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Synthesis and Characterization of Cellulose Acetate-Hydroxyapatite Micro and Nano Composites Membranes for Water Purification and Biomedical Applications

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Abstract

In this work, we report facile synthesis and characterization of new cellulose acetate-hydroxyapatite membranes for water purification and biomedical applications. The membranes were synthesized from a polymer solution in N, N'-dimethylformamide (12% wt.) where different concentrations of hydroxyapatite (1, 2, 4% wt. based on the amount of polymer) were dispersed using sonication. The synthesis of membranes was carried out by precipitation employing phase inversion using deionized water. The morphological and structural characterization of the synthesized membranes was carried out using SEM, EDS and FT-IR. Thermal characterization (TGA & DTG) and water flows analysis of the synthesized membranes was also carried out. The SEM analysis confirmed the presence of hydroxyapatite micro/nanostructured particles in the membrane as well as significant changes in the morphology of the membranes surface. The presence of inorganic compounds was also found to influence the thermal or hydrodynamic properties of the composite membranes,

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leading to a more stable hydrodynamic behavior, flow variation in time being much lower compared to the control membrane of cellulose acetate.

Keywords: Micro and Nano Composite Membranes; Cellulose Acetate; Hydroxyapatite; Water Purification and Biomedical Applications

Introduction

Among the portfolio of currently used functional materials, polymeric membranes have a special place because of their main property selectivity [1]. One of the most studied areas for polymeric membranes is the area of biomedical applications, especially hemodialysis and controlled drug release [2]. A relatively new and little studied field is that of membranes for osseointegration - polymeric membranes which favor welding metal implants, or grafts to bones, especially membranes used for dentistry [3]. Any polymer, which has the ability to form a solution, can be used in the preparation of membranes, either by solvent evaporation [4], or by precipitation with a suitable nonsolvent [5].

Cellulose derivatives are among the most widely used polymers in the preparation of membranes for water purification and biomedical applications [6, 7]. The prime reason for this is the widespread nature of cellulose (the material with the highest abundance - $5x10^{11}$ tons generated annually in the biosphere [8]), good mechanical strength [9, 10], thermal stability [11, 12] and easy availability [13, 14]. Lately, an increasing interest about the synthesis of polymeric composites based on cellulose derivatives and micro or nano-hydroxyapatite particles, especially for applications in osteointegration has been established. This is mainly because, through hydrolysis in the body, cellulose breaks down, releasing glucose, with no adverse effect on the organism [15, 16]. These investigations were based on the compatibility between derivatives of cellulose and hydroxyapatite [17], the influence on the properties of the polymers [18] and improvement in the capacity to remove pollutants using cellulose derivatives. Various types of composites with hydroxyapatite were prepared to remove harmful substances [19], Cr (VI) from aqueous solutions [20], or Ni^{2+} and Cd^{2+} [21]. Other studies aimed the synthesis of cellulose-polymer-hydroxyapatite composites, the two polymers having synergistically biological activity in the integration of bone implants, as well as chitosan [22], poly-L-lactic acid [23, 24] or gelatin [25].

The main applications of the micro/nano composites based on cellulose and hydroxyapatite has been focused on the synthesis of materials for osseointegration [26]. These composite

materials were obtained either by entrapping hydroxyapatite nanoparticles in cellulose fibers networks [27-29], or by electrochemical techniques [30, 31] or dispersing the inorganic particles within the polymer solution, followed by the polymer precipitation [32, 33]. The most used cellulose derivatives are cellulose acetate [34] and carboxymethyl cellulose [35] due to their solubility in a wide range of polar aprotic organic solvents (in contrast to cellulose, which usually dissolves in highly toxic mixtures).

So, in the paper we present the facile synthesis and characterization of new composite membranes based on cellulose acetate (CA) and hydroxyapatite (HA). The membranes were synthesized by dispersing hydroxyapatite particles in the polymer solution, followed by the membranes precipitation by phase inversion method.

