# BIO-ENHANCED HYDROGEL: HARNESSING CORN HUSK FIBRE IN SODIUM ALGINATE FOR IMPROVED FERTILISER NUTRIENT DELIVERY

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## ABSTRACT

Efficient nutrient delivery remains a critical challenge in modern agriculture, as excessive fertiliser use contributes to nutrient leaching, soil degradation, and environmental pollution. Improving nutrient utilisation with reduced ecological harm is therefore imperative, necessitating the development of effective controlled-release systems. Hydrogels have recently emerged as promising carriers due to their high water retention and biocompatibility, though conventional formulations often lack sufficient structural integrity and nutrient-holding capacity. The present study focuses on the development of a bio-enhanced hydrogel by incorporating sodium alginate with corn husk fibre, an abundant agricultural by-product, to enhance nutrient delivery performance. The hydrogel was produced through a simple mixing-mediated process in an aqueous environment that can be easily scaled up. Its physicochemical properties were investigated in terms of reswelling behaviour, water absorption, gel fraction, and biodegradability. The results indicated that the 1:1 corn husk fibre-to-sodium alginate formulation exhibited the highest water-absorption capacity (281.57%) and gel fraction (681.87%), showing favourable water uptake and structural integrity. The highest reswelling capacity (166.52%) was found at the 1.5: ratio. Moreover, the hydrogel demonstrated excellent biocompatibility with soil microorganisms, thus promoting soil health and fertility. Overall, this study developed a bio-enhanced hydrogel with structural integrity, highlighting its potential as an eco-friendly and efficient controlled-release fertiliser matrix capable of increasing agricultural yield while minimising environmental impact.

**Keywords:** *Agricultural waste, biodegradability, biopolymer composites, controlled-release matrix, SDG 2, SDG 12*

## INTRODUCTION

Sustainable agriculture faces persistent challenges, such as soil degradation, inefficient fertiliser use, and water scarcity, which collectively threaten food security and environmental stability [1]. To address these issues, innovative, eco-friendly materials are needed to improve resource efficiency while maintaining ecological integrity. Hydrogels have gained increasing attention as promising agricultural materials due to their ability to retain water, regulate nutrient release, and improve soil properties, thereby supporting sustainable crop production [2]-[3].

Research demonstrated that biopolymer-based hydrogels not only enhance water retention but also promote plant growth by providing a consistent nutrient supply over time. For instance, studies indicated that these hydrogels can improve crop yields by minimising nutrient leaching and enhancing nutrient uptake efficiency [1]-[4]. They are, therefore, crucial in contemporary agricultural practices [4]-[5]. Conventional fertilisers are often highly water-soluble and dissolve rapidly in soil moisture, which accelerates nutrient loss through leaching, runoff, volatilisation, and related environmental damage [1]. Slow or controlled-release systems, therefore, offer an important strategy for synchronising nutrient availability with plant demand while reducing ecological harm [6].

Biopolymer-based hydrogels are particularly attractive for agricultural applications because they are generally biodegradable, biocompatible, non-toxic, and derived from renewable resources, thereby reducing the environmental persistence associated with many petroleum-based superabsorbents [7]-[9]. Their abundant hydrophilic functional groups, especially hydroxyl and carboxyl groups, promote strong water absorption and retention, while their three-dimensional networks can also serve as carriers for the controlled release of fertilisers and other agrochemicals [3]-[4]. These characteristics align well with the current efforts to develop agricultural inputs that conserve water, improve nutrient delivery, and support more sustainable farming systems.

In addition to their role in controlled nutrient release, biopolymer-based hydrogels play a significant role in soil rehabilitation and improved microbial dynamics. Hydrogels synthesised from natural polymers, such as starch, alginate, and cellulose, have porous structures that enhance water retention and simultaneously provide a favourable environment for beneficial soil microorganisms [10]. These microbes support nutrient cycling and organic matter decomposition, promoting healthier root zones and sustained plant growth [11].

