

<http://www.pjbs.org>

PJBS

ISSN 1028-8880

Pakistan Journal of Biological Sciences

ANSI*net*

Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan



Research Article

Valorization of Thai Purple Yam (*Dioscorea alata* L.) Starch into a Biodegradable Hydrogel-Based Nitrogen Fertilizer for Controlled Nutrient Release and Water Retention

¹Warisa Pilahome and ²Witaya Pimda

¹Department of Plant Science, Faculty of Agricultural Innovation and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima 30000, Thailand

²Department of Applied Biology, Faculty of Sciences and Liberal Arts, Rajamangala University of Technology Isan, Nakhon Ratchasima 30000, Thailand

Abstract

Background and Objective: Improving fertilizer-use efficiency and soil water retention is essential for sustaining crop production under increasing water scarcity. This study aimed to valorize starch extracted from Thai purple yam (*Dioscorea alata* L.) into a biodegradable hydrogel-based nitrogen fertilizer with slow-release and water-retention functionalities. **Materials and Methods:** Yam starch hydrogels were synthesized through citric acid crosslinking and loaded with calcium nitrate to produce a starch-hydrogel slow-release fertilizer (SH-SRF). The swelling behavior, soil water-retention capacity, nitrate-release characteristics, biodegradability and plant-growth performance under water-deficit conditions were evaluated using lettuce and tomato as model crops. **Results:** The optimized hydrogel exhibited a swelling ratio of 5.94 g/g and significantly improved soil water retention, maintaining 9.87% residual moisture after 7 days compared with 0.44% in unamended soil. In a soil-column system, conventional $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ released nearly all nitrate within 10 days, whereas SH-SRF extended nutrient release to 30 days, with cumulative NO_3^- release of 1.68%, 91.23% and 100% after 1, 20 and 30 days, respectively. The hydrogel showed partial biodegradability with 17.3% mass loss after 20 days. Under water-deficit conditions, SH-SRF markedly enhanced seedling performance. Lettuce treated with SH-SRF showed improved growth and biomass, whereas plants in the control and conventional fertilizer treatments failed to survive. A similar trend was observed in tomato, where SH-SRF produced superior growth compared with other treatments. **Conclusion:** These results demonstrate that Thai purple yam starch can be converted into a biodegradable hydrogel fertilizer that simultaneously regulates nutrient release and improves soil moisture retention, offering a sustainable strategy for crop production in water-limited agricultural systems.

Key words: Biodegradable hydrogel, nitrate release, slow-release fertilizer, starch-based hydrogel, water retention

Citation: Pilahome W. and W. Pimda, 2026. Valorization of Thai purple yam (*Dioscorea alata* L.) starch into a biodegradable hydrogel-based nitrogen fertilizer for controlled nutrient release and water retention. Pak. J. Biol. Sci., 29: 455-467.

Corresponding Author: Witaya Pimda, Department of Applied Biology, Faculty of Sciences and Liberal Arts, Rajamangala University of Technology Isan, Nakhon Ratchasima 30000, Thailand

Copyright: © 2026 Warisa Pilahome and Witaya Pimda. This is an open access article distributed under the terms of the creative commons attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Ensuring global food security while minimizing environmental impacts remains a major challenge for modern agriculture. Although fertilizers play a critical role in sustaining crop productivity, their widespread use is often linked to nutrient losses and broader environmental degradation¹. Over the past several decades, increasing food demand has driven global fertilizer consumption from 32 million metric tons in 1961 to more than 200 million metric tons in 2020². These trends highlight the urgent need for nutrient-delivery systems that enhance efficiency while reducing adverse environmental effects.

Nitrogen (N) is one of the most essential macronutrients for plant growth and productivity, yet conventional N fertilizers often exhibit low use efficiency, with approximately 50-70% of applied N lost through volatilization and leaching into the surrounding environment³. Losses are particularly severe in sandy soils, where rapid percolation elevates N concentrations in groundwater⁴. In addition, under deficit-irrigation conditions, reduced soil moisture limits nutrient mobility and root uptake, further lowering N use efficiency⁵.

Slow-release fertilizers (SRFs) have emerged as promising alternatives for synchronizing nutrient availability with plant demand and reducing nutrient losses⁶. Among these, hydrogel-based SRFs have received increasing attention due to their capacity to absorb substantial amounts of water, enhance soil moisture retention and regulate nutrient release⁷. However, many commercial hydrogels are synthesized from petroleum-derived polymers with limited biodegradability⁸, prompting interest in safer and more sustainable replacements.

These concerns have increased interest in natural, renewable and biodegradable polymer matrices, with starch-based hydrogels receiving particular attention⁹. Starch is widely available, low cost and environmentally benign and its hydroxyl-rich structure enables chemical modification to produce hydrogels with tunable swelling and mechanical properties¹⁰. Citric acid (CA) is an attractive crosslinker for starch-based hydrogels because it is inexpensive, readily available and environmentally friendly, while its carboxyl groups can form ester linkages with starch. CA is also classified as Generally Recognized as Safe (GRAS) and can degrade without harmful byproducts, making it a promising crosslinker for sustainable agricultural applications¹¹.

As sustainability concerns intensify, research interest has expanded beyond conventional starch sources such as corn, cassava, potato and wheat toward non-conventional biomass resources as alternative, renewable and potentially low-cost

sources of starch¹². Thai purple yam (*Dioscorea alata* L.) is a promising yet relatively underexplored starch source for hydrogel production. Although the tuber possesses a high starch content¹³, its commercial utilization remains limited and purified starch is not commercially available. Consequently, the extraction and utilization of starch from Thai purple yam provides an opportunity to valorize a locally available agricultural resource into value-added biodegradable materials. Compared with commonly used starch sources, the application of Thai purple yam starch in hydrogel-based fertilizer systems has received little attention, despite its potential for sustainable agricultural applications.

Although starch-based hydrogels have been extensively investigated as slow-release fertilizer matrices^{14,15}, relatively few studies have examined starch derived from non-conventional tropical tubers. In particular, the potential of Thai purple yam starch as a precursor for biodegradable hydrogel fertilizers remains largely unexplored. Furthermore, limited information is available on the water-retention, nutrient-release, biodegradation and plant-growth performance of CA crosslinked hydrogels derived from this starch source. Therefore, evaluating Thai purple yam starch as a feedstock for sustainable hydrogel fertilizer production may contribute to the valorization of a non-conventional biomass resource and the development of environmentally friendly fertilizer delivery systems.

To address these gaps, this study valorized starch extracted from Thai purple yam through the development of a CA crosslinked biodegradable hydrogel fertilizer. The hydrogel was designed to provide both slow nutrient release and water-retention functionality under water-limited conditions. Its swelling behavior, soil water-retention capacity, nitrate-release profile, biodegradability and effects on seedling growth under deficit irrigation were systematically evaluated.

MATERIALS AND METHODS

Plant material and chemicals: Tubers of Thai purple yam (*D. alata*) were obtained from local households in Nakhon Ratchasima, Thailand, in April 2025 (Fig. 1a). The tubers were soaked in tap water to remove surface dirt and sprouts were removed with a knife. The cleaned tubers were stored at 4°C and used within one week. All chemicals used in this study were of analytical grade and obtained from local suppliers.