Materials and methods

The synthesis of the Hydroxyapatite particles as well as the composites was carried out using the following protocol:

Hydroxyapatite particles synthesis: Hydroxyapatite particles were synthesized from samples of cancellous bone, obtained after removal of cortical components, in accordance with the procedure reported in literature [36, 37]. Bovine bone samples were mechanically cleaned, followed by heat treatment at 500 °C for one hour to remove organic components. The main heat treatment was performed at 1200 °C for six hours with a heating rate of 10 °C / min. After cooling in air, the samples were grounded in an agate ball mill and sieved. For this study, hydroxyapatite particles with dimensions less than 40 μm were used.

Composite membranes preparation: In order to obtain membranes, first of all cellulose acetate (Sigma Aldrich), was dissolved in N, N'-dimethylformamide (DMF) (Riedel de Haen) by mechanical stirring for 24 hours. Subsequently, the hydroxyapatite particles were dispersed in the polymer solution at concentrations of 1, 2, and 4% by sonication for 30 minutes. A film of polymer solution was deposited on a glass support at 200 μm thick and immersed into the coagulation bath containing deionized water. The membrane synthesis is considered definitive when the polymeric film gets detached from the support. After synthesis, the membranes are washed and stored in deionized water until further use.

Characterization of the synthesized materials. The scanning electron microscopy was performed on a FEI XL 30 ESEM TMP microscope equipped with an EDAX Sapphire device. Infrared spectroscopy was performed on a Bruker Vertex 70 instrument, on ATR germanium crystal, measurements being performed in the range of 550-4000 cm^{-1} with a

resolution of 1 nm. For each spectrum 32 successive measurements were performed, the final spectrum being their average. The TGA study was carried out on a Q500 TA Instrument in nitrogen atmosphere from room temperature (RT) to 800 ºC at a heating rate of 10 ºC/min. Differential Scanning Calorimetry (DSC) study was carried out on a Netzsch DSC 204 F1 Phoenix equipment. The sample was heated from RT to 300 ºC at a heating rate of 5 °C/min in nitrogen atmosphere (20 mL/min flow rate).

Water flows were measured on membrane disks with a diameter of 45 mm, with vacuum, under membranes of 0.01 bar. Each flux was determined by measuring the flow time of 20 ml of deionized water, 5 successive measurements being performed to determine the membranes stability and the error bars.

Results and discussions

The phase inversion method was chosen for the synthesis of the composite membranes based on CA and HA because phase inversion is one of the most versatile method for obtaining porous polymeric films. Eventually, any polymer whose behavior in a suitable solvent is well known, can be used to prepare polymeric membranes by phase inversion. By immersion of the cellulose acetate solution film in DMF deposited onto the glass support in water, the nonsolvent (water) begins to extract the solvent from the polymer solution, first from the interface, and then from the structure of the film, causing the precipitation of the membrane. Polymer chains eluted at the lower part of the film, go up to the film surface during the precipitation process, jamming to the surface and generating the active layer of the membrane. At the same time, vacant gaps (pores generation), have a conical shape due to large quantities of polymer which are activated at the lower part of the polymer solution film. This leads to asymmetry of the membranes obtained (conical shape of pores in the membrane structure, with different diameters on one side and the other of the precipitated polymer film - shorter diameter on the active surface, longer on the porous surface).

SEM microscopy highlights both the surface morphological changes and the emergence of hydroxyapatite crystals in the composite membranes (**Fig. 1**). For an eloquent analysis, the microscopy was performed both on the active and on the porous surface of the membrane. On the active surface, a slight decrease of the average diameter of the pores and shape in the case of composite membranes compared to membranes made of pure CA was noticed. This can be explained by weak chemical interaction between the acetate groups of the polymer and the

phosphate groups of HA. These interactions actually generate internal defects in the membrane structure, defects, which were also observed in the study of the water flow. Also, in the case of the composites, we can notice on the surface, the emergence of HA crystals with average dimension of the crystallites around 20 to 30 μm. The change effects in the diameter and shape of the pores can be noticed on the porous surface of the membranes with noticeable differences between the membranes considered.

