopoulos, & Chappard, 1992). This significant interest has been paid to pHEMA in the biomedical fields due to its various outstanding characteristics such as biocompatibility and the high hydrophilicity (Filmon et al., 2002). Owing to the expected desirable characteristics of the CMCs-g-HEMA copolymer, its synthesis through different efficient grafting techniques such as photo-induced graft copolymerization is needed. Also, the determination of the optimum grafting conditions and the structural characteristics of the resulting copolymer need to be extensively investigated. Moreover, pHEMA is a highly hydrophilic polymer due to the large number of pendant primary hydroxyl groups. These hydroxyl groups can allow the formation of self-physically crosslinked hydrogel matrices through formation of H-bonds in the absence of crosslinking agents. Therefore, exploring these hydrogel characteristics of the synthesized copolymer could be beneficial specifically for drug delivery purposes where crosslinking agents can be detrimental (Wichterle & Lim, 1960). Also, it would be useful to investigate how the physicochemical properties of these copolymer-based matrices can be controlled via the well design of the experimental conditions. In this study, Cs was carboxymethylated then photo-induced graft copolymerized with HEMA in a mild aqueous medium using 2,2-dimethoxy-2-phenyl acetophenone (PI) as photo-initiator. The grafting process was confirmed and the effects of reaction conditions on the extent of grafting were investigated. Then, both chemical and physical characteristics of the copolymer (solubility profiles, thermal stability, crystallography and surface morphology) have been studied. In addition, the self-hydrogel nature of the developed copolymers was investigated by studying their cyclic swelling–deswelling behavior.

2. Experimental

2.1. Materials

Chitosan (Cs), 2-hydroxyethyl methacrylate (HEMA) and 2,2-dimethoxy-2-phenyl acetophenone (PI) were purchased from Acros Organics (New Jersey, USA). Monochloroacetic acid was obtained from Riedel–De Haenag Seelze (Hanover, Germany). Isopropyl alcohol, acetic acid and all other reagents were of analytical grade and used as received.

2.2. Methods

2.2.1. Preparation and characterization of Cs, CMCs and graft copolymer

2.2.1.1. Characterization of Cs. The average molecular weight (M_w) of the Cs under investigation was determined to be 318 kDa using the Mark-Houwink viscometry method (El-Sherbiny, 2009), in a solvent of 0.1 M acetic acid/0.2 M NaCl maintained at 25 °C. The efflux times of both solvent and Cs solutions were determined using Cannon–Fenske routine viscometer (Cannon Instrument Co., State College, PA, USA). Each sample was measured three times. Moreover, the percent of *N*-deacetylation of the Cs used in this study was found to be 73.6% as determined by FTIR using the following relationship (Roberts, 1992):

$$\%\text{N-deacetylation} = 100\left[1 - \left(\frac{A_{1655}}{A_{3340}}\right)\left(\frac{1}{1.33}\right)\right] \quad (1)$$

where A is the absorbance at the given wave number. These two absorption signals (1655 and 3340 cm^{-1}) correspond to the amide and the primary amino groups of Cs respectively. The factor (1.33) represents the value of the ratio of A_{1655}/A_{3340} for the fully N-acetylated Cs.

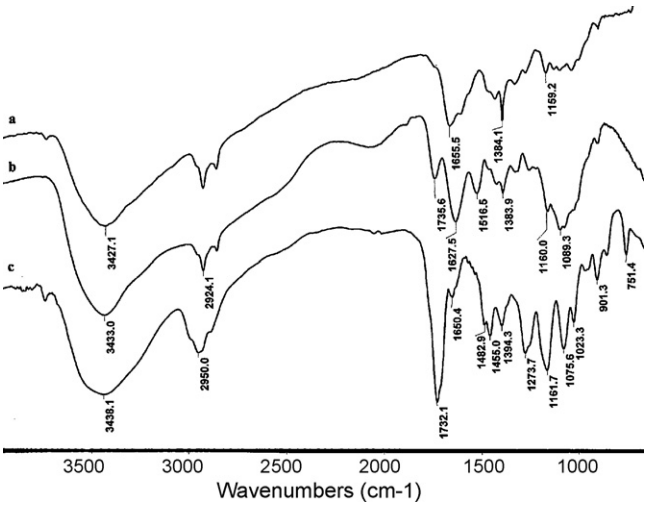


Fig. 1. FTIR spectra for (a) Cs, (b) CMCs and (c) CMCs-g-HEMA.

