Malays. J. Anal. Sci. Volume 29 Number 6 (2025): 1628


MALAYSIAN JOURNAL OF ANALYTICAL SCIENCES

Journal homepage: https://mjas.analis.com.my/

Research Article

Urea uptake and water retention properties of potassium polyacrylate hydrogel for agricultural applications

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Received: 26 May 2025; Revised: 2 September 2025; Accepted: 17 September 2025; Published: 28 December 2025

Abstract

Global food security faces challenges due to resource scarcity and climate change, necessitating sustainable agricultural solutions. This study investigates the use of super-absorbent polymer (SAP) hydrogels to enhance water and fertilizer retention, improving productivity with *Brassica rapa subsp. Chinensis* (Japanese Pak Choy) cultivation. Hydrogels at concentrations of 0.25, 0.50, 1.0, and 2.0 wt % were tested, with higher concentrations demonstrating superior water absorption attributed to increased surface area and hydrogen bonding. Dry hydrogels absorbed more urea than swollen ones, owing to their greater swelling capacity. Optimal urea uptake occurred at lower concentrations, moderate temperatures, and pH levels between 6.5 and 7.5, as confirmed through Fourier transform infrared spectroscopy analysis. Furthermore, the water-holding capacity of soil improved significantly, with soils containing hydrogels retaining up to 230% water after 24 h. Seed germination studies revealed that higher hydrogel concentrations led to better germination rates and early cotyledonary development of Pak Choy seedlings. Additionally, soils with higher hydrogel content remained wet and moist for up to 7 days, unlike soils with little or no hydrogel. These results demonstrate that SAP hydrogels effectively enhance water retention, fertilizer uptake, and early plant growth, offering a sustainable approach to improving agricultural productivity and addressing global food security challenges.

Keywords: Functional groups analysis; germination; nitrogen-based fertilizer; porous structure; urea uptake

Introduction

Global food security continues to face increasing mounting pressure from population growth, limited natural resources, and climate change, with water scarcity and fertilizer inefficiency being among the most pressing challenges. Conventional farming practices often result in significant nutrient losses, with reports showing that up to 40–70% of nitrogen, 50–70% of potassium, and 80–90% of phosphorus applied to soils are lost through leaching, runoff, or volatilization [1-2]. Urea, one of the most widely used nitrogen fertilizers, is particularly inefficient, with over 40% of applied nitrogen lost to the atmosphere as ammonia or to groundwater as nitrate, causing both environmental and economic consequences [3-4]. Concurrently, increasing drought frequency and poor soil water-holding capacity limit fertilizer uptake, further reducing crop productivity. Hence, addressing these dual challenges of water and nutrient management is critical for advancing sustainable agriculture [5-6].

Meanwhile, food insecurity and malnutrition remain critical issues, partially addressed by advancements in urban farming [7]. Urban farming in developing countries enhances food security by providing fresh produce to urban populations through diverse farming initiatives [7]. The role of water in food security, nutrition, and well-being has often been overlooked in nutritional studies, which have historically focused on sanitation, hygiene, and child growth. Recently, the environmental role of water has gained increased attention [8]. Water-conserving techniques help reduce water and nutrient loss while alleviating plant moisture stress. Biodegradable hydrogels, which address water scarcity and environmental concerns, enhance soil water retention, benefiting arid agriculture and improving farming practices [7].

Superabsorbent polymer (SAP) hydrogels have emerged as a promising solution to these issues. SAP hydrogels are three-dimensional, crosslinked, hydrophilic networks capable of absorbing and retaining water and dissolved nutrients many times their own weight [4]. Their unique structure enables efficient swelling, water retention, and gradual release of moisture and nutrients, directly benefiting plant roots [9]. Recent advances in biodegradable SAPs have extended their applications in agriculture, where they not only mitigate drought stress but also reduce fertilizer leaching, improve soil aeration, and support early seedling establishment. In particular, SAPs have shown high affinity for urea absorption due to their hydrogen-bonding and electrostatic interactions, making them ideal carriers for controlled fertilizer release [4].

Fertilizers are essential for crop cultivation, with urease inhibitors offering a simple way to reduce ammonia loss from fertilized soil. Due to the increasing use of bulk blend and compound fertilizers, there is an urgent need for enhanced efficiency and stabilization techniques. However, the effectiveness of urease inhibitors when combined with phosphorus (P) and potassium (K) fertilizers alongside urea remains unclear [1]. A major issue arises as over half of applied fertilizers fail to reach plants due to runoff caused by from rainfall and irrigation, leading to financial losses and environmental contamination. Slow-release fertilizers (SRFs) address this issue by provide a solution by gradually releasing nutrients in accordance with plant needs, reducing waste and pollution [3]. Additionally, biofertilizers, which utilize microorganisms, stimulate plant growth and improve nutrient uptake, supporting sustainable agriculture.

The efficiency of urea uptake by SAP hydrogels is influenced by several environmental factors, including concentration, pH, temperature, and time. At higher concentrations, urea uptake may plateau due to the saturation of available binding sites [4]. Meanwhile, pH plays a critical role in the ionization of functional groups (e.g., –COOH/–COO$^-$), affecting electrostatic repulsion and swelling capacity of the hydrogel [9-10]. Temperature influences both urea solubility and the diffusion kinetics within the hydrogel matrix, while uptake over time reflects the swelling equilibrium behavior of the network. Despite the importance of these parameters, few studies have systematically examined their combined effects on urea absorption by hydrogels under agricultural conditions.