Starch isolation: The yam starch was isolated following the method of Oliveira *et al.*¹⁶ with minor modifications. Briefly, the yam tubers were peeled, cut into small pieces (1 cm thick) and rinsed three times with 10 g/L NaCl solution to

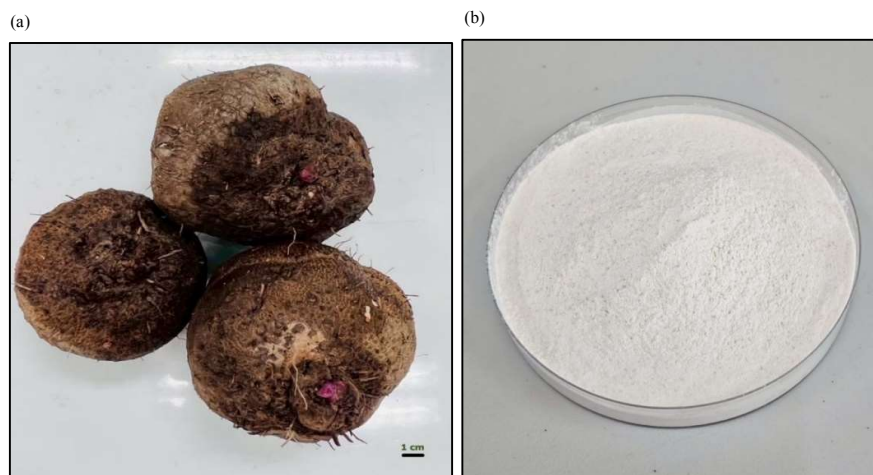


Fig. 1(a-b): (a) Tubers and (b) Starch extracted from Thai purple yam used in the study

remove latex. The pieces were then ground in 5 g/L potassium sorbate solution (1:2 w/v) using a blender to obtain a starch slurry. The slurry was filtered through cheesecloth and washed with distilled water until the filtrate became clear. The filtrate was allowed to settle overnight at 4°C and the supernatant was discarded. The settled starch layer was resuspended and washed several times with water to remove impurities. The starch was collected, oven-dried at 50°C for 72 hrs, ground using a mortar and pestle, sieved through a 60-mesh screen and stored in zip-lock bags until use (Fig. 1b).

Preparation of yam starch hydrogel: Yam starch hydrogel (SH) was prepared using a solution-casting method. In brief, yam starch (5 g) was dispersed in distilled water (100 mL) and stirred until fully hydrated. The suspension was then heated to 90°C under continuous stirring until complete gelatinization was achieved. The gelatinized mixture was subsequently cooled to 60°C, after which CA was added at concentrations of 0, 20, 40 and 60% (w/w, relative to starch) to determine the optimal crosslinker content for maximum swelling capacity and hydrogel stability. The mixture was stirred for 15 min and the pH was adjusted to 5.5-7.0 using 0.1 M NaOH. The resulting solutions were poured into cubic molds (1 cm³) and allowed to settle at room temperature for 2 hrs. Crosslinking was induced by heating the samples in an oven at 90°C, followed by drying at 50°C to a constant weight. The dried hydrogels were rinsed gently with a minimal amount of distilled water to remove unreacted CA while preserving the integrity of the crosslinked network, then oven-dried again at 50°C before use in subsequent experiments. The formulation showing the highest swelling capacity was selected for investigating the effect of glycerol on hydrogel

properties. After pH adjustment, glycerol was incorporated at concentrations of 0, 0.8, 1.6 and 2.4% (v/v, relative to the total mixture).

Preparation of starch-hydrogel slow-release fertilizer: To prepare the starch-hydrogel slow-release fertilizer (SH-SRF), 2 g of Ca(NO₃)₂·4H₂O was incorporated into the hydrogel mixture (100 mL) during the final step of SH preparation, prior to casting and drying. After drying, the SH-SRF samples were rinsed briefly with a minimal amount of distilled water to remove only unbound surface nitrate while preserving the nitrate entrapped within the hydrogel network. The actual NO₃⁻ loading was determined by immersing 1 g of dried SH-SRF in 100 mL of distilled water until equilibrium desorption was reached. The released NO₃⁻ was quantified using a digital nitrate meter (LAQUAtwin NO3-11, Horiba (Thailand) Ltd.). The incorporated NO₃⁻ (Q_{inc}) was calculated using the following equation, adapted from Mondal *et al.*¹⁷:

$$Q_{inc} \text{ (mg/g)} = \frac{C_d \times V_d}{m}$$

where, Q_{inc} is the NO₃⁻ content (mg/g dry SH-SRF), C_d is the NO₃⁻ concentration in the desorption medium (mg/L), V_d is the desorption volume (L) and m is the mass of dry SH-SRF (g).

Swelling properties: The swelling behavior of the prepared SH in distilled water was evaluated using a gravimetric method¹⁸. A 1.0 g sample of dried hydrogel (W₀, g) was enclosed in a nylon bag and then immersed in 100 mL of distilled water at room temperature to allow swelling until

equilibrium was reached. The swollen hydrogel was withdrawn from the water, residual surface water was wiped off with filter paper and then weighed (W_s , g). The swelling ratio (R_s) was calculated using the following equation:

$$R_s(\text{g/g}) = \frac{W_s \times W_0}{W_0}$$

Water retention capacity: The water retention capacity of SH was determined using a weight method¹⁵. In brief, the test soil was oven-dried at 100°C to constant weight and sieved using a 2-mm mesh. Then, 200 g of the sieved soil was placed in a 250 mL beaker and 2.0 g of dried hydrogel was buried 2 cm below the soil surface. A control group contained only the soil. Subsequently, 50 mL of distilled water was slowly added to each beaker and the total mass was recorded at predetermined time intervals until a constant weight was reached. The water retention rate (R_{wr}) was calculated using the following equation:

$$R_{wr}(\%) = \frac{W_t - W}{W_0 - W} \times 100$$

where, W is the initial weight of the beaker containing dry soil and hydrogel, W_0 is the total weight after adding water and W_t is the weight of the beaker at time t .

Biodegradability test: The biodegradability of the prepared SH was evaluated using a soil burial method¹⁹. The SH (0.5 g) was buried in a nylon mesh bag at a depth of 5 cm in 400 g of soil. The pots were kept at room temperature and distilled water was added to maintain soil moisture at around 30%. During the 20-day study, samples were removed from the soil every 2 days, washed thoroughly with distilled water to remove any attached soil, then dried and weighed. The biodegradability (R) of the SH was calculated using the following equation:

$$R(\%) = \frac{W_i - W_t}{W_i} \times 100$$

where, W_i denotes the initial weight of SH and W_t represents its weight at the predetermined time t .

Slow-release study in water and soil column: The slow-release performance of the prepared SH-SRF and pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ was evaluated in deionized water and simulated soil columns at room temperature²⁰. In brief, 1.5 g of dried SH-SRF, containing 0.23 g NO_3^- and 0.44 g $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$

(containing 0.23 g NO_3^-), as the control, was immersed in a beaker containing 100 mL of distilled water. At specified time intervals, 1.0 mL of the release medium was withdrawn from the beaker for NO_3^- quantification and immediately replenished with an equal volume of distilled water to ensure a consistent volume. The NO_3^- cumulative release rate (R_{cr}) was calculated using the following equation:

$$R_{cr}(\%) = \frac{M_t}{M_0} \times 100$$

where, M_t denotes the amount of NO_3^- released at time t and M_0 represents the amount of loaded NO_3^- (g).