2.2.1.2. Preparation of CMCs. The water-soluble CMCs was prepared by a modified method described previously in our earlier study (El-Sherbiny, 2009). The substitution degree (D_S) of the synthesized CMCs was determined using potentiometric titration (Ge & Luo, 2005). A solution of 150 mg of CMCs dissolved in 50 ml of distilled water was adjusted to pH < 2 by adding hydrochloric acid. The CMCs solution was then titrated with 0.1 M aqueous NaOH and the pH value was simultaneously recorded. The NaOH amount was determined by the second order differential method and the D_S value was calculated as follows:

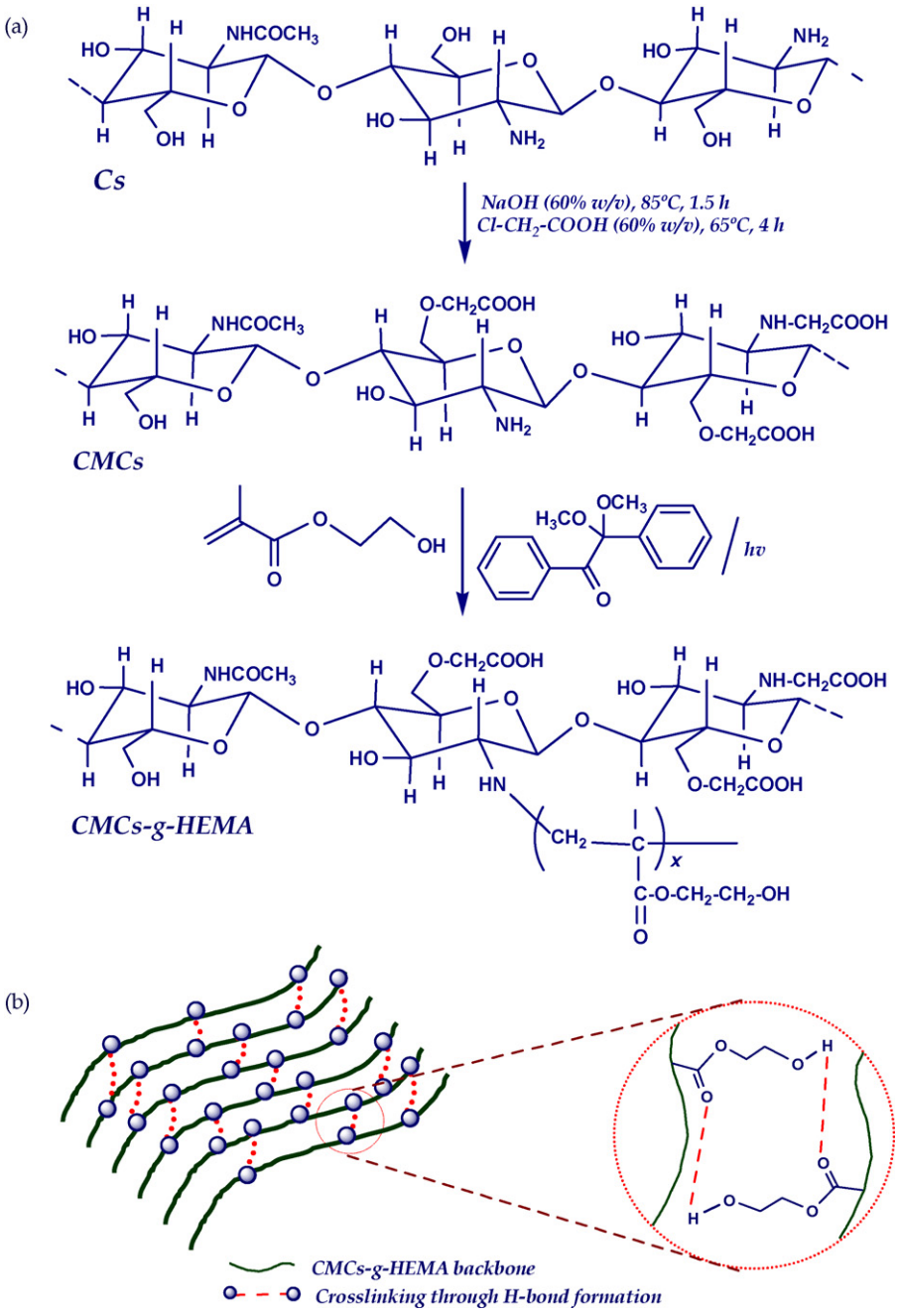
$$D_S = \frac{161 \times V \times C}{m_{CMCs} - 58 \times V \times C} \quad (2)$$

where m_{CMCs} is the mass (g) of CMCs, V and C are the volume and molarity of NaOH solution respectively. The values 58 and 161 represent the molecular weights of the carboxymethyl group and the glucosamine unit of Cs respectively. Also, the average viscosity molecular weight of the CMCs, dissolved in 0.1 M aqueous NaCl, was estimated at 25 °C using the following relationships (Ge and Luo, 2005):

$$\begin{aligned} \eta_r &= \frac{t}{t_0} \\ \eta_{sp} &= \eta_r - 1 \\ [\eta] &= \frac{4\eta_{sp}^{1.02} \times \ln\ \eta_r}{C^{1.01}(3\eta_{sp} + \ln \eta_r)} \\ [\eta] &= 7.92 \times 10^{-5} M_v^{1.00} \end{aligned} \quad (3)$$

where t and t_0 are the delivery times of CMCs solution and the solvent respectively, C is the concentration of CMCs (g/ml), η_r and $[\eta]$ are the relative and intrinsic viscosities respectively. M_v is the viscosity average molecular weight of CMCs.