The presence of hydroxyapatite in the structure of composite membranes has also been highlighted by the use of EDS qualitative analysis (**Fig. 2**). Unlike the pure CA membranes, where we identified only C and O in the polymer structure, in the case of composite membranes, we noticed the emergence of Na, P and Ca from the HA. The presence of the Cl identified in spectra was attributed to the water where the membranes were stored prior to analyses.

The FT-IR analysis exhibits slight differences between the control membrane spectrum and the spectra of the composite membranes (**Fig. 3**). In the hydroxyapatite spectrum, the peak at 1027 cm^{-1} is assigned to the vibrational rotation of the bonds in the phosphate group. In the spectrum of CA, the peaks association is as follows: at 1748 cm^{-1} for -COO- groups, 1230 cm^{-1} for CO groups, 1400 cm^{-1} for CH bonds, 1044 cm^{-1} for the deformation vibrations of bonds in CH and OH groups, 903 cm^{-1} for the deformation vibrations of bonds in COC, CCO and CCH groups [20]. We can see that in the case of -C-H bonds, by increasing the HA concentration within the composite membranes, the peaks shift to the right due to the influence of PO_4^{3-} groups from the HA, occurring in the same region of the spectrum. Although the intensity of the peaks specific to phosphate groups in infrared is large, there are not two distinct peaks for the vibrations of the C-H and P-O bonds because of the very close value in the spectrum and also due to the low percentage of phosphate groups in composite membranes compared to C-H bonds in the polymer structure.

Figure 3 also shows the thermal stability curves and the thermal degradation profile for pure CA, and composite membranes with various concentrations of HA. The thermal stability and the degradation of the materials was studied using thermogravimetric analysis (TGA). As shown in **Fig. 3**, all the membranes were found to have similar behavior, with two degradation steps. The first step of degradation occurs between 25 °C and 300 °C and can be attributed to the evaporation of the solvent, and the second step, above 300 °C is due to the degradation of the CA chain because of dehydration, depolymerization and decomposition of

glucose units in the polymer structure. [38]. The lack of an additional degradation step in the case of composite membranes corresponding to the inorganic compound (HA) degradation, proves that synthesized materials are thermally stable. [39].

The thermal stability of the materials is shown in the thermal analysis curves by measuring the decomposition temperature at maximum loss of 5% ($Td_{5\%}$). According to **Fig. 3** and the Table inserted in the **Fig. 3** we can see a linear reduction of CA thermal stability after incorporation of HA in the polymer matrix. Similar behavior was noticed by S. Saska and collaborators, by incorporation of HA into the bacterial cellulose matrix, [38] and that could be explained by the fact that the presence of the inorganic compound may induce some changes in the structure of the polymer, due to breaking hydrogen bonds and decrease of CA crystallinity.

Thermal properties of the synthesized composite membranes were also studied by DSC. **Fig. 4** displays the DSC curves of the CA and CA-HA composite membranes showing an endothermic peak around 251 °C for all the analysed samples, which is attributed to cellulose acetate melting. Crystallinity percent was calculated as the ratio of the melting enthalpy of the studied material (ΔH_m) and the melting enthalpy of completely crystalline material (ΔH^o_m =58.8 J/g value proposed by Cerqueira et. al [40]) according to formula (1) [41]

$$\chi_c = \frac{\Delta H_m}{\Delta H^o_m} \times 100 \qquad (1)$$

Calculated values of the melting enthalpy are summarized in the Table inserted in **Fig. 4** and a reduction in the crystallinity degree in the case of composite membranes compared to pure CA was observed. These data are in accordance with the values reported on the TGA. Due to the strong overlap between Tg and the melting temperature (Tm), the T_g values were identified on the cooling curves and an increase of Tg with the increase of HA percent in the polymer matrix was observed. This could lead to a wide range of application for the composite membranes.