This study aims to fill this gap by investigating the uptake of urea and commercial fertilizer solutions by SAP hydrogels under varying concentrations, pH level, temperatures, and time intervals. Although previous studies have reported the use of hydrogels use for improving water retention and nutrient delivery, limited studies have evaluated the uptake of both pure urea and commercial fertilizer solutions under varying environmental conditions. This study addresses this gap by systematically examining urea uptake with respect to concentration, temperature, pH, and time, and extending the analysis to a commercial fertilizer AB solution. In addition to the swelling degree, evaluation on the soil water-holding capacity, swelling behavior, and seed germination in hydrogel-amended soils were carried out. Fourier transform infrared (FTIR) spectroscopy was further employed to elucidate the interactions between urea and hydrogel functional groups in both dry and swollen states. Hence, this work highlights the potential of SAP hydrogels to address the dual challenges of fertilizer inefficiency and water scarcity by integrating water and nutrient management functions, supporting sustainable agricultural practices and self-watering systems for food security.

Materials and Methods

Materials

Potassium polyacrylate hydrogels, based on super-absorbent polymers (SAP), in granular form were procured from Zhong Ma Chemicals. These hydrogels were acquired in a dehydrated state, displaying a white color. Meanwhile, nitrogen-rich urea fertilizer was sourced from HmBG Chemicals. Additionally, organic planting soil containing micro, cocopeat, red burnt soil, fine sand, old humus and charcoal along with Japanese Pak Choy (*Brassica rapa subsp. Chinensis*) seeds were purchased from a local nursery, in Negeri Sembilan, Malaysia.

Preparation of SAP hydrogels

To determine which type of hydrogel samples should be used for further investigation, two distinct methods were employed to prepare hydrogels for the urea uptake study. In the first method, SAP hydrogel granules were applied directly in their dry state. In the second method, the dry SAP granules were soaked in distilled water for 24 h, allowing them to expand and form swollen hydrogels. These swollen hydrogels were then cut into uniform pieces measuring 1 cm × 1 cm × 1 cm prior to use.

Both samples (dry state and pre-cut swollen hydrogel state) where then used in the urea uptake study. First, urea powder was dissolved in distilled water to prepare a 45 wt% urea solution. Each hydrogel sample (dry and pre-cut swollen hydrogels) was initially weighed (W_i) and then immersed in 50 g of the urea solution for 24 h. After immersion, the hydrogels were removed from the solution and reweighed to obtain the final weight (W_f). The percentage of urea solution absorbed at each concentration was calculated using Equation 1.

$$\text{Urea uptake (\%)}: [(W_f - W_i)/ W_i] \text{ x } 100\% \qquad (1)$$

where W_f is the final weight of hydrogel after immersion in urea solution and Wi is the initial weight of hydrogel before immersion.

Urea uptake capacity of hydrogel in aqueous solution

For further investigation of urea uptake capacity, the dry-state hydrogel was used due to its excellent urea uptake from the previous section. The investigation of SAP-mediated fertilizer uptake focused on several variables, including concentration, temperature, pH, and time (kinetic analysis). For this study, only dry hydrogels were chosen to examine the factors influencing the percentage of urea uptake. Various urea concentrations were prepared by dissolving the desired urea by mass (1 g) in water to produce solutions of 15, 30, and 45 wt % urea.

The effect of temperature was investigated at different temperature levels: 20, 40, and 60 °C, while maintaining a constant urea concentration of 45%, which was determined to be the optimum concentration based on preliminary experiments. Briefly, urea powder was dissolved in distilled water to achieve a 45% concentration, and the solution was heated using a hot plate to reach temperatures of 20, 40, and 60 °C.

In the pH investigation, a 45% urea solution at 20 °C was adjusted to pH levels of 4, 7, and 9 using hydrochloric acid (HCl) or sodium hydroxide (NaOH). The preparation of the urea solution at a concentration of 45% followed the same procedure as in the temperature study. Meanwhile, the pH of the urea solution was adjusted using HCl to achieve the desired pH levels. To examine the effect of concentration, temperature, and pH, dry hydrogels were immersed in the respective urea solutions under specified conditions for 30 min. Subsequently, the samples were removed from the urea solutions, dried using filter paper, and weighed. The percentage of urea uptake was then calculated according to Equation 1.

Simultaneously, the time-dependent swelling degree was measured using the optimal concentration, temperature, and pH of the urea solution. The immersing time intervals were set at 0.5, 1, 2, 3, 4, 5, 6, 12, 24, and 36 h, all conducted at room temperature (25 ± 2 °C). The swollen hydrogels were removed, gently blotted with filter paper to remove surface water, and weighed immediately. The swelling degree (SD, %) was calculated using the Equation 2:

$$SD(\%) = [Wt-Wd]/Wd\times100 \qquad (2)$$

where Wt is the weight of the swollen hydrogel at time t, and Wd is the initial dry weight of the hydrogel

The swelling degree of urea solution adsorption in hydrogel data was fitted to the pseudo-second-order (PSO) model, where q_e (g/g) and q_t (g/g) are the urea solution absorbency of the product at equilibrium and at time t, respectively [11]. Meanwhile, k_2 ($g{\cdot}mg^{-1}$ min^{-1}) is the rate constant of the PSO model, as expressed in equation 3.

$$q_t = \frac{k_2 qe^2 t}{1+\ k_2 q_e t} \qquad (3)$$

Characterization of SAP hydrogels

The functional groups within SAP hydrogels (both in dry and swollen states), before and after immersion in urea solutions, were identified using attenuated total reflectance-Fourier transform infrared spectroscopy (ALPHA; Bruker) with a resolution of 1 cm^{-1} within the wavenumber range of 4,000–650 cm^{-1}. This analysis aimed to detect changes in functional groups during the process. Additionally, a thorough examination of the FTIR spectrum focused on identifying the presence of nitrogen within the hydrogel structure.