2.2.1.3. Graft copolymerization. A solution of 0.2 g CMCs dissolved in 10 ml of distilled water was prepared. To this solution was added, with stirring, the appropriate quantity of PI (0.0052–0.0182 mol/L based on the total volume of solvents in reaction mixture) dissolved in 5 ml of THF. The solution was then flushed with nitrogen for 20 min. The predetermined volumes (370–1490 μl) of HEMA (corresponding 0.205–0.821 mol/L based on the total volume of solvents in reaction mixture) were added gradually with stirring for 10 min. The graft copolymerization was then initiated by irradiation with an incandescent broad-spectrum lamp (Philips Comptalux, 150 W), positioned 20 cm from the reaction mixture. Irradiation was continued for variable predetermined periods (30–180 min). The reaction mixture was filtered and the crude product was dried



Scheme 1. Preparation of CMCs and CMCs-g-HEMA copolymer.

and weighed. The homopolymer formed was extensively extracted in a Soxhlet apparatus by refluxing with methanol for 24 h. The residual graft copolymer obtained was washed with distilled water, dried and weighed. The percent grafting (G%) and the grafting efficiency (GE%) of the copolymers were calculated as follows (Shantha, Bala, & Panduranga, 1995):

$$G\% = 100\left[\frac{W_g - W_0}{W_0}\right] \quad (4)$$

$$GE\% = 100\left[\frac{W_g}{W_g + W_h}\right] \quad (5)$$

where W_g, W_h and W_o are the weights of graft copolymer, homopolymer and CMCs, respectively. Both G% and GE% represent the mean values ± SD of three independent grafting experiments.

2.2.2. Characterization

Both CMCs and CMCs-g-HEMA copolymer were characterized by FTIR. The dried samples were pressed with KBr and their FTIR spectra were recorded on a Perkin Elmer Paragon 1000 FTIR spectrometer within the wave number range of 4000–600 cm^{-1} at 25 °C. The elemental analysis for Cs, CMCs and the prepared CMCs-g-HEMA copolymer were performed in Carlo Erba elemental analyzer EA 1108 using a flash combustion technique. Differential scanning calorimetry (DSC) was carried out using Perkin Elmer DSC7 in a nitrogen atmosphere from −30 to 300 °C at scanning rate of 10 °C/min. The samples (10–15 mg) were weighed into aluminium pans and sealed. An empty aluminium pan of approximately equal weight was used as a reference. The crystallography patterns of the polymer samples were investigated using 2D-X-ray equipment (Rigaku Micro Max 007 microfocus rotating-anode X-ray gener-

ator (Cu Kα) coupled with Osmic "Blue" confocal optics and a Rigaku RAxis VI++ image-plate detector). Images were recorded and analysed with Crystal clear (1.3.6-SPI, Pflugrath, JW, 1999, Acta Crystallogr. D 50, 1718–1725). The surface morphology of the polymer samples was investigated by scanning electron microscope (Cambridge Stereoscan S-250 mk 3 SEM). Samples were placed on an aluminium mount, sputtered with gold using Bal-tec. scd. 050 sputter coater. The sample scanned at an accelerating voltage of 20 kV.

2.2.3. Solubility of the graft copolymer

The solubility extent of the prepared CMCs-g-HEMA copolymer samples was examined in various solvents at intervals up to 24 h. In each case, about 1.5 mg of graft copolymers (G%: 19, 200 and 857%) were shaken in 10 ml of solvent. At each interval, the solutions were filtered and the filtrates were evaporated to the complete dryness to check for any residue.

2.2.4. Equilibrium swelling measurements

The swelling behavior of four samples of CMCs-g-HEMA copolymers with different grafting yields (G%: 19, 200, 425 and 857%) was determined at 37 °C in distilled water using a cyclic swelling procedure. The swelled samples were weighed at intervals after blotting the surface liquid until equilibrium swelling was attained. The swelled samples were then completely dried at 40 °C under vacuum and reweighed. This swelling–deswelling process was repeated three times for each sample. The percent of swelling was calculated by the following equation:

$$\text{Swelling\%} = 100\left[\frac{W_t - W_o}{W_o}\right] \quad (6)$$

where W_o is the initial weight and W_t is the weight of the swelled copolymer at time t. Each data point is a mean of three independent determinations.