Water flows studies in **Fig. 5** shows both the hydrodynamic stability of the membranes, and the uniform degree of hydroxyapatite particles dispersion in the structure of the synthesized composite materials. The greatest variation of the water flow was measured for the membranes of CA. This is because the component layers of the polymer get compact, and

the structure becomes increasingly stable, as water goes through the membrane pores. The next membrane in terms of stability to flow measurement had 4% HA. Even if composite membranes are generally more stable, a high percentage of filler cannot be dispersed uniformly throughout, consequently forming islands of filler with high concentration and high volume in the membrane structure where there is no filler. The most hydro dynamically stable membranes had 1, or 2% hydroxyapatite, both due to the presence of the filler, and to the more homogeneous dispersion degree. Also, we can notice that by increasing the HA concentration within the composite membranes, the water flow increases from 8.29 L/m^{2}h in the case of CA to 20.96, 23.25, or 26.73 L/m^{2}h for composite membranes with 1, 2, and 4 wt.% HA added.

Future research will target the study of the influence of hydroxyapatite particles size, as well as their source and the membranes synthesis method - through phase inversion and solvent evaporation on the properties of composite membranes. Also, we will conduct biocompatibility and cell proliferation studies in order to open new research directions for membranes used in osteointegration - composite membrane with hydroxyapatite, of biocompatible and bio absorbable polymers. In addition these membranes will also be subjected for their evaluation in water purification applications.

Conclusions

In this article, we have reported some of our preliminary studies on the facile synthesis and characterization of new CA-HA structured composite membranes. Cellulose based membranes offers a number of advantages in terms of low cost , environmental friendliness, biodegradability, easy availability, adsorption, distillation and extraction to name a few as opposed to their synthetic counterparts. The membranes were obtained by phase inversion from a polymer solution (12% cellulose acetate in DMF hydroxyapatite micro particles) dispersed by ultrasounds at various concentrations compared to the polymer (1, 2, 4% wt.). The synthesized membranes were described morphologically (through SEM) and structurally (by FT-IR, TGA, DTG), and the study of the water flows was also conducted. The SEM analysis highlighted the presence of micro-structured hydroxyapatite particles in the membrane structure, the particles generating as well changing the surface morphology. On the active area, we noticed a slight decrease in the average diameter of the pores, and their shape changing in the case of composite membranes, compared to pure CA membranes. The

interactions between the hydroxyapatite and the polymer particles actually generate as well defects in the internal structure of the membrane. They cause morphology changes, and were spotted in the study of the water flows. Indeed the water flow has been found to generally depend on the average pore diameter of the membrane and membranes active layer morphology. Water flows increased by increasing the concentration of hydroxyapatite, ranging from 8.29 L/m^2h for the CA membrane to 20.96, 23.25 or 26.73 L/m^2h for the composite membranes with 1, 2, and 4 wt. % HA. This behavior can be attributed to the uniform addition of hydroxyapatite particles within the membrane structure coupled with controlled porosity that results in a much easier flow in the membrane. The hydroxyapatite presence was highlighted by EDS spectra (in the case of composite membranes P and Ca elements can be found) and through FT-IR spectroscopy and thermal analysis. The TGA curves exhibited a similar behavior between membranes, with two stages of degradation - one for the solvent, and the second for the polymer chain degradation. Besides, we also noticed that the presence of the inorganic compound might induce some changes in the structure of the polymer, due to breaking hydrogen bonds and decrease of CA crystallinity. Furthermore, a decrease of the crystallinity degree was also noticed in the DSC curves for CA-HA composites membranes compared to pure CA.

