



Development of CMC hydrogels loaded with silver nano-particles for medical applications

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ARTICLE INFO

Article history:

Received 21 June 2012

Received in revised form 7 August 2012

Accepted 25 August 2012

Available online 1 September 2012

Keywords:

Carboxymethyl cellulose (CMC)

Hydrogels

Silver nanoparticles

Swelling behavior

ABSTRACT

Innovative CMC-based hydrogels with great potentials for usage in medical area were principally synthesized as per two strategies. The first involved reaction of epichlorohydrin in alkaline medium containing silver nitrate to yield silver nano-particles (AgNPs)-loaded CMC hydrogel. While CMC acted as stabilizing for AgNPs, trisodium citrate was added to the reaction medium to assist CMC in establishing reduction of Ag^+ to AgNPs. The second strategy entailed preparation of CMC hydrogel which assists the *in situ* preparation of AgNPs under the same conditions. In both strategies, factors affecting the characterization of AgNPs-loaded CMC hydrogels were studied. Analysis and characterization of the so obtained hydrogels were performed through monitoring swelling behavior, FTIR spectroscopy, SEM, EDX, UV–vis spectrophotometer and TEM. Antimicrobial activity of the hydrogels was examined and mechanisms involved in their synthesis were reported.

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1. Introduction

Superabsorbent hydrogels are three-dimensional crosslinked hydrophilic, linear or branched polymers. They have the ability to absorb large quantities of water, saline or physiological solutions compared with general absorbing materials (Pourjavadi, Ayyari, & Amini-Fazl, 2008; Pourjavadi, Harzandi, & Hosseinzadeh, 2004). Hydrogel networks can be formed by conventional crosslinking methods or free-radical polymerization processes. The latter are initiated by thermal and redox systems or by the use of free-radical initiators activated by irradiation in the form of E-beams, microwaves, X-rays, or light (including UV, visible, or near infrared light) (Abdel-Aal, Gad, & Dessouki, 2006). The excellent hydrophilic properties of hydrogels along with their high swelling ratio, and biocompatibility, promote their usage widely in agriculture (Ibrahim, El Salmawi, & Zahran, 2007), biomedical area as antibacterial materials (Murthy, Mohan, Varaprasad, Sreedhar, & Raju, 2008), tissue engineering (Kim et al., 2008), biosensors (Adhikari & Majumdar, 2004; Pourjavadi, Ghasemzadeh, & Soleyman, 2007), sorbents for the removal of heavy metals (Guilherme et al., 2007) and drug delivery (Rodriguez, Alvarez, & Concheiro, 2003; Zhang, Yang, & Chung, 2002).

Sodium carboxymethyl cellulose (CMC) is biocompatible and biodegradable polymer. It is, therefore, often used in the biomedical field (Chang, Duan, Cai, & Zhang, 2010). Recently, much research

and development efforts have been devoted to the production of hydrogels containing metal nano-particles which are highly suitable for biomedical applications (Thomas, Namdeo, Mohan, Bajpai, & Bajpai, 2008). Particularly, nanosilver based wound dressings have received approval for clinical applications but dermal toxicity is reported (AshaRani, KahMun, Hande, & Valiyaveetil, 2009). That is why combination of a gel system with silver nano-particles will be a better choice for the treatment of wounds. A gel system in a form such as three-dimensional gel (nano, micro, and hydrogel) networks are quite appropriate for the *in situ* production of silver nano-particles than most of the conventional non-aqueous or polymers based synthetic approaches (Mohan et al., 2010).

Silver-based nanostructure materials have gained much attention to control infections (Rai, Yadav, & Gade, 2009). The use of silver nano-particles (Ag-NPs) have exhibited improved antibacterial properties than bulk silver due to high surface area and high fraction of surface atoms, leading to incorporating more NPs inside the bacteria and promoting its efficacy in a sustained manner (Bajpai, Mohan, Bajpai, Tankhiwale, & Thomas, 2007). The main advantage of Ag-NPs is that even nanomolar concentrations are effective than micro molar concentration of silver ions (Kong & Jang, 2008). In addition, Ag-NPs have proven relatively nontoxic to human cells (Vimalaa, Mohana, Sivudua, Varaprasad, & Raju, 2010). Nano-particles can be incorporated into the hydrogel matrix by simply mixing the NPs with the preformed hydrogel, by adding the NPs during the gelation process or the NPs can be entrapped during the swelling of the material (Hamming, Qiao, Messersmith, & Brinson, 2009; Haraguchi, Farnsworth, Ohbayshi, & Takehisa, 2003; Liu, Hu, Liu, Liu, & Chen, 2006; Zhang, Lee, Jang, & Nah, 2004).

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The aim of the present work is to develop CMC hydrogel containing silver nano-particles inside the interconnecting polymer, i.e. networks of CMC hydrogel matrix. Cross linking of CMC is affected by epichlorohydrin in alkaline medium. Formation of silver nano-particles inside the hydrogel matrix is investigated.

