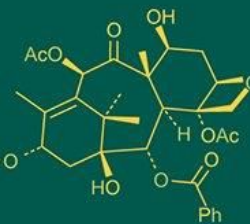


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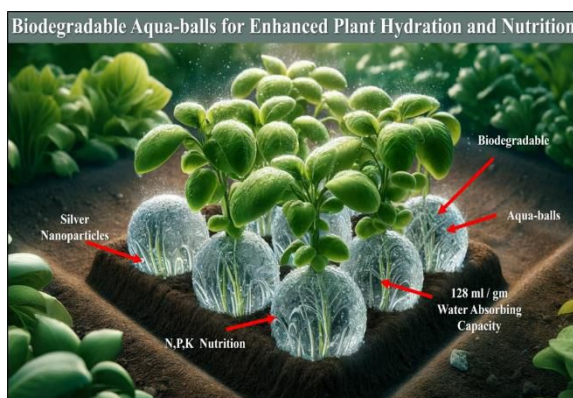
Biodegradable aqua-balls for enhanced plant hydration and nutrition

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Abstract

This paper presents the development of a novel hydrogel-based aqua ball designed to enhance plant hydration and nutrition in sustainable agricultural practices. The hydrogel consists of a polymeric matrix made from carboxymethyl cellulose (CMC) and starch, which are physically or chemically cross-linked to create a highly hydrophilic structure. The aqua balls exhibit exceptional water absorption and retention capabilities, absorbing up to 248 mL of water per 2 grams of material, ensuring a gradual release of moisture into the soil. This slow water release supports sustained hydration for plant roots, particularly in drought-prone conditions. In addition to water retention, the hydrogel is enriched with essential macro- and micronutrients, promoting consistent and robust plant growth. Silver nanoparticles are incorporated into the matrix to provide bacteriostatic properties, reducing soil-borne pathogens and enhancing plant health. This dual functionality of water and nutrient release, along with microbial control, reduces the need for synthetic fertilizers and pesticides, contributing to more sustainable and environmentally friendly agricultural practices. The study highlights the potential of this hydrogel-based technology to optimize water utilization, improve nutrient absorption, and mitigate plant diseases, marking a significant advancement in agricultural innovation.



Highlights

- Exceptional water absorption and retention, absorbing up to 248 mL of water per 2 grams, with gradual moisture release for sustained plant hydration.
- Enriched with essential macro- and micronutrients to promote consistent and robust plant growth.
- Incorporation of silver nanoparticles for bacteriostatic properties, reducing soil-borne pathogens and enhancing plant health.
- Dual functionality reduces the need for synthetic fertilizers and pesticides, contributing to sustainable and eco-friendly agricultural practices.

Keywords: Biodegradable aqua balls, CMC, starch, silver nanoparticles, plant hydration, nutrient release, antimicrobial properties

Introduction

Sustainable agriculture has become an urgent global imperative, driven by the mounting challenges associated with traditional farming practices, including water scarcity, soil degradation, and the excessive use of chemical fertilizers and pesticides ^[1]. The environmental consequences of these conventional methods are profound: from groundwater

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contamination and declining soil fertility to disruptions in ecosystem balance [2]. Additionally, the heavy reliance on irrigation and synthetic agrochemicals has not only accelerated resource depletion but also led to the buildup of hazardous residues, threatening both biodiversity and human health [3]. As the global population continues to grow, the need for efficient, eco-friendly agricultural innovations has never been more critical [4]. In response to these pressing challenges, the development of biodegradable hydrogel-based solutions has emerged as a revolutionary advancement in agricultural technology [5]. Hydrogels, known for their remarkable ability to absorb and retain vast amounts of water, present a promising strategy to optimize water use, improve soil structure, and enhance nutrient absorption [6]. By minimizing water loss and enabling controlled nutrient release, these materials offer a sustainable means to boost plant hydration and growth, even under conditions of limited water availability [7].

One of the most innovative hydrogel-based technologies is the Next-Gen Biodegradable AquaBalls, which are crafted from carboxymethyl cellulose (CMC) and starch—both eco-friendly, biodegradable polymers [8]. These AquaBalls are engineered to tackle multiple agricultural challenges concurrently [9]. By embedding silver nanoparticles within the hydrogel matrix, AquaBalls not only provide a slow and sustained release of water but also exhibit potent antimicrobial properties, effectively combating soil-borne pathogens that cause plant diseases [10]. This dual functionality promotes healthier plant growth while minimizing the need for chemical treatments [11]. Furthermore, the controlled release of vital nutrients embedded in the AquaBalls ensures a steady supply of nourishment, reducing the frequency of fertilizer applications and mitigating nutrient runoff [12].