Hydrogels were prepared from SAP granules by dissolving different amounts of SAP in 100 mL of distilled water for 24 h to produce hydrogel samples at concentrations of 0.25, 0.50, 1.0, and 2.0 wt %. These samples were allowed to swell and absorb water until equilibrium was reached before further testing. The water-swelling capacity of the SAPs was evaluated using the tea bag method. First, SAP hydrogels at 0.5% and 1.0% concentrations were placed in tea bags, secured with threads, and submerged in 100 mL of room-temperature tap water for 24 h. After reaching equilibrium, the tea bags were dried for 15 min, excess water was removed using the blotting technique, and the bags were weighed with filter paper and a sponge. Equations 4 and 5 were then used to calculate the swelling percentage (Q) and equilibrium swelling percentage (Q_{eq}), respectively.

$$Q\ (\%) = \frac{W-Wo}{Wo} \text{ x } 100\% \qquad (4)$$

$$Qeq\ (\%) = \frac{Weq-Wo}{Wo} \text{ x } 100\% \qquad (5)$$

where W is the weight of the swollen hydrogels, W_0 is the weight of the SAP hydrogels, and W_{eq} is the weight of the swollen hydrogels after reaching the equilibrium phase [12].

Hydrogel fertilizer uptake

A stock feeding solution of the eco-hydro fertilizer AB was prepared by dissolving nutrient A and nutrient B separately in 10 L of water. Then, 50 mL of each nutrient solution was mixed and diluted in 10 L of water at a 1:200 ratio. Hydrogels (0.25%, 0.50%, 1.0%, and 2.0%) were immersed in 100 mL of this feeding solution at room temperature. The tea bag method was adapted to study hydrogel fertilizer absorption. Tea bags containing the hydrogels were weighed, wetted, and immersed in the solution. Absorption kinetics were evaluated by removing the tea bags at various intervals (2 min to 48 h) until equilibrium absorption was reached. The blot-dry method was then applied to remove excess fluid, and weight measurements were taken using filter paper and a sponge. Fertilizer absorption was calculated using Equation 3.

Water holding capacity of planting soil

The water-holding capacity of organic planting soil was evaluated using soil that had been oven-dried at 60 °C for 24 h prior to the experiments. The soil with added hydrogels was examined by reinforcing 50 g of soil with varying percentages of SAP hydrogels (0.25%, 0.5%, 1.0%, and 2.0% w/w). Pots with holes at the base were prepared and sealed with tea bags. The initial weight of each pot, including the soil and SAP hydrogels, was recorded (W_0). The samples were then soaked with tap water for 24 h, after which excess water was removed using tissue paper. The final weight of each pot (W_1) was then measured. A control sample without SAP hydrogels was also tested. The water-holding capacity (W_h) was calculated by comparing W_0 and W_1, representing the ratio of moisture retained in the soil relative to its dry weight after gravity drainage.

$$Wh(\%) = \frac{W1-Wo}{Wo} \text{ x } 100\% \quad (5)$$

Seed germination study

Seed germination and early growth were evaluated by preparing pots containing 100 g of organic planting soil mixed with varying percentages of SAP hydrogels (0.25%, 0.50%, 1.0%, and 2.0%). A control pot without SAP hydrogels was also included. Each pot contained 20 Japanese Pak Choy seeds, totaling 100 seeds across all pots, with replicates of three pots per condition. The experiment was conducted under controlled conditions: temperature of 25 °C, natural daylight, and equal watering [7, 13]. Germination was assessed by observing radicle emergence within 3 days, while seedling development during the cotyledonary phase was measured by the ability of the seeds to reach this stage. Germination and seedling percentages were calculated using Equations (7) and (8), respectively.

$$Germination\ (\%) = \frac{G3}{T0} \text{ x } 100\% \quad (6)$$

$$Seedling\ at\ cotyledonary\ (\%) = \frac{Sc}{T0} \text{ x } 100\% \quad (7)$$

where G_3 is the number of germinated seeds on Day 3 after sowing; T_0 is the total seed count in each pot, with $T_0 = 20$ seeds for this study; and S_c is the count of seedlings exhibiting fully expanded cotyledons. The germination of Japanese Pak Choy seeds was recorded on D_1 (x = 1) and D_2 (x = 2) following sowing for each sample. On Day 3 (D_3) after sowing, the number of seedlings with fully expanded cotyledons was recorded [7].

Results and Discussion

Physicochemical properties of hydrogel

Urea solution uptake measurements for dry and swollen state hydrogels at a 45% urea concentration were found to be 20608 % and 190 %, respectively. Dry hydrogels absorb urea more effectively than swollen hydrogels due to their higher swelling capacity. This is because dry hydrogels have a less occupied internal structure, allowing greater liquid absorption. The presence of hydrophilic OH functional groups enables hydrogel to attract water. In the dry state, more OH groups are available for absorption, whereas in the swollen state, most OH groups have already participated in previous swelling, reducing their ability to attract additional water molecules from the urea solution [14-16].

During urea solution uptake, the dry SAP increased in size during soaking. The initially spacious hydrogel network gradually fills with water in the urea solution, reducing available gaps until saturation is reached. Meanwhile, in dry hydrogels, more space can absorb the urea solution, resulting in physical swelling while remaining transparent, as the urea solution is also transparent. In contrast, swollen hydrogels have limited absorption space due to prior water saturation, reaching saturation faster. Additionally, the crystalline structure of urea causes any unabsorbed solution to crystallize over time, adhering to the hydrogel's surface [14]. Furthermore, the reduction of internal gaps during swelling results from the collapse of loosely cross-linked regions in the hydrogel network as water molecules fill available pores, a typical feature of SAP hydrogels with partially flexible chains [17].