3. Results and discussion

3.1. Characterization of CMCs and CMCs-g-HEMA Copolymer

The CMCs used in this investigation was prepared by a method reported in our earlier study (El-Sherbiny, 2009). The intrinsic viscosity of the prepared CMCs in 0.1 M aqueous NaCl at 25 °C was found to be 5.1 dL/g and its D_S value is 0.48 as estimated with aid of potentiometric titration. The structural changes of Cs and its derivatives (CMCs and CMCs-g-HEMA) were confirmed by FTIR (Fig. 1). The IR spectrum of Cs (Fig. 1a) shows a strong peak at 3427 cm^{-1} which is assigned to the O–H stretching vibration, N–H extension vibration and the intermolecular H-bonds of the polysaccharide moieties. The weak peak at 1656 cm^{-1} is attributed to the amide C=O stretching. The IR spectrum of CMCs (Fig. 1b) shows a strong new peak at 1736 cm^{-1} that is due to the C=O asymmetric stretching vibration of the carboxylate group whereas, the peak appeared at 1384 cm^{-1} represents the symmetric stretching of the carboxylate C=O. The C–O absorption signal of the secondary O–H group became stronger and shifted to 1089 cm^{-1}. This tends to show that the substitution occurs mainly at the C_6 position. In case of IR spectrum of CMCs-g-HEMA (Fig. 1c), the new peak appeared at 1274 cm^{-1} is attributed to (pHEMA) side chains. Also, in the IR spectra of the prepared CMCs-g-HEMA copolymer, the absorption peaks at around 1100 cm^{-1} that are characteristic for the polysaccharide backbone became weaker. This can be attributed to the high grafting extents. The IR spectrum of CMCs-g-HEMA shows also the absence of clear absorption in the range of 1400–1420 cm^{-1}, representing vinylic double bonds in conjunction with ester group, and also there is no absorption due to vinyl unsaturation was observed at 1620–1640 cm^{-1}. This tends to point to the disappearance of the vinylic double bonds of HEMA due to grafting process. The preparation of CMCs and CMCs-g-HEMA copolymer is shown in Scheme 1a. As illustrated in the scheme, the expected initiation site for the grafting process is the primary amino group on C_2 position. This suggestion was confirmed in several reported studies for this type of free radical-induced graft copolymerization onto CMCs backbone (Sabaa et al., 2010).

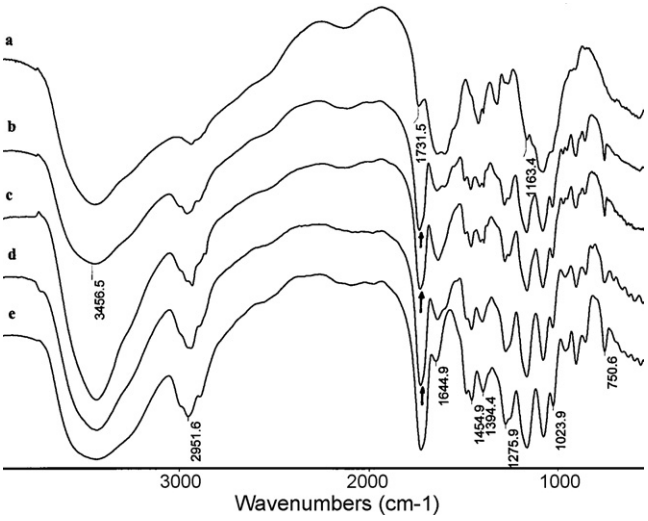


Fig. 2. FTIR for CMCs-g-HEMA with different grafting yields: (a) G% = 5%, (b) G% = 200%, (c) G% = 425%, (d) G% = 590% and (e) G% = 857%.

3.2. Proof of grafting

There are some experimental evidences that confirm the occurrence of the grafting process. As discussed above, the FTIR spectra of CMCs-g-HEMA showed the characteristic peaks of both CMCs and pHEMA. Moreover, as shown in Fig. 2, the intensity of the C=O absorption peak at 1732 cm^{-1} was increased with increasing the G%. The higher weights of the graft products as compared with that of the starting CMCs after the extensive removal of the homopolymer can be also taken as evidence of grafting. The occurrence of grafting can be also deduced from the decreasing of *N*-content upon comparing the measured elemental analysis data of both CMCs (C, 38.41; N, 5.32; H, 5.36) and CMCs-g-HEMA, G%: 590% (C, 50.82; N, 0.56; H, 7.34). Besides, the solubility behavior of the graft copolymers was found to be different from that of CMCs and pHEMA.