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Despite these benefits, previous studies have revealed important limitations that continue to constrain agricultural hydrogel design. These include insufficient mechanical stability, variable performance under unfavourable soil conditions, an incomplete understanding of long-term soil interactions, and major challenges in achieving precise nutrient-release control at the field scale [7]. Crucially, natural polymers alone often fail to provide adequate structural integrity for controlled-release fertiliser systems. Additionally, studies on alginate-based composites remain fragmented, with retention and slow-release mechanisms still poorly understood. These unresolved gaps directly motivate the present effort to develop and optimise a reinforced biopolymer network.

To overcome these structural and functional limitations, this study explores the development of a novel bio-enhanced composite hydrogel by reinforcing sodium alginate with corn husk fibre. Sodium alginate, a naturally derived polysaccharide from brown seaweed, is highly valued for its water-holding capacity, biodegradability, and gel-forming characteristics. Its practical application is enhanced by its simple ionic cross-linking with polyvalent cations such as $Ca^{2+}$, which enables the formation of adjustable gel networks under aqueous conditions [12]. To provide the mechanical reinforcement that pure natural polymers lack, we incorporate corn husk fibre, an abundant, lignocellulosic agricultural by-product that also enhances soil aeration and supports beneficial microbial activity [10]. More broadly, cellulose-rich agricultural fibres are attractive reinforcing materials because they are renewable, readily available, environmentally compatible, mechanically robust, and readily modifiable, while also contributing to overall soil moisture retention and fertiliser release.

By integrating these two bio-resources, this research focuses on optimising the hydrogel composition, characterising its physicochemical properties, and evaluating its agronomic potential as an environmentally sustainable, controlled-release fertiliser carrier. The findings are expected to contribute to the advancement of green technologies for soil and crop management, supporting long-term agricultural resilience and sustainability in the ASEAN region and beyond.

## METHODOLOGY

### Materials

Sodium alginate and corn husk fibre were used as the main raw materials for hydrogel synthesis. Sodium alginate (purity ≥ 90%) was procured from Sigma-Aldrich (USA) and served as the primary polymer matrix for the hydrogel formulation. Corn husks were collected from corn harvested in Marang, Terengganu (Malaysia). Calcium chloride ($CaCl_2$), supplied by R&M Chemicals (Malaysia), was used as an analytical-grade cross-linking agent for hydrogel gelation. Deionised water was employed as the solvent for all preparations and for irrigation during plant growth trials to avoid contamination and ensure consistency.

### Preparation of Corn Husk Fibre

The corn husks were thoroughly washed with clean water to remove dirt and impurities, then oven-dried to eliminate residual moisture. The dried husks were cut and milled into smaller fibres to achieve a uniform particle size in the range of 250–500 µm. The processed corn husk fibres were stored in airtight containers to maintain purity and prevent contamination until further use. These prepared fibres were subsequently incorporated into the sodium alginate hydrogel formulations for enhanced fertiliser nutrient delivery applications.

### Preparation of Sodium Alginate and Corn Husk Fibre Hydrogel

The bio-enhanced hydrogel for sustainable agriculture was prepared by first dissolving sodium alginate in 100 mL of water to obtain a homogeneous solution. Corn husk fibre was then incorporated into the mixture at corn husk fibre-to-sodium alginate ratios of 1:2, 1:1, 1.5:1, 2:1, and 2.5:1. These ratios were systematically selected to evaluate the transition of the hydrogel from a polymer-dominated matrix to a fibre-dominated composite, allowing us to identify the precise threshold at which the reinforcing fibre optimises structural performance versus where it disrupts the cross-linked network. Subsequently, 1 g of $CaCl_2$ solution was added to initiate cross-linking, where calcium ions interacted with the sodium alginate to form a stable three-dimensional gel network encapsulating the corn husk fibres. The formed hydrogel was washed thoroughly to remove residual calcium chloride and then dried to the desired moisture content. The flow process for the preparation of sodium alginate and corn husk fibre hydrogel is shown in Figure 1.