2. Materials and methods

2.1. Materials

Carboxymethyl cellulose (CMC) having high molecular weight ($M_w = 10,000$ Da), epichlorohydrin (ECH) (98%), PS Panreac Quimica SA, Barcelona, sodium hydroxide, trisodium citrate and silver nitrate were of laboratory grade chemicals.

2.2. Methods

2.2.1. Preparation of CMC hydrogels

Definite amount of CMC was dissolved in 1% NaOH solution with continuous mechanical stirring until a homogeneous viscous mixture was obtained then different concentrations of epichlorohydrin (1–10% based on weight of bath) was added drop wise with continuous stirring. The formed paste, was transferred to Petri dish, dried in an oven at 80 °C for 5 min then cured for 3–7 min at different temperature (120–140 °C).

2.2.2. Synthesis of CMC hydrogel post loaded Ag nano-particle

Optimum conditions for preparation of CMC hydrogel (obtained from Section 2.2.1) were utilized to prepare hydrogel paste in form of thick disk. The disk was steeped in distilled water for 24 h, then transferred to silver nitrate solution (10 mg AgNO_3 in 30 ml distilled water) for another 24 h. The disk was taken out and put in trisodium citrate solution (20 mg dissolved in 30 ml distilled water) for another 24 h to reduce Ag^+ ions into silver nano-particles within the swollen gel. The dark brown color of the disk indicated formation of silver nano-particles. The disk was dried in an oven, grinded, and finally sieved with mesh size No. 350 to yield fine hydrogel containing silver nano-particles (Thomas, Mohan, Sreedhar, & Bajpai, 2007).

2.2.3. One step process for preparation of CMC hydrogels containing silver nano-particles (in situ process)

Definite amount of CMC was dissolved in 1% NaOH solution with continuous mechanical stirring until a homogeneous viscous mixture was obtained then epichlorohydrin was added drop wise. Silver nitrate solution was then added in different concentration (0.5–3%) till pale brown color is observed. The paste was dried in an oven at 80 °C for 15 min, and then cured at 130 °C for 3 min.

2.3. Characterization and analysis

2.3.1. Swelling behavior

The swelling behavior of the prepared hydrogel with or without silver nano-particles was determined through calculating the ratio (Q) of the gels from the equation (Xuejun, Netti, Ambrosio, Nicolais, & Sannino, 2004):

$$Q = \frac{W_e}{W_d}$$

where W_e is the weight of the swollen hydrogel and W_d is the dry weight of the pure hydrogel.

2.3.2. FTIR spectroscopy

FTIR analysis was recorded on a Perkin Elmer Bx 11-FTIR Spectrophotometer, using the potassium bromide disk technique, in the

range of 4000–400 cm^{-1} . The disk was prepared from grinded samples (2 mg) and KBr (45 mg) using 400 kg/cm pressure for 10 min.

2.3.3. Scanning electronic microscopy

Surface morphology of prepared hydrogel was examined on a JEAOL JXA-840 scanning electron microscope (SEM). The prepared hydrogel samples were coated with a thin layer of palladium gold alloy after mounting on a double sided carbon tape.

2.3.4. Energy dispersive X-ray spectrum (EDX)

An elemental analysis of the particles was implemented by a SEM equipped with an energy dispersive X-ray spectrum (EDX), which can provide a rapid qualitative and quantitative analysis of the elemental composition.

2.3.5. UV–vis spectrophotometer

Preliminary characterization of the hydrogels containing silver nano-particles was carried out using UV–vis spectrophotometer. Usually, silver (Ag) nano-particles exhibit unique and tunable optical properties due to their surface plasmon resonance (SPR) that are dependent on shape, size and size distribution of the nano-particles (Hebeish, El-Rafie, Abdel-Mohdy, Abdel-Halim, & Emam, 2010). UV–vis absorption spectra of the hydrogels containing silver nano-particles were recorded on a Shimadzu 160A Model UV–vis spectrophotometer with a scan range of 200–600 nm. For this study, silver nano-particles were extracted from hydrogel–silver nanocomposites (10 mg/ml) over a period of a week, centrifuged at 1000 rpm for 30 min, and the supernatant was used to measure the absorption spectra. The distilled water was used as a blank solution.

2.3.6. Transmission electron microscopy (TEM)

Transmission electron microscopy (TEM) was used to determine the size of silver nano-particles inside the hydrogel. The swollen hydrogels were grounded with the help of a soft ball and the resulted hydrogel containing silver nano-particles was dispersed in 1 ml of distilled water for 3 day to extract the silver nano-particles from the hydrogel network into the aqueous phase. As per our observations, this grinding process was highly efficient to determine the size of silver nano-particles in the hydrogel, since there is no change in the size of nano-particles.

