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Synthesizing Novel Biodegradable Hybrid hydrogels for Sustainable Agriculture

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ABSTRACT

Hydrogels, known for their ability to retain large amounts of water, have emerged as a promising solution for improving soil moisture retention and reducing irrigation needs. However, synthetic hydrogels often present environmental and economic drawbacks due to their high cost and non-biodegradable nature. This study aims to address these challenges by developing environmentally friendly hybrid hydrogels using organic waste materials, specifically coffee husks, cross-linked with ethylenediamine, maleic acid, Polyvinyl Alcohol (PVA), and borax. The hydrogels were synthesized using a simple chemical process, and their physical properties were characterized by Fourier Transform Infrared (FTIR) Spectroscopy. The swelling properties of the hydrogels were evaluated in the laboratory using a UV-Vis Spectrophotometer, with the hydrogels achieving a water absorption capacity of up to 2000% of their weight. Additionally, the hydrogels' water retention capacity was tested in pilot farms, demonstrating their effectiveness in real-world agricultural conditions. Machine learning algorithms were also employed to predict the water retention capacity of the hydrogels, achieving a high level of accuracy. Biodegradability tests showed that the hydrogels degrade efficiently, offering an eco-friendly alternative to traditional synthetic materials. The findings of this study highlight the potential of these hybrid hydrogels as a sustainable solution for enhancing water management and improving agricultural productivity in water-scarce regions, particularly in arid and semi-arid areas.

Keywords: Hybrid Hydrogels, Biodegradable, water Management, Machine Learning

Introduction

Water scarcity remains a significant challenge in agricultural production, especially in arid and semi-arid regions, where irregular rainfall patterns and high evaporation rates strain water resources. Traditional irrigation methods, such as flood and sprinkler irrigation, are inefficient and lead to substantial water losses through evaporation and runoff, reducing the available water for crops. As global water demand continues to rise, innovative solutions are urgently needed to address water scarcity in agriculture.

Hydrogels have gained attention as an effective water retention material in agriculture due to their high water-absorbing capacity. These materials consist of cross-linked polymer networks that can absorb large amounts of water and retain it in the soil, making it available to plants during dry spells. Hydrogels can help conserve water by reducing evaporation and improving water retention in the soil, leading to enhanced crop yields and reduced irrigation needs [1]. Despite their potential, the use of hydrogels in agriculture is currently limited by several factors, including high production costs, environmental concerns related to non-biodegradable synthetic polymers, and variations in their performance depending on soil type and environmental conditions.

Recent studies have focused on developing hybrid hydrogels that combine natural and synthetic polymers, aiming to combine the advantages of both types of materials [2-4]. Natural polymers, such as starch and cellulose, offer biodegradability

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and sustainability, while synthetic polymers contribute to the mechanical strength and durability of hydrogels [2]. By developing hybrid hydrogels, it is possible to achieve a balance between water retention, mechanical strength, and environmental compatibility.

Recent developments in hydrogel science and engineering have targeted enhancing the property, environmental and specific niche characteristics of hydrogels especially as a soil amendment. There has also been significant advancement in developing of superabsorbent polymer (SAP) hydrogels with improved water absorbing and releasing characteristics to the plants [5]. SAPs have been modified to swell to hundreds of their weight in water and that makes them useful in regions experiencing minimal rainfall. Slow release of moisture from these hydrogels helps increase the water holding capacity of the soil thus making the water continually available to crops in water scarce environments [6]. One more breakthrough has been achieved in the creation of bio-synthetic hydrogels; the composites of synthetic and natural polymers [7]. Whereas, members of the synthetic polymers show good mechanical strength and water absorption ability, cellulose and chitosan polymers are eco-friendly and biodegradable. Scientists have focused on applying these substances to fabricate composite hydrogels capable of swelling in water and breaking down with no production of toxic byproducts.

This innovation fits the performance specifications of modern agriculture as well as the issue of ecological sensitivity to synthetic substances [8]. Another step forward in the development of hydrogel systems is the design of intelligent hydrogels, whose response is based on external signals including temperature, pH, and moisture [9]. Porous hydrogels are those that can change their characteristics in response to varied environmental conditions and are ideal for use in precision agricultural [1]. For example, osmotic hydrogels swell when temperature is low by stretching and absorbing more water and shrink at high temperatures while releasing water to crops [10]. Hence, the plant get water at the appropriate time as opposed to watering the plants at random when most of it could be wasted through evaporation.