### Water Absorption Test

Water absorption capacity test is crucial for evaluating materials such as hydrogels or absorbent polymers, especially for agricultural and moisture management applications. Uniform samples were prepared, and their initial dry weight was recorded after they were dried at room temperature until a constant weight was reached. The samples were then immersed in distilled water for 24 h. After the absorption period, the samples were removed from the distilled water, and excess water was gently removed before the final wet weight was measured. Higher percentages indicate greater water-holding capacity. This method provides valuable data for assessing material suitability for applications requiring water retention, aiding in optimisation efforts such as developing efficient superabsorbent hydrogels for agricultural water management. The water absorption was calculated as:

$$\text{Water adsorption test (\%)} = \frac{W_w - W_d}{W_d} \times 100\% \quad (1)$$

where:

$W_w$ = weight of the wet hydrogel after water absorption, and

$W_d$ = weight of the dry hydrogel before water absorption.

### Gel Fraction Test

The gel fraction assay is crucial for assessing cross-linking in hydrogels and evaluating their structural integrity and mechanical properties. Hydrogel samples were prepared and weighed before immersion in a solvent to determine the initial dry weight. After soaking, samples were re-weighed to find the final dry weight. The gel fraction, defined as the percentage of the dry weight forming the cross-linked gel network, was calculated as:



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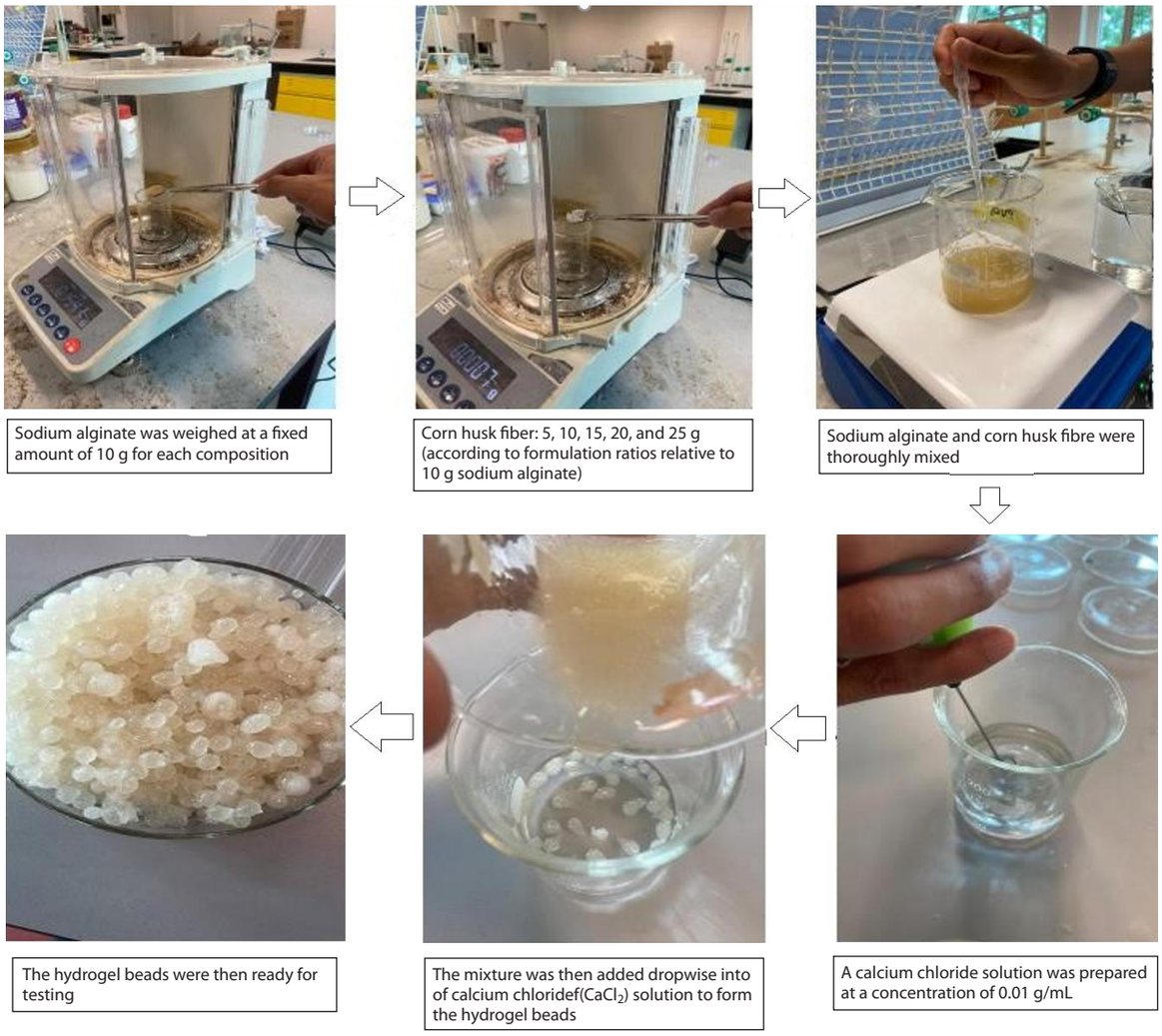


