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Original Research Article

Physico-Chemical Characterisation of Hydrogel Seed Coating for Sustainable Agriculture

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Abstract: Hydrogel technology has become increasingly important in agricultural applications, addressing critical challenges such as water scarcity, nutrient management, and crop sustainability. This research focuses on developing hydrogel seed coatings, emphasising polysaccharides like carrageenan and alginate combined with oligo-chitosan for cross-linking. The study also examines the preparation and swelling properties of carrageenan-alginate hydrogels. Hydrogels offer promising solutions for improving water retention and moisture management, which are key factors in combating the growing problem of water scarcity. Moreover, hydrogels can be designed for controlled nutrient release, enhancing plant nutrient absorption and supporting more efficient agricultural nutrient management. This research seeks to contribute to developing innovative seed coatings that optimise resource use and promote crop growth. The study provides a comprehensive analysis of the preparation process for carrageenan-alginate hydrogels, focusing on the critical role of oligo-chitosan cross-linking in achieving optimal hydrogel properties. The swelling behaviour and characteristics of the hydrogels are thoroughly explored to assess their responsiveness to environmental conditions and suitability for specific agricultural applications. The outcomes of this research can substantially impact agricultural practices by improving crop establishment, yield, and sustainability. By leveraging the advantages of hydrogel seed coatings, this study supports the development of environmentally sustainable and resource-efficient agricultural methods, aligning with the growing demand for resilient and eco-friendly agricultural practices.

Keywords: hydrogel; carrageenan; alginate; swelling; seed coating

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1. Introduction

Hydrogels are three-dimensional polymer-based networks applied in various fields, including drug delivery, the food industry, and agriculture (Benito-Peña *et al*., 2016; Du *et al*., 2021; Hu *et al*., 2021; Maringgal *et al*., 2021). Ensuring food security and sustainability in agriculture is becoming increasingly challenging due to soil and water pollution. The initial seed planting stage is crucial, as it directly influences germination, disease resistance, and pest resilience. To address these challenges, sustainable and biodegradable seed coatings have emerged as promising solutions to protect seeds and enhance growth and yield. The seed coating process involves applying a thin layer of materials using several methods, such as film coating, pelleting, and encrusting (Javed *et al*., 2022). The application of hydrogels in agriculture represents a significant advancement, as this can mitigate water scarcity by improving soil water retention and reducing the frequency and volume of irrigation (Albalasmeh *et al*., 2022). This highly absorbent natural polymer could retain and release water, marking a significant agricultural advancement. Since the hydrogel is oxygen permeable, which could improve the water intake, it provides seeds with continuously occurring moisture and the oxygen required for germination metabolism, radical emergence, and elongation (Dingley et al., 2025). Moreover, seed coatings using hydrogels can also be incorporated with crop nutrients, which are gradually released, enhancing plant nutrient absorption (Rizwan *et al*., 2021). The abundant renewable resources such as alginate and carrageenan can be used as hydrogels for seed coatings because they have a high capacity for water absorption and retention, which can gently release water to plants when needed (Adjuik *et al*., 2022).

Alginate isolated from brown algae's cell walls (*Laminaria digitata* and *Ascophyllum nodosum*) contains calcium, magnesium, and sodium salts of alginic acid. It is a linear water-soluble polysaccharide consisting of α-D-mannuronic acid and β-L-guluronic acid. Different forms of alginates are used in various industries, which is due to their unique thickening, stabilising, suspending, gel-producing, and emulsion-stabilising properties (Łabowska *et al*., 2019). Carrageenan is a type of sulphated polysaccharide obtained from the cell walls of different species of red seaweeds. There are 3 main types of carrageenan, each with unique chemical structures and properties: kappa carrageenan (κ-carrageenan), iota carrageenan (ι-carrageenan), and lambda carrageenan (λ-carrageenan) (Cosenza *et al*., 2014). Alginate and carrageenan are highly sought-after hydrogels due to their excellent mechanical strength, moisture retention, and swelling capacity, making them ideal for various applications in agriculture, packaging, cosmetics, biosensors, biomedicine, and wastewater treatment (Leyva-jim *et al*., 2023; Selvakumaran & Idayu, 2015; Skrzypczak *et al*., 2021).