2.3.7. Antibacterial activity

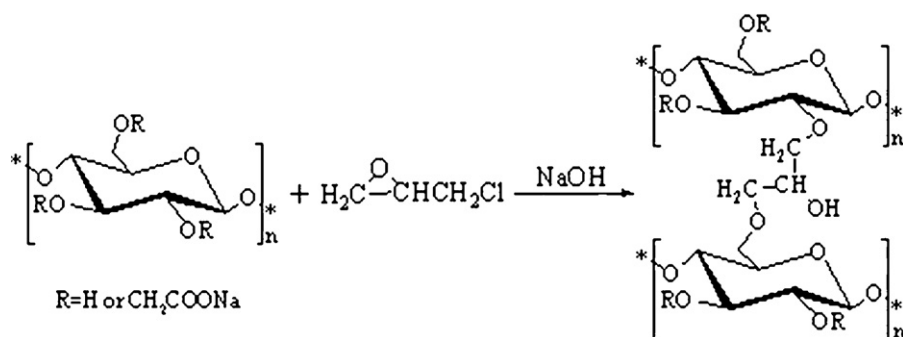
Antimicrobial activity of the prepared hydrogel was evaluated using agar diffusion test according to AATCC Standard Test Method 147-1988.

3. Results and discussion

3.1. Mechanism of CMC hydrogel post loaded with silver nano-particles

Carboxymethyl cellulose (CMC) was converted to hydrogel using epichlorohydrin (ECH) as a cross linking agent under aqueous alkaline conditions. The proposed reaction mechanism of cross linking of CMC with ECH is illustrated in Scheme 1 (Yang, Fu, Liu, Zhou, & Li, 2011). Under alkaline conditions, the hydroxyl groups of CMC become alcoholate anion. The alcoholate anion attacks the epoxy groups of ECH to form a monoether of chloropropanediol. A new epoxy group will yield by chloride displacement rearrangements of the chloropropanediol monoether. When the new epoxy groups react with the hydroxyl groups of another CMC, the crosslinking reaction occurs between ECH and CMC (Yang et al., 2011).

When a fully swollen hydrogel in the form of disk is put in the aqueous AgNO_3 solution, Ag^+ ions is replaced by H^+ or Na^+ ions in



Scheme 1. Reactions involved in synthesis of the CMC hydrogel using ECH as crosslinker.

the CMC hydrogel. Therefore, Ag^+ ions are still accessible for reduction into nano-silver by trisodium citrate solution forming silver nano-particles within the swollen network.

3.2. Reaction mechanism for formation of silver nano-particles (in situ)

Nano-particles NPs can be incorporated into the hydrogel matrix by simply mixing the NPs with the preformed hydrogel, by adding the NPs during the formation of the hydrogel or during the swelling of the hydrogel (Hamming et al., 2009; Haraguchi et al., 2003; Liu et al., 2006; Zhang et al., 2004).

In our study, the formation of silver nano-particles inside the network of CMC hydrogel was carried out during the formation of hydrogel matrix. Our approach depends on the dual function of CMC as reducing and stabilizing agent for silver nano-particles during the formation of CMC hydrogel containing silver nano-particles. The negatively charged carboxyl groups in CMC attract the positively charged silver cations. For the synthesis of silver nano-particles, the generally accepted mechanism suggests a two-step process, i.e. atom formation and then polymerization of the atoms. In the first step, a portion of metal ions in a solution is reduced by the available reducing groups of the CMC. The atoms thus produced act as nucleation centers and catalyze the reduction of the remaining metal ions present in the bulk solution. Subsequently, the atoms coalesce leading to the formation of metal clusters. The surface ions are again reduced and the process is stabilized by the interaction with the polymer so preventing further coalescence (Goia, 2004).

3.3. Swelling studies

Swelling capacity of a superabsorbent polymer can be changed by either change in concentration of cross linker, or reaction temperature or both (Zohuriaan & Kabiri, 2008).

3.4. Synthesis of CMC hydrogel: effect of the process parameters

3.4.1. Effect of concentration of epichlorohydrin

Fig. 1a shows the effect of ECH concentration on the swelling ratio of CMC/ECH hydrogel. It is seen that, increasing the concentration of ECH from 1 to 3% (based on weight of bath) is accompanied by an increase in swelling ratio; this could be attributed to the hydrophilic character of carboxyl group of CMC which absorb a lot of water to enhance the space in the hydrogel. Further increase in the concentration of ECH results in decrement in the swelling ratio of the prepared hydrogel. It is likely that the gel network exhibits higher density as the concentration of ECH increases, thereby restricting the penetration of the water molecules into the hydrogel networks.

3.4.2. Effect of curing temperature and curing time

Fig. 1b shows the effect of curing temperature on the swelling ratio of the hydrogel. It is seen that, raising the curing temperature from 120 to 130 °C enhance the swelling ratio of the prepared hydrogel. Further increase in curing temperature has no significant effect on the swelling ratio. Obviously, 130 °C represents optimum curing temperature for preparation of the CMC hydrogel particles with ECH as crosslinker.

Fig. 1c shows the effect of time on the swelling properties of CMC/ECH hydrogel. It is seen that the swelling attained its maximum values after 5 min. Prolonging the time has practically no effect on the swelling ratio.

From the above results, it can be concluded that, the proper conditions for synthesis of CMC/ECH hydrogel entails using 3% ECH (based on weight of bath) along with curing at 130 °C for 3 min.