The FTIR spectra in **Figure 1** shows the functional groups present in the SAP hydrogel, urea crystals, dry hydrogel, and pre-swollen hydrogel (SAP soaked in distilled water for 24 h), confirming the incorporation of urea into the polymer matrix. The broad absorption bands observed between 3328 and 3431 cm^{-1} correspond to overlapping OH and NH_2 stretching vibrations. The distinction between these groups is evident from the appearance of the bands in the dry hydrogel and SAP hydrogel, where the bands are broader and more intense, reflecting extensive hydrogen bonding among the OH groups in the polymer backbone. In contrast, the pre-swollen hydrogel exhibits narrower bands in the same region, consistent with water-mediated interactions and reduced intermolecular hydrogen bonding. The presence of two distinct peaks at approximately 3445 and 3345 cm^{-1} in the urea crystal spectrum confirms primary amine (NH_2) stretching, consistent with the characteristic FTIR signature of urea [6,18].

Additional bands between 1460 and 1573 cm^{-1} can be attributed to N–H bending and C–N stretching vibrations. In urea crystals, these peaks are sharp and intense, while in urea-loaded hydrogels, they appear broader and less intense, indicating hydrogen-bonding interactions between the amine groups of urea and the carboxylate groups of the SAP matrix. In addition, characteristic peaks were observed at 1586 cm^{-1} (N–H bending), 1453 cm^{-1} (CH_2 bending), 1148 cm^{-1} (C–O stretching), and 1001 cm^{-1} (C–O–C stretching). These features are consistent with urea-polymer interactions reported in recent hydrogel-urea composite studies [6, 19].

Study of urea solution uptake performance

Effect of urea concentration

During the study of urea concentration, dry hydrogels were preferred due to their superior urea uptake performance compared to swollen hydrogels. The urea uptake increased with higher urea concentrations, reaching 20,608%, 24,558%, and 27,981% for 15, 30, and 45 wt % solutions, respectively. This indicates that uptake capacity is enhanced as the external solute concentration increases, driven by stronger osmotic driving forces [20-21]. The physical appearance of the hydrogels also changed after soaking, forming transparent, swollen structures whose size increased with higher urea uptake, as shown in **Figure 2(a)**. Urea molecules penetrate the hydrogel network, disrupting hydrogen bonds between polymer chains, which makes the network more flexible and enhances water absorption. As a result, the hydrogel network becomes more flexible and allows for increased water uptake [22]. Higher urea concentrations further disrupt polymer interactions, creating more internal space and allowing greater water and solvent absorption. The additional urea molecules create more space within the hydrogel structure, enabling a larger amount of water or solvent molecules to be absorbed. Consequently, the hydrogel swells further and expands in size [23-25].

The functional analysis aimed to study changes in the functional groups in the hydrogel structure. **Figure 2(b)** presents the FTIR spectra of urea crystals and hydrogels soaked in urea solutions at various concentrations. Characteristic bands of urea were detected in all urea-loaded hydrogels but were absent in the dry sample (SAP hydrogel). The broad and intense absorption peaks in the range of 3426–3326 cm^{-1}