This research delves into the synthesis, characterization, and practical applications of biodegradable AquaBalls in contemporary farming practices [13]. It evaluates their performance in enhancing water management, improving nutrient delivery, and providing microbial protection, all while emphasizing environmental sustainability [14]. By integrating these advanced materials into agricultural systems, AquaBalls offer a forward-thinking solution that not only reduces the ecological footprint of farming but also enhances crop yield and resilience [15]. This work aims to demonstrate how AquaBalls can transform conventional agriculture into a more efficient and sustainable enterprise, paving the way for greener, resource-conserving farming techniques that align with the principles of environmental stewardship and food security [16].

Materials and Methods

All the materials, including Carboxymethyl Cellulose (CMC), Starch, Silver Nitrate (AgNO_3), Sodium Borohydride (NaBH_4), NPK Nutrients (Nitrogen, Phosphorus, Potassium), and Citric Acid (27%), were purchased from Sigma-Aldrich, Mumbai. Distilled water was used for all preparation and experimental procedures.

Method

To prepare the carboxymethyl cellulose (CMC) hydrogel solution, 9 g of sodium CMC powder was weighed using an analytical balance. The CMC powder was then added to 100 ml of deionized water in a beaker and stirred continuously with a magnetic stirrer to prevent clumping. The mixture

was heated to 80°C on a hot plate while stirring until the CMC was completely dissolved. This process continued for six hours, after which the solution was allowed to cool to room temperature. For the preparation of the starch suspension, 4 g of starch powder was weighed and dispersed in 50 ml of deionized water in a separate beaker, with vigorous stirring to ensure uniform dispersion. The starch suspension was heated on a hot plate at a temperature of $80\text{--}90^\circ\text{C}$ to facilitate gelatinization. Stirring continued until a homogeneous suspension was obtained, and then the solution was cooled to room temperature.

To blend the CMC solution and starch suspension, the two were combined in a 1:0.5 ratio based on the desired hydrogel properties. The mixture was stirred vigorously to ensure thorough blending of the components. If necessary, the pH was adjusted using a buffer solution to optimize hydrogel formation and stability. The cross-linking process was initiated by introducing a 27% citric acid solution as a cross-linking agent to enhance the mechanical strength and stability of the hydrogel. Sufficient time was allowed for complete gelation to occur.

Silver nanoparticles were incorporated into the hydrogel using a chemical reduction method. First, a 12 mM silver nitrate solution was prepared by dissolving AgNO_3 in distilled water, serving as the silver ion precursor. A freshly prepared 6 mM solution of sodium borohydride (NaBH_4) was then added slowly to the silver nitrate solution under continuous stirring, acting as a reducing agent. The color change from colorless to yellow or brown indicated the formation of silver nanoparticles, which were then added to the hydrogel solution. Finally, NPK (nitrogen, phosphorus, and potassium) nutrients were incorporated into the formulation to further enhance the AquaBalls' capability to support plant growth.