3.4.3. Effect of silver nitrate concentration

Table 1 shows the effect of silver nitrate concentration on the swelling ratio of the hydrogel. It is evident that as the concentration of silver nitrate increases from 0.5 to 1.5%, the swelling ratio of the hydrogel increases from 11.5 to 13.86%. This could be attributed to the capability silver nano-particles embedded in the hydrogel to increase the pores and free spaces within the networks structure of the prepared hydrogel and; as a consequence adsorbs more water.

Reduction of silver ions to silver nano-particles within the prepared hydrogel, convert it to yellowish transparent matrix (Fig. 2).

3.5. FTIR spectroscopy

Fig. 3 represents FTIR spectra of the CMC and the CMC hydrogel. The bands at 1422, 1608, 2931, and 3420 cm^{-1} are assigned to the stretching vibration of COO^- (symmetric), COO^- (asymmetric), C–H (aliphatic), and O–H, respectively. The bands observed at 1608 and 1422 cm^{-1} in the spectrum of CMC/ECH hydrogel indicate that the carboxyl groups of CMC exist in the hydrogels after crosslinking. It can be seen also from the spectrum of CMC/ECH hydrogels that, some typical peaks appear at 1327, 1262, and 1064 cm^{-1} . The peaks at 1327 and 1262 cm^{-1} belong to stretching vibration of C–O–C and C–C stretching vibration respectively, of the reacted ECH with

Table 1
Effect of silver nitrate concentration on swelling ratio of the hydrogel.

Concentration of silver nitrate (%)	Swelling ratio
0.0	7.1
0.5	11.52
1.5	13.86
Silver nitrate loaded in prepared hydrogel	10.6

Conditions used: epichlorohydrin, 3%; curing temperature, 130 °C; curing time; 3 min.

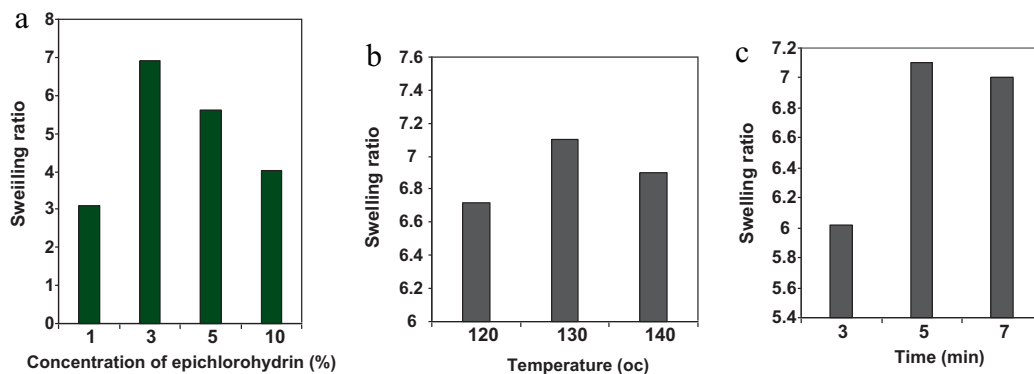


Fig. 1. (a) Effect of epichlorohydrin concentration on swelling ratio of CMC/ECH hydrogel. (b) Effect of curing temperature on swelling ratio of CMC/ECH hydrogel. (c) Effect of curing time on swelling ratio of CMC/ECH hydrogel.

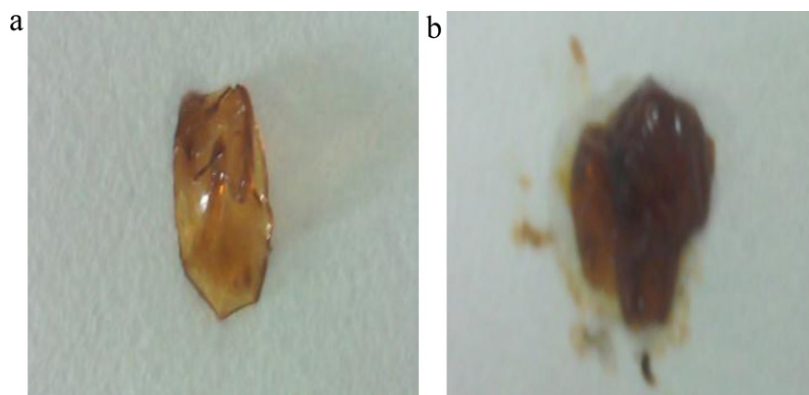


Fig. 2. Photographs of (a) hydrogel and (b) hydrogel containing silver nano-particles.

CMC. Whereas the band appeared at 1064 cm^{-1} is characteristic for bending vibration of $-\text{OH}$ group.

3.6. UV-vis spectrophotometer

A typical absorption spectrum of the silver colloidal solution is shown in Fig. 4. This band is assigned to the surface plasmon absorption (SPR) of the nanosilver particles. It peaks at 425 nm and has a band width at half maximum of 130 nm, which is an indication of the particle size distribution (Xiabin et al., 2007).