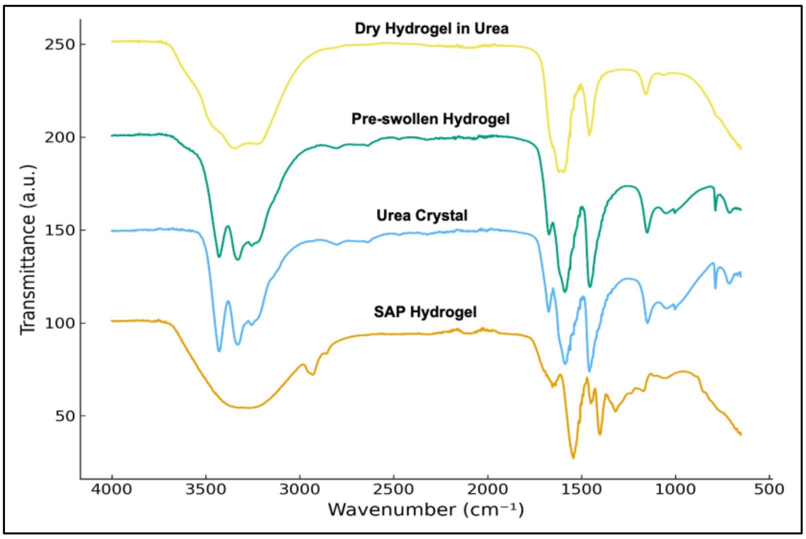


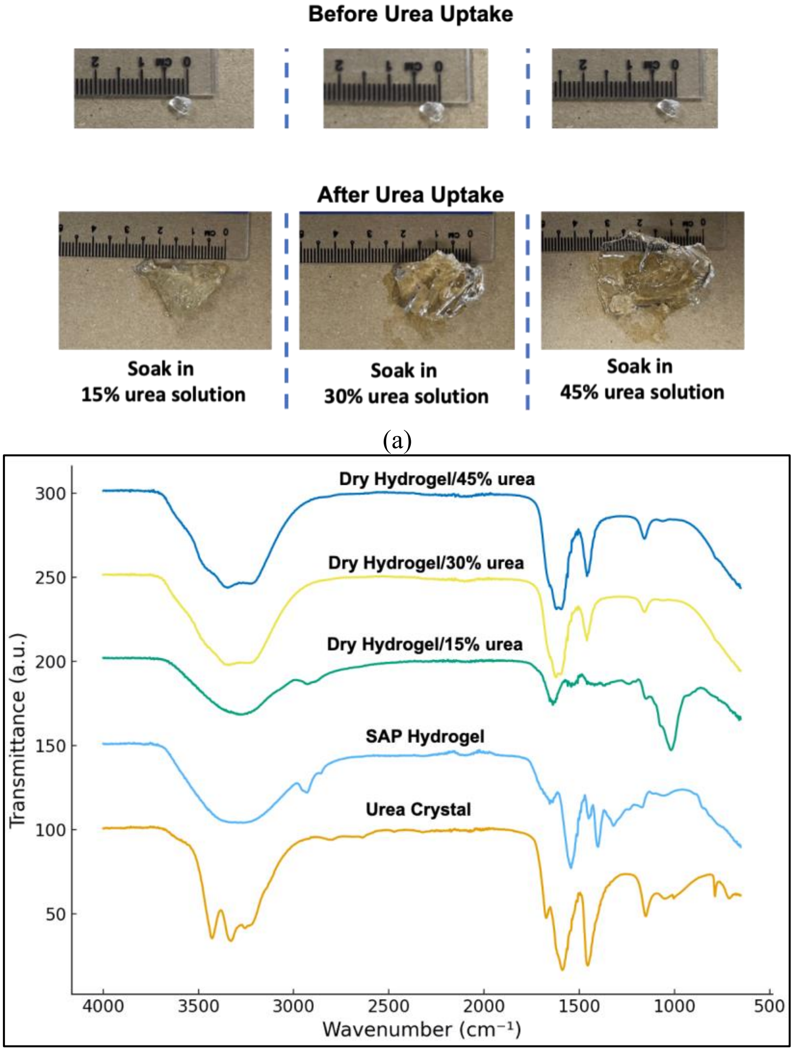
Figure 1. FTIR spectra of (a) SAP hydrogel, (b) urea crystals, (c) pre-swollen hydrogel in urea and (d) dry hydrogel in urea

correspond to the stretching vibrations of NH_2 and OH groups. The presence of two distinct peaks within this region is consistent with the NH_2 nature of urea, in agreement with previous reports [6, 26]. The broadness of these bands also reflects hydrogen-bonding interactions between urea molecules and the hydrogel matrix.

In addition, medium to strong absorption peaks between 1400 and 1500 cm^{-1} are attributed to C–N stretching vibrations of urea, with their intensities increasing at higher urea concentrations, confirming greater urea incorporation. Other characteristic vibrations observed include a weak band at 2799 cm^{-1} (–CH_2 stretching), a medium band at 1586 cm^{-1} (–NH bending), and strong bands at 1148 and 1001 cm^{-1} corresponding to C–O stretching. These assignments are consistent with earlier FTIR studies on urea-polymer composite hydrogels, which reported similar spectral features for NH_2-containing urea and its hydrogen-bonding interactions with polymer backbones [6, 19-20]. Notably, the highest intensity of both –NH and C–N bands was observed in the hydrogel prepared with a 45% urea solution, indicating maximal uptake at this concentration.

Effect of temperature of urea solution

Figure 3 shows the effect of temperature on hydrogel swelling in the urea solution. At 20 °C, the hydrogel successfully absorbed urea and swelled. However, at 40 and 60 °C, urea crystallized on the hydrogel surface within 30 min, forming a coating that limited further penetration of the solution into the hydrogel matrix. This suggests that once crystallization begins, the



(b)

Figure 2. (a) Physical appearance of the hydrogels before and after soaking in different urea solution percentage and (b) FTIR spectrum of urea, SAP hydrogel and hydrogels at different urea concentration

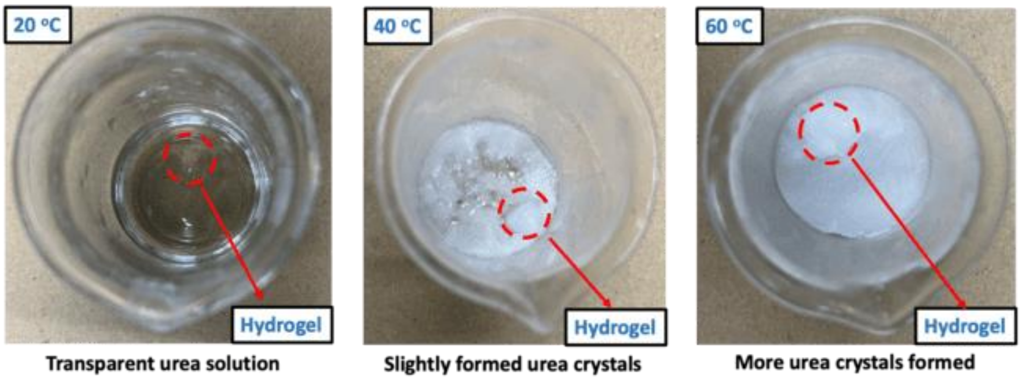


Figure 3. Dry hydrogels soaked at different temperature for 30 min

process shifts from internal absorption to surface deposition, restricting hydrogel swelling capacity [14].