**Figure 1** Flow process for the preparation of sodium alginate and corn husk fibre hydrogel

$$\text{Gel fraction (\%)} = \frac{W_f}{W_I} \times 100\% \quad (2)$$

where:
$W_f$ = final dry weight of the insoluble residue after solvent extraction and drying, and
$W_I$ = initial dry weight of the hydrogel sample.

## Reswelling Test

The reswelling test remains important for evaluating the water absorption and reabsorption capability of hydrogel materials following drying and rehydration cycles. Uniform hydrogel samples were prepared, dried, and then rehydrated with distilled water for a set period. After excess water was removed, the samples were re-weighed to determine the reswelling ratio, indicating the hydrogel can recover its water-absorbing capacity after drying. The reswelling ratio was calculated as:

$$\text{Reswelling ratio (\%)} = \frac{W_s - W_d}{W_d} \times 100\% \quad (3)$$

where:
$W_s$ = final weight after complete absorption during the reswelling cycle, and
$W_d$ = initial weight of the dried sample before the cycle begins.

## Biodegradability (Soil Burial Test)

Biodegradability testing of the bio-enhanced hydrogel, which leverages sodium alginate, corn husk fibre, and fertiliser nutrients for sustainable agriculture, typically involves monitoring the material's degradation over 24 days. The duration of the testing period may vary, depending on factors such as the intended application of the hydrogel and the environmental conditions to which it is subjected. Typically, testing periods range from a few weeks to several months to simulate realistic degradation scenarios. For this study, 25 hydrogel beads, each weighing approximately 5 g, were prepared. The beads were buried in soil at a depth of 2 cm to simulate agricultural conditions. Specific testing durations should be determined based on factors such as the hydrogel's expected lifespan in the target environment and regulatory requirements for biodegradability testing in agricultural applications. Biodegradability was calculated as follows:



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$$\text{Biodegradability (\%)} = \frac{W_I - W_f}{W_I} \times 100\% \quad (4)$$

where:
$W_I$ = initial weight, and
$W_f$ = final weight.