Fig. 4 also shows the UV-vis spectra of the Ag nano-particles in the hydrogel. The SPR bands of the Ag nano-particles in the hydrogel show different peak positions and peak widths with changing silver nitrate concentration.

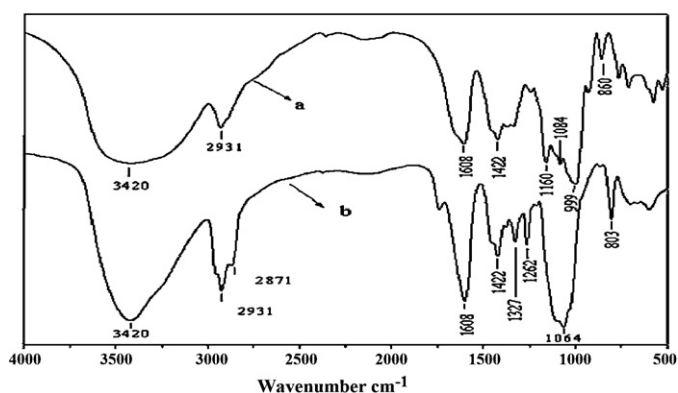


Fig. 3. IR spectra of (a) CMC and (b) CMC/ECH hydrogels.

Comparing with Fig. 4b and c for the Ag nano-particles in the hydrogel, a blue shift is seen as the concentration of Ag nano-particles increase in the hydrogel matrix. This result indicates that CMC are good stabilizing agents for silver nano-particles (Hebeish et al., 2010). In addition, the blue shifts and the narrower widths of the SPR bands confirm the smaller size and more uniform size distribution of the silver nano-particles by increasing concentration of it in the hydrogel matrix.

3.7. Scanning electron microscopy (SEM) and energy dispersive X-ray spectrum (EDX) analysis

Scanning electron microscopy images of CMC hydrogel and hydrogel containing silver nano-particles as well as EDX analysis

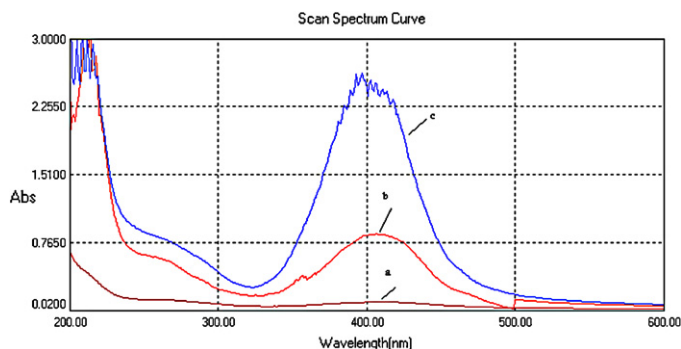


Fig. 4. UV-vis spectra of (a) silver nanoparticles post loaded in hydrogel, (b) hydrogel prepared in presence of 0.5% silver nitrate, (c) hydrogel prepared in presence of 1.5% silver nitrate.