The study focuses on creating hydrogel seed coatings using polysaccharides like carrageenan and alginate combined with chitosan for cross-linking. Cross-linked hydrogels can absorb large quantities of water without dissolving due to the presence of hydrophilic groups on the polymer backbone, while the cross-links between polymer chains prevent disintegration (Liu *et al*., 2022). Oligo-chitosan integrated into hydrogels for agricultural purposes serves as a sustainable and effective delivery system for nutrients, pesticides, and growth-promoting agents, enhancing plant growth and soil health (Wang & Zhuang, 2022). This study aims to optimise hydrogel composition, characterise the prepared hydrogel, and assess germination on corn seed.

2. Materials and Methods

2.1. Materials

Oligo-chitosan was purchased from Ken Microbes Biotech (Selangor, Malaysia), while κ-carrageenan and sodium alginate were purchased from Eva Chem (Malaysia). All chemicals were used without further purification. Sweet corn seeds were bought from Crop Power (Selangor, Malaysia).

2.2. Preparation of the Carrageenan-alginate Hydrogel

Carrageenan powder was measured at 2.0, 1.8, 1.6, 1.4, and 1.2 g kg^{-1} of alginate, and the mixtures were labelled accordingly, as shown in Table 1. The powders were then thoroughly mixed in a container. Next, 100 mL of boiled distilled water was added to a 250 mL conical flask. While stirring the water continuously at a temperature above 80°C, the hydrogel powder mix was gradually added over 20 min. Once the powder was fully dissolved, the mixture was transferred into a cube mould and left to set at room temperature for 24 h. The resulting hydrogel was washed with distilled water to remove unreacted monomers and dried in an oven below 40°C until a constant weight was achieved.

Table 1. Sample names and their composition materials.

Non-modified Carrageenan-alginate hydrogel			Modified Carrageenan-alginate hydrogel	
Sample	**Carrageenan (g)**	**Alginate (g)**	**Sample**	**Oligo-chitosan (% v/v)**
C-Alg0	2.0	0	CR0	0
C-Alg1	1.8	0.2	CR1	1
C-Alg2	1.6	0.4	CR2	3
C-Alg3	1.4	0.6	CR3	5
C-Alg4	1.2	0.8	CR4	7

2.3. Preparation of Modified Hydrogels

To start, a 10% oligo-chitosan solution was prepared by dissolving oligo-chitosan in 30 mL of distilled water. The carrageenan and alginate powders were combined in the same proportion used in the previous non-modified hydrogel method. The powder mixture was added to 90 mL of boiled distilled water, and the solution was heated at 80°C with constant stirring. Subsequently, 10 mL of oligo-chitosan from the stock solution, at concentrations of 1%, 3%, 5%, and 7%, was gradually introduced into the hydrogel solution with continuous stirring until a uniform mixture was achieved.

2.4. Physical Characterisation

2.4.1 Swelling studies

Hydrogel swelling investigations were conducted at room temperature in buffer solutions with pH values of 1.2, 7, and 12. Each hydrogel sample was immersed in a petri dish containing a 30 ml buffer solution. The hydrogels were removed regularly, and the surface water was gently blotted away using filter paper before weighing. Additional swelling studies were carried out in a fresh medium for accuracy. The swelling ratio was determined by Equation (1):

$$Swelling\ ratio\ (\%) = \left[\frac{W_t - W_o}{W_o}\right] \times 100 \quad (1)$$

The term W_o represents the initial weight of the composite (%), and W_t is the weight of the swollen composite (g) at a predetermined time, t. The swelling experiment continued until the hydrogels reached equilibrium. Tests were conducted in triplicate to minimise error and are reported as a mean value. Once equilibrium was reached, the samples were prepared for the reswelling test. The fully hydrated gels were placed in Petri dishes and then in an oven at 37°C. At specific time intervals, the samples were taken out of the oven. The dry weight of the samples was measured using a Sartorius scale at room temperature. Dried samples were transferred to separate Petri dishes with a pH of 7 buffer solution to observe reswelling. This experiment was also conducted at room temperature in triplicate for increased precision.

2.4.2 Microstructure analysis for surface study by scanning electron microscopy (SEM)

The images of the surface hydrogels were recorded using the S-4800 scanning electron microscope (Hitachi Co., Ltd, Matsuda, Japan) at an accelerating voltage of 5 kV.