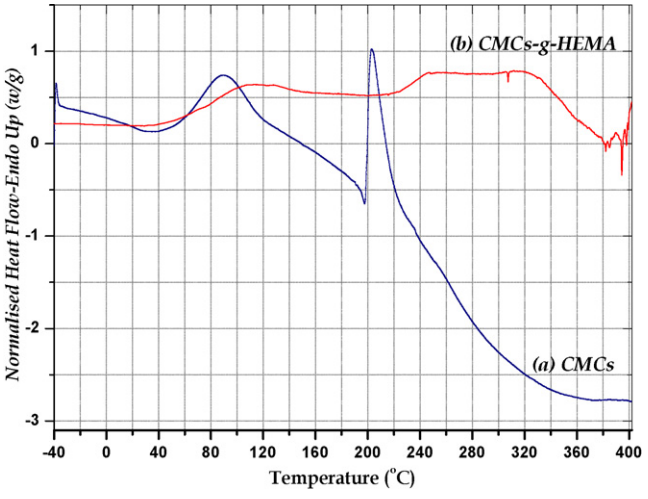


Fig. 3. Differential scanning calorimetry (DSC) of (a) CMCs and (b) CMCs-g-HEMA.

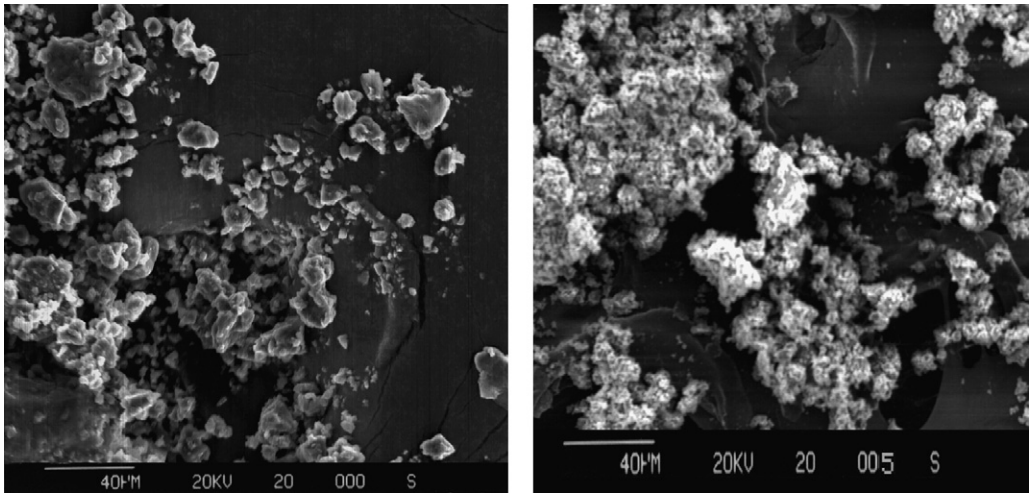


Fig. 4. Scanning electron micrographs of CMCs powder (left) and CMCs-g-HEMA (G%: 425%) (right).

The CMCs is soluble in water and pHEMA is soluble in methanol while the produced copolymers with considerable grafting extent were found to be insoluble in both solvents. Another experimental evidence of grafting is the difference in the thermal behavior of both CMCs and its graft copolymer, CMCs-g-HEMA (Fig. 3). As shown from the figure, the thermogram of CMCs shows a broad transition around 94 °C and a sharp endotherm at 205 °C. In the thermogram of CMCs-g-HEMA copolymer, there is a very broad transition around 110 °C in addition to a second broad exotherm started at 246 °C. In both CMCs and CMCs-g-HEMA, the transitions around 94–110 °C are attributed to the loss of bound water. The decomposition of CMCs and its graft copolymer would have resulted in the exothermic transitions started at about 225 and 342 °C respectively.

The surface morphology of the synthesized CMCs-g-HEMA copolymer (G5: 425%) as compared to CMCs is illustrated in Fig. 4. As apparent, CMCs has the appearance of irregular plate-like structures with relatively smooth surfaces. The grafting of HEMA onto the backbone of CMCs results in very irregular clusters characterized by dense surface rugosity and roughness. This change in surface morphology may lead to significant advantages for applications where the interface with biological systems is important, such as drug delivery.