Result and Discussion

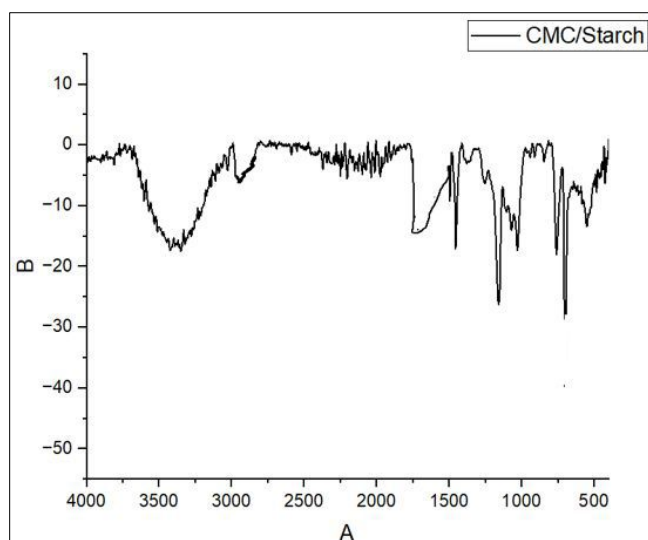


Fig 1: IR spectra of AquaBalls

The infrared (IR) spectrum of CMC/Starch hydrogel shown in Fig.1 typically exhibits characteristic absorption bands corresponding to the stretching vibrations of hydroxyl (OH) and carboxylate (COO^-) groups in CMC, starch, and their derivatives. Broad and intense absorption band in the range of $3200\text{--}3600\text{ cm}^{-1}$ indicates OH stretching vibrations, while peaks around $1600\text{--}1700\text{ cm}^{-1}$ are attributed to COO^-

stretching vibrations. Additional absorption bands in the fingerprint region ($1500\text{--}600\text{ cm}^{-1}$) may indicate the presence of hydrogen bonding interactions within the hydrogel network. The presence of C-O-C glycosidic linkages in the polysaccharide backbone of both CMC and starch is evidenced by peaks in the range of $1000\text{--}1200\text{ cm}^{-1}$. Overall, the IR spectrum provides valuable information about the chemical composition, molecular structure, and interactions within the CMC/starch hydrogel network.

In a scanning electron microscopy (SEM) image of silver nanoparticles incorporated into a hydrogel matrix (Fig.2), the morphology and distribution of the nanoparticles within the hydrogel can be observed at high magnification. The SEM image reveals the surface topography of the hydrogel, showing the presence of embedded silver nanoparticles as distinct, often spherical or irregularly shaped features. This confirms successful incorporation of silver nanoparticles into hydrogel matrix.

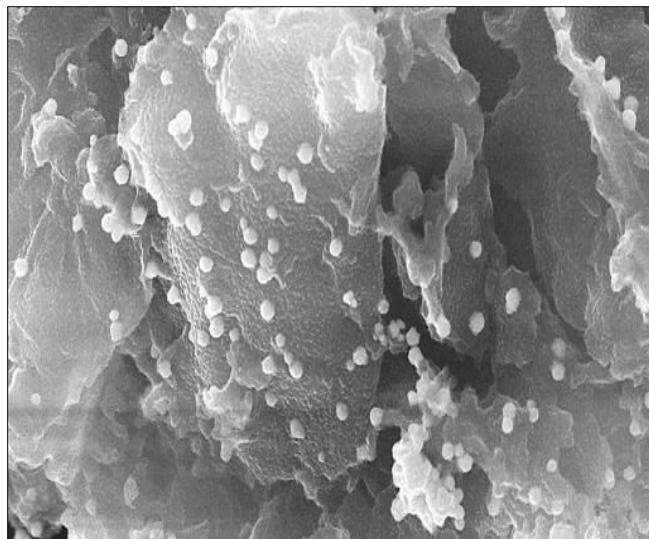


Fig 2: SEM image of silver nanoparticle incorporated Aquaball

$$Q = \frac{250\text{ g}-2\text{ g}}{2\text{ g}} = \frac{248\text{ g}}{2\text{ g}} = 124$$

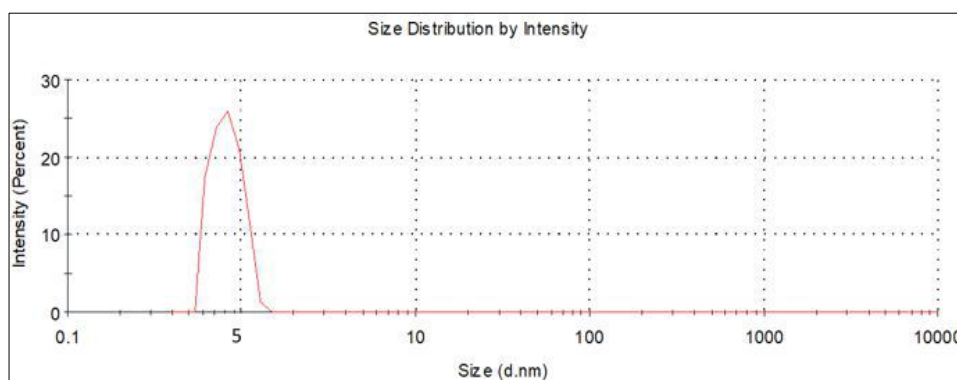


Fig 3: DLS study of silver nanoparticles

The DLS examination of the sample is depicted in Fig.3. It reveals that the particle size distribution is primarily concentrated within the range of 5-7 nm. This finding highlights the predominant diameter of silver nanoparticles suspended within the solution.