2.4.3 Moisture content

The moisture content of the hydrogels was assessed following the standard procedure outlined by the International Association of Official Analytical Chemistry (AOAC 1995). The samples underwent a 24-h drying process in an oven set at 100°C. The moisture content was then computed using Equation (2):

$$Moisture\ content = \left[\frac{[m_i - m_f]}{m_i}\right] \times 100 \tag{2}$$

Where m_i is the initial mass and m_f is the final mass of each sample.

2.5. Chemical Characterisation Using Fourier Transform Infrared (FTIR)

To examine the hydrogel structure, 4 mg of dried samples from unmodified and modified hydrogels were pulverised and mixed with KBr powder at a 1:10 ratio. The mixture was then compressed into sample pellets using a 500 kg cm^{-2} pressure hydraulic press. The samples were subsequently analysed using a Fourier Transform Infrared (FTIR) spectroscope (Nicolet 670 FTIR, USA), with 16 scans per sample taken at a resolution of 4 cm^{-1} across a range of 370 to 4000 cm^{-1}, at intervals of 1.0 cm^{-1} (Chavda *et al*., 2012; Martinez-Garcia *et al*., 2022).

2.6. Germination Application

Seed germination tests were conducted in a seedling tray, each with 5 cm in height and 3 cm in diameter, filled with topsoil. Germination was conducted at 25°C, with seeds buried approximately 5 mm deep in a hydrogel containing corn seeds placed on top of the soil. Three replications of the germination test, each containing 30 seeds, were conducted with daily watering. A seed was considered germinated when the radicle extended 2–3 mm. Germination counts were recorded daily until the emergence of three leaves. The moisture content of the substrate was continuously monitored during the germination period. The corn was planted in triplicates: a control (non-hydrogel) group and a group with seeds coated in a carrageenan-alginate hydrogel cross-linked with oligo chitosan. Each replicate included 30 corn seeds planted in a seedling tray. The quality of the plants was evaluated on root parameters and stem length after 14 days.

3. Results and Discussions

3.1. Physical Characterisation

3.1.1 Swelling of the gels

Swelling is attributed to changes in the polymeric chains and disruption of hydrogen bonds. Figure 1 shows that the swelling rate was initially elevated due to the dominance of ionic chemical potential differences driving the swelling process. Over time, a balance was reached between internal and external ions, leading to an equilibrium state. At this point, polymer-solvent interactions, less influenced by ionic chemical potential differences, became the dominant factor, causing a reduction in the swelling rate (Hezaveh & Muhamad, 2013). Among the samples, C-Alg0 exhibited the highest swelling at 21.0%, followed by C-Alg1, C-Alg2, and C-Alg3 (9.7%, 1.5%, and -0.3%). As time progressed, all hydrogel samples swelled at a similar rate until the first 20 s before each sample exhibited a distinct swelling rate. Only the C-Alg0 sample reached an equilibrium level of swelling after 70 s, while the other samples showed a decreasing trend in swelling.

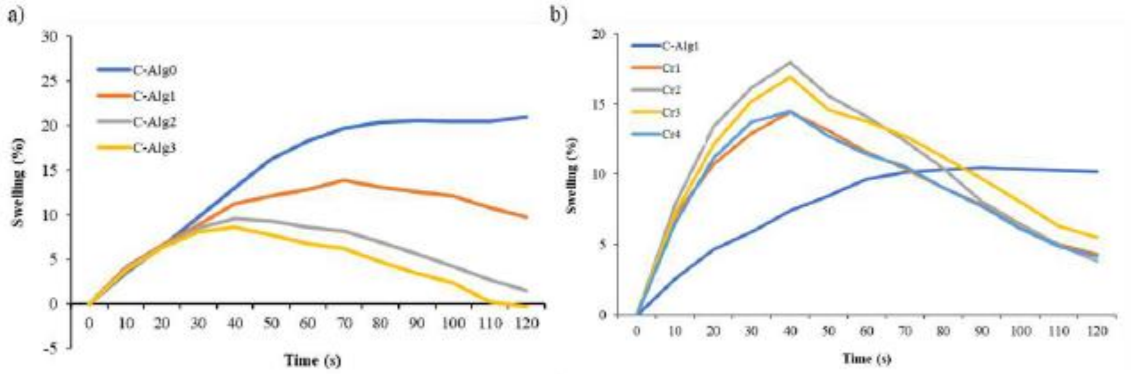

Figure 1. Swelling of a) non-cross-linked hydrogels, b) modified hydrogels.

