Heliyon 10 (2024) e28972

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Assessment of energy cane bagasse-derived cellulosic microfiber hydrogels on the growth of potted chili peppers

Jaabili S. Gosukonda [1], Venkata N. Degala, Hari P. Singh *

Agricultural Research Station, Fort Valley State University, Fort Valley, GA, 31030, USA

A R T I C L E I N F O

Keywords:
Saccharum spp.
Capsicum annuum
Cross-linked
Hydrogel
Soil moisture
Water holding capacity
Root-to-shoot ratio

A B S T R A C T

Energy cane (*Saccharum* spp.) bagasse, a type of biomass waste, is often underutilized, burned, or left to dispose of itself. This research aimed to evaluate the potential of converting this bagasse into high-value cellulosic microfiber hydrogels (CMH) for water conservation and potted chili (*Capsicum annuum*) plant growth. CMH offers a biodegradable alternative to synthetic polyacrylamide (PA) hydrogels and provides the dual benefit of improved water use efficiency and reduced environmental impact due to their ability to naturally break down in the soil. In this study, CMH and PA hydrogels were compared for water retention value (WRV), and reswelling kinetics (RK), as well as their effects on plant height, leaf count, root-to-shoot ratios (R:S ratio), and soil moisture retention. Two versions of CMH, CMH65 and CMH60, were prepared with varying cellulose-chitosan ratios: 65:35 and 60:40, respectively. The hydrogels were tested at four concentrations (0, 0.5, 1.0, and 2.0% w/w) by being mixed in Promix® soil. Observations were recorded over a 16-day period without additional water. Also, the WRV of hydrogels at 240 min and RK (10–180 min) were compared over three swelling-deswelling cycles. The PA hydrogel exhibited higher WRV (exceeding 450%) compared to CMH (45%). However, PA led to reduced plant height, leaf count, and R:S ratio when compared to higher concentrations of CMH65 and CMH60. In general, CMH60 (0.5% and 2%) exhibited superior plant growth. All hydrogels exhibited a significant decrease ($p < 0.05$) in WRV across successive cycles. Notably, during cycle 2, both CMH65 and CMH60 peaked in WRV at 10 and 20 min, respectively, compared to cycle 1. This study demonstrates the potential of bagasse-derived hydrogels as a value-added product for water conservation and crop growth.

1. Introduction

Energy cane (*Saccharum* spp.), a perennial lignocellulosic crop, thrives on marginal lands and delivers high biomass yield with minimal inputs [1]. This crop boasts numerous benefits, including bioenergy generation, carbon sequestration, soil improvement, and economic prospects [2,3]. In 2020, global energy cane biomass production increased to 1.6 billion tons, significantly contributing to the renewable energy landscape with an impressive energy potential of 17 GJ per ton [4,5]. However, this bioenergy production generates non-economic by-products, leading to substantial biomass waste. An estimated 140 billion metric tons of biomass waste accumulates annually [6]. This cellulose-rich waste, containing 38–50% cellulose, is often underutilized, burned, or left to decompose,

* Corresponding author.
E-mail address: singhh@fvsu.edu (H.P. Singh).
[1] Houston County High School, Warner Robins, GA, 31088, USA.

https://doi.org/10.1016/j.heliyon.2024.e28972
Received 25 October 2023; Received in revised form 27 February 2024; Accepted 27 March 2024
Available online 30 March 2024

contributing to climate change, soil and water contamination, and air pollution, with crop residue burning accounting for 18% of global CO_2 emissions [7,8].

To address this pressing issue, cellulose-based hydrogels (CMHs) emerge as a promising waste-management solution due to their biodegradability and biocompatibility [9,10]. Energy cane bagasse, the fibrous residue after juice extraction, is a valuable resource rich in cellulose and abundant OH groups, making it ideal for high-value CMH production [11,12]. The presence of hydrophilic groups such as -OH, -CONH-, -$CONH_2$-, and -SO_3H groups enables hydrogels to absorb and retain water, rendering them beneficial for various applications by forming a three-dimensional cross-linking polymer network structure [13,14]. Due to these unique properties, hydrogels are insoluble in water but can absorb and retain large amounts of water–several hundred times their dried weight–even under pressure while maintaining stability and network structure [15,16]. This remarkable versatility translates into a diverse range of applications, from supporting crop growth in agriculture [17] to aiding wound healing in healthcare [18] and enhancing everyday products like diapers and insoles [19].

In agriculture, CMHs serve as soil conditioners, enhancing soil structure and aeration, facilitating improved root penetration and nutrient uptake, resulting in increased crop yields [17,20]. For instance, CMHs have been applied as soil amendments to promote the growth of maize, wheat, and okra [21,22, 23]. Furthermore, these hydrogels also function as carriers for controlled-release fertilizers and pesticides, ensuring gradual chemical release, minimizing environmental impact, and providing sustained support for crop growth [24,25]. Notably, the water-retention property of these hydrogels holds immense potential for reducing irrigation frequency in arid and semi-arid regions facing water scarcity challenges [9,25].

Recognizing the potential ecological drawbacks associated with the use of synthetic hydrogels, despite their attractive qualities of low cost and high efficiency, this study proposes a sustainable alternative: a cost-effective and energy-efficient method for extracting cellulose micron-sized fibers [26,27]. The innovative approach of utilizing energy cane bagasse in hydrogel preparation not only offers a sustainable solution for biomass waste management but also paves the way for developing functional materials with diverse applications. Though promising, the production and application of hydrogels derived from energy cane bagasse remain underexplored, particularly regarding their impact on plant growth and water conservation.