Besides swelling, the recent study has shifted towards the action to transport nutrients by hydrogels. Hydrogels using encapsulated fertilizers and agrochemicals have been introduced and designed to release nutrients to plants regularly [11]. This innovation decreases the number of time fertilizer is applied thereby reducing nutrient run off and polluting the environment, making it easier to adopt sustainable methods in farming. Artificial Intelligence (Al) hydrogel fertilizers have shown enhanced crop yield coupled with minimized environmental impact of agriculture [12]. Further research advancements to increase the efficiency of hydrogels preparation have involved cost effective synthesis techniques like radiation synthesis and use of locally sourced natural materials [2]. Such developments have effectively brought the cost of hydrogels down to a level that is more accessible to the smallholder farmers in the developing world making it easy for these technologies to become part of the agricultural market.

Therefore, the modern hydrogel science and new generation hydrogels like superabsorbent, hybrid, stimulus responsive and nutrient encapsulating hydrogels, are opening new horizons for efficient and effective agriculture [13]. Hydrogels do work on solving some of the important problems like water shortage, eroding soil health, and environmental issues making them an important device to tackle future agriculture challenges [14].

Methodology

A mixed-methods approach was adopted for this study, incorporating both laboratory experiments and field trials. The laboratory experiments focused on the synthesis and characterization of the hybrid hydrogels, while the field trials aimed to evaluate the practical application of these hydrogels in enhancing soil water retention and supporting crop growth. In the field, various hydrogel formulations were tested to identify the most effective compositions for improving water retention in different soil types.

The hybrid hydrogels were synthesized using coffee husks as the primary natural polymer, which were cross-linked with a combination of ethylenediamine, maleic acid, Polyvinyl Alcohol (PVA), and borax.

The swelling behavior of hydrogel samples was assessed using the gravimetric method. The swelling ratio was then calculated using the formula:

$$Swelling\ ratio\,(\%) = \frac{w_1 - w_0}{w_1}$$

where w_0 represents the dry weight of the sample and w_1 is the swollen weight [15]. The procedure was repeated in triplicate to ensure reproducibility.

To evaluate the water retention capacity of sandy soil and clay soil with and without hydrogel, a standard procedure was followed in which the experiment aimed to simulate typical soil moisture retention and assess the effect of hydrogel on this process.

To investigate the effect of pH on the water uptake capacity of the hydrogel, a controlled experiment was designed to evaluate how variations in pH levels influence the swelling behavior of the hydrogel when immersed in aqueous solutions of different pH values.

To complement the experimental evaluations, machine learning (ML) models were developed to predict the water retention capacity of the hydrogels based on their chemical composition and environmental conditions. The Figure below shows the methodology of the hydrogel synthesis process:

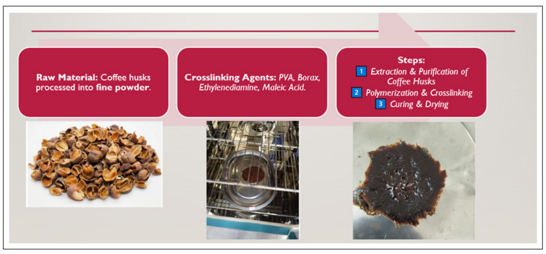

Figure 1: A table showing the process of hydrogel synthesis

Results and Discussion

Swelling Behavior of Hydrogel in Different Saline Solutions

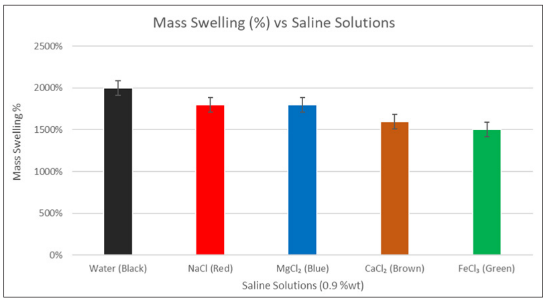

Figure 2: A graph of mass swelling % vs saline solutions

The swelling behavior of the hydrogel was tested in five different saline solutions: distilled water (as a control), and aqueous solutions of NaCl, $MgCl_2$, $CaCl_2$, and $FeCl_3$. It evident that the hydrogel swells most effectively in distilled water, reaching a swelling percentage of 2000% as shown in Figure 2. However, the presence of salts in the solutions results in a significant reduction in the hydrogel's swelling capacity. Notably, the hydrogel swells to a lesser extent in saline solutions, with NaCl and $MgCl_2$ resulting in the highest swelling (1800%), followed by $CaCl_2$ and $FeCl_3$ (1600% and 1500%, respectively) as shown in Figure 2.

