International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18 (2026) pp. 1-10
© Cerebration Science Publishing
https://doi.org/10.70917/ijcisim-2026-1102
Article

Preparation and characterization of sodium alginate and silicon dioxide composites

Wenrui Wan [1,*]

[1] Faculty of Science, University of Technology Sydney, PO Box 123, Broadway, NSW 2007, Australia
* Correspondence author: wrwanedu@163.com

Abstract: Sodium alginate is a natural anionic polysaccharide with good biocompatibility, biodegradability, water solubility, and film-forming ability, but its poor water resistance, limited stability, and low mechanical strength restrict its wider application. In this study, sodium alginate/silicon dioxide composites were prepared through calcium ion-induced gelation. Silicon dioxide was introduced into the sodium alginate gel network during the gel formation process to improve the structural characteristics of the alginate-based material. The effects of silicon dioxide concentration and the volume ratio of sodium alginate solution to silicon dioxide dispersion on product morphology were investigated. The results showed that the addition of silicon dioxide changed the appearance of the gel particles from semi-transparent to white, indicating the incorporation of the inorganic component. Among the tested conditions, the best morphology was obtained when 10 mg/mL sodium alginate solution and 5 mg/mL silicon dioxide dispersion were mixed at a volume ratio of 8:2. FTIR analysis showed changes in the absorption bands related to –OH, $–COO^-$, and C–O groups, suggesting interactions between sodium alginate and silicon dioxide. UV–vis spectra showed a new absorption peak at approximately 473 nm, further supporting the formation of the composite material. This study provides a simple method for preparing sodium alginate-based inorganic composites.

Keywords: sodium alginate; silicon dioxide; composite materials; calcium ion-induced gelation; FTIR spectroscopy

1. Introduction

Sodium alginate (SA) is a naturally occurring anionic polysaccharide mainly extracted from brown algae [1]. Owing to its abundant availability, low cost, non-toxicity, good water solubility, film-forming ability, biodegradability, and biocompatibility, SA has attracted considerable attention in food packaging, biomedicine, environmental treatment, textile processing, and other material-related fields [2]. As a renewable biomass-based polymer, SA is particularly suitable for the development of environmentally friendly materials. In recent years, increasing concerns about plastic pollution and the environmental persistence of petroleum-based packaging materials have promoted the search for biodegradable alternatives [3]. In this context, SA-based films and gels have been widely investigated because they can reduce moisture transfer, limit oxygen permeability, protect food surfaces from contamination, and potentially extend the shelf life of fresh products [4].

Despite these advantages, the practical application of sodium alginate is still limited by several inherent weaknesses. Pure SA materials generally show poor water resistance, insufficient mechanical strength, and limited structural stability, especially under humid or aqueous conditions [5]. These drawbacks restrict their performance in functional packaging, gel materials, adsorption systems, and other applications that require stable structure and durability [6]. Therefore, modification of SA has become an important strategy to improve its functional properties. Among various approaches, the incorporation of inorganic particles into the SA matrix is considered effective because inorganic components can enhance the structural stability, mechanical behavior, and physicochemical properties of polymer-based composites [7].

Silicon dioxide (SiO_2) is an important inorganic non-metallic material with high chemical stability, strong adsorption capacity, good dispersibility, low toxicity, and large specific surface area. Nanoscale SiO_2 is especially attractive as a reinforcing phase because its surface contains abundant hydroxyl groups, which may interact with the hydroxyl, ether, and carboxyl groups of sodium alginate through hydrogen bonding or other interfacial interactions [8-9]. The introduction of SiO_2 into an SA matrix may therefore improve the morphology, compactness, and stability of SA-based gel materials. In addition, SiO_2 can act as an inorganic filler within the polymer network, which may contribute to the formation of a more uniform and stronger composite structure [10]. For these reasons, SA/SiO_2 composites have potential value in the development of biodegradable films, adsorption materials, and functional gel systems.

Calcium-ion-induced gelation is a simple and mild method for preparing sodium alginate-based materials. SA can rapidly form gels in the presence of Ca^{2+} because calcium ions coordinate with guluronic acid blocks in the alginate chains, producing a three-dimensional crosslinked network [11]. This gelation process provides a convenient route for introducing SiO_2 particles into the SA matrix. Compared with methods that require high temperature, toxic solvents, or complex reaction conditions, calcium-induced gelation can be carried out at room temperature in an aqueous environment, making it suitable for the preparation of environmentally friendly composite materials.