The concentration of the cross-linker significantly impacts the hydrogel's swelling capacity of the hydrogel. An increment of the cross-linker concentration reduces the swelling capacity, while a lower concentration yields higher swelling (Palanivelu *et al*., 2022), as shown in Figure 1b. The graph indicates that the swelling ratio of hydrogel decreased noticeably as the oligo-chitosan concentration increased. Oligo-chitosan reduces swelling while enhancing the physical stability of the hydrogel. Consequently, the modified hydrogels CR1, CR2, CR3, and CR4 demonstrated improved physical stability with reduced swelling due to the addition of oligo-chitosan. This reduction in swelling is attributed to the formation of extensive cross-linked chains, which restrict the mobility of the matrix. The incorporation of oligo-chitosan as a cross-linker modified the swelling behaviour of the hydrogels in various buffer solutions, suggesting that oligo-chitosan had a significant impact on the molecular structure of the hydrogel (Hezaveh & Muhamad, 2013).

3.1.2 Microstructure using SEM

SEM is widely used to analyse the microstructure of hydrogels, offering high-resolution images that reveal detailed surface characteristics. Examining hydrogel texture is essential to confirm structural integrity and characterise the microstructure of carrageenan-alginate hydrogels cross-linked with oligo-chitosan (Chavda *et al*., 2012). Figure 1a shows the SEM images of carrageenan-alginate hydrogel with oligo chitosan as a cross-linking agent, revealing a unique network of interconnected pores, which enhances macropore connectivity. This porous architecture promotes molecule and nutrient diffusion, improving hydrogel performance. The SEM findings also highlighted the efficacy of oligo-chitosan as a cross-linker, indicating the successful interconnection of the carrageenan and alginate polymer chains.