The diffraction patterns of Cs and its prepared derivatives, CMCs and CMCs-g-HEMA were investigated using 2D-XRD as illustrated in Fig. 5. As appeared from the diffractogram of Cs (Fig. 5i), there are three main crystalline bands corresponding to 2θ values of 18.25°, 11.49° and 8.38°, respectively as well as many broad and weak crystalline peaks. This diffractogram of the Cs used in this investigation reveals a high degree of crystallinity. The diffractogram of the prepared CMCs is illustrated in Fig. 5ii. As appeared from the figure, CMCs has a range of crystalline bands in addition to two broad bands appeared at 2θ values of 26.33° and 21.43°. It was found also that, the CMCs diffractogram keep some of the characteristic bands of Cs. For instance, CMCs diffractogram still show the bands at 2θ values of ~21.43°, ~18.46°, 16.10°, 11.49° and 10.40°. Grafting of HEMA onto the CMCs backbone turned the resulting graft copolymer, CMCs-g-HEMA into an amorphous material. The diffractogram of CMCs-g-HEMA (Fig. 5iii) reflects its amorphous nature with appearance of four broad bands at 2θ values of 10.8° (very weak), 7.3°, 4.9° and 3.2°. The amorphous character of the CMCs-g-HEMA copolymer may be due to the occurrence of the grafting process in a haphazard manner along the CMCs backbone leading to destroying the regularity of the packing of the original CMCs chains.

3.3. Effect of photo-initiator concentration

The influence of the photo-initiator (PI) concentration on the grafting extent is illustrated in Fig. 6. With other reaction conditions maintaining constant, the grafting parameters, G% and GE% increased with increasing the concentration of PI, in the range from 0.0052 to 0.0182 mol/L, reaching a maximum value at PI of 0.0078 mol/L, then dropped again. This phenomenon may be clarified by a mechanism similar to that suggested for grafting onto Cs (Li, Li, Liao, & Feng, 1993) where, upon increasing the PI amount, more CMCs macroradicals are generated and consequently more active sites on the CMCs backbone could react with HEMA leading to increasing of G% and GE%. On the other hand, the excessive PI creates a plenty of radicals, which would, instead, terminate the

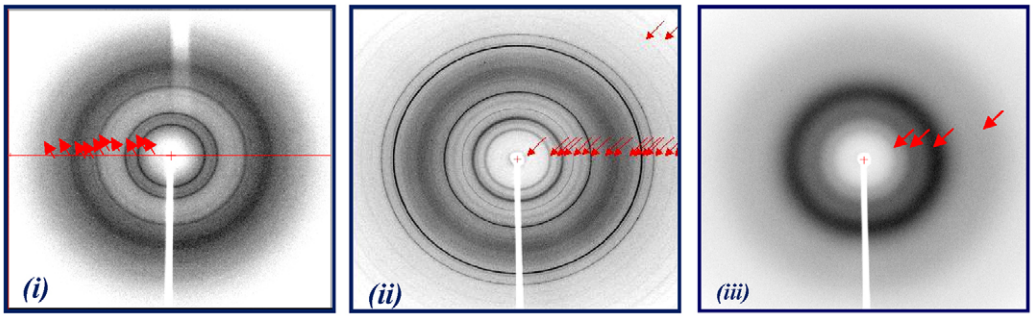


Fig. 5. 2D-XR diffraction patterns of (i) Cs, (ii) CMCs and (iii) CMCs-g-HEMA (G%: 857%).

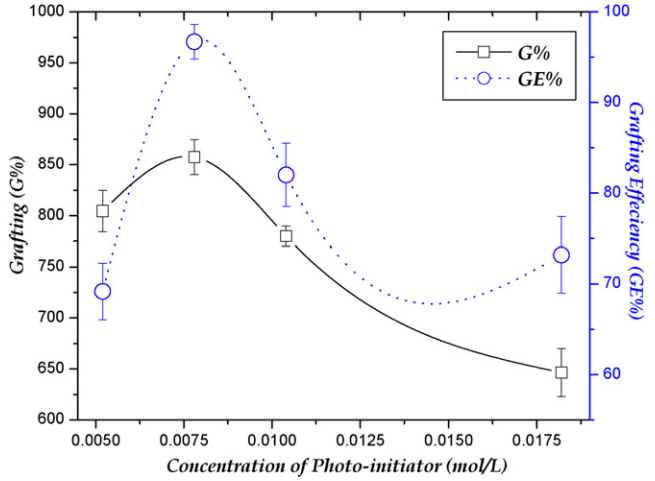


Fig. 6. Effect of photo-initiator concentration onto the grafting parameters. CMCs: 0.2 g; HEMA: 0.615 mol/L; time of reaction: 90 min.