The simulated soil column was constructed by packing approximately 15 cm of oven-dried sandy loam soil into a polyvinyl chloride (PVC) tube (6 cm in diameter and 20 cm in height), which was sealed at the bottom with non-woven fabric to prevent soil loss. Prior to the experiment, the soil was wetted with water to facilitate natural settling and compaction, simulating field conditions. Then, approximately 3.2 g of dried SH-SRF containing 0.5 g NO_3^- and 0.952 g of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (having 0.5 g NO_3^-) were buried separately in the soil columns. Next, 50 mL of distilled water was gradually introduced to the soil column at specific time intervals. The leachate was allowed to escape freely and was fully collected from the bottom of the soil column for the determination of released NO_3^- . The cumulative release rate of NO_3^- in the soil was calculated using the same equation as described above.

Effect of SH-SRF on crop growth: A pot experiment was conducted to evaluate the growth-promoting effects of the prepared hydrogels on early-stage 'Green Oak Leaf' lettuce (*Lactuca sativa*) and 'Sida' tomato (*Solanum lycopersicum*) seedlings. Briefly, plastic pots (8 cm × 10 cm) were filled with 0.5 kg of sandy soil and initially irrigated to field capacity. Five uniform seedlings of similar height were transplanted into each pot and watered daily for one week to allow establishment. Subsequently, 3.2 g of SH-SRF containing 0.5 g NO_3^- or 0.952 g of $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (containing 0.5 g NO_3^-) were buried 3 cm below the soil surface and approximately 3 cm away from the plant roots. Pots without fertilizer and those with NO_3^- -unloaded SH were included as the controls. The pots were kept under outdoor conditions at $32 \pm 1^\circ\text{C}$ (day) and $24 \pm 2^\circ\text{C}$ (night) with 75-80% relative humidity and were irrigated with 10 mL of water every other day to simulate water-deficit conditions. At the end of the experiment, the growth indicators of lettuce and tomato plants were recorded, including the plant height, number of leaves, leaf area, fresh weight and dry weight. The dry weight was determined by oven-drying at 60°C to constant weight.

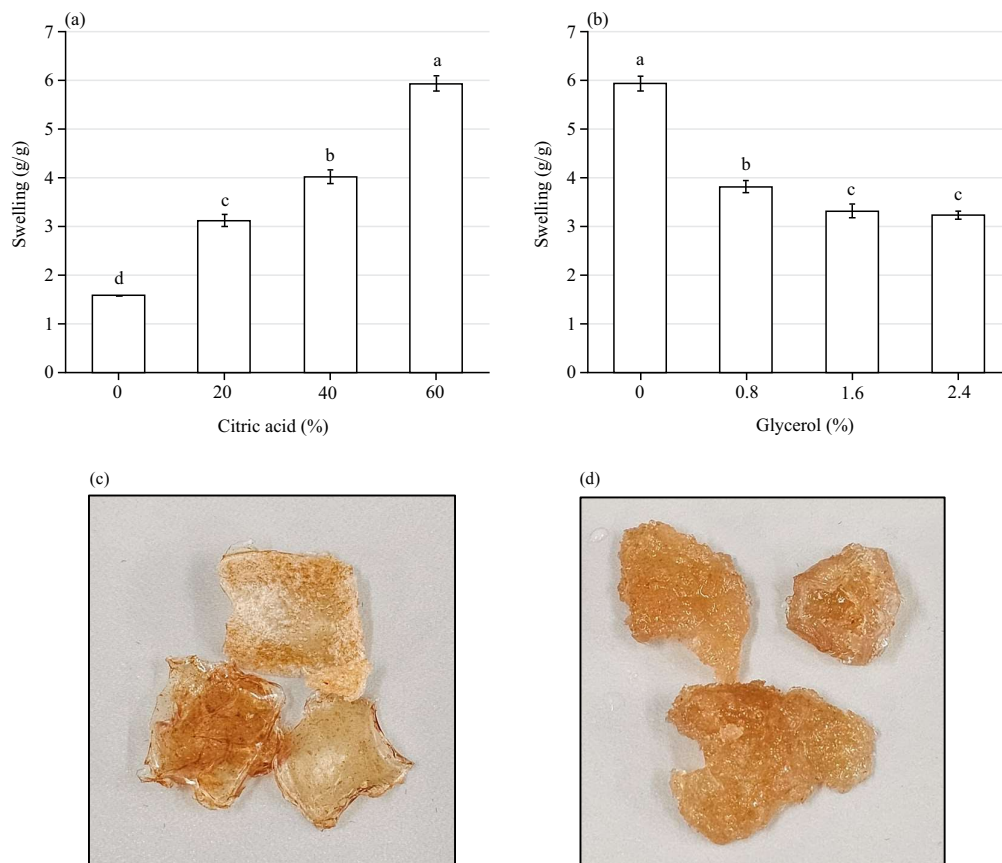


Fig. 2(a-d): Swelling behavior of SH in deionized water at room temperature (a) Effect of CA concentration (0-60%, w/w relative to starch) on swelling, (b) Effect of glycerol concentration (0-2.4%, v/v relative to the total mixture) on swelling, (c) SH appearance before swelling and (d) SH appearance at equilibrium

Statistical analysis: All experiments were performed in triplicate and the results are expressed as the Mean $\pm$ Standard Deviation (SD). Statistical analyses were conducted using SPSS software (Version 22.0, IBM Corp., Chicago, IL, USA). Differences among the treatment means were evaluated by One-way Analysis of Variance (ANOVA) and *post hoc* comparisons were performed using Duncan's multiple range test (DMRT). Statistical significance was established at $p < 0.05$.

RESULTS

Swelling behavior of hydrogels: The swelling behavior of SH was strongly influenced by the CA content. As shown in Fig. 2a, the swelling ratio increased markedly with increasing CA concentration in the hydrogel formulation. After reaching equilibrium swelling at 72 h, the control hydrogel without CA exhibited the lowest swelling ratio (1.58 ± 0.02 g/g). In contrast, the incorporation of CA significantly enhanced the swelling capacity, yielding swelling ratios of

3.12 ± 0.12 , 4.02 ± 0.14 and 5.94 ± 0.15 g/g for CA contents of 20, 40 and 60%, respectively. Because the hydrogel containing 60% CA exhibited the highest swelling performance, this formulation was selected for subsequent experiments.

The effect of glycerol on swelling behavior was also evaluated, as presented in Fig. 2b. The swelling ratio decreased progressively with increasing glycerol content. Hydrogels containing 0.8, 1.6 and 2.4% glycerol exhibited swelling ratios of 3.81 ± 0.13 , 3.32 ± 0.13 and 3.23 ± 0.08 g/g, respectively, corresponding to reductions of 35.86%, 44.11% and 45.62% compared with the hydrogel without glycerol. Since glycerol negatively affected swelling capacity, the formulation containing 60% CA without glycerol was selected for fabrication of SH-SRF.