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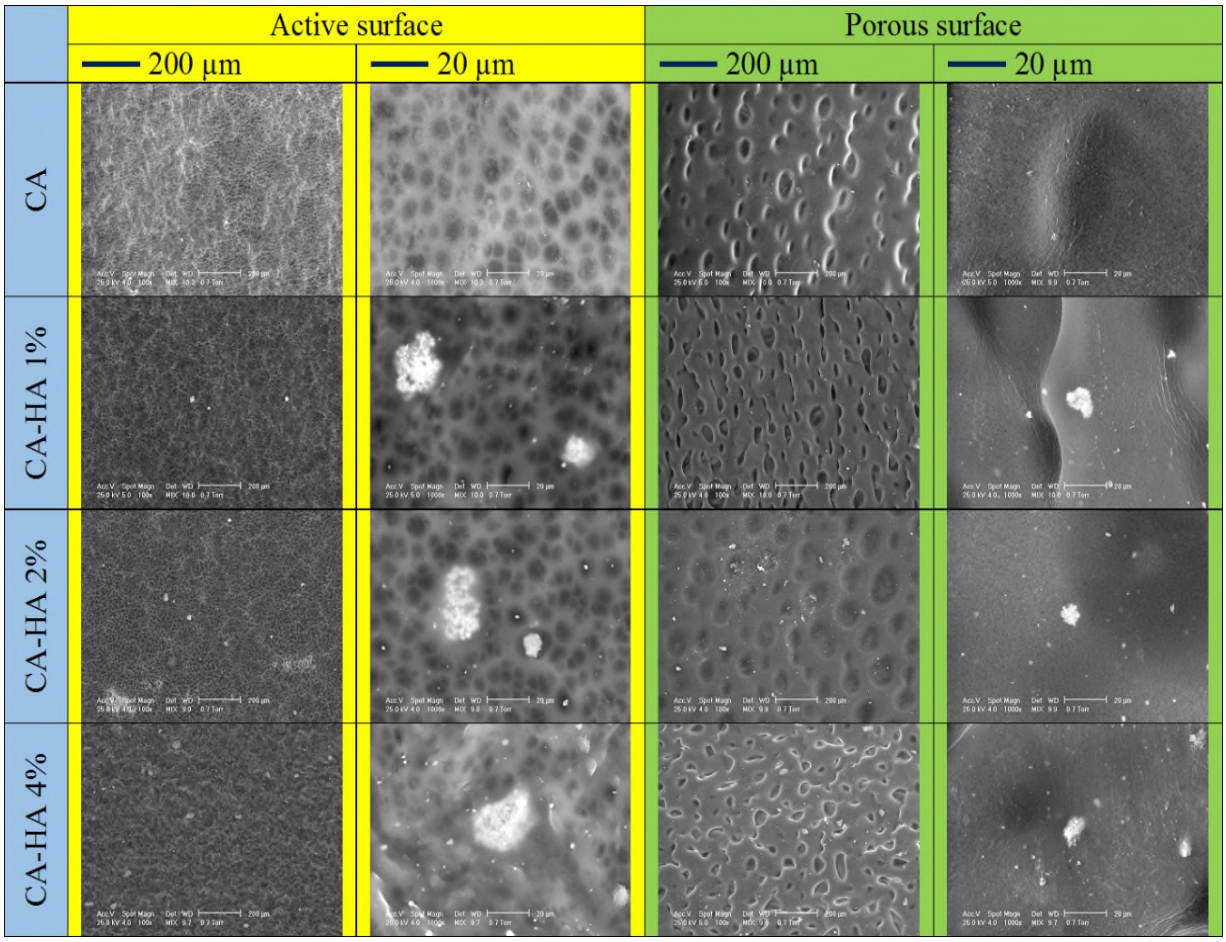