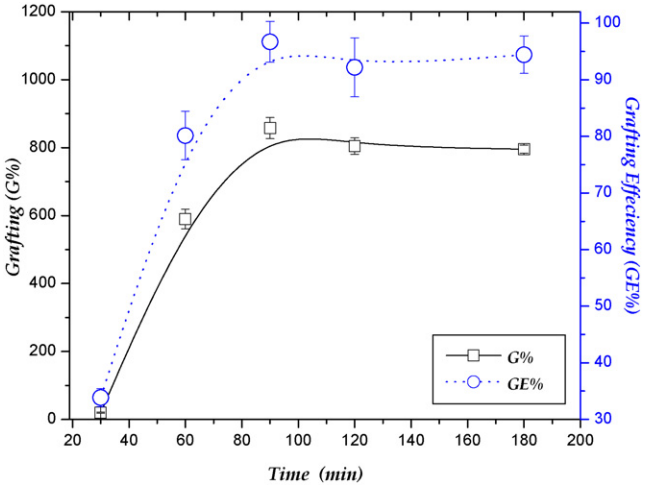


Fig. 8. Effect of the reaction time on the grafting parameters. CMCs: 0.2 g; PI: 0.0078 mol/L; HEMA: 0.615 mol/L.

propagation of the graft copolymerization. Consequently, this will lead to a decrease in G% and GE%. Moreover, at higher concentrations of the photo-initiator, PI, the formation of more homopolymer can be expected due to the non-availability of sites on CMCs at which PI can generate more free radicals and thus the unutilized PI can motivate the occurrence of more homopolymerization (Joshi & Sinha, 2007).

3.4. Effect of monomer (HEMA) concentration

The graft copolymerization of HEMA onto CMCs was conducted at various concentrations of HEMA. Fig. 7 shows the influence of the HEMA concentration onto the yield of graft copolymerization. As appeared from the figure, there is an increase in both G% and GE% upon increasing the HEMA concentration up to a certain value (0.615 mol/L under the experimental conditions) and then they decreased again with the monomer further increasing. This behavior can be attributed to the limited number of active centres available for grafting on the CMCs backbone then upon increasing the monomer quantity, more competition occurs between the HEMA molecules for the same sites leading to increasing the grafting extent until saturation of the CMCs backbone. At higher monomer concentrations, however, the excessive monomer molecules could induce significantly more chain transfer and termination reactions leading to more homopolymerization instead of grafting. This speculation was confirmed upon collecting and weighing the resulting homopolymers. Moreover, once the CMCs-g-HEMA copolymer is formed, the excess monomer can shield the graft copolymer, which in consequence will inhibit the grafting rate. Repeating the grafting experiments three times showed a good level of consistency in the obtained grafting results with a coefficient of variation less than 5% in most experiments.

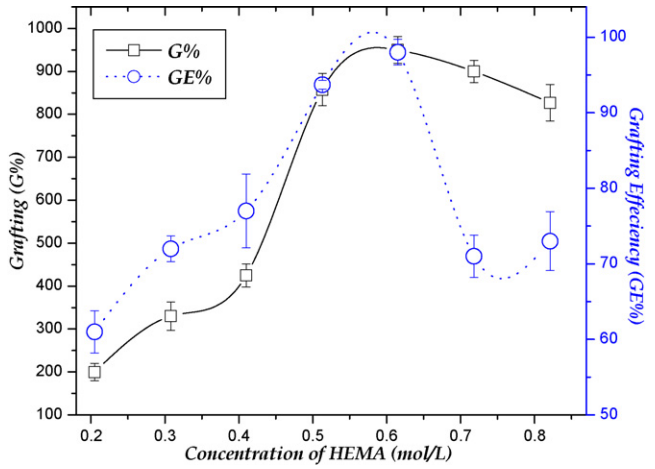


Fig. 7. Effect of monomer (HEMA) concentration onto the grafting parameters. CMCs: 0.2 g; PI: 0.0078 mol/L; time of reaction: 90 min.

3.5. Effect of reaction time

Fig. 8 illustrates the effect of reaction time onto the grafting yield of HEMA onto CMCs. As shown from the figure, the influence of reaction time on grafting parameters was investigated through determination of G% and GE% at different times from 30 up to 180 min. Both G% and GE% increased with increasing the reaction time, and levelled off after about 90 min, reaching saturation value of grafting. This levelling off in the grafting parameters beyond certain reaction time can be attributed to the depletion in both the free radicals and the available amount of HEMA in the reaction. The data points in the figure represent the mean values of three trials with ± SD range less than 5% in most cases which reveals a consistency in the obtained grafting results.

3.6. Solubility results

The solubility results of the synthesized CMCs-g-HEMA copolymers of different grafting yields (G%: 19, 200 and 857%) in various solvents are summarized in Table 1. As shown in the table, the copolymers of low grafting percent (19%) were found to be soluble in distilled water, ethanol, aqueous NaOH solution (1 M) and the mixture of acetic acid (2%): ethanol (1:1). These water soluble copolymers can be further investigated for various biomedical applications. The solubility of the copolymers in these solvents decreased upon increasing the grafting percentages. In acetonitrile, THF, DMSO, toluene and ethyl acetate, the prepared CMCs-g-HEMA copolymers were found to be entirely insoluble and showed, instead the characteristics of hydrogels and swelled to various extents depending on both type of solvent and the G% of the copolymer. In HCl (5 M), HNO_3 (1 M) and glacial acetic acid, the copolymers were insoluble and disintegrated rapidly.