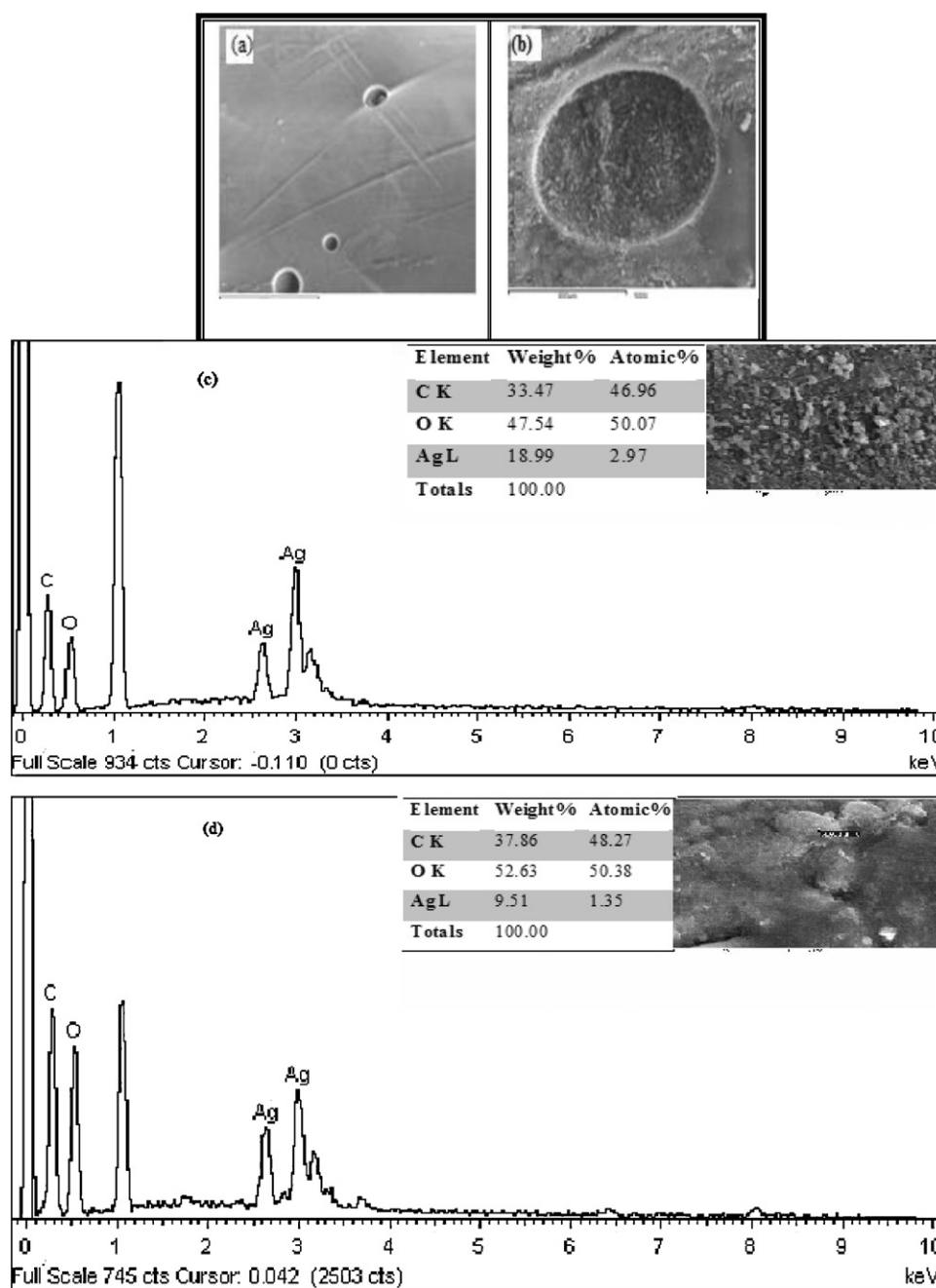


Fig. 5. SEM and EDS of CMC/Ag hydrogel–nanoparticle where (a) SEM image of CMC hydrogel, (b) SEM image of pore on CMC surface, and (c) SEM and EDS of silver nanoparticles in the CMC hydrogel surface *in situ* formation. (d) SEM and EDS of silver nanoparticle post loaded in hydrogel.

of hydrogel–silver nano-particles in case of loaded silver nano-particles (AgNPs) hydrogel and *in situ* prepared AgNPs one are shown in Fig. 5.

Fig. 5a depicts a clear and flat surface of the hydrogel with some macropores. These pores allow water molecules to diffuse into hydrogel to form the large pores cause swelling of CMC hydrogel. On the other hand, silver nano-particles are clearly visible as spherical particles shapes throughout the surface of the hydrogel–silver nano-particle prepared by *in situ* technique in Fig. 5c; the EDX analysis of hydrogel–silver nano-particles prepared by *in situ* process also appears in the same figure. The EDX quantitative analysis confirms the nanostructure which contains about 18.99 wt% Ag, 47.54 wt% oxygen, and about 33.47 wt% carbon, while Fig. 5d represents SEM image of Ag nano-particles on the surface of the hydrogel

in case of post loaded silver nano-particles technique as well as. EDX analysis shows the elemental content as follows: carbon, 37.86 wt%; oxygen, 52.63 wt%; Ag, 9.51 wt%.

Comparing the results of EDX obtained in Fig. 5c with that obtained in Fig. 5d would reveal that, higher content of Ag nano-particles is obtained when the hydrogel containing silver nano-particles are prepared using *in situ* technique.

3.8. Transmission electron microscopy (TEM)

To demonstrate the shape of silver nano-particles within the hydrogel network, TEM images shown in Fig. 6, were carried out for both type of hydrogels, namely, hydrogel–Ag nano-particles embedded in the hydrogel and hydrogel–Ag nano-particles

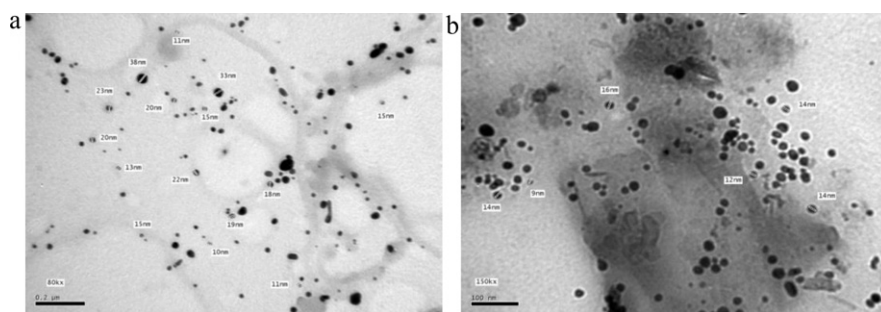


Fig. 6. TEM image of the silver nanoparticles (a) post loaded silver nanoparticles in the hydrogel; (b) nanoparticles formed by *in situ* technique.