Visual observations of the hydrogels before and after swelling (Fig. 2c-d) confirmed that the swollen samples maintained structural integrity without visible dissolution or disintegration, indicating the formation of stable crosslinked starch-based hydrogel networks.

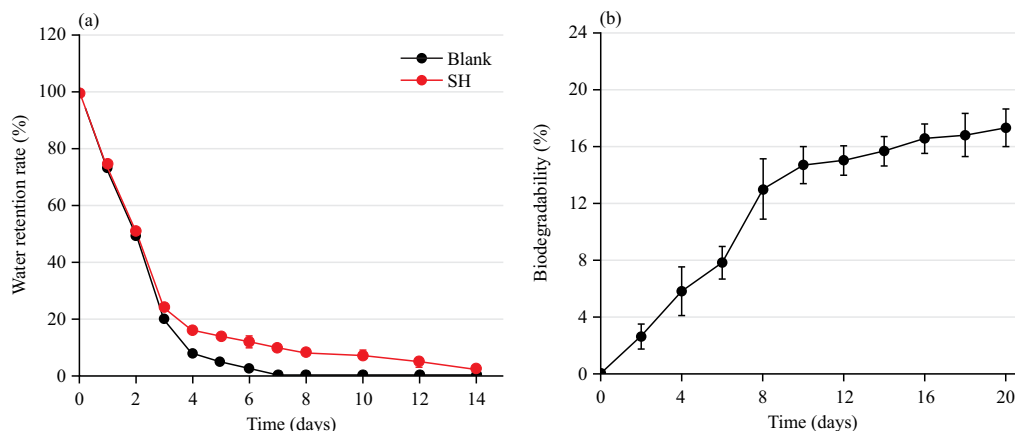


Fig. 3(a-b): (a) Water retention capability and (b) Biodegradability of SH in sandy soil under outdoor conditions

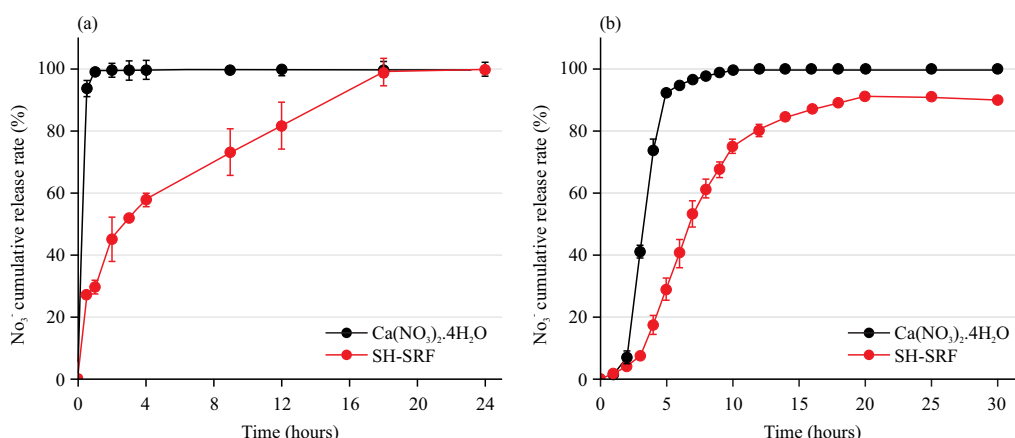


Fig. 4(a-b): Release profiles of pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ and SH-SRF in (a) Deionized water and (b) Soil column

Water retention capacity and soil biodegradability: The water retention capacity of soil amended with the prepared SH is presented in Fig. 3a. Soil moisture gradually decreased over time due to evaporation; however, soils containing SH consistently exhibited higher water retention than the control soil. On day 3, the water retention rates of the control and SH-amended soils were 19.89% and 23.94%, respectively. The difference became more pronounced over time. By day 7, water retention in the control soil decreased sharply to 0.44%, whereas the SH-amended soil retained 9.87% of its initial water content. These results demonstrate that the hydrogel effectively reduced water loss and extended moisture availability in soil.

Biodegradability is an essential requirement for environmentally friendly agricultural hydrogels. The biodegradation of the SH samples was evaluated using a soil burial method (Fig. 3b). The hydrogel showed a gradual decrease in weight over the 20-day incubation period, with a total weight loss of 17.3%, indicating progressive degradation under soil conditions.

Slow-release behavior: The slow-release performance of SH-SRF was evaluated in both aqueous medium and simulated soil column systems. Prior to release testing, the nitrate loading of SH-SRF was determined. Based on the incorporation of 2 g $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ during synthesis, the hydrogel contained 0.155 g NO_3^- per gram of dry hydrogel, corresponding to a loading efficiency of 82.1% relative to the theoretical maximum (0.189 g NO_3^-/g). This high retention efficiency suggests that the mild rinsing step primarily removed loosely bound nitrate while preserving ions entrapped within the hydrogel matrix. All release profiles presented in this study were calculated using the experimentally determined nitrate content.

The cumulative release profiles of NO_3^- from SH-SRF and pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ are shown in Figs. 4a-b. In aqueous medium (Fig. 4a), pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ released nearly 100% of its nitrate within 1 hr, reflecting its high solubility and the absence of a carrier matrix. In contrast, SH-SRF released only 29.69% within the same period, indicating that the hydrogel structure effectively limited immediate nutrient dissolution.