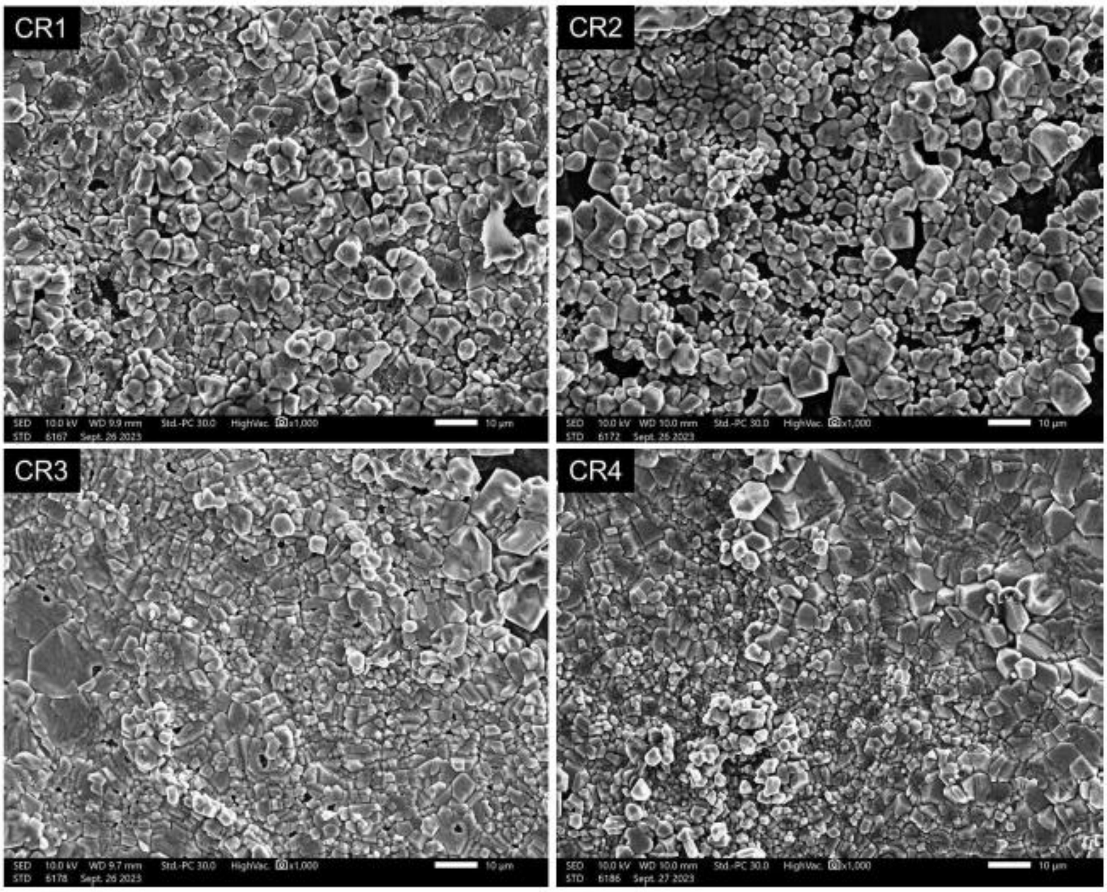

Figure 2. SEM micrograph of carrageenan-alginate hydrogels with oligo chitosan as crosslinker.

3.1.3 Moisture content

The moisture content of the hydrogel reflects its ability to absorb and retain water, a crucial factor for various applications. Water content in hydrogels can vary significantly depending on their composition and specific properties. As shown in Table 2, C-Alg2 and C-Alg1 exhibited a higher moisture content among non-crosslinked samples, which were 8.21% and 8.14%, respectively.

Table 2. The moisture content of non-crosslinking and crosslinking hydrogel

	Types	m_i	m_f	MC (%)
Non-crosslinking hydrogel	C-Alg0	7.381	7.270	1.50
	C-Alg1	8.910	8.185	8.14
	C-Alg2	7.810	7.169	8.21
	C-Alg3	7.660	7.355	3.98
	C-Alg4	7.794	7.498	3.80
Crosslinking hydrogel	CR1	8.846	8.057	8.92
	CR2	9.620	9.358	2.72
	CR3	8.453	8.033	4.97
	CR4	10.226	9.254	9.51

As for the modified hydrogel, CR4 demonstrated the highest moisture content at 9.51% (Table 2). These results suggest that cross-linked hydrogels have a greater water-holding capacity, maintaining high moisture content even at elevated temperatures. This high-water retention and vapour adsorption make the hydrogel film suitable for packaging applications, especially for moisture-sensitive foods or items exposed to high humidity (Tavassoli-Kafrani *et al*., 2016). Figure 3 illustrates the overall moisture content comparison between modified and non-modified hydrogels.

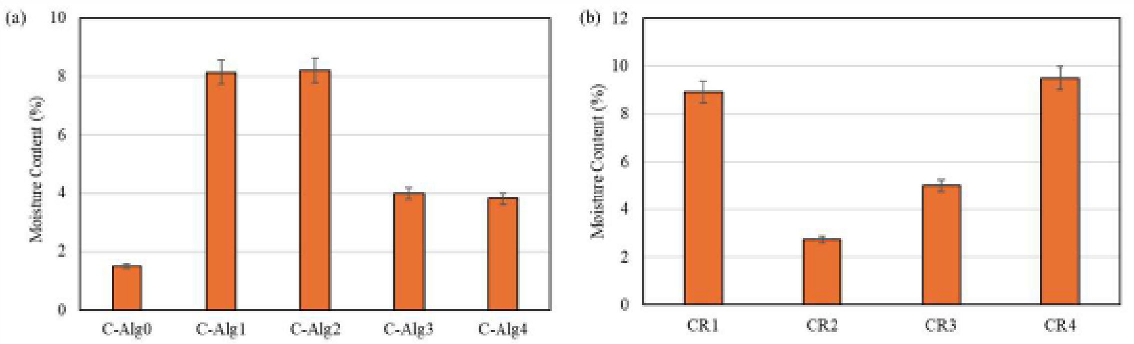

Figure 3. The moisture content of (a) carrageenan-alginate (non-crosslinking) hydrogel and (b) crosslinking hydrogel

3.2. Chemical Characterisation Using FTIR

The FTIR spectra of the modified hydrogels are shown in Figure 4. According to Yan *et al*. (2024), the characteristic prominent bands of carrageenan appeared as peaks at 1277, 926 and 844 cm^{-1}, attributed to the ester sulphated, 3,6-anhydride galactose and D-galactose-4-sulfate groups, respectively, as illustrated in Figure 4a. The broadband peaks at 3275.79, 3293.53, and 3290.49 cm^{-1} are due to the -OH stretching in carrageenan and alginate. An absorption band at 1635.65cm^{-1} in sample CR1 corresponds to the stretching frequency of CH_2 groups, indicative of the highest carrageenan concentration. A prominent peak at 1569.34 cm^{-1} results from N-H stretching of secondary amides (-$CONH_2$), observed in the modified hydrogel of CR4, which has the highest chitosan content. The high carrageenan content in CR1 is further evidenced by the CH_2 absorption band at 1635.65 cm^{-1}, which disappears in other samples. Additionally, several peaks from 1017 cm^{-1} until 1150 cm^{-1} faded due to the decreasing carrageenan content and increasing alginate presence.