Table 2

The antibacterial activity of hydrogel nanocomposites.

Inhibition zone (mm)			
G –ve		G +ve	
<i>E. Coli</i>	<i>P. aeruginosa</i>	<i>S. aureus</i>	<i>B. subtilis</i>
13	15	14	13

prepared by *in situ* technique. To carry out this analysis, CMC hydrogel containing nano-particles were put in distilled water for 3 days, and then their suspension was sonicated for 3 h. This allows the nano-particles to come out of the swollen hydrogel network as a result of the relaxation of polymeric chain entanglements around the nano-particles.

Fig. 6a and b reveals the presence of released silver nano-particles in both cases and in uniform distribution. The nano-particles size ranging from 10 to 38 nm in case of Ag nano-particles embedded in the hydrogel while the particles size range from 9 to 16 nm in case of *in situ* preparation technique. It is also obvious that, the nano-particles do not form aggregates. This may be due to excellent stabilization of silver nano-particles by carboxylate anions present in the gel macromolecular chain.

3.9. Antibacterial activity

The antibacterial activity of hydrogel nanocomposites was carried out against two Gram –ve bacteria (*E. coli* and *P. aeruginosa*) and against two Gram +ve bacteria (*S. aureus* and *B. subtilis*) using disc plate technique. The results obtained are set out in Table 2. It is seen that, the prepared hydrogel containing silver nano-particles has high antibacterial properties as evidenced by higher inhibition zone. This is true regardless of the kind of bacterial used. This could be attributed to the fact that silver nano-particles can interact with sulfur-containing proteins from cell membrane and phosphorus containing compounds in cells, attacking the respiratory chain, with cell division leading to cell death (Rai et al., 2009).

4. Conclusion

CMC based hydrogel was successfully prepared using epichlorohydrin in alkaline medium. Also, silver nano-particles were prepared successfully using two different process: the first included synthesis of silver nano-particles inside the preformed hydrogel polymeric matrix while the *in situ* technique includes synthesis of silver nano-particles inside the interconnecting polymer networks of CMC hydrogel during its formation. The prepared hydrogels are characterized using swelling behavior, UV spectrophotometer, FTIR, TEM, SEM and EDX. *In situ* silver nano-particles hydrogels exhibited high antibacterial activity against Gram positive and Gram negative bacteria. Therefore, it should be considered as potential candidates for medical field.