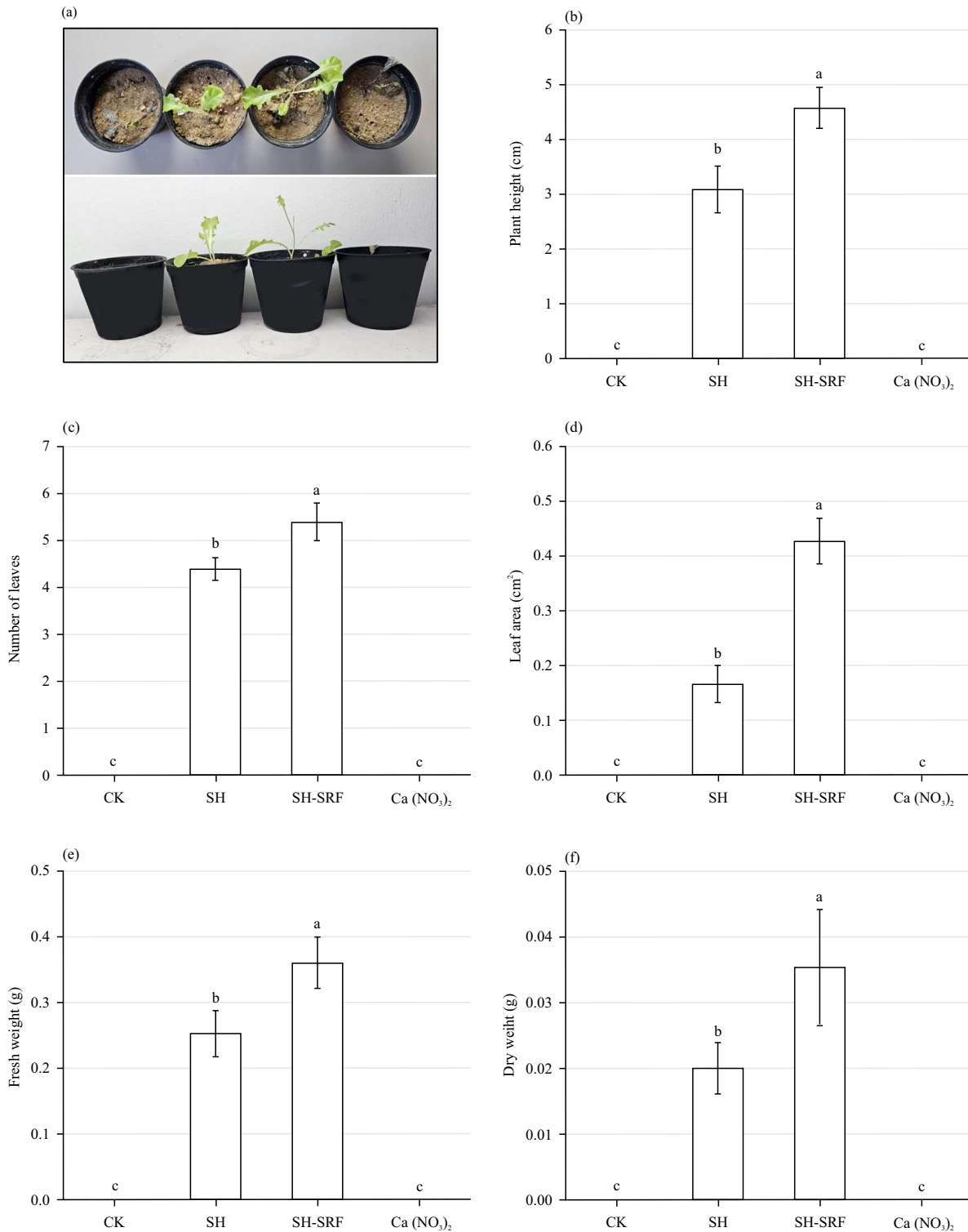


Fig. 5(a-f): Effects of different treatments on the growth of 'Green Oak Leaf' lettuce seedlings after 20 days (a) Images of four groups of lettuce plants, (b) Plant height, (c) Number of leaves, (d) Leaf area, (e) Fresh weight and (f) Dry weight. The bars represent the mean ± standard error of the mean. Different small letters in the figure indicate significant differences between treatments at p < 0.05.

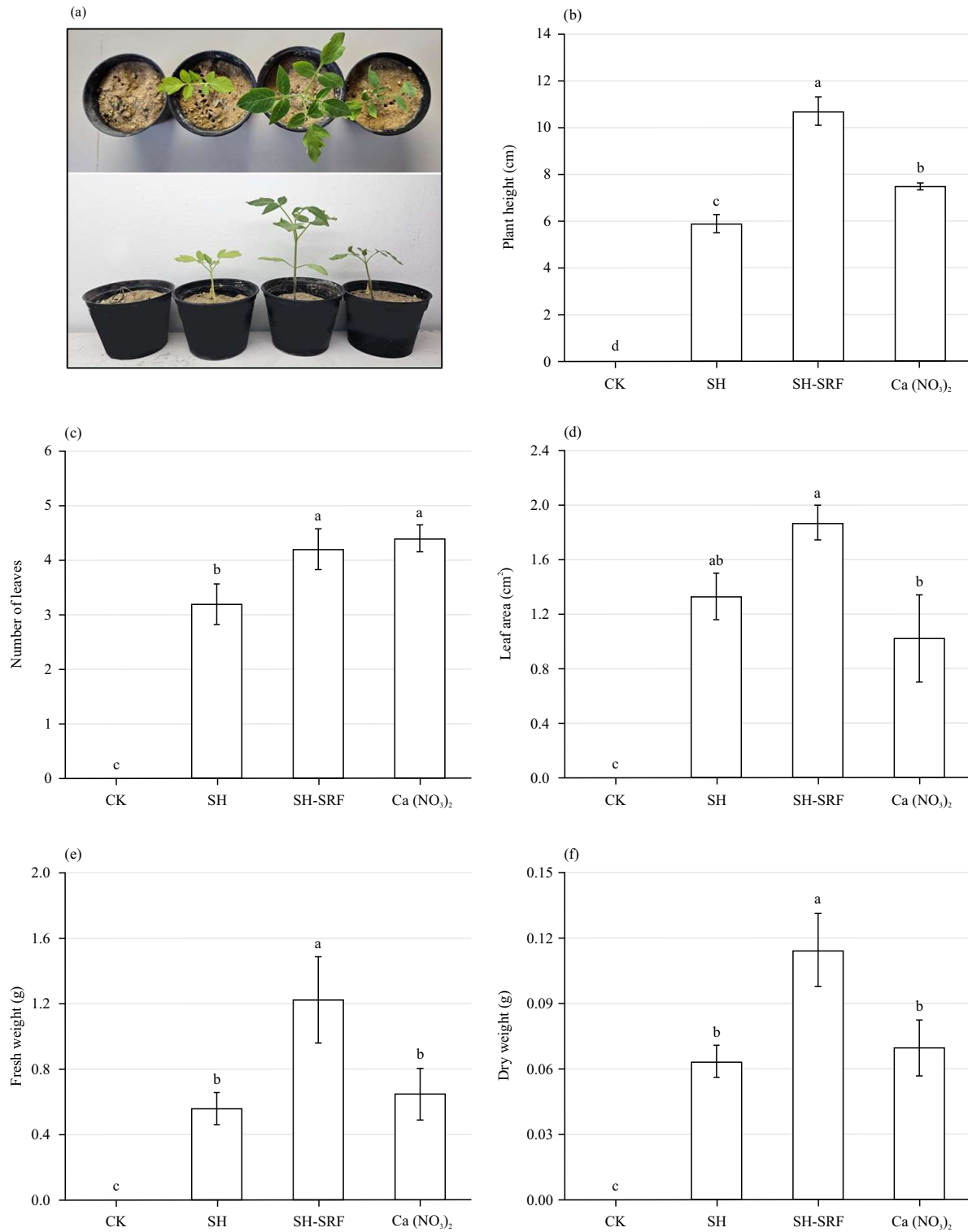


Fig. 6(a-f): Effects of different treatments on the growth of 'Sida' tomato seedlings after 20 days (a) Images of four groups of tomato plants, (b) Plant height, (c) Number of leaves, (d) Leaf area, (e) Fresh weight and (f) Dry weight. The bars represent the Mean ± Standard error of the mean. Different small letters in the figure indicate significant differences between treatments at p < 0.05.

The cumulative release from SH-SRF increased gradually to 81.82% at 12 h and 99.08% at 18 hr, reaching complete release at 24 hrs. These results confirm that the hydrogel matrix significantly moderates the release rate compared with conventional fertilizer.

The slow-release behavior under soil conditions over 30 days is presented in Fig. 4b. In the soil column system, pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ exhibited rapid nutrient release, reaching nearly complete release within 10 days. In contrast, SH-SRF showed a more controlled release pattern, with cumulative nitrate release of 1.68%, 91.23% and 100% at 1, 20 and 30 days, respectively. The extended release duration demonstrates that the hydrogel matrix effectively regulates nutrient diffusion in soil, thereby reducing the risk of rapid nutrient loss and improving fertilizer efficiency.