## RESULTS AND DISCUSSION

### Water-Absorption Capacity

A series of experiments was conducted to examine the effects of corn husk fibre content on water barrier characteristics and biodegradability in sodium alginate hydrogel. The research findings presented in Figure 2 demonstrate the impact of corn husk fibre concentration in sodium alginate hydrogels on water absorption across different concentrations ranging from 1:2, 1:1, 1.5:1, 2:1, and 2.5:1. At a 1:2 ratio, the hydrogel exhibited a remarkable water-absorption capacity of 223.41%, indicating significant water retention capability. Increasing the corn husk fibre ratio to 1:1 resulted in a further enhancement of water absorption to 281.57%. However, at a 1.5:1 ratio, a slight decrease in water absorption (269.30%) compared to the 1:1 concentration was observed, possibly due to structural changes within the hydrogel or interactions among its components. This phenomenon suggests a delicate balance in hydrogel formulation that influences its water-absorption capacity [3]-[4]. Subsequent increases in the ratio to 2:1 led to a significant decrease in water absorption (203.79%), potentially attributed to saturation effects or alterations in hydrogel porosity. Finally, at a 2.5:1 ratio, water absorption capacity (61.73%) was substantially decreased, indicating either a saturation threshold or limited water-absorption potential. The overall pattern highlights the concentration-dependent behaviour of corn husk fibre hydrogels, where lower concentrations correlate with higher water absorption and vice versa. Understanding these variations is important for optimising hydrogel formulations to achieve the desired water-retention properties essential for sustainable agricultural applications [13].

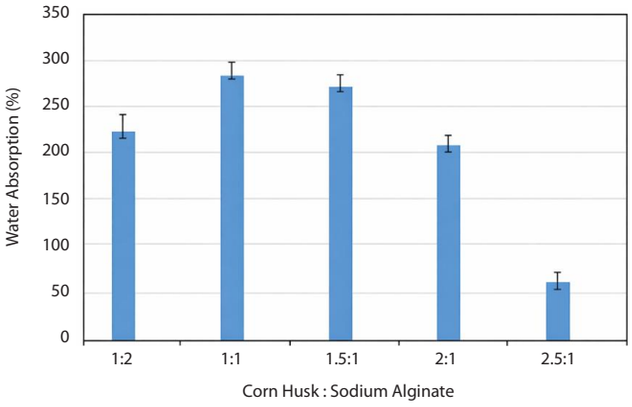


**Figure 2** Water absorption of sodium alginate with corn husk fibre hydrogel

### Gel Fraction

Figure 3 illustrates the gel fraction of a bio-enhanced hydrogel incorporating sodium alginate and corn husk fibre at various concentrations, presented as percentages. At a 1:2 ratio, the hydrogel showed an exceptionally high gel fraction of 445.42%, which indicates a dense and interconnected network structure conducive to efficient cross-linking among its components. This dense network further intensified as the concentration increased to 1:1, reaching a gel fraction of 681.87%, suggesting enhanced cross-linking density facilitated by higher concentrations of sodium alginate and corn husk fibre. El-Diehy et al. [14] demonstrated that the increase in sodium alginate decreased the gel fraction. Despite a slight decrease to 517.27% at a 1.5:1 concentration of corn husk fibre, the hydrogel maintained its dense network structure, possibly due to interactions among its components or compositional changes. Similarly, at a 2:1 ratio, the gel fraction remained at 577.21%, indicating robust gel formation. However, at the maximum corn husk fibre concentration of 2.5:1, the gel fraction decreased to 375.41%, suggesting potential saturation effects or limitations in cross-linking efficiency. The study by [15] found that using sodium alginate increased the fertiliser's water-retention capacity.

