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Preparation and Swelling Behaviour of Calcium-Alginate and Calcium Alginate-Chitosan Hydrogel Beads

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Abstract

Hydrogels are three-dimensional crosslinked polymeric structures that are able to swell in an aqueous environment. Use of the natural polymer, Sodium Alginate (SA), as the scaffold material in hydrogels has been highly pursued thanks to the polymer's biocompatibility. SA, which is a naturally occurring non-toxic polysaccharide found in marine brown algae, is one of the polysaccharides employed to fabricate small hydrogel beads. The reinforcement of alginate beads has been done by incorporating polymers, such as chitosan. These beads can be prepared using an ionotropic gelation method. In this research, the swelling ability of the calcium alginate and chitosan-treated calcium alginate beads in solutions with different pH values was investigated. They exhibited significant swelling rates when exposed to the slightly alkaline environment. Thus, these beads are a good candidate to be studied as a polymeric carrier for drug delivery in the intestinal tract.

Keywords: Hydrogel, Sodium alginate, Chitosan, Swelling behavior, Ionotropic gelation.

1 | Introduction

Hydrogels, chemically or physically crosslinked three-dimensional networks composed of hydrophilic polymers, can absorb and retain large amounts of aqueous fluids, and the absorbed water is hardly removable even under some pressure [1], [2]. Their affinity to absorb water is attributed to the presence of hydrophilic groups such as –OH, –CONH–, –$CONH_2$–, and –SO_3H in polymers forming hydrogel structures [3], [4]. Due to their remarkable characteristics, including tunable physical, chemical, and biological properties, high biocompatibility, versatility in fabrication, and similarity to native Extracellular Matrix (ECM), hydrogels have drawn much attention in a wide variety of fields such as drug delivery system, tissue engineering, artificial muscles, wound dressing, enzyme biosensor, contact lens, separation devices, sensors, chemical valves, metal

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particle preparation, dye adsorption, agriculture (controlled release of fertilizers or pesticides, filters, catalysis, and optically transparent materials) [2], [5], [6].

High swelling rate is an important property of hydrogels. They mainly need several hours to reach maximum absorption capacity. The slow swelling of dried hydrogels is due to the slow diffusion of water into the glassy matrix of the dried hydrogels [7], [8].

Hydrogels made of polysaccharides, such as chitosan and alginate, have been proposed for many biomedical and pharmaceutical purposes in recent years [9], [10]. Chitosan is recognized as one of the most important and abundant natural polyaminosaccharides [11]. It is generally produced from the deacetylation of chitin, which is also known as the second most abundant polymer in nature after cellulose. It can be extracted from crustacean shells such as prawns, crabs, insects, fungi, Baphnia magna resting eggs, Bat guano, and other sources [12]. Sodium Alginate (SA), a salt of alginic acid (brown algae), a linear copolymer of α-guluronic acid and α-mannuronic acid, has the ability to form a gel/meshwork in the presence of divalent cations such as $CaCl_2$. This gel shrinks at acidic pH and erodes at alkaline pH [13], [14]. Both polymers are biodegradable and are used to produce hydrogels with well-known properties, which are employed for the biomedical field [9].

Hydrogels have undergone remarkable evolution since their first introduction in the 1960s, when poly (2-hydroxyethyl methacrylate) (pHEMA) was proposed as one of the earliest hydrogel systems for biomedical use. Over the decades, research has shifted toward natural polymer-based hydrogels due to their inherent biocompatibility, biodegradability, and resemblance to biological tissues [15]. Among the naturally derived materials, alginate and chitosan have been considered particularly attractive because of their abundance, low cost, and ability to form stable networks under mild processing conditions [16]. The combination of these polymers has enabled the design of hybrid hydrogels with improved physicochemical and biological properties, making them promising candidates for next-generation biomedical applications [17].

Despite these advantages, several challenges remain. Alginate-based hydrogels, while easy to prepare and biocompatible, often suffer from poor mechanical stability in aqueous environments and uncontrolled dissolution in physiological conditions [18]. Chitosan, on the other hand, exhibits excellent film-forming ability and antibacterial properties but is insoluble in neutral and alkaline media, which limits its independent application [19]. By combining alginate and chitosan, researchers aim to mitigate these drawbacks; however, understanding the swelling behavior of the resulting hydrogels under different aqueous conditions is critical to optimizing their performance [20].

Recent investigations have increasingly focused on the modification of hydrogel structures to overcome inherent limitations such as insufficient mechanical stability, uncontrolled degradation, and restricted responsiveness to environmental stimuli [21]. The ionic interactions between the carboxyl groups of alginate and the amino groups of chitosan result in enhanced stability, biocompatibility, and tunable swelling characteristics [22], [23]. These interactions not only improve the structural integrity of the hydrogel network but also provide functional properties such as pH- and ion-sensitivity, making them suitable for advanced biomedical applications [24]. For instance, studies have demonstrated that altering the alginate-to-chitosan ratio significantly affects equilibrium swelling, drug release profiles, and mechanical properties of the hydrogel beads [25].