In this study, 50 mL of urea solution was used for every 0.1 g of dry hydrogel. While this volume was sufficient to initiate swelling, crystallization became more pronounced at elevated temperatures due to rapid water evaporation, which increased the local concentration of urea until supersaturation was reached, resulting in precipitation. Thus, the reduced swelling at higher temperatures was not caused by decreased solubility of urea, as urea solubility generally increases with temperature, but rather by accelerated water loss that destabilized the solution equilibrium. Using a larger immersion volume or sealed conditions could minimize this effect by reducing local supersaturation. In addition, no direct thermodynamic analysis (enthalpy or entropy of dissolution) was conducted in this work; however, the observations are consistent with recent reports showing that water evaporation at elevated temperatures can drive local supersaturation and crystallization of urea and other salts in aqueous systems [6, 14, 27-28]. These findings highlight the importance of considering both temperature and solvent volume in evaluating hydrogel swelling and solute uptake behavior.

Effect of pH of urea solution

Figure 4 illustrates the effect of the pH of urea solution on the hydrogel swelling behavior. At pH 4.0, the urea uptake was 470%, increasing to a maximum of 804% at pH 7.0, then decreasing sharply to 271% at pH 9.0. The hydrogel swells as water penetrates into the polymer matrix, facilitated by the presence of hydrophilic functional groups. Specifically, the carboxyl (–COOH) groups of the hydrogel partially dissociate into carboxylate anions ($–COO^–$), depending on the pH. Electrostatic repulsion between negatively charged $–COO^–$ groups along adjacent polymer chains drives network expansion, thereby increasing the size and swelling capacity of the hydrogel [15,21, 22]. Thus, the repulsion specifically involves $–COO^–$ groups within the polymer backbone, and this electrostatic interaction directly contributes to the observed enlargement of the hydrogel dimensions. The carboxylate groups ($–COOH/–COO^–$) of the SAP are the main functional ionic groups. At pH 7, partial ionization enhances electrostatic repulsion, increasing swelling. At pH 9, excess sodium ions from NaOH neutralize charges, reducing repulsion and swelling. Thus, ion balance strongly influences uptake behavior [9-10].

Meanwhile, the maximum swelling observed at pH 6.5–7.5 is attributed to the ionization of carboxylic acid groups. At acidic pH (e.g., 4.0), most groups remain protonated (–COOH), limiting repulsion and reducing swelling. Near neutral pH, partial ionization produces carboxylate anions ($–COO^–$) alongside –COOH, resulting in both hydrogen bonding and strong electrostatic repulsion among $–COO^–$ groups, thereby maximizing swelling. At alkaline pH (>9.0), full ionization occurs, but excess counterions (Na^+) shield the $–COO^–$ repulsion, leading to reduced swelling. Similar pH-responsive swelling behavior has been reported for carboxylated hydrogels in recent studies [9].

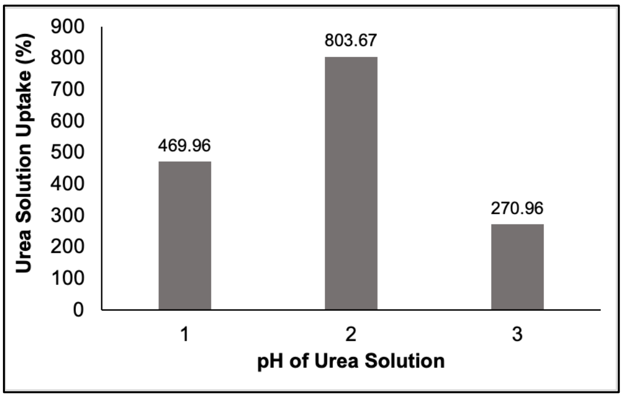


Figure 4. Urea solution uptake at different pH

Swelling degree

Figure 5(a) presents the swelling degree (SD) of the cellulose hydrogel in urea solution over time. A biphasic swelling profile was observed, where a rapid uptake occurred within the first 5 h, followed by a slower increase up to 10–12 h, with equilibrium reached in 24 h. This time-dependent swelling behavior reflects typical hydrogel dynamics, where fast water uptake is initially driven by a strong osmotic gradient, while the subsequent slower phase results from polymer network relaxation and reduced concentration gradients [15,29]. The physical image in **Figure 5(b)** supports this observation, as hydrogels progressively expanded in size and became more transparent with increased soaking duration until stabilization at 24–36 h. The swelling mechanism is governed by osmotic pressure differences between the external urea solution and the hydrogel interior [15-16]. Water molecules diffuse into the hydrogel to balance solute concentration, facilitated by the hydrophilic hydroxyl groups in cellulose that enhance water-polymer interactions. The SD is further influenced by hydrogel composition, cross-linking density, and porosity, all of which determine both the absorption capacity and diffusion rate.

In addition, mechanistic insights beyond immersion measurements can be derived from the swelling data, which were fitted to the PSO model. The PSO model was selected because it is widely used to describe swelling processes where both diffusion and solute-polymer interactions contribute to uptake. The linearized form is expressed in Equation 3. The close agreement between the experimental data and the PSO model indicates that swelling of cellulose hydrogel in urea solution is governed not only by Fickian diffusion, but also by physicochemical interactions, such as hydrogen bonding between urea and cellulose chains [11]. These results are consistent with recent studies reporting that biopolymer hydrogels exhibit similar swelling profiles, characterized by rapid initial water uptake followed by stabilization, often well-described by PSO kinetics [4,9].