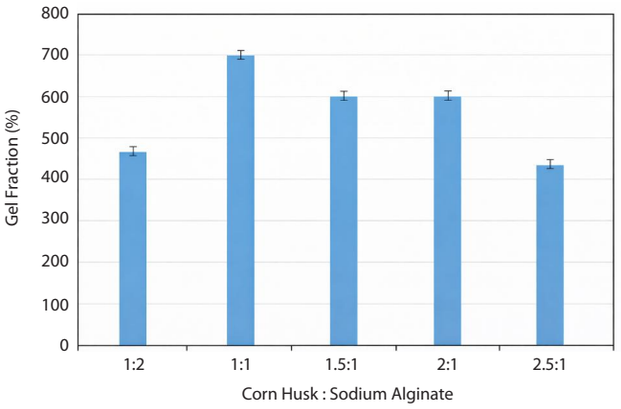


**Figure 3** Gel fraction of sodium alginate with corn husk fibre hydrogel

### Reswelling Capacity

Figure 4 shows non-linear reswelling behaviour with increasing corn husk fibre to-sodium alginate ratio. The reswelling increased from 33.63% at a 1:2 ratio. This capacity notably increased to 62.36% at a 1:1 ratio, indicating enhanced water uptake at higher concentrations of both sodium alginate and corn husk fibre. Particularly noteworthy is the sharp rise in reswelling capacity to 166.52% at a 1.5:1 ratio, which suggests that this formulation provided a favourable balance between the hydrophilic sodium alginate matrix and the water-accessible sites associated with the corn husk fibre. However, at a 2:1 ratio, the reswelling capacity decreased to 34.01%, potentially due to saturation effects or alterations in hydrogel structure. Nevertheless, at the highest concentration, 2.5:1, the reswelling capacity increased again to 81.17%, indicating the reswelling behaviour is influenced by the combined effects of fibre content, polymer network structure, and water accessibility. Hou et al. [15] suggested that at high sodium alginate loading, the sodium alginate may fill voids in the hydrogel network, effectively blocking



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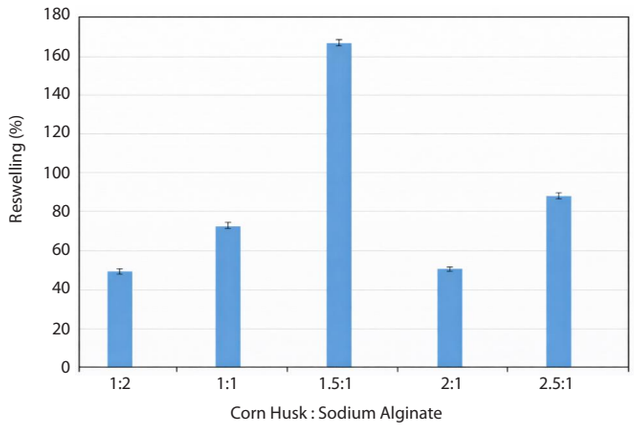


**Figure 4** Reswelling of sodium alginate with corn husk fibre

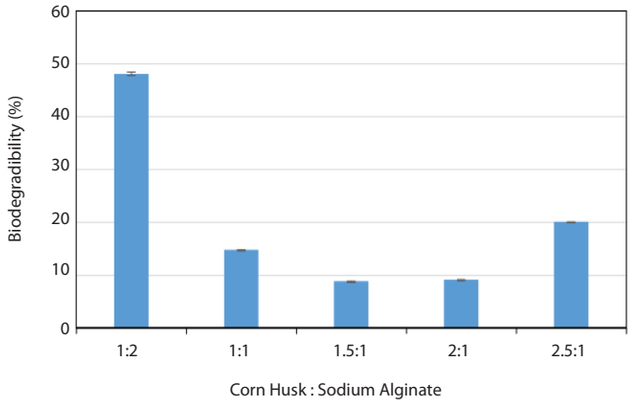


**Figure 5** Biodegradability of sodium alginate with corn husk fibre

water-accessible space and thus limiting the amount of water that can ultimately be absorbed [16].

## Biodegradability Properties

Figure 5 depicts the biodegradability of a bio-enhanced hydrogel containing sodium alginate and corn husk fibre at various concentrations. Initially, at a 1:2 ratio, the hydrogel exhibited moderate breakdown, with a biodegradability of 48.02%. However, this biodegradability decreased to 14.73% at a 1:1 ratio, indicating a slower rate of breakdown compared to the 1:2 ratio. A similar pattern was observed at 1.5:1 and 2:1 ratios, which suggests a tendency towards reduced breakdown with higher concentrations of sodium alginate and corn husk fibre. Notably, at the maximum concentration of 2.5:1 corn husk fibre, the biodegradability significantly increased to 20.03%, suggesting a potential shift in degradation behaviour at this concentration. These findings highlight a correlation between the concentration of corn husk fibre and sodium alginate and the biodegradability of the bio-enhanced hydrogel, with higher breakdown rates observed at lower concentrations. Understanding these variations is pivotal in order to evaluate the hydrogel's sustainability and environmental impacts. Biodegradable polymers provide an effective and environmentally friendly approach for controlled plant nutrient delivery and recovery. Their natural degradation in soil reduces nutrient losses and improves fertiliser efficiency while minimising ecological impact. Overall, these materials offer a sustainable pathway to enhance crop productivity and promote greener agricultural practices [17].