Fig 4: Practical application of Aquaballs

Fig.4 depicts a practical scenario where two Aquaballs are placed within the mud surrounding a plant. It was observed that initially the plant's soil appeared to be dry, indicating a lack of moisture. As water was added to the soil, the Aquaballs begin to absorb the water, expanding in size. This expansion is visually represented in the figure as the Aquaballs increase in diameter, demonstrating their water absorption capacity.

Water Swelling Test and Results

Water swelling tests are conducted to evaluate the extent to which a material absorbs water when exposed to aqueous environments. This test provides insights into the material's ability to swell, which is crucial for various applications such as in the pharmaceutical, agricultural, and polymer industries.

Methodology

The prepared hydrogel sample (2 gm) was weighed and then immersed in a beaker containing distilled water. The beaker was placed in an environment with controlled temperature to ensure consistent test conditions. After 2 hours, the swollen hydrogel sample was removed from the water. The excess water on the surface of the hydrogel was gently blotted with a filter paper to ensure accurate measurement of the absorbed water. The weight of the swollen hydrogel was measured immediately using an analytical balance.

Results:

The extent of swelling was calculated by comparing the weight of the hydrogel before and after immersion in water. The degree of swelling (Q) is given by the formula:

$$Q = \frac{W_s - W_d}{W_d}$$

Where

- W_s is the weight of the swollen hydrogel,

- W_d is the weight of the dry hydrogel.

Calculations

Aqua ball exhibited an impressive swelling capacity, absorbing 124 times its dry weight in water.

Antimicrobial activity



Fig 5: Antimicrobial study of Aquaballs

The antibacterial assay was conducted to evaluate the antimicrobial activity of the hydrogel samples against microbes *Phytophthora* which negatively impact plant growth. Two samples were tested: S-1, which was the hydrogel without silver nanoparticles, and S-2, which was the hydrogel incorporating silver nanoparticles. The results of the assay indicated that S-2 exhibited significant antibacterial activity against the target microbes as shown in Fig.5. This suggests that the incorporation of silver nanoparticles into the hydrogel conferred antimicrobial properties, effectively inhibiting the growth or viability of the microbes responsible for harmful effects on plant growth. The observed antibacterial activity of S-2 highlights its potential utility in plant care applications, where protection against soil-borne pathogens and microbial

contaminants is crucial for promoting healthy plant growth and development. Further investigation and optimization of S-2 may lead to the development of innovative solutions for combating plant diseases and enhancing overall plant health in agricultural and horticultural settings.



Fig 6: Synthesized aqua balls

The image presented in Figure 6 showcases the synthesized aqua balls prepared using the described method. These aqua balls are small, spherical granules with a rough, textured surface. The granules exhibit a beige to light brown colour, indicating the presence of both carboxymethyl cellulose (CMC) and starch as primary components. The texture suggests that the aqua balls have been well-formed and dried, ensuring their Figure 7 illustrates the water swelling test of the synthesized aqua balls, showcasing their impressive water absorption and retention capabilities. The sequence of images captures the transformation of a 2-gram dry aqua ball into its fully swollen state after being immersed in water. Initially, the dry aqua ball is placed in a container, and water is gradually added. As the water is absorbed, the aqua ball begins to swell, visibly increasing in size. The final images depict the aqua ball after it has absorbed 228 mL of water, demonstrating its significant volumetric expansion. This test highlights the aqua ball's exceptional ability to absorb water up to 114 times its dry weight, which is crucial for applications in agriculture. The fully swollen state ensures sustained hydration for plant roots, supporting consistent moisture availability and promoting robust plant growth.