In this study, sodium alginate and silicon dioxide were used as the main raw materials to prepare SA/SiO_2 composites through calcium-ion-induced gelation. During gel formation, SiO_2 was introduced into the sodium alginate network to obtain composite materials with improved morphology and structural characteristics. The effects of SiO_2 concentration and the volume ratio of sodium alginate solution to SiO_2 dispersion on product formation were investigated. The prepared composites were characterized by morphological observation, Fourier transform infrared spectroscopy (FTIR), and ultraviolet–visible spectroscopy (UV–vis). By analyzing the influence of preparation conditions and the spectral features of the products, this work aims to determine suitable preparation parameters and provide a reference for the further development and application of sodium alginate/silicon dioxide composite materials.

2. Materials and Methods

2.1. Materials

The main raw materials used in this study were sodium alginate, calcium chloride hexahydrate, and silicon dioxide. Sodium alginate was used as the polymer matrix because of its ability to form gels in the presence of divalent calcium ions. Calcium chloride hexahydrate was used as the calcium ion source to induce the crosslinking of sodium alginate. Silicon dioxide was introduced as the inorganic component to prepare sodium alginate/silicon dioxide composites [12]. All reagents were of analytical grade and were used without further purification. Deionized water was used throughout the preparation process. The chemicals and reagents used in this experiment are listed in Table 1.

Table 1. Chemicals and reagents

Chemical/Reagent	Specification	Manufacturer
Sodium alginate	AR	Shanghai Aladdin Biochemical Technology Co., Ltd.
Calcium chloride hexahydrate	AR	Shanghai Aladdin Biochemical Technology Co., Ltd.
Silicon dioxide	AR	Shanghai Aladdin Biochemical Technology Co., Ltd.

2.2. Instruments

The instruments used in the preparation and characterization of sodium alginate/silicon dioxide composites are shown in Table 2. An electronic balance was used for accurate weighing of the raw materials. A drying oven was used during sample treatment. The UV–vis spectrophotometer was used to record the optical absorption spectra of the samples, while the FTIR spectrometer was used to analyze the functional groups and possible interactions between sodium alginate and silicon dioxide in the prepared composites.

Table 2. Instruments used in the experiment

Instrument	**Model**	**Manufacturer**
Electronic balance	AUY120	Shimadzu, Japan
Drying oven	DZF-6020	Shanghai Yiheng Scientific Instrument Co., Ltd., China
UV–vis spectrophotometer	UV3600PLUS	Shimadzu, Japan
FTIR spectrometer	Nicolet iS10	Thermo Fisher Scientific, USA

2.3. Preparation of Solutions

2.3.1. Preparation of Sodium Alginate Solution

A sodium alginate solution with a concentration of 10 mg/mL was prepared according to the designed experimental procedure. First, 0.5 g of sodium alginate powder was accurately weighed using an electronic balance. The powder was then added into a 250 mL beaker containing 50 mL of deionized water. The mixture was stirred until the sodium alginate was fully dissolved and a uniform viscous solution was obtained. The prepared sodium alginate solution was used as the polymer matrix for the following composite preparation.

2.3.2. Preparation of Calcium Chloride Solution

A calcium chloride solution with a concentration of 20 mg/mL was prepared as the crosslinking solution. Specifically, 0.40 g of calcium chloride hexahydrate was weighed and transferred into a 100 mL beaker. Then, 20 mL of deionized water was added to dissolve the calcium chloride hexahydrate completely. The obtained calcium chloride solution provided Ca^{2+} ions, which could coordinate with sodium alginate chains and induce gel formation during the composite preparation process [13].

2.3.3. Preparation of Silicon Dioxide Dispersion

A silicon dioxide dispersion with a concentration of 5 mg/mL was prepared by dispersing 0.10 g of silicon dioxide in 20 mL of deionized water. Since silicon dioxide particles tend to aggregate in aqueous systems, ultrasonic treatment was applied to promote uniform dispersion [14]. The obtained SiO_2 dispersion was then mixed with sodium alginate solution at different designed volume ratios for composite preparation.