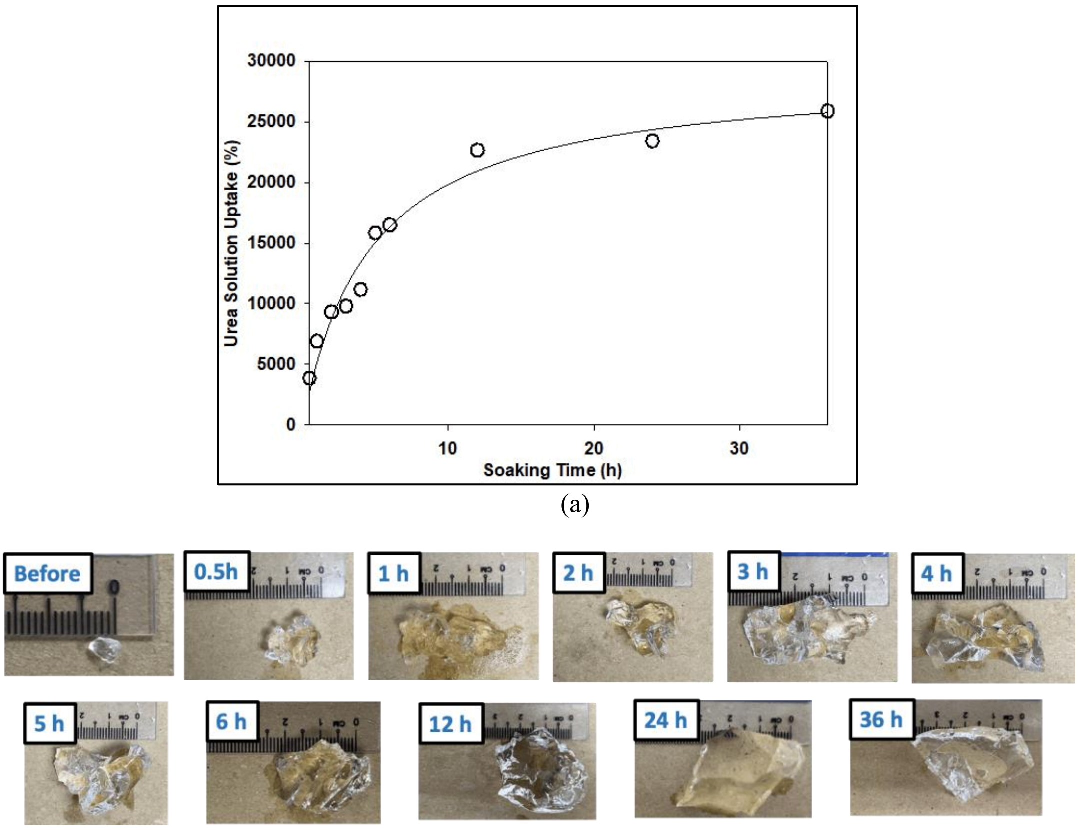
Impact of SAP hydrogels on seed development

Water and fertilizer uptake

The water swelling capacity of dry hydrogels was examined at concentrations of 0.5 and 1.0 wt %. Each dry hydrogel particle had an average diameter of approximately 3 mm. Upon immersion in water, the samples exhibited significant volumetric expansion. Representative images of both the dry and swollen hydrogels are provided in **Figure 6**.

In the experiment, dry hydrogels were placed in a tea bag and immersed in tap water, allowing them to absorb water until reaching equilibrium. The results showed that hydrogels with concentrations of 0.5 and 1.0 wt % achieved swelling percentages of up to 270% and 350%, respectively. Higher hydrogel concentrations resulted in a higher equilibrium swelling ratio than lower concentrations, likely due to an increased surface area interacting with water. This interaction forms hydrogen bonds, enhancing water absorbency [8]. In this study, the swelling and uptake behavior of the hydrogel is primarily governed by hydrogen bonding between the carboxylate groups of potassium polyacrylate and water molecules, consistent with established swelling mechanisms in SAPs [30]. Additionally, the swelling mechanism is mainly driven by water diffusion filling the cellulose pores of the hydrogel [31].

Figure 7(a) illustrates the fertilizer uptake profiles of dry hydrogels at varying concentrations of fertilizer (0.25–2.00%) over time. A clear concentration-dependent trend was observed, where higher hydrogel loadings facilitated greater fertilizer absorption and retention. At low loading (0.25%), uptake stabilized at about 220%, whereas 0.50% hydrogel reached approximately 300%, indicating improved but limited retention. Higher concentrations (1.00% and 2.00%) exhibited markedly greater uptake capacities of approximately 450% and 530%, respectively, reflecting the ability of denser hydrogel matrices to swell and entrap more fertilizer [32]. This concentration-dependent behavior can be attributed to



(a)

(b)

Figure 5. (a) Swelling degree of urea solution uptake and (b) physical appearance of hydrogel at different time interval

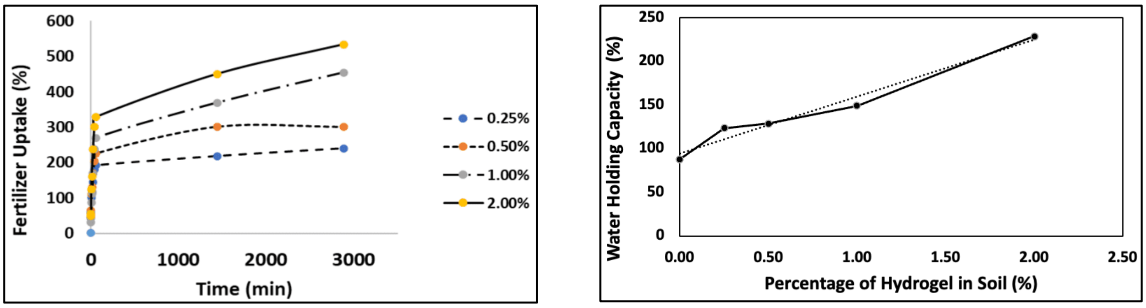
the enhanced water-holding capacity and larger polymeric networks of hydrogels, which provide more active sites for nutrient absorption and enable controlled release [33-35]. Similar trends have been reported in recent studies, where hydrogel-based soil amendments significantly improved water retention, reduced nutrient leaching, and enhanced controlled fertilizer delivery for sustainable agriculture [2, 33, 36-37].