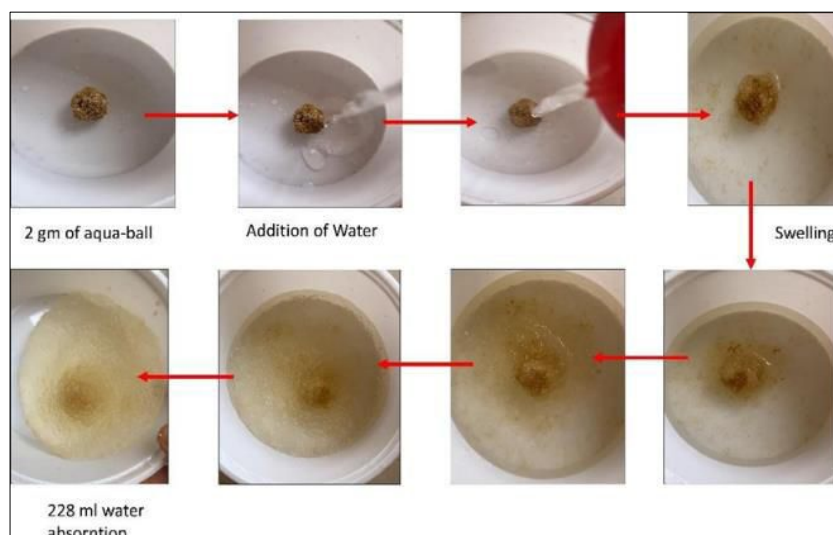


Fig 7: Actual performance of aqua-balls

Biodegradation study

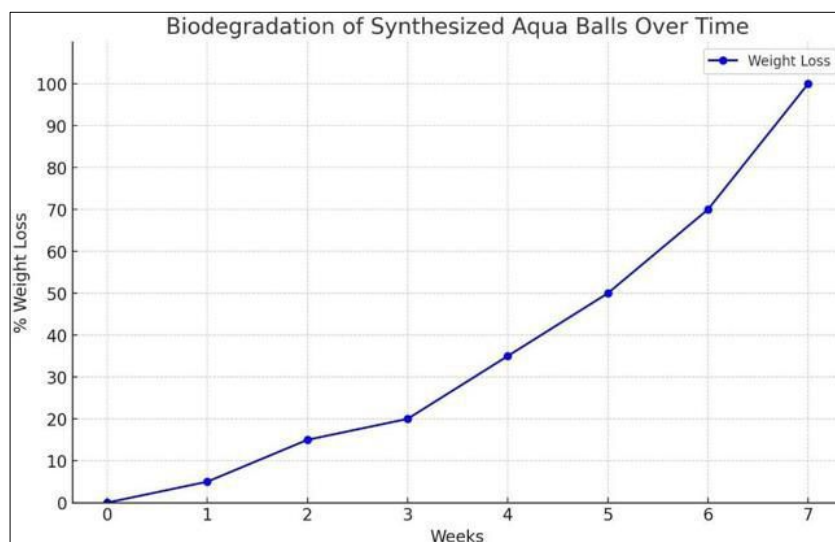


Fig 8: Biodegradation Study

	Time (weeks)	Weight (grams)	Weight Loss (%)
1	0	2.0	0
2	1	1.9	5
3	2	1.7	15
4	3	1.6	20
5	4	1.3	35
6	5	1.0	50
7	6	0.6000000000000001	70
8	7	0.0	100

Fig 8: Weight loss study

The data indicates that the synthesized aqua balls undergo substantial biodegradation over a 7-week period, with a steady increase in weight loss each week. By the end of the 7th week, the aqua balls have fully degraded, demonstrating their effective biodegradability. This characteristic makes them suitable for sustainable agricultural applications, ensuring they do not contribute to long-term environmental pollution while providing essential hydration and nutrients to plants during their functional period.

Conclusion

The development of biodegradable hydrogel-based AquaBalls marks a significant advancement in sustainable agricultural technology. By integrating carboxymethyl cellulose (CMC), starch, and silver nanoparticles, this

invention addresses key challenges such as water scarcity, nutrient management, and plant disease control. The AquaBalls' ability to absorb and retain large volumes of water ensures a gradual and sustained release of moisture to plant roots, promoting efficient water usage, particularly in drought-prone regions. Additionally, the slow release of essential macro- and micronutrients supports consistent plant growth while reducing the dependency on synthetic fertilizers. The inclusion of silver nanoparticles further enhances the functionality of the AquaBalls by controlling pathogenic soil microflora, thus reducing plant diseases and improving overall plant health. This dual approach of water and nutrient management, coupled with microbial control, not only boosts agricultural productivity but also contributes to environmental sustainability. In summary, AquaBalls

offer a comprehensive solution to modern agricultural challenges, promoting eco-friendly practices while ensuring optimal plant hydration and nutrition.

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