2.4. Preparation of Sodium Alginate/Silicon Dioxide Composites

Sodium alginate/silicon dioxide composites were prepared through calcium-ion-induced gelation [15]. In a typical procedure, the prepared sodium alginate solution and silicon dioxide dispersion were mixed at the designed ratio. The mixed solution was treated by ultrasonication to obtain a relatively homogeneous suspension and to improve the distribution of SiO_2 particles in the sodium alginate matrix.

After the mixture was prepared, 10 mL of the sodium alginate/silicon dioxide mixed suspension was drawn into a 2 mL syringe and added dropwise into 10 mL of calcium chloride solution [16]. The calcium chloride solution was continuously stirred during the dropping process to ensure uniform gel formation. When the sodium alginate-containing droplets came into contact with Ca^{2+} ions, gel particles were formed rapidly due to ionic crosslinking between calcium ions and sodium alginate chains. The reaction was carried out at room temperature under continuous stirring for 1 h.

After gelation, the obtained products were collected by centrifugation and washed several times with deionized water to remove residual calcium chloride and loosely attached particles. The washed samples were frozen at −20 °C for 24 h and then freeze-dried to obtain white solid sodium alginate/silicon dioxide composites [17]. These dried samples were used for subsequent morphology observation and spectral characterization.

2.5. Optimization of Preparation Conditions

To investigate the influence of preparation conditions on the morphology of the composites, two main factors were studied: the concentration of silicon dioxide and the volume ratio of sodium alginate solution to silicon dioxide dispersion [18].

First, the effect of SiO_2 concentration was investigated while keeping other experimental conditions unchanged. The concentrations of SiO_2 dispersion were set as 0, 0.5, 1, 2, and 5 mg/mL. For each experiment, 5 mL of 10 mg/mL sodium alginate solution was mixed with 5 mL of SiO_2 dispersion at the corresponding concentration. The mixed solution was then added dropwise into 20 mg/mL calcium chloride solution under stirring. The morphology and appearance of the resulting gel products were observed and compared.

Second, the effect of the volume ratio of sodium alginate solution to silicon dioxide dispersion was studied. The total volume of the sodium alginate solution and SiO_2 dispersion was fixed at 10 mL. The volumes of 10 mg/mL sodium alginate solution were set as 1, 2, 5, and 8 mL, while the corresponding volumes of 5 mg/mL SiO_2 dispersion were 9, 8, 5, and 2 mL, respectively. Therefore, the volume ratios of sodium alginate solution to SiO_2 dispersion were 1:9, 2:8, 5:5, and 8:2. The prepared mixtures were added into calcium chloride solution under the same conditions, and the resulting product morphologies were compared to determine the most suitable preparation ratio.

2.6. Characterization Methods

The morphology of the prepared products was first evaluated by direct visual observation. The shape, uniformity, transparency, and compactness of the gel particles obtained under different preparation conditions were compared. This observation was used to assess the influence of SiO_2 concentration and sodium alginate/SiO_2 volume ratio on composite formation.

Fourier transform infrared spectroscopy was used to analyze the functional groups of sodium alginate and sodium alginate/silicon dioxide composites [19]. The spectra were recorded in the range of 4000–500 cm^{-1} using the KBr pellet method. The changes in characteristic absorption peaks, especially those related to –OH, $–COO^-$, C–O, and Si–O groups, were used to evaluate the possible interactions between sodium alginate and silicon dioxide.

UV–vis spectroscopy was used to further characterize the optical absorption behavior of the samples [20]. The spectra were recorded in the range of 200–1000 nm. The UV–vis absorption spectra of sodium alginate, silicon dioxide, and the prepared composites were compared to identify any new absorption features caused by composite formation. These characterization results were used to support the successful preparation of sodium alginate/silicon dioxide composites.

3. Results

3.1. Effect of SiO_2 Concentration on Product Morphology

The effect of silicon dioxide concentration on the morphology of the sodium alginate/silicon dioxide composite products was first investigated. In this experiment, 5 mL of 10 mg/mL sodium alginate solution was mixed with 5 mL of silicon dioxide dispersion at different concentrations. The mixed solution was then added dropwise into 20 mg/mL calcium chloride solution under stirring at room temperature. The concentrations of silicon dioxide were set as 0, 0.5, 1, 2, and 5 mg/mL. The morphologies of the products obtained under different silicon dioxide concentrations are shown in Figure 1.