Effects of SH-SRF on seedling growth under water deficit conditions:

To evaluate the practical applicability of the prepared SH-SRF for enhancing plant growth through controlled water and nutrient release, pot experiments were conducted under water-deficit conditions using 'Green Oak Leaf' lettuce and 'Sida' tomato. Four treatments were established: (i) Soil only (CK), (ii) Unloaded SH, (iii) SH-SRF and (iv) Pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$.

The growth performance of lettuce seedlings under the four treatments is presented in Fig. 5. As shown in Fig. 5a, lettuce seedlings treated with SH-SRF exhibited the healthiest and most vigorous growth after 20 days of cultivation under water-deficit conditions. In contrast, seedlings in the CK and pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ treatments failed to survive under the simulated drought conditions. Although seedlings treated with unloaded SH were able to withstand drought stress due to improved soil water retention, their growth performance remained noticeably inferior to that observed in the SH-SRF treatment. Growth parameters further confirmed these observations (Fig. 5b-f). Lettuce seedlings treated with SH-SRF showed significantly improved growth, reaching a plant height of 4.6 cm with an average of 5.4 leaves per plant. In addition, the SH-SRF treatment resulted in the largest leaf area (0.4 cm^2) and the highest biomass accumulation, with fresh and dry weights of 0.36 g and 0.04 g, respectively. These results indicate that the combined effects of water retention and controlled nutrient release provided by SH-SRF significantly enhanced lettuce seedling growth under drought conditions.

A similar trend was observed in tomato seedlings (Fig. 6). As illustrated in Fig. 6a, tomato seedlings grown in soil amended with SH-SRF appeared healthier and more vigorous than those in the other treatments. The SH-SRF

treatment produced the best growth performance, with a plant height of 10.7 cm, an average of 4.2 leaves per plant, a leaf area of 1.88 cm^2 and fresh and dry weights of 1.23 g and 0.11 g, respectively (Fig. 6b-f). In contrast, seedlings in the CK treatment failed to survive due to the combined absence of fertilizer and severe water deficit. Tomato seedlings treated with pure $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ survived but exhibited noticeably weaker growth compared with those receiving SH-SRF, likely due to the rapid dissolution and loss of nutrients from the soil.

DISCUSSION

The potential of Thai purple yam starch for producing SH was demonstrated by its high water-absorption capability. Swelling capacity is a key property of hydrogel-based fertilizers because it influences water uptake, water retention and nutrient-release behavior, which are important for improving fertilizer-use efficiency and maintaining soil moisture in agricultural systems²¹. In the present study, swelling capacity increased with increasing CA concentration. A similar trend has been reported for CA-crosslinked corn starch hydrogels, where increasing CA content resulted in greater swelling capacity²². This behavior may be attributed to changes in the hydrophilic functionality of the starch network following esterification with CA. Although esterification consumes some hydroxyl groups of starch, the crosslinked network retains unreacted hydroxyl groups and contains carboxyl-derived functionalities from CA, which can enhance interactions with water²³. These hydrophilic groups facilitate water uptake through hydrogen bonding with surrounding water molecules. In addition, carboxyl-containing polymer networks can exhibit strong hydration in aqueous environments, contributing to greater hydrogel swelling²⁴.

The addition of glycerol significantly affected the swelling behavior of SH, with swelling capacity decreasing as glycerol content increased. Similar reductions in swelling capacity have been reported for glycerol-containing hydrogels, including polyvinyl alcohol (PVA) hydrogel films²⁵ and PVA/gum karaya hydrogels²⁶. Glycerol is a low-molecular-weight plasticizer that can interact with polymer chains through hydrogen bonding, thereby modifying intermolecular interactions and the structure of the polymer network. These interactions may reduce the availability of hydrophilic sites for water binding and alter the hydration behavior of the hydrogel network²⁷. Therefore, the reduced swelling capacity observed in the present study may be associated with glycerol-induced changes in network structure that limited water uptake.

Effective soil water retention is essential for agricultural productivity, particularly under conditions of water scarcity and climate variability, as it preserves plant-available water,

reduces irrigation demand and supports resilient cropping systems²⁸. Hydrogels have therefore attracted attention as soil amendments because of their ability to absorb large quantities of water and gradually release it over time, helping plants withstand drought stress²⁹. In the present study, SH was evaluated for its ability to enhance soil water retention following the swelling behavior analysis. The incorporation of SH into sandy soil markedly slowed moisture loss compared with the control. This improved water retention can be attributed to the hydrophilic polymer network of the hydrogel, which enables water absorption and storage within its three-dimensional structure³⁰.

The swelling capacity of the hydrogel plays a key role in this process by allowing the polymer network to act as a temporary water reservoir that gradually releases water into the surrounding soil matrix as soil moisture decreases. Once incorporated into soil, swollen hydrogel particles can reduce water loss and help maintain more stable soil moisture conditions over time. Hydrogels may also improve soil physical properties and nutrient retention, thereby supporting root development and plant growth^{29,31}.

The SH samples were also evaluated for soil biodegradability using a soil burial method and gradual biodegradation was observed. This degradation can be attributed to typical soil biodegradation processes, including the removal of un-crosslinked starch, cleavage of crosslinked starch chains and subsequent microbial decomposition of starch-based polymers³². Soil microorganisms produce enzymes such as amylases that break down starch-based materials into smaller fragments, leading to progressive disintegration of the hydrogel network¹⁹. This biodegradability represents an important environmental advantage over conventional petroleum-based hydrogels, which may persist in soil for extended periods⁸. The gradual degradation observed in this study suggests that SH functions as a temporary soil amendment, providing water-retention benefits during early plant growth stages while eventually decomposing into environmentally benign products.

The slow-release behavior of SH-SRF was investigated under both aqueous and soil conditions to evaluate its nutrient release performance in different environments. The release profile in aqueous medium exhibited a typical two-stage behavior, characterized by an initial rapid release followed by a slower and more gradual release phase. The initial burst release can be attributed to the diffusion of NO_3^- ions located on or near the surface of the hydrogel particles, whereas the subsequent sustained-release stage is mainly governed by the diffusion of NO_3^- ions entrapped within the internal hydrogel network. The three-dimensional crosslinked

polymer matrix creates tortuous diffusion pathways that restrict nutrient transport and prolong the residence time of water and dissolved ions within the hydrogel structure, thereby contributing to controlled and sustained nutrient release³³. Compared with release in aqueous medium, nutrient release in soil columns occurred at a substantially slower rate. This slower release is consistent with previous research showing that soil conditions can restrict water availability and mass transfer, thereby reducing water penetration into the hydrogel matrix and slowing nutrient dissolution and diffusion²⁰. In addition, the swelling behavior of the hydrogel plays a crucial role in regulating nutrient release, as water uptake controls the expansion of the polymer network and the formation of diffusion pathways for ion transport.

The SH-SRF prepared in this study exhibited controlled nutrient release comparable to that reported for recently developed starch-based or starch-derived slow-release fertilizers^{34,35}. The relatively simple preparation procedure used in this study further supports the potential of SH-SRF as an effective and sustainable carrier for controlled nutrient delivery in agricultural applications.