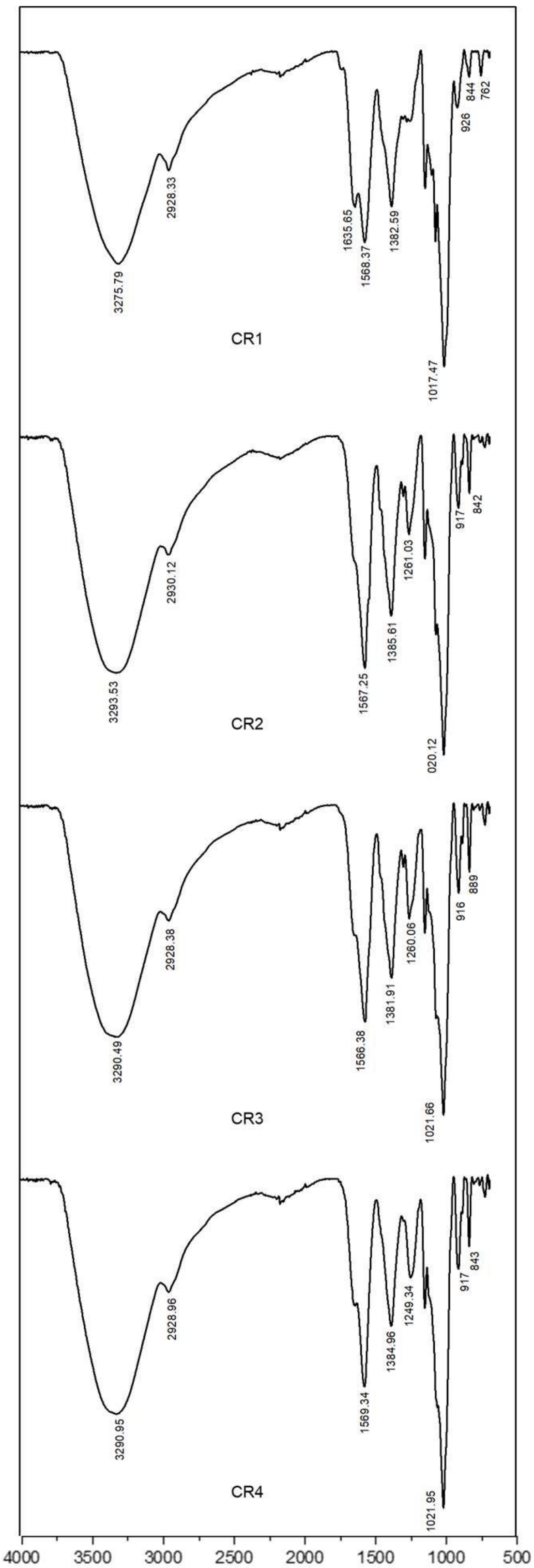

Figure 4. FTIR spectra of (a) CR1 (b) CR2 (c) CR3 (d) CR4

3.3. Germination of Corn Seed

The germination rate of corn seeds coated with carrageenan-alginate hydrogel, using oligo chitosan as a cross-linking agent, was significantly higher than the uncoated seeds. This increase in germination rate was a notable outcome of the study, emphasising the hydrogel's effectiveness as a seed-coating material. Our finding aligns with previous research that demonstrated the potential of hydrogel seed coatings to create favourable germination conditions (Skrzypczak *et al*., 2021).

Figure 5 shows the variations in stem and root growth with three replicates. The high root volume can be seen for the control sample since the root was inside the soil (Figure 5a). Roots system compaction is a highly desirable trait, as it enhances water and nutrient uptake. However, excessive root growth can compromise plant health by limiting space for optimal root development and nutrient absorption. To address this, seedlings would require transplanting from trays into larger pots with fresh potting soil. In contrast, the hydrogel coating can mitigate excessive root growth, allowing seedlings to thrive without immediate transplanting. Furthermore, hydrogel-coated seedlings improve their quality due to reduced soil-borne disease risks (Abdukerim et al., 2024).