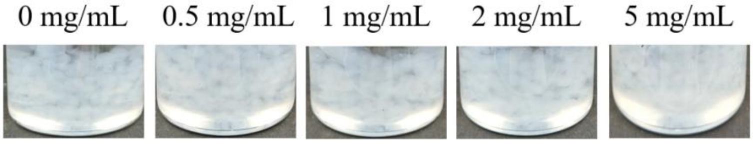

Figure 1. Morphology of products prepared with different SiO2 concentrations

When the concentration of silicon dioxide was 0 mg/mL, only sodium alginate solution was added into the calcium chloride solution. After the sodium alginate solution was dropped into the calcium chloride solution, the system became semi-transparent, and a large number of spherical semi-transparent gel particles were formed in the solution. With the extension of reaction time, no obvious change was observed in the state of the solution.

When the concentration of silicon dioxide was 0.5 mg/mL, the sodium alginate/silicon dioxide mixed solution was added into the calcium chloride solution. A large number of white spherical particles were rapidly produced in the solution. Compared with the product prepared without silicon dioxide, the opacity of the product increased. As the reaction proceeded, the state of the solution still showed no obvious change.

When the concentration of silicon dioxide was further increased to 1, 2, and 5 mg/mL, a large number of white spherical particles were also rapidly formed after the sodium alginate/silicon dioxide mixed solution was added into the calcium chloride solution. Under these conditions, the products maintained a spherical gel-like morphology, and no obvious change in the solution state was observed with prolonged reaction time. These results show that the introduction of silicon dioxide changed the visual appearance of the sodium alginate gel particles from semi-transparent to white, while spherical gel particles could be obtained under the investigated silicon dioxide concentrations.

3.2. Effect of SA/SiO_2 Volume Ratio on Product Morphology

The effect of the volume ratio of sodium alginate solution to silicon dioxide dispersion on product morphology was further investigated. In this experiment, the total volume of sodium alginate solution and silicon dioxide dispersion was fixed at 10 mL. The volume of 10 mg/mL sodium alginate solution was set as 1, 2, 5, and 8 mL, and the corresponding volume of 5 mg/mL silicon dioxide dispersion was 9, 8, 5, and 2 mL, respectively. Therefore, the volume ratios of sodium alginate solution to silicon dioxide dispersion were 1:9, 2:8, 5:5, and 8:2. The resulting morphologies are shown in Figure 2.

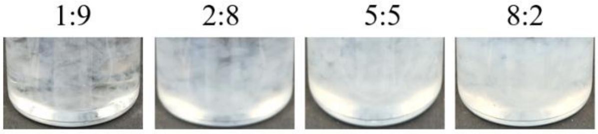

Figure 2. Morphology of products prepared with different SA/SiO_2 volume ratios

When the volume of sodium alginate solution was 1 mL and the volume of silicon dioxide dispersion was 9 mL, a large amount of amorphous gel was produced after the mixed solution was added into the calcium chloride solution. The gel was relatively loose and did not show an obvious regular shape. This result indicates that when the sodium alginate content in the mixed solution was low, the obtained product could not form a clear spherical morphology.

When the volume of sodium alginate solution was increased to 2 mL and the volume of silicon dioxide dispersion was 8 mL, a large amount of white gel was produced in the solution. Compared with the product obtained at the sodium alginate volume of 1 mL, the product showed a certain degree of shape formation. White spherical gel particles began to appear, although the overall morphology was still not fully regular.

When the sodium alginate solution volume was 5 mL and the silicon dioxide dispersion volume was 5 mL, a large amount of white gel solid was obtained. The overall morphology of the gel solid became spherical. Compared with the products prepared at lower sodium alginate volumes, the spherical morphology was more obvious.

When the sodium alginate solution volume was further increased to 8 mL and the silicon dioxide dispersion volume was 2 mL, the product morphology became more regular. The obtained product showed better uniformity and a spherical shape. In addition, as the volume of sodium alginate solution increased, the firmness of the obtained gel solid gradually increased. Among the tested volume ratios, the product prepared with 8 mL of 10 mg/mL sodium alginate solution and 2 mL of 5 mg/mL silicon dioxide dispersion showed the best morphology.