The water-holding capacity of the soil was evaluated by incorporating varying concentrations of dry hydrogels (0.25, 0.50, 1.00, and 2.00% w/w) into organic planting soil, as illustrated in **Figure 7(b)**. The results revealed a concentration-dependent improvement in soil moisture retention, with higher hydrogel percentages exhibiting substantially greater water-holding capacity compared to the untreated control. Notably, soil mixed with 2.00% hydrogel achieved more than a two-fold increase in water retention, reflecting the superior ability of the hydrogel to absorb and store water within its three-dimensional polymeric matrix [37]. This enhanced soil-water interaction prolongs water availability in the rhizosphere, contributing to sustained soil moisture [9, 12-13].

Seed germination and initial growth of Pak Choy

Germination of Pak Choy seeds was studied, as shown in **Table 1**, with experiments conducted in triplicate. The organic planting soil was added with different percentages of hydrogel-containing fertilizer in different pots. The germination percentage improved from 65% in the control (0.00% hydrogel) to 80% at 2.00% hydrogel. Specifically, on Day 1 after sowing, five seeds germinated for the 2.0% hydrogel, and the number decreased for lower hydrogel concentrations. The higher germination and seedling percentages with increasing hydrogel concentrations are attributed to sustained soil moisture [33]. A higher percentage of hydrogels also resulted in better seedling development, with seedlings reaching the cotyledonary stage 3 days after sowing. This improvement is due to the ability of the hydrogel to retain and gradually release moisture, thereby stabilizing water availability during germination. These findings are supported by a recent study showing that cellulose-based hydrogels with superior water retention properties significantly enhanced seed germination even without external watering [38].

Figure 6. Dry and swollen hydrogels showing volumetric expansion after water absorption



(a) (b)

Figure 7. (a) Fertilizer uptake over time (b), and water holding capacity as influenced by different hydrogel concentrations (0.25–2.00% w/w).

Meanwhile, the initial growth of Pak Choy seedlings was significantly enhanced by hydrogel application up to 2% (w/w), which positively correlated with cotyledonary development. **Figure 8** shows the visual assessment of the development of cotyledon and the number of leaves after 10 days of sowing. As shown in the control seedlings (0.00% hydrogel), typically only two cotyledonary leaves were present, while seedlings treated with 0.50–1.00% hydrogel developed three leaves. Notably, seedlings treated with 2.00% hydrogel consistently developed four leaves, indicating accelerated leaf emergence and stronger early vigor. These outcomes highlight the efficacy of hydrogel supplementation (up to 2.00% w/w) in promoting uniform and vigorous early-stage growth of Pak Choy [13].

Table 1. Effect of hydrogel incorporation on seed germination and early seedling establishment

Percentage of Hydrogel (%)	Germination Percentage (%)	Seedling at Cotyledonary (%)
0.00	65	61.5
0.25	70	85.7
0.50	75	93.3
1.00	75	93.3
2.00	80	100.0

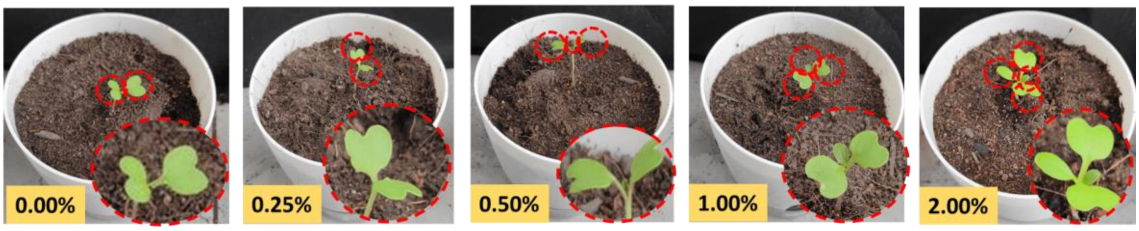


Figure 8. Cotyledonary development of Pak Choy seedlings grown under different hydrogel concentrations (After 10 days)

Conclusions

In conclusion, hydrogels represent a valuable innovation in agriculture due to their exceptional capacity to absorb and retain water, making them highly effective for improving soil moisture and nutrient availability. The findings revealed that dry hydrogels exhibited significantly greater urea uptake capacity than pre-swollen hydrogels, with the process strongly influenced by solution concentration, temperature, and pH. The optimal uptake occurred at elevated urea concentrations, moderate temperatures, and near-neutral pH (6.5–7.5). The kinetic analysis confirmed rapid initial uptake followed by gradual stabilization. Furthermore, this study demonstrated enhanced urea uptake, improved soil water retention, and better seedling development when using potassium polyacrylate hydrogels. These findings highlight the potential of potassium polyacrylate hydrogels as a practical soil amendment to enhance water and nutrient efficiency, contributing to sustainable farming practices.

Acknowledgement

This work was funded by the Ministry of Higher Education (MOHE) of Malaysia under the Fundamental Research Grant Scheme (FRGS/1/2024/STG05/USIM/02/4) and partially supported by Universiti Kebangsaan Malaysia research grant (Grant Numbers GUP-2024-063).

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