The pot experiment under water-deficit conditions further confirmed the practical effectiveness of SH-SRF in promoting plant growth under combined water and nutrient stress. Both lettuce and tomato seedlings treated with SH-SRF exhibited significantly better growth performance compared with the CK, unloaded SH and conventional $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ treatments. In lettuce, SH-SRF resulted in the highest plant height, leaf number, leaf area and biomass accumulation, while CK and $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ treatments failed to support plant survival under severe drought conditions. Although the unloaded SH improved survival by enhancing soil water retention, its growth performance remained inferior to SH-SRF, indicating that water retention alone was insufficient to support optimal plant development without a sustained nutrient supply. A similar trend was observed in tomato seedlings, where SH-SRF produced the most vigorous growth, whereas plants treated with conventional fertilizer showed weaker performance despite surviving the drought stress.

The superior plant growth observed in the SH-SRF treatment can be attributed to the synergistic effects of improved soil moisture retention and controlled nitrate release from the hydrogel matrix. Unlike conventional $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ fertilizer, which dissolves rapidly and is prone to leaching under water-limited conditions, SH-SRF regulates nutrient availability through its crosslinked polymer network, enabling a more sustained and efficient nutrient supply to plant roots⁷. Simultaneously, the hydrogel structure maintains

soil moisture by acting as a water reservoir, thereby reducing water stress and improving nutrient uptake efficiency³. The combined regulation of water and nutrient availability creates a more favorable rhizosphere environment, supporting continuous plant growth under drought conditions.

Overall, these results demonstrate that SH-SRF functions as an integrated soil amendment that simultaneously improves water retention and nutrient-use efficiency. The ability of the starch-based hydrogel system to sustain plant growth under water-limited conditions highlights its potential as a sustainable and environmentally friendly alternative to conventional fertilizers in drought-prone agricultural systems.

CONCLUSION

This study demonstrated the successful valorization of Thai purple yam starch into a biodegradable hydrogel-based N fertilizer with water-retention and slow-release functionalities. The hydrogel, prepared from yam starch, CA and $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, exhibited favorable swelling behavior, enhanced the water-holding capacity of sandy soil and sustained nitrate release for up to 30 days. These properties indicate its potential to improve water and nutrient management while reducing N losses in agricultural systems. The hydrogel also showed partial biodegradability, allowing it to function during early crop establishment before gradually degrading in the soil. Pot experiments further demonstrated its agronomic benefits under deficit irrigation, where lettuce and tomato seedlings exhibited improved survival, growth and biomass accumulation compared with untreated soil and soil receiving conventional $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ fertilizer. Overall, the integration of water-retention and controlled-release functions within a biodegradable material derived from a non-conventional starch resource highlights the potential of Thai purple yam starch as a value-added agricultural biomaterial. This hydrogel-based fertilizer offers a promising strategy for enhancing crop productivity, improving N use efficiency and conserving water in drought-prone and sandy-soil environments. Future studies should evaluate its long-term effects on soil properties and crop performance under field conditions.

SIGNIFICANCE STATEMENT

This study demonstrates the potential of Thai purple yam starch as a renewable and biodegradable material for developing a hydrogel-based N fertilizer. The developed starch hydrogel simultaneously improved soil water

retention and prolonged nitrate release compared with conventional calcium nitrate fertilizer. Its effectiveness in supporting lettuce and tomato growth under water-deficit conditions highlights its potential to improve fertilizer-use efficiency and crop resilience while adding value to an underutilized agricultural resource. The approach offers a promising, more sustainable alternative for nutrient and water management in water-limited agricultural systems.

ACKNOWLEDGMENT

The authors would like to thank the Department of Plant Science, Faculty of Agricultural Innovation and Technology and the Department of Applied Biology, Faculty of Sciences and Liberal Arts, Rajamangala University of Technology Isan, Thailand, for providing laboratory facilities essential to this study.

REFERENCES

1. Kodama, T.K., M.S. Nagano, H.H. Miyata, A.R. Ometto and C. Beal, 2024. A comprehensive analysis of sustainable fertilizer-related publications within the context of circular economy: Insights from the field of business management. *Cleaner Prod. Lett.*, Vol. 7. 10.1016/j.clpl.2024.100077.
2. Chai, Y., D.J. Pannell and P.G. Pardey, 2023. Nudging farmers to reduce water pollution from nitrogen fertilizer. *Food Policy*, Vol. 120. 10.1016/j.foodpol.2023.102525.
3. El Idrissi, A., F. Tayi, O. Dardari, Y. Essamlali and I. Jioui *et al.*, 2024. Urea-rich sodium alginate-based hydrogel fertilizer as a water reservoir and slow-release N carrier for tomato cultivation under different water-deficit levels. *Int. J. Biol. Macromol.*, Vol. 272. 10.1016/j.ijbiomac.2024.132814.
4. Shohag, M.J.I., S. Tian, N. Sriti and G. Liu, 2024. Enhancing Bok Choy growth through synergistic effects of hydrogel and different nitrogen fertilizer forms. *Sci. Hortic.*, Vol. 336. 10.1016/j.scienta.2024.113400.
5. Amare, D.G., F.A. Zimale and G.G. Sulla, 2024. Effect of irrigation regimes on nutrient uptake and nitrate leaching in maize (*Zea mays* L.) production at Birr-Farm, Upper Blue Nile, Ethiopia. *Heliyon*, Vol. 10. 10.1016/j.heliyon.2024.e38005.
6. Hamoud, Y.A., H. Shaghaleh, X. Guo and K. Zhang, 2023. pH-responsive/sustained release nitrogen fertilizer hydrogel improves yield, nitrogen metabolism, and nitrogen use efficiency of rice under alternative wetting and moderate drying irrigation. *Environ. Exp. Bot.*, Vol. 211. 10.1016/j.envexpbot.2023.105376.
7. Duan, Q., S. Jiang, F. Chen, Z. Li and L. Ma *et al.*, 2023. Fabrication, evaluation methodologies and models of slow-release fertilizers: A review. *Ind. Crops Prod.*, Vol. 192. 10.1016/j.indcrop.2022.116075.