3.3. FTIR Spectral Results

Fourier transform infrared spectroscopy was used to characterize sodium alginate and sodium alginate/silicon dioxide composites. The FTIR spectra are shown in Figure 3. In the original experiment, SA–SiO_2-1 to SA–SiO_2-5 were composites prepared by changing the concentration of silicon dioxide while keeping the other experimental conditions unchanged. SA–SiO_2-6 to SA–SiO_2-9 were composites prepared by changing the volume of sodium alginate solution while maintaining the silicon dioxide content.

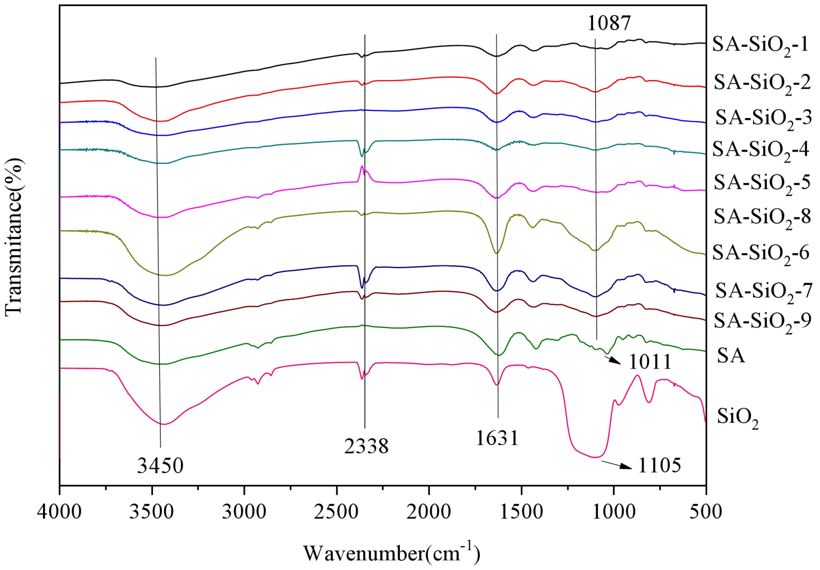

Figure 3. FTIR spectra of sodium alginate and SA–SiO$_2$ composites

The FTIR spectrum of pure sodium alginate showed characteristic absorption peaks. The broad absorption peak around 3450 cm^{-1} was assigned to the stretching vibration of –OH groups. The absorption peak around 1631 cm^{-1} was related to the asymmetric stretching vibration of –COO$^-$ groups. The peak located around 1150 cm^{-1} was associated with the C–O stretching vibration in C–O–H.

For the sodium alginate/silicon dioxide composites prepared with different silicon dioxide concentrations, the absorption peaks around 3436 cm^{-1}, 1000–1200 cm^{-1}, and 1631 cm^{-1} changed as the silicon dioxide content increased. According to the spectra, with the increase of silicon dioxide concentration, the stretching amplitude of these absorption peaks became more obvious. This result was observed in the spectra of SA–SiO$_2$-1 to SA–SiO$_2$-5.

For the composites prepared with different sodium alginate volumes under the same silicon dioxide content, the spectra of SA–SiO$_2$-6 to SA–SiO$_2$-9 showed that the absorption peaks in the regions of 3000–3400 cm^{-1}, 1000–1200 cm^{-1}, and around 1631 cm^{-1} became broader as the amount of sodium alginate increased. The FTIR results therefore showed changes in the characteristic absorption peaks of sodium alginate after the formation of sodium alginate/silicon dioxide composites.

3.4. UV–vis Spectral Results

UV–vis spectroscopy was used to compare the absorption spectra of sodium alginate, silicon dioxide, and the prepared sodium alginate/silicon dioxide composite materials. The UV–vis spectra are shown in Figure 4.