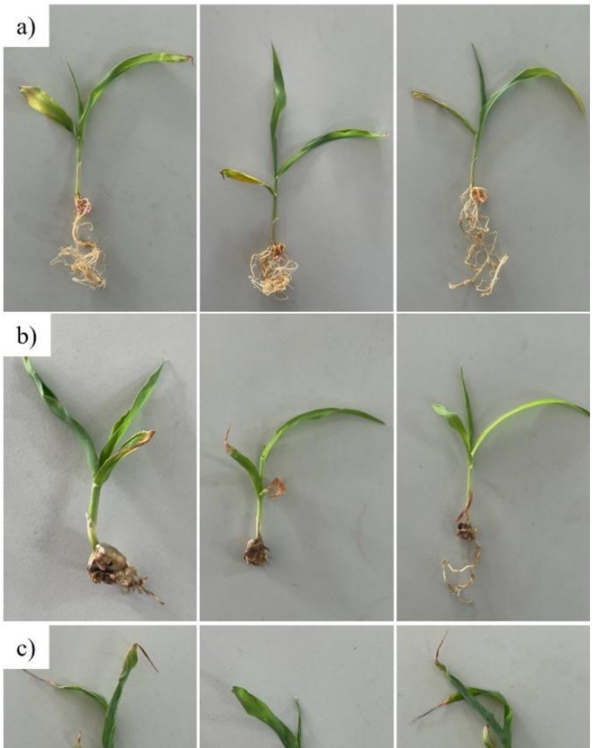

Figure 5. Corn seedlings of a) control, b) C-Alg1, and c) CR1.

Figure 6 illustrates the top three samples with the highest germination rates: the control sample (non-hydrogel seed), C-Alg1, and CR1. The control sample showed the longest stem at 13 cm, while the hydrogel-coated samples (C-Alg1 and CR1) have stem lengths of 3.7 cm and 2.3 cm, respectively. Although the hydrogel samples have shorter root lengths than the control, the increase in stem was notable, indicating a promising factor for potential high-yield crop production.

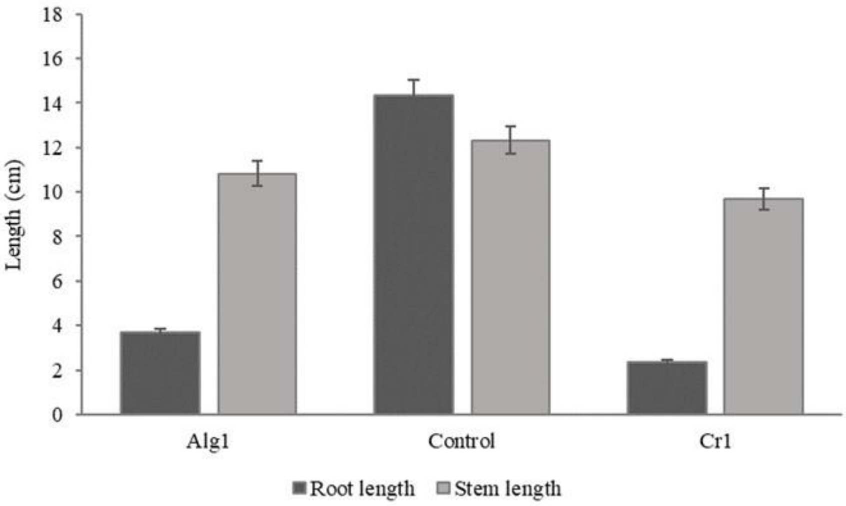

Figure 6. Roots and stem length after 14 days with three replications.

4. Conclusions

The study showed that using cross-linked carrageenan-alginate hydrogels as seed coatings in agriculture has significantly promoted seed germination and improved early corn seedling growth. A detailed investigation into the preparation of these hydrogels has yielded valuable insights into their physical and chemical properties. These findings underscore the potential of carrageenan-alginate hydrogels to enhance crop performance, conserve water, and support sustainable agricultural practices. It is recommended that carrageenan-alginate hydrogels be further developed for broader applications in agriculture. Their ability to improve crops, conserve water, and promote sustainability position for addressing the global challenges related to food security and resource conservation. As research in this field advances, continued innovation in hydrogel technologies holds significant promise for a more resilient and sustainable agricultural future.

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