8. Liu, Y., J. Wang, H. Chen and D. Cheng, 2022. Environmentally friendly hydrogel: A review of classification, preparation and application in agriculture. *Sci. Total Environ.*, Vol. 846. 10.1016/j.scitotenv.2022.157303.
9. Nanda, D., D. Behera, S.S. Pattnaik and A.K. Behera, 2025. Advances in natural polymer-based hydrogels: Synthesis, applications, and future directions in biomedical and environmental fields. *Discover Polym.*, Vol. 2. 10.1007/s44347-025-00017-5.
10. Wang, H., L. Yang, Y. Yang, D. Zhang and G. Hao, 2025. Multifunctional natural starch-based hydrogels: Critical characteristics, formation mechanisms, various applications, future perspectives. *Carbohydr. Polym.*, Vol. 357. 10.1016/j.carbpol.2025.123458.
11. Dey, M., S. Bera, M. Hunter and L. Pal, 2026. Advances in citric acid-crosslinked starch biopolymer chemistry, processing, and applications in sustainable packaging-a critical review. *Carbohydr. Polym.*, Vol. 80. 10.1016/j.carbpol.2026.125104.
12. Koshenaj, K. and G. Ferrari, 2024. A comprehensive review on starch-based hydrogels: From tradition to innovation, opportunities, and drawbacks. *Polymers*, Vol. 16. 10.3390/polym16141991.
13. Srivichai, S. and P. Hongprabhas, 2020. Profiling anthocyanins in Thai purple yams (*Dioscorea alata* L.). *Int. J. Food Sci.*, Vol. 2020. 10.1155/2020/1594291.
14. Salimi, M., B. Channab, A. El Idrissi, M. Zahouily and E. Motamedi, 2023. A comprehensive review on starch: Structure, modification, and applications in slow/controlled-release fertilizers in agriculture. *Carbohydr. Polym.*, Vol. 322. 10.1016/j.carbpol.2023.121326.
15. Gungula, D.T., F.P. Andrew, J. Joseph, S.A. Kareem and J.T. Barminas *et al.*, 2021. Formulation and characterization of water retention and slow-release urea fertilizer based on *Borassus aethiopum* starch and *Maesopsis eminii* hydrogels. *Results Mater.*, Vol. 12. 10.1016/j.rinma.2021.100223.
16. Oliveira, A.R., A.E.C. Ribeiro, Í.C. Gondim, E.A. dos Santos and É.R. de Oliveira *et al.*, 2021. Isolation and characterization of yam (*Dioscorea alata* L.) starch from Brazil. *LWT*, Vol. 149. 10.1016/j.lwt.2021.111843.
17. Mondal, M.I.H., M.R. Khatun and M.A.K. Azad, 2026. Enhancement of the physiological activity, yield and antioxidant content of tomato using slow-release urea fertilizer based on PVA/PE/HA/CA hydrogel. *Carbohydr. Polym. Technol. Appl.*, Vol. 15. 10.1016/j.carpta.2026.101178.
18. Salehi, B., B. Zhang, K. Nowlin, L. Wang and A. Shahbazi, 2024. A multifunctional cellulose- and starch-based composite hydrogel with iron-modified biochar particles for enhancing microalgae growth. *Carbohydr. Polym.*, Vol. 327. 10.1016/j.carbpol.2023.121657.
19. Malekzadeh, E., A. Tatari and M.D. Firouzabadi, 2024. Effects of biodegradation of starch-nanocellulose films incorporated with black tea extract on soil quality. *Sci. Rep.*, Vol. 14. 10.1038/s41598-024-69841-2.
20. Gu, S., W. Zhang, X. Tan, P. Wang and Z. Shi *et al.*, 2025. Preparation and characterization on a dual-layer slow-release urea fertilizer coated using ethyl cellulose and phosphoric acid-carbamate di-esterified starch-based chitosan hydrogel. *Carbohydr. Polym.*, Vol. 368. 10.1016/j.carbpol.2025.124212.
21. Park, J., W. Guan and G. Yu, 2025. Smart hydrogels for sustainable agriculture. *EcoMat*, Vol. 7. 10.1002/eom2.70011.
22. Duquette, D., C. Nzediegwu, G. Portillo-Perez, M.J. Dumont and S. Prasher, 2020. Eco-friendly synthesis of hydrogels from starch, citric acid, and itaconic acid: Swelling capacity and metal chelation properties. *Starch Stärke*, Vol. 72. 10.1002/star.201900008.
23. Lipatova, I.M. and A.A. Yusova, 2021. Effect of mechanical activation on starch crosslinking with citric acid. *Int. J. Biol. Macromol.*, 185: 688-695.
24. Bu, X., J. Pei, F. Zhang, H. Liu, Z. Zhou *et al.*, 2018. The hydration mechanism and hydrogen bonding structure of 6-carboxylate chitooligosaccharides superabsorbent material prepared by laccase/TEMPO oxidation system. *Carbohydr. Polym.*, 188: 151-158.
25. Cai, Y., J. Che, M. Yuan, X. Shi, W. Chen and W.E. Yuan, 2016. Effect of glycerol on sustained insulin release from PVA hydrogels and its application in diabetes therapy. *Exp. Ther. Med.*, 12: 2039-2044.
26. Černá, E., V. Neděla, E. Tihlaříková, J. Brtníková and Z. Fohlerova *et al.*, 2025. Glycerol-enhanced gum karaya hydrogel films with a sandwich-like structure enriched with octenidine for antibacterial action against multidrug-resistant bacteria. *ACS Omega*, 10: 29530-29546.
27. Tarique, J., S.M. Sapuan and A. Khalina, 2021. Effect of glycerol plasticizer loading on the physical, mechanical, thermal, and barrier properties of arrowroot (*Maranta arundinacea*) starch biopolymers. *Sci. Rep.*, Vol. 11. 10.1038/s41598-021-93094-y.
28. Kuneski, A.C., H. Haridevan, E. Ninkovic, E. McLeary, D. Martin and G. Kirchhof, 2025. Tissue paper-based hydrogels for soil water maintenance and nitrogen release. *Gels*, Vol. 11. 10.3390/gels11080599.
29. Abdelghafar, R., A. Abdelfattah and H. Mostafa, 2024. Effect of super absorbent hydrogel on hydro-physical properties of soil under deficit irrigation. *Sci. Rep.*, Vol. 14. 10.1038/s41598-024-57786-5.
30. Sugiyama, H., K.I. Katoh, N. Sekine, Y. Sekine, T. Watanabe and T. Ikeda-Fukazawa, 2024. Effects of hydrophilic groups of polymer on change in hydrogen-bonding structure of water in hydrogels during dehydration. *Chem. Phys. Lett.*, Vol. 856. 10.1016/j.cplett.2024.141655.

31. Ali, K., Z. Asad, G.H.D. Agbna, A. Saud, A. Khan and S.J. Zaidi, 2024. Progress and innovations in hydrogels for sustainable agriculture. *Agronomy*, Vol. 14. 10.3390/agronomy14122815.
32. Adjuik, T.A., S.E. Nokes and M.D. Montross, 2023. Biodegradability of bio-based and synthetic hydrogels as sustainable soil amendments: A review. *J. Appl. Polym. Sci.*, Vol. 140. 10.1002/app.53655.
33. Kumari, P., N. Kumari, C. Mohan, C. Chinglenthoba and K.T.T. Amesho, 2024. Environmentally benign approach to formulate nanoclay/starch hydrogel for controlled release of zinc and its application in seed coating of *Oryza sativa* plant. *Int. J. Biol. Macromol.*, Vol. 257. 10.1016/j.ijbiomac.2023.128278.
34. Ma, L., Y. Song, Z. Li, D. Zhang and K. Li *et al.*, 2025. Development of slow-release humic acid fertilizer using starch-based hydrogel. *Ind. Crops Prod.*, Vol. 226. 10.1016/j.indcrop.2025.120648.
35. Chen, F., C. Miao, Q. Duan, S. Jiang and H. Liu *et al.*, 2023. Developing slow release fertilizer through *in-situ* radiation-synthesis of urea-embedded starch-based hydrogels. *Ind. Crops Prod.*, Vol. 191. 10.1016/j.indcrop.2022.115971.