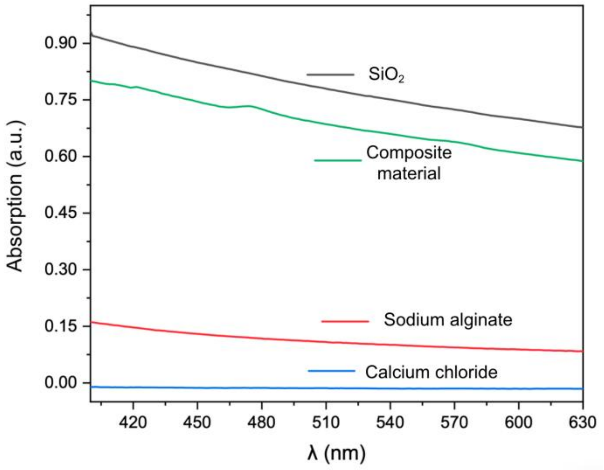

Figure 4. UV–vis spectra of sodium alginate, SiO$_2$, calcium chloride, and SA–SiO$_2$ composite.

As shown in Figure 4, the composite material exhibited a new absorption peak at approximately 473 nm. This absorption peak was not observed in the spectra of silicon dioxide, sodium alginate, or calcium chloride. The appearance of this new peak was recorded only in the sodium alginate/silicon dioxide composite material.

According to the experimental results, the new absorption peak at around 473 nm may be related to the interaction between sodium alginate and silicon dioxide. Since this peak was not present in the individual raw materials, the UV–vis spectra provided further evidence that the prepared material was a sodium alginate/silicon dioxide composite. Together with the morphology results and FTIR spectral results, the UV–vis result supported the formation of the composite material under the experimental conditions used in this study.

4. Discussion

4.1. Influence of SiO_2 on Gel Formation

The formation of sodium alginate-based gel particles mainly depends on the coordination between Ca^{2+} and guluronic acid blocks in the alginate chains. This ionic crosslinking produces a three-dimensional gel network, which serves as the structural basis of the composite particles. When SiO_2 is introduced during this process, it can be incorporated into the forming alginate network rather than being added after gelation. Therefore, the inorganic component becomes part of the composite structure during calcium-induced gel formation.

The presence of SiO_2 changes the appearance and internal composition of the gel particles. The transition from semi-transparent alginate gels to white composite particles indicates that SiO_2 was successfully introduced into the system. This change is not only a visual difference but also reflects the presence of an inorganic phase inside or on the surface of the gel matrix. Since SiO_2 contains abundant surface hydroxyl groups, it may interact with hydroxyl, ether, and carboxyl groups in sodium alginate. These interactions can influence the arrangement of alginate chains and contribute to the formation of a more integrated composite structure.

4.2. Influence of SA/SiO_2 Volume Ratio

The volume ratio of sodium alginate solution to SiO_2 dispersion is critical because sodium alginate is the main gel-forming component. When the proportion of sodium alginate is too low, there are not enough polymer chains to build a continuous Ca^{2+}-crosslinked network. As a result, the product tends to be loose and poorly shaped. This explains why low sodium alginate content is unfavorable for the formation of regular gel particles.

With increasing sodium alginate content, the gel network becomes more complete and stable. A higher amount of sodium alginate provides more binding sites for Ca^{2+}, which improves the structural integrity of the particles. At the same time, SiO_2 acts as an inorganic component embedded in the polymer network. The optimized 8:2 volume ratio of sodium alginate solution to SiO_2 dispersion therefore represents a suitable balance: sodium alginate provides sufficient gel-forming matrix, while SiO_2 contributes to the composite nature of the material. This balance is responsible for the more regular, uniform, and firmer spherical morphology observed under the optimized condition.

4.3. Interaction Mechanism between Sodium Alginate and SiO_2

FTIR analysis provides important evidence for the interaction between sodium alginate and SiO_2. The changes in the absorption regions related to –OH, $–COO^-$, and C–O groups suggest that the chemical environment of sodium alginate was affected after the introduction of SiO_2. In particular, the broadening of the –OH absorption band indicates stronger hydrogen-bonding interactions in the composite system. This is consistent with the presence of hydroxyl groups on both sodium alginate chains and the SiO_2 surface.

The changes in the 1000–1200 cm^{-1} region may be associated with the overlapping contribution of C–O vibrations from sodium alginate and Si–O-related vibrations from SiO_2. Meanwhile, the variation near 1631 cm^{-1} suggests that carboxylate groups in sodium alginate may also participate in the composite structure. Therefore, the composite formation is likely governed by two processes: Ca^{2+}-induced ionic crosslinking of sodium alginate and interfacial interactions between sodium alginate and SiO_2. These two effects jointly contribute to the formation of the sodium alginate/SiO_2 composite material.