## Comparative Performance Analysis

To position the experimental findings within the context of contemporary advancements in biopolymer hydrogel technology, Table 1 compares the physicochemical properties and performance of the developed bio-enhanced composite with findings reported in recent literature. The comparison focuses on key properties, including water absorption, gel fraction, reswelling, and biodegradability. This comparison provides a basis for evaluating the performance of the developed composite and highlights the effects of optimising the sodium alginate-to-corn husk fibre ratio on its physicochemical and functional properties.

**Table 1** Comparison of physicochemical properties and performance of the developed bio-enhanced composite with previous studies

| Properties | Findings in the Present Study | Previous Findings | Scientific Significance |
|---|---|---|---|
| Water-Absorption Capacity | 281.57% water absorption achieved at an optimal 1:1 corn husk fibre-to-sodium alginate ratio. | Optimal water absorption in biopolymer hydrogels relies heavily on balancing hydrophilic groups and composite formulation density. | High sodium alginate provides excellent initial water-retention capacity but must be balanced with agricultural fibres to avoid network instability [3], [15]. |
| Gel Fraction | 681.87% gel fraction peaked at a 1:1 ratio, decreasing at the highest ratio of 2.5:1. | Higher concentrations of sodium alginate can lead to self-aggregation, which decreases cross-linking efficiency and gel fraction. | The 1:1 ratio provides an ideal matrix-to-filler ratio that maximises calcium-mediated ionic cross-linking density [14]. |
| Reswelling Capacity | 166.52% reswelling peaked at a 1.5:1 ratio. | High sodium alginate loading fills structural voids, which blocks water-accessible space and limits reswelling. | Incorporating moderate concentrations of corn husk fibre (1.5:1) prevents polymer matrix compaction, maintaining porous spaces for rehydration [16]. |
| Biodegradability (24-Day Mass Loss) | Moderate mass loss (14.73% to 48.02%) depending on formulation ratios. | Biopolymers undergo natural, environmentally safe degradation in agricultural soils, preventing polymer accumulation. | Fibre-to-polymer formulation ratios regulate microbial accessibility and degradation rates, proving highly suitable for controlled nutrient delivery [17]. |



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## CONCLUSIONS

In summary, blending corn husk fibre with sodium alginate yielded a hydrogel with greatly enhanced moisture absorption and structural stability. Notably, a 1:1 corn husk fibre-to-sodium alginate ratio produced the highest water uptake (~281.6%) and densest gel network (~681.9% gel fraction), indicating an optimal formulation. This composition balanced strong swelling with network integrity. Although a 1.5:1 fibre blend produced the greatest reswelling capacity (166.5%), higher fibre content beyond 1:1 reduced total absorption and cross-link density. These results suggest that moderate fibre incorporation maximises the hydrogel's water-retaining performance while preserving structural robustness. These findings have practical implications for sustainable agriculture. The optimised hydrogel can reduce irrigation needs and fertiliser runoff by storing water and slowly releasing nutrients in the soil. Using husk, an abundant waste from corn production, adds value to crop residues and aligns with circular economy principles. The developed hydrogel thus offers a scalable, eco-friendly soil amendment that boosts crop yields and conserves resources. In practical terms, farmers could employ this biohydrogel to improve soil moisture management and nutrient delivery under water-limited conditions, aligning with sustainable farming objectives.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

## AUTHORS' CONTRIBUTION

Wan Zarina Wan Mohamed conceptualised the study and drafted the manuscript. Mohamad Ridhuan Zikry Razali collected and analysed the data. Tuan Azmar Tuan Daud and Noor Halini Baharim reviewed and edited the manuscript critically for intellectual content. All authors read and approved the final version of the manuscript.

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