Table 1
Solubility of CMCs-g-HEMA of different G% in various solvents.

Solvent used	Solubility observation		
	G%: 19%	G%: 200%	G%: 857%
Distilled water	Soluble	Partially soluble	Swell
Anhydrous ethanol	Soluble	Partially soluble	Swell
Acetonitrile	Swell	Swell	Partially swellable
THF	Swell	Swell	Partially swellable
DMSO	Swell	Swell	Highly swellable
Aqueous NaOH (1 M)	Soluble	Swell	Partially swellable
Hydrochloric acid (5 M)	Disintegrate	Swell	Swell
Nitric acid (1 M)	Disintegrate	Disintegrate	Insoluble, disintegrate
Glacial acetic acid	Disintegrate	Disintegrate	Insoluble, disintegrate
Acetic acid (2%)	Partially soluble	Swellable	Partially swellable
Acetic (2%):ethanol (1:1)	Soluble	Partially soluble	Highly swellable
Ethyl acetate	Insoluble	Completely insoluble	Completely insoluble
Toluene	Completely insoluble	Completely insoluble	Completely insoluble

3.7. Swelling behavior

The cyclic swelling profiles of CMCs-g-HEMA copolymers with different grafting percentages are illustrated in Fig. 9. Generally, the existence of hydrophilic moieties such as hydroxyl and carboxylic groups tends to increase the hydrophilicity of a polymeric material and consequently increases its swelling values attained at equilibrium. However, as apparent in Fig. 9, the graft copolymers with the higher G% (857%) attained the lowest swelling values at equilibrium. Decreasing the grafting percent to 19% leads to a marked increase in the equilibrium swelling. The swelling profile was almost consistent in all the three swelling–deswelling cycles. This behavior can be attributed to the association of the hydroxyl groups in the grafted (pHEMA) side chains through formation of H-bonds (see Scheme 1b) leading to a reduction in the swelling capacity of the copolymer. The early dissolution of the copolymer with G%: 19% and the disintegration of the copolymers with G%: 200% and 425% at different time points tend also to confirm this explanation (see also Table 2).

Based on the promising swelling results obtained for the prepared CMCs-g-HEMA copolymers, a comprehensive study was carried out to develop a series of IPN hydrogel matrices based on the copolymer for exploring their potential application for drug delivery purposes. The IPN matrices were prepared at the optimum conditions estimated from the current study in presence of various crosslinking agents. The results of this extensive study will be presented elsewhere.

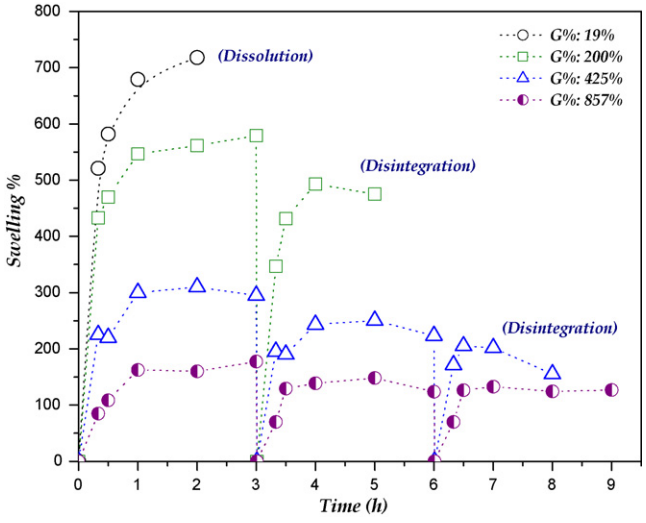


Fig. 9. Cyclic swelling profiles of CMCs-g-HEMA with different grafting yields in distilled water at 37 °C.

Table 2
The equilibrium swelling (%) of CMCs-g-HEMA copolymers with different grafting percents in distilled water at 37 °C.

G%	Equilibrium swelling (%)		
	First cycle	Second cycle	Third cycle
19	718.2	–	–
200	579.4	475.1	–
425	295.0	224.5	167.1
857	177.4	123.9	126.8

4. Conclusion

In the current contribution, CMCs was prepared, characterized and then further modified via photo-induced graft copolymerization of HEMA onto its backbone. The photo-induced grafting process was confirmed and the effects of reaction conditions on grafting yields were studied. Moreover, the chemical and physical characteristics of the developed CMCs-g-HEMA copolymers (solubility characteristics, thermal stability, crystallographic patterns, surface morphology and the swelling profiles) have been investigated. This preliminary investigation of the synthesized graft copolymers revealed a hydrogel nature of them and showed that they can be tailored and utilized as significant polymeric candidates in drug delivery.

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