The swelling of hydrogels is not only a passive absorption process but also a functional property that can be precisely tuned to meet application-specific requirements. For example, in controlled drug delivery systems, a rapid initial swelling may facilitate burst release, while sustained swelling ensures prolonged therapeutic effects [26]. In tissue engineering, excessive swelling may compromise the mechanical integrity of scaffolds, whereas insufficient swelling could limit nutrient and oxygen transport [27]. Similarly, in environmental applications such as the removal of heavy metals or dyes from wastewater, the SR directly influences the adsorption capacity and reusability of hydrogel beads [27].

Therefore, a systematic investigation of swelling dynamics in alginate–chitosan hydrogels not only addresses fundamental scientific questions but also provides practical insights for their utilization in real-world

scenarios. By studying the effects of polymer composition, ionic crosslinking, and external environmental parameters, this work contributes to the rational design of hydrogel systems with optimized structural, mechanical, and functional characteristics. Ultimately, such insights may accelerate the translation of hydrogel-based technologies into clinically and industrially relevant applications [17], [27], [28].

The current study aimed to investigate the swelling behavior of dry calcium–alginate and calcium alginate–chitosan beads in different aqueous media. Calcium-alginate hydrogel beads prepared by dropping alginate solution into $CaCl_2$/chitosan solution, or into $CaCl_2$ solution.

2 | Materials and Methods

SA and chitosan of medium molecular weight were obtained from Sigma (USA). Calcium chloride was purchased from Merck. All reagents were at least analytical grade and were used as received.

Preparation of calcium alginate beads

1.3% calcium solution (w/v) and 1.0% alginate solution (w/v) were prepared by dissolving 1.3 g of calcium chloride dihydrate and 1.0 g of SA in 100 mL of deionized water. The calcium-alginate beads were prepared by dropping 10 mL alginate solution into a gently stirred 30 mL $CaCl_2$ solution for 15 min. The wet calcium-alginate beads remained for 15 min under gentle magnetic stirring in the media, and then the formed calcium alginate beads were collected and rinsed with deionized water and dried in air overnight.

Preparation of alginate–chitosan mixed

The alginate-chitosan beads tested in the study were prepared by dropping aqueous alginate solution into mixed chitosan-calcium chloride gelling solution, which was prepared as follows: Beads: 1% alginate solution (w/v) was prepared by dissolving 1.0 g SA in 100 mL deionized water. The weighted amounts of calcium chloride and chitosan were dissolved in 100 mL of 1% acetic acid solution. Ten milliliters of alginate solution was dropped into 30 mL mixed gelling solution through a 0.45 mm syringe needle. The spherical beads were cured for 30 min in the gelling solution at room temperature with gentle stirring, and then the beads were filtered, rinsed with deionized water, and dried in air overnight.

Swelling studies

Swelling characteristics of the beads were determined by immersing dried test beads in two aqueous media: Simulated Gastric Fluid (SGF, pH 1.5) and Simulated Intestinal Fluid (SIF, pH 6.8). Accurately weighed amounts of beads were immersed in 40 mL media solution, and the beads were removed from the swelling medium at specific time intervals. They were blotted with filter paper to absorb water on the surface and then weighed immediately. The Swelling Ratio (SR) of the sample was calculated according to the following expression:

$$SR\ \% = [\ (W\text{-}W_0)\ /\ W_0\ )] \times 100\ (1),$$

where W is the weight of the swollen beads and W_0 is the initial weight of the beads.

3 | Results and Discussion

Swelling characteristics

Fig. 1 illustrates the swelling behavior of pure calcium-alginate beads. As shown in *Fig. 1*, the test beads exhibited significant swelling rates when exposed to the slightly alkaline environment. The hydrogel beads show a high swelling in SIF at pH 6.8 and have a lower swelling in SGF at pH=1.5.

Fig. 2 shows the swelling profiles of alginate-chitosan mixed beads. It can be seen that they swell in SIF less than pure calcium–alginate beads due to two factors: the formation of a more entangled system developed by the blending of alginate and chitosan, and the presence of the polyelectrolyte complex between the amino groups of chitosan and the carboxylate groups of alginate. These two parameters significantly improve the

stability of the alginate–chitosan mixed beads. The polymer network is denser and exhibits increased resistance to osmotic pressure, so that the rate of disintegration and consequent weight loss of the samples was limited in the presence of chitosan.

The same beads tend to shrink when exposed to the acidic environment of SGF. Alginate-chitosan mixed beads show more swelling in SGF than pure calcium-alginate because of the hydration of hydrophilic groups and protonization of chitosan amino groups. These results confirm the pH-sensitive swelling behavior of the prepared beads.