References

- Abdel-Aal, S. E., Gad, Y. H., & Dessouki, A. M. (2006). Use of rice straw and radiation-modified maize starch/acrylonitrile in the treatment of wastewater. *The Journal of Hazardous Materials*, B129, 204–215.
- Adhikari, B., & Majumdar, S. (2004). Polymers in sensor applications. *Progress in Polymer Science*, 29, 699–766.
- AshaRani, P. V., KahMun, G. L., Hande, M. P., & Valiyaveetil, S. (2009). Cytotoxicity and genotoxicity of silver nanoparticles in human cells. *The American Chemical Society (ACS) Nano Journal*, 3, 279–290.
- Bajpai, S. K., Mohan, Y. M., Bajpai, M., Tankhiwale, R., & Thomas, V. (2007). Synthesis of polymer stabilized silver and gold nanostructures. *Journal of Nanoscience and Nanotechnology*, 7, 2994–3010.
- Chang, C., Duan, B., Cai, J., & Zhang, L. (2010). Superabsorbent hydrogels based on cellulose for smart swelling and controllable delivery. *European Polymer Journal*, 46, 92–100.
- Goia, D. V. (2004). Preparation and formation mechanisms of uniform metallic particles in homogeneous solutions. *Journal of Material Chemistry*, 14, 451–458.
- Guilherme, M. R., Reis, A. V., Paulino, A. T., Fajardo, A. R., Muniz, E. C., & Tambourgi, E. B. (2007). Superabsorbent hydrogel based on modified polysaccharide for removal of Pb²⁺ and Cu²⁺ from water with excellent performance. *Journal of Applied Polymer Science*, 105, 2903–2909.
- Hamming, L. M., Qiao, R., Messersmith, P. B., & Brinson, L. C. (2009). Effects of dispersion and interfacial modification on the macroscale properties of TiO₂ polymer–matrix nanocomposites. *Composites Science and Technology*, 69, 1880.
- Haraguchi, K., Farnsworth, R., Ohbayashi, A., & Takehisa, T. (2003). Compositional effects on mechanical properties of nanocomposite hydrogels based on poly(*N,N*-dimethylacrylamide) and clay. *Macromolecules*, 36, 5732–5741.
- Hebeish, A. A., El-Rafie, M. H., Abdel-Mohdy, F. A., Abdel-Halim, E. S., & Emam, H. E. (2010). Carboxymethyl cellulose for green synthesis and stabilization nanoparticles. *Carbohydrate Polymers*, 82, 933–941.
- Ibrahim, S. M., El Salmawi, K. M., & Zahran, A. H. (2007). Synthesis of crosslinked superabsorbent carboxymethylcellulose/acrylamide hydrogels through electron-beam irradiation. *Journal of Applied Polymer Science*, 104, 2003–2008.
- Kim, J., Lee, K., Hefferan, T., Currier, B., Yaszemski, M., & Lu, L. (2008). Synthesis and evaluation of novel biodegradable hydrogels based on poly(ethylene glycol) and sebacic acid as tissue engineering scaffolds. *Biomacromolecules*, 9, 149–157.
- Kong, H., & Jang, J. (2008). Antibacterial properties of novel poly(methyl methacrylate) nanofiber containing silver nanoparticles. *Langmuir*, 24(17), 2051–2056.
- Liu, T. Y., Hu, S. H., Liu, T. Y., Liu, D. M., & Chen, S. Y. (2006). Magnetic-sensitive behavior of intelligent ferrogels for controlled release of drug. *Langmuir*, 22, 5974–5978.
- Mohan, Y. M., Vimala, K., Thomas, V., Varaprasad, K., Sreedhar, B., Bajpai, S. K., et al. (2010). Controlling of silver nanoparticles structure by hydrogel networks. *Journal of Colloid and Interface Science*, 342, 73–82.
- Murthy, P. K., Mohan, Y. M., Varaprasad, K., Sreedhar, B., & Raju, K. M. (2008). First successful design of semi-IPN hydrogel–silver nanocomposites: A facile approach for antibacterial application. *Journal of Colloid and Interface Science*, 318, 217–224.
- Pourjavadi, A., Ayyari, M., & Amini-Fazl, M. S. (2008). Taguchi optimized synthesis of collagen-g-poly(acrylic acid)/kaolin composite superabsorbent hydrogel. *European Polymer Journal*, 44, 1209–1216.
- Pourjavadi, A., Ghasemzadeh, H., & Soleyman, R. (2007). Synthesis, characterization, and swelling behavior of alginate-g-poly(sodium acrylate)/kaolin superabsorbent hydrogel composites. *Journal of Applied Polymer Science*, 105, 2631–2639.
- Pourjavadi, A., Harzandi, A. M., & Hosseinzadeh, H. (2004). Modified carrageenan synthesis of a novel polysaccharide-based superabsorbent hydrogel via graft copolymerization of acrylic acid onto kappa-carrageenan in air. *European Polymer Journal*, 40, 1363–1370.
- Rai, M., Yadav, A., & Gade, A. (2009). Silver nanoparticles as a new generation of antimicrobials. *Biotechnology Advances*, 27, 76–83.
- Rodriguez, R., Alvarez, C., & Concheiro, A. (2003). Cationic cellulose hydrogels: Kinetics of the cross-linking process and characterization as pH-/ion-sensitive drug delivery systems. *Journal of Controlled Release*, 86, 253–265.

- Thomas, V., Mohan, M., Sreedhar, B., & Bajpai, K. (2007). A versatile strategy to fabricate hydrogel–silver nanocomposites and investigation of their antimicrobial activity. *Journal of Colloid and Interface Science*, 315, 389–395.
- Thomas, V., Namdeo, M., Mohan, Y., Bajpai, S. K., & Bajpai, M. (2008). Review on polymer, hydrogel and microgel metal nanocomposites: A facile nanotechnological approach. *Journal of Macromolecular Science Part A: Pure and Applied Chemistry*, 45(1), 107–119.
- Vimalaa, K., Mohana, K. M., Sivudua, K. S., Varaprasad, K., & Raju, K. M. (2010). Fabrication of porous chitosan films impregnated with silver nanoparticles: A facile approach for superior antibacterial application. *Colloids and Surfaces B: Biointerfaces*, 76, 248–258.
- Xiabin, J., Yu, H., Xu, X., Chen, X., Lu, T., & Zhang, P. (2007). Preparation and antibacterial effects of PVA–PVP hydrogels containing silver nanoparticles. *Journal of Applied Polymer Science*, 103(1), 125–133.
- Xuejun, X., Netti, A., Ambrosio, L., Nicolais, L., & Sannino, A. (2004). Preparation and characterization of a hydrogel from low-molecular weight hyaluronic acid. *Journal of Bioactive and Compatible Polymers*, 19, 5.
- Yang, S., Fu, S., Liu, H., Zhou, Y., & Li, X. (2011). Hydrogel beads, based on carboxymethyl cellulose for removal heavy metal ions. *Journal of Applied Polymer Science*, 119, 1204–1210.
- Zhang, Y.-Q., Lee, J. H., Jang, H.-J., & Nah, C.-W. (2004). Preparing PP/clay nanocomposites using a swelling agent. *Composites Part B: Engineering*, 35, 133–138.
- Zhang, X., Yang, Y., & Chung, T. (2002). The influence of cold treatment on properties of temperature-sensitive poly(*N*-isopropylacrylamide) hydrogels. *Journal of Colloid and Interface Science*, 246, 105–111.
- Zohuriaan, M. J., & Kabiri, K. (2008). Superabsorbent polymer materials: A review. *Iranian Polymer Journal*, 17, 451–477.