Fig. 1 SEM micrographs of synthesized membranes

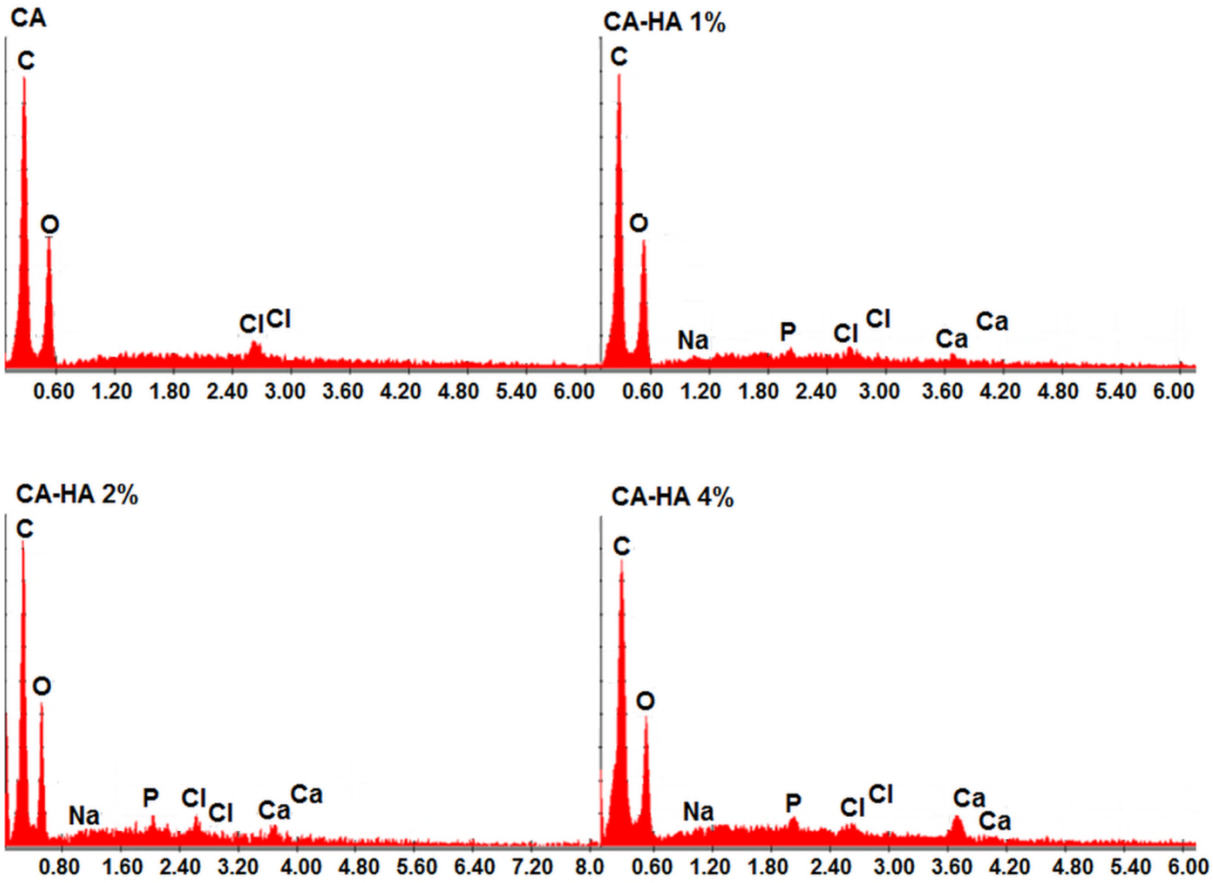


Fig. 2 Qualitative EDS spectra of synthesized membranes

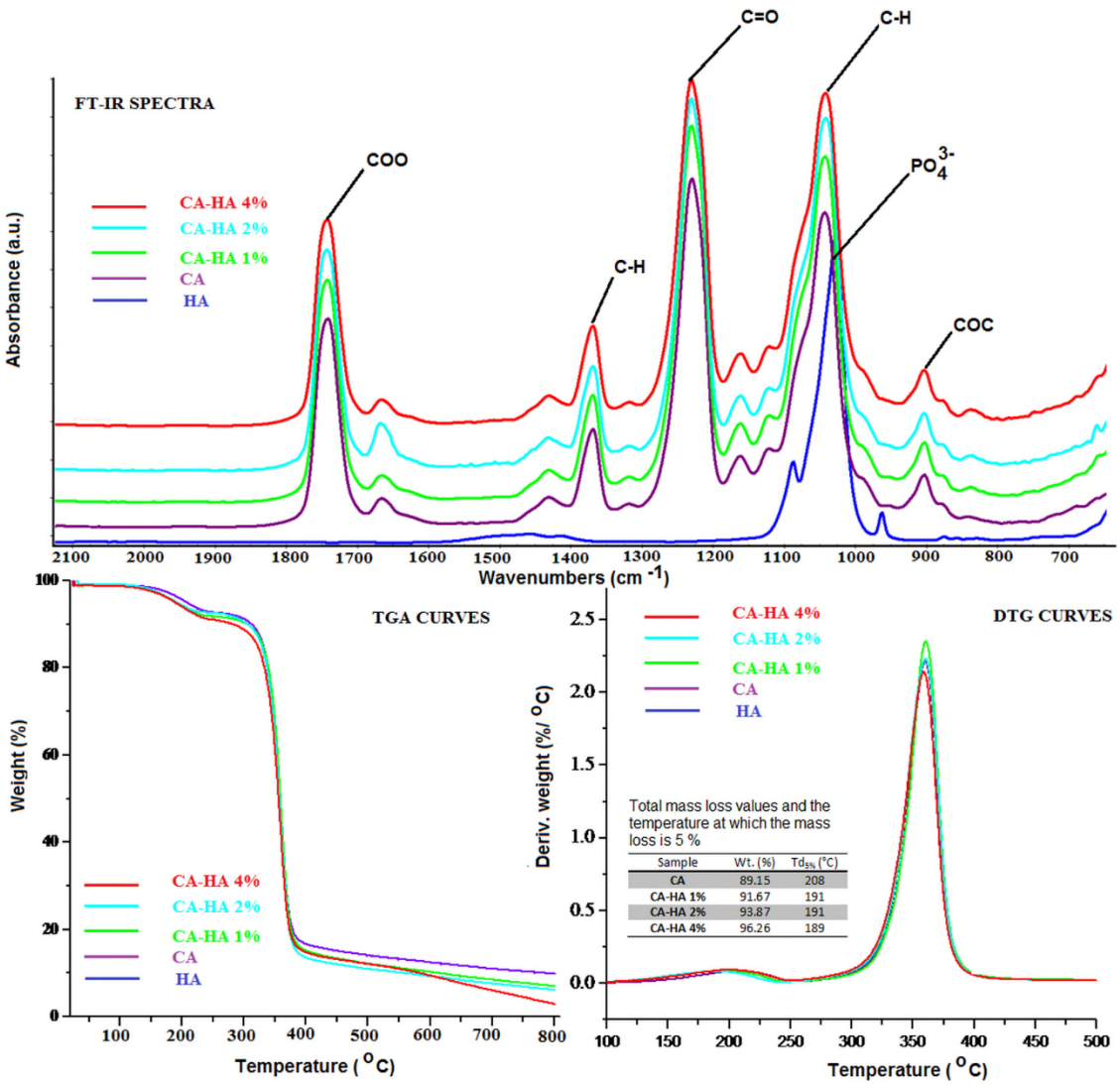


Fig. 3 FT-IR spectra and TGA curves of synthesized membranes