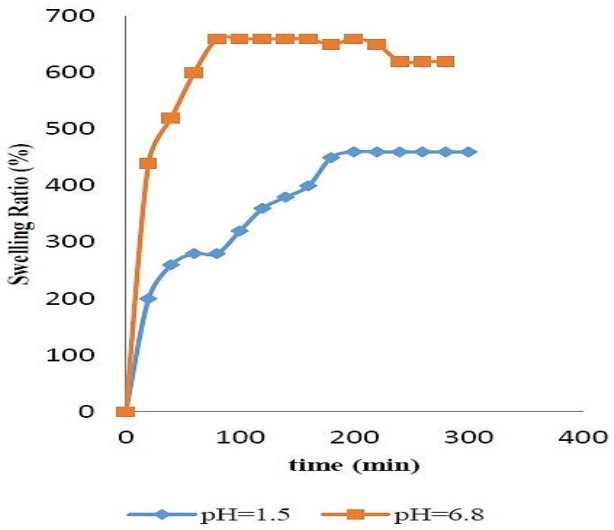

Fig. 1. Swelling characteristics of pure calcium-alginate beads in SGF (pH 1.5) and SIF (pH 6.8).

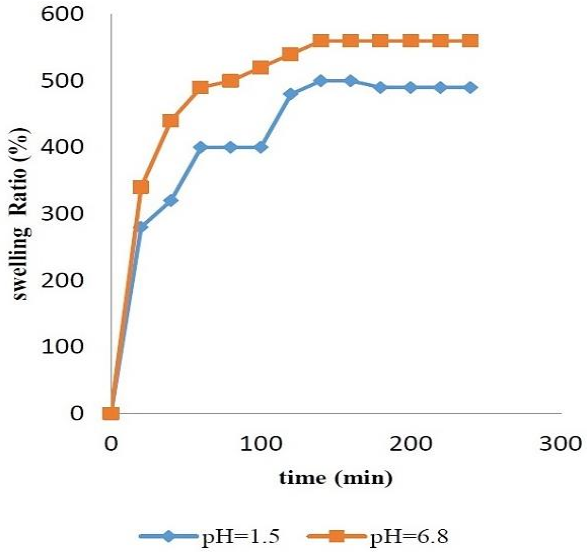

Fig. 2. Swelling characteristics of alginate-chitosan mixed beads in SGF (pH 1.5) and SIF (pH 6.8).

4 | Conclusion

The results of this study demonstrated that both polymer composition and environmental conditions strongly influence the swelling behavior of hydrogel beads. Calcium–alginate beads exhibited a relatively high SR in

neutral aqueous media, but their structural stability was compromised under acidic and alkaline conditions. In contrast, calcium–alginate–chitosan beads displayed a more controlled swelling profile, with enhanced resistance to acidic shrinkage and alkaline erosion. This improvement can be attributed to the electrostatic interactions between the carboxyl groups of alginate and the protonated amino groups of chitosan, which strengthen the hydrogel network and reduce premature degradation [15].

Experimental findings of the present work further confirmed the pH-sensitivity of these networks. The swelling degree at pH 6.8 was considerably higher than that observed at pH 1.5, indicating that both calcium–alginate and alginate–chitosan mixed beads undergo significant changes depending on the surrounding medium. Such behavior makes these beads promising candidates for site-specific drug delivery in the intestinal tract, where pH values are favorable for controlled swelling and sustained release [17], [18].

A notable trade-off was observed: calcium–alginate beads exhibited higher swelling capacity but lower structural stability, while calcium–alginate–chitosan beads provided reduced but more controlled swelling alongside improved integrity [16], [21]. Compared with dual-network systems relying on synthetic crosslinkers [19], the simple alginate–chitosan blend used here achieved a favorable balance without the need for chemical additives, highlighting the potential of natural polymer combinations.

From an application perspective, the pronounced difference in swelling between acidic and neutral/basic media observed in this study underscores the suitability of these hydrogels as polymeric carriers for oral drug delivery, particularly in targeting intestinal release. While calcium–alginate beads may be advantageous where rapid swelling and uptake are desirable, the alginate–chitosan beads provide better control and stability, making them suitable for sustained and site-specific delivery systems [22], [25].

In conclusion, this study not only confirms the pH-responsive swelling behavior of calcium–alginate and alginate–chitosan beads but also demonstrates their potential for intestinal-targeted drug delivery. Future research should focus on optimizing polymer ratios, incorporating bioactive crosslinkers, and performing in vivo studies to evaluate therapeutic efficacy and stability under physiological conditions. Such efforts will contribute to the rational design of natural hydrogel-based carriers for advanced biomedical applications [20], [21], [23].

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Conflicts of Interest

The authors declare no conflict of interest.

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