4.4. Evidence from UV–vis Spectroscopy

The UV–vis result further supports the formation of a composite structure. The appearance of a new absorption peak around 473 nm, which was absent in the individual raw materials, indicates that the prepared material had optical characteristics different from sodium alginate, SiO_2, and calcium chloride. This difference may be attributed to structural or interfacial changes caused by the combination of sodium alginate and SiO_2 during gelation.

Together with the FTIR results, the UV–vis spectrum confirms that the product was not simply a physical mixture of the starting materials. Instead, the spectral changes suggest that interactions occurred between the organic alginate matrix and the inorganic SiO_2 component.

4.5. Overall Evaluation of the Composite Preparation

Overall, calcium-ion-induced gelation provides a simple and mild route for preparing sodium alginate/SiO_2 composites. The process can be carried out in an aqueous system at room temperature, avoiding harsh reaction conditions. The optimized preparation condition was obtained when 10 mg/mL sodium alginate solution and 5 mg/mL SiO_2 dispersion were mixed at a volume ratio of 8:2.

The results indicate that SiO_2 incorporation can improve the morphology and firmness of sodium alginate gel materials. This study therefore provides a useful reference for preparing alginate-based inorganic composite materials. Such composites may have potential in biodegradable materials, adsorption systems, and functional packaging applications.

5. Conclusion

In this study, sodium alginate/silicon dioxide composites were successfully prepared through calcium ion-induced gelation. Sodium alginate was used as the main gel-forming matrix, while SiO_2 was introduced into the alginate network during the gel formation process. The effects of SiO_2 concentration and the volume ratio of sodium alginate solution to SiO_2 dispersion on product morphology were investigated. The results showed that the introduction of SiO_2 changed the appearance of the sodium alginate gel particles, and the volume ratio of sodium alginate to SiO_2 had an important influence on the regularity and firmness of the products. Among the tested conditions, the best morphology was obtained when 10 mg/mL sodium alginate solution and 5 mg/mL SiO_2 dispersion were mixed at a volume ratio of 8:2.

FTIR analysis showed changes in the absorption bands related to –OH, $–COO^-$, and C–O groups, suggesting that interactions occurred between sodium alginate and SiO_2 in the composite system. UV–vis spectroscopy further supported the formation of the composite material, as a new absorption peak appeared at approximately 473 nm, which was not observed in the individual raw materials.

Overall, this study provides a simple and mild method for preparing sodium alginate-based inorganic composite materials. The incorporation of SiO_2 may improve the structural characteristics of sodium alginate gels and broaden their potential applications. The results can provide a reference for the further development of alginate-based composite materials.

However, this study mainly focused on morphology observation and spectral characterization. Further research should evaluate the mechanical strength, water resistance, thermal stability, and adsorption performance of the prepared composites. In addition, application tests in food packaging, environmental adsorption, or biomedical materials could be conducted to further assess their practical value.

References

1. Santana, I., Felix, M., & Bengoechea, C. (2024). Seaweed as basis of eco-sustainable plastic materials: focus on alginate. Polymers, 16(12), 1662.
2. Tammina, S. K., Priyadarshi, R., Khan, A., Manzoor, A., Rahman, R. S. H. A., & Banat, F. (2025). Recent developments in alginate-based nanocomposite coatings and films for biodegradable food packaging applications. International Journal of Biological Macromolecules, 295, 139480.
3. Abdulla, S. F., Shams, R., & Dash, K. K. (2025). Edible packaging as sustainable alternative to synthetic plastic: a comprehensive review. Environmental Science and Pollution Research, 32(52), 29566-29580.
4. Metha, C., Pawar, S., & Suvarna, V. (2024). Recent advancements in alginate-based films for active food packaging applications. Sustainable Food Technology, 2(5), 1246-1265.