FTIR spectrum of the Hybrid Hydrogel

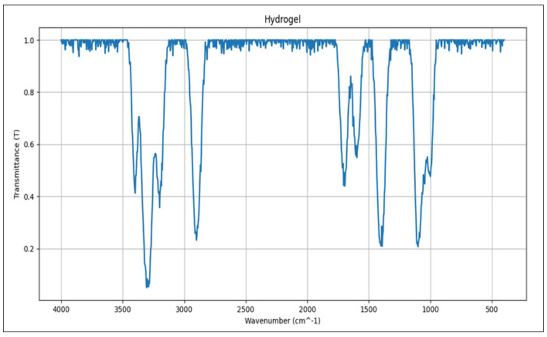

Figure 3: FTIR spectrum of the hybrid hydrogel

As shown in Figure 3., the FTIR spectrum shows prominent peaks around 3300 cm^{-1} (O-H stretch) and 1700 cm^{-1} (C=O stretch), indicating the presence of hydroxyl and carbonyl groups from PVA, cellulose, and citric acid. Key functional groups like B-O (around 1000 cm^{-1}) from Borax, CO_3^{2-} (around 1400 cm^{-1}) from Sodium Bicarbonate, and N-H (around 3300 cm^{-1}) from Ammonium Persulfate are clearly identified.

Water Retention in Sandy and Clay Soils with and without Hydrogel

The experiment aimed to evaluate the impact of a hydrogel on water retention in sandy soil and clay soil over a period of 20 days. The results highlight the significant role of the hydrogel in enhancing water retention, particularly in sandy soil, which typically has poor moisture-holding capacity. The following discusses the observed trends and the implications of these results.

In sandy soil, without the hydrogel, water retention decreased dramatically over time. At Day 0, the water retention was 30%, but by Day 20, it had dropped to a mere 5% as shown in Figure 4. This behavior is expected, as sandy soils have larger particles and greater permeability, which allows water to drain quickly, resulting in rapid loss of moisture.

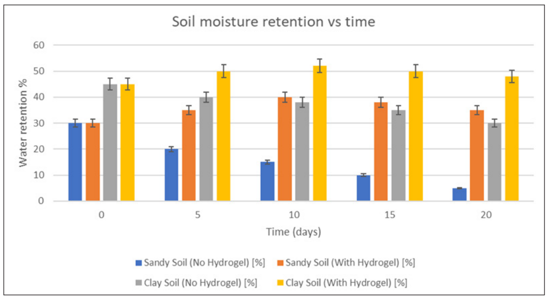

Figure 4: A bar chart of soil moisture retention vs time

Swelling Behavior as a Function of pH

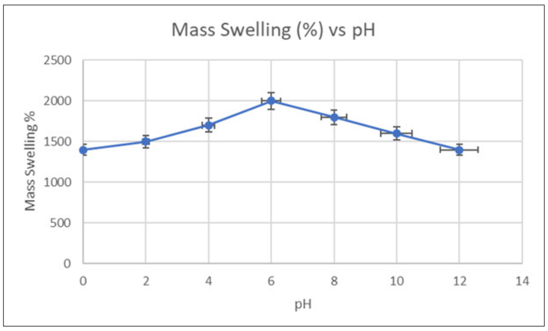

Figure 5: Mass swelling vs pH

The graph of mass swelling (%) versus pH (Figure 5) provides valuable insights into how the swelling behavior of the hydrogel changes across different pH levels. The data reveals that the hydrogel exhibits a characteristic response to pH variations, with a peak swelling capacity observed at pH 6, followed by a decline in swelling at both lower and higher pH values.

The maximum swelling capacity of 2000% at pH 6 suggests that the hydrogel is most effective at absorbing water in slightly acidic to neutral conditions as shown in Figure 5. This behavior is consistent with the typical swelling properties of hydrogels, which can be influenced by the charge density and ionic interactions in the surrounding environment. At pH 6, the hydrogel is likely in an optimal state for interaction with water molecules, leading to maximal hydration and swelling.

Sample Result from the Hydrogel predictor

Once a trained model was developed, the farmers were required to key in values of farm size, altitude and temperature and then the app will predict the amount of hydrogel needed. Figure 6., shows the farmer's 2-acre farm at 1500 meters altitude required 2.47 kg of hydrogel, calculated at 3.09 grams per plant for 800 plants, to manage soil moisture over 90 days under high rainfall conditions (above 1200 mm/year) and a mild 23°C temperature. Hydrogel was recommended to mitigate water fluctuations, but drainage systems such as trenches or raised beds were prioritized to prevent root rot caused by excessive rainfall. The farmer was advised to select water-tolerant crops like rice or taro and monitor rainfall patterns to optimize irrigation adjustments, ensuring hydrogel efficacy in balancing moisture retention and drainage in the high-rainfall environment.

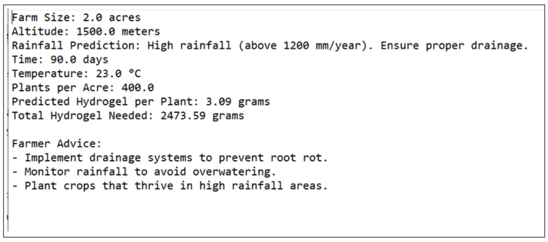

Figure 6: sample predictor results

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