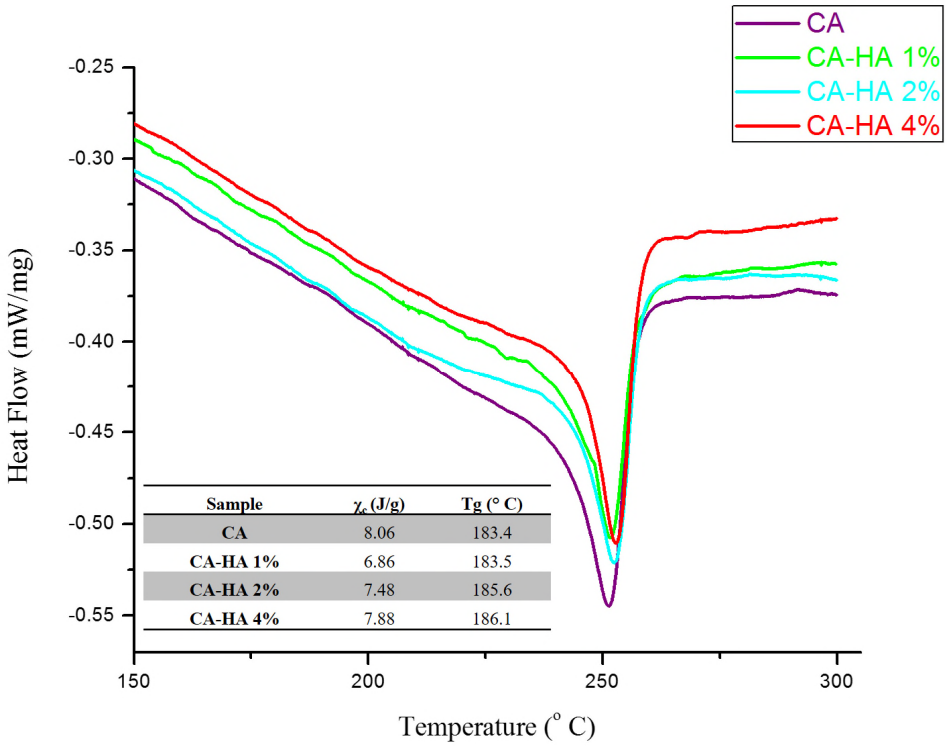


Fig. 4 DSC curves of synthesized membranes

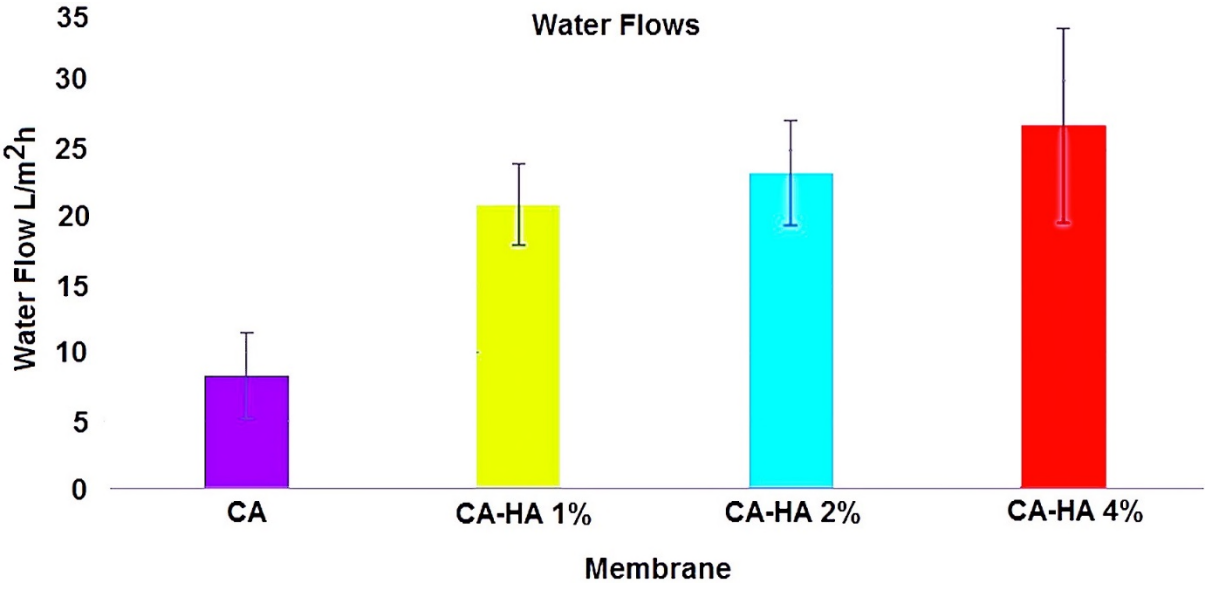


Fig. 5 Water flows of synthesized membranes



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Synthesis and characterization of cellulose acetate-hydroxyapatite micro and nano composites membranes for water purification and biomedical applications

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