5. Abedi-Firoozjah, R., Bahramian, B., Tavassoli, M., Majlesi, M., Ghaderi, S., Assadpour, E., ... & Jafari, S. M. (2025). Alginate-based edible films/coatings/nanofibers in food packaging: A comprehensive review of recent advances. Carbohydrate Polymer Technologies and Applications, 100955.
6. Li, S., Ren, Y., Hou, Y., Zhan, Q., Jin, P., Zheng, Y., & Wu, Z. (2024). Polysaccharide-based composite films: Promising biodegradable food packaging materials. Foods, 13(22), 3674.
7. Yerramathi, B. B., Muniraj, B. A., Donadi, J., Bandi, K., & Kola, M. (2025). Transformation of alginate based films into food packaging material-confines and possibilities as a renewable resource: A review. Reactive and Functional Polymers, 215, 106358.
8. D'Angelo, A., Mortalò, C., Comune, L., Raffaini, G., Fiorentino, M., & Catauro, M. (2025). Sol–gel synthesized silica/sodium alginate hybrids: comprehensive physico-chemical and biological characterization. Molecules, 30(17), 3481.
9. Alenezi, H., Gad, E. S., Albassami, N. A., Alatawi, I. S., Alshareef, S. A., Aljowni, M. A., ... & Saleh, A. K. (2025). Development of oxidized sodium alginate/silica hybrid as efficient adsorbent for anionic and cationic dyes: mechanism and thermodynamic studies. Biomass Conversion and Biorefinery, 15(12), 18247-18261.
10. Khoj, M. A. (2024). Fabrication of silica/calcium alginate nanocomposite based on rice husk ash for efficient adsorption of phenol from water. RSC advances, 14(33), 24322-24334.
11. Ručigaj, A., Golobič, J., & Kopač, T. (2024). The role of multivalent cations in determining the cross-linking affinity of alginate hydrogels: A combined experimental and modeling study. Chemical Engineering Journal Advances, 20, 100678.
12. Sonawane, L. D., Mandawade, A. S., Gite, A. B., Shinde, S. D., Patil, G. E., Nikam, L. K., ... & Shinde, M. S. (2025). Sol–gel synthesis of silicon oxide (SiO2) nanoparticles: exploring gas sensing and photocatalytic applications. Journal of Materials Science: Materials in Engineering, 20(1), 8.
13. Zhang, L., Shen, B., Zheng, C., Huang, Y., Liang, Y., Fei, P., ... & Lai, W. (2024). Chitosan/oxidized sodium alginate/Ca2+ hydrogels: Synthesis, characterization and adsorption properties. Food Hydrocolloids, 156, 110368.
14. Rashid, A., Qayum, A., Bacha, S. A. S., Liang, Q., Liu, Y., Kang, L., ... & Ma, H. (2024). Preparation and functional characterization of pullulan-sodium alginate composite film enhanced with ultrasound-assisted clove essential oil Nanoemulsions for effective preservation of cherries and mushrooms. Food Chemistry, 457, 140048.
15. Wei, J., Yang, S., Zhu, Z., Lu, J., Zhang, B., Zhang, M., & Wei, W. (2025). Low-Temperature Dried Alginate/Silica Hybrid Aerogel Beads with Tunable Surface Functionalities for Removal of Lead Ions from Water. Gels, 11(6), 397.
16. Desoky, A. A., Ereiba, K. T., Bakr, A. M., & Abdraboh, A. S. (2025). Enhancement of bioactivity and molecular docking analysis of bioglass loaded zein and sodium alginate composite beads for biomedical applications. Scientific Reports, 15(1), 13460.
17. Parvez, S., & Wani, I. A. (2024). Calcium Alginate Beads Loaded with Green Tea Extract: Impact of Drying Methods on Its Structure, Release Behavior, and Storage Stability. ACS Food Science & Technology, 4(4), 935-946.
18. Liu, X., Liu, L., Huang, F., Meng, Y., Chen, Y., Wang, J., ... & Liang, Y. (2025). pH-sensitive chitosan/sodium alginate/calcium chloride hydrogel beads for potential oral delivery of rice bran bioactive peptides. Food Chemistry, 470, 142618.
19. ElTatawy, R. A., Ismail, A. M., Ayoup, M. S., Ismail, M. M., & Fetouh, H. A. (2024). Preparation and kinetic studies of a new antibacterial sodium alginate gelatin hydrogel composite. Scientific Reports, 14(1), 29206.

---

20. Khan, M. A. A., Hasan, M. M., Hossain, M. K., Adhikery, D., Hakim, M., Mohanta, L. C., ... & Sarker, A. K. (2025). Extraction and characteristic properties analyses of sodium alginate derived from the Sargassum oligocystum brown seaweed alga of the Bay of Bengal. Next Materials, 6, 100417.