Therefore, this study aims to bridge this knowledge gap by producing hydrogels using cellulosic microfibers extracted from energy cane bagasse. Additionally, the study aimed to investigate the potential of CMH as a soil amendment to enhance water use efficiency and promote the growth of chili peppers (*Capsicum annuum)* in potting soil. A comparative analysis was conducted between CMHs and commercially available polyacrylamide hydrogels, considering factors such as water retention values (WRV), reswelling kinetics (RK) and growth characteristics, including chili plant height, leaf count, root-to-shoot ratios (R:S ratios), and moisture retention in potting soil. This comprehensive approach positions the study as a valuable contribution to understanding the application of energy cane bagasse-derived hydrogels in the realm of plant growth and soil enhancement.

2. Materials and methods

2.1. *The synthesis of cellulosic microfiber hydrogels (CMH)*

Energy cane bagasse was obtained from field experiments conducted at the Agricultural Research Station at Fort Valley State University (FVSU). Fig. 1 illustrates the flow diagram depicting the methodology employed in this study. The bagasse samples were dried at 55 °C in an oven for 60–72 h until a constant weight was achieved. Subsequently, the dried sample was ground to a particle size of 1–5 mm using a Thomas Wiley Laboratory Mill. According to the protocol outlined by Zhang et al. (2014) [28], acid and alkaline delignification of the bagasse sample were performed using nitric acid and potassium chlorate, respectively. The extracted cellulose microfibers were then purified and neutralized by thorough washing and filtering with distilled water until achieving a neutral pH. Finally, these cellulose microfibers were stored.

The extracted cellulose fibers were first modified according to the Bruneel and Schacht (1993) methodology [29], followed by further functionalization using the Pagliaro (1998) protocol [30] to produce reactive cellulose. The reactive cellulose fibers were washed with acetone twice and dried at room temperature [27].

Two ratios of reactive cellulose and carboxymethylated chitosan were mixed to assess their impact on the formation of cellulose-chitosan cross-linked gels, as well as their water retention values and reswelling kinetics. The carboxymethylated chitosan was synthesized following the methodology described by Yang et al. (2016) [31]. To prepare the cellulose-chitosan hydrogels, a 1 wt% solution of reactive cellulose was heated together with a 1 wt% solution of chitosan at two different ratios: CMH65 (cellulose = 65% and

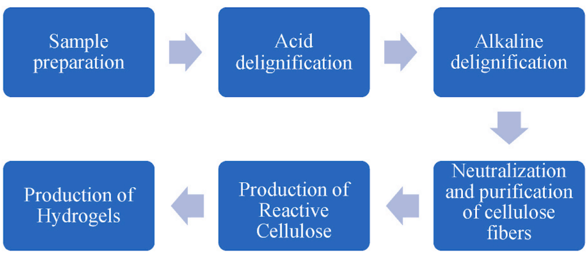

Fig. 1. Flow diagram illustrating the methodology.

chitosan = 35%) and CMH60 (cellulose = 60% and chitosan = 40%). The mixture was stirred at a temperature of 60 °C for 1 h, followed by magnetic stirring at 500 rpm for 1 min. Subsequently, the samples were left undisturbed at room temperature for a period of 4–6 h to facilitate the formation of a cross-linked polymer gel comprising cellulose and chitosan, which was referred to as the cellulosic microfiber hydrogel (CMH).

2.2. Assessment of water retention values (WRV) of hydrogels

Assessment of the water retention value (WRV) of the hydrogels is important for determining their capacity to absorb and retain water. To evaluate the WRV, the CMH65, CMH60, and polyacrylamide (PA) hydrogels were dried at 50 °C for 12 h, followed by additional drying and weighing of the hydrogels at 1-h intervals until a constant weight (dry weight = W_d) was reached. Subsequently, these dried hydrogels were submerged in water for 240 min. After removing the swollen hydrogels from the water, any excess water on the gel surface was carefully removed, and the weight of the soaked hydrogel was measured as the wet weight (W_t). The swollen hydrogels were then dried overnight at 50 °C in an oven until a constant weight was attained. This soaking and drying process was repeated for a total of three cycles.

Polyacrylamide hydrogels have been extensively studied for agricultural applications due to their high-water retention capabilities, particularly in areas like soil hydration, plant growth, and controlled release of plant nutrients [32]. Therefore, comparing the water retention values (WRVs) of polyacrylamide hydrogels, a commercially available standard, with those of cellulose microfiber hydrogels, which are naturally biodegradable, is a valuable exercise for assessing the trade-off between performance and sustainability. Understanding the swelling-deswelling kinetics of the hydrogels is crucial for most of these applications, as it directly influences the release and delivery of nutrients, pesticides, and other important compounds.

The water retention value (WRV) is typically expressed as a weight or volume ratio of absorbed water to dry hydrogel (calculated using Equation (1)), revealing its capacity for water storage and sustained release, making it crucial for applications like soil conditioning and promoting plant growth.

$$WRV = (W_t - W_d)/W_d \times 100 \tag{1}$$

where,

WRV = Water retention value.

W_d = Dry weight of the hydrogel.

W_t = Wet weight of the wet hydrogel at time t.

2.3. Assessment of water reswelling kinetics (RK) of hydrogels

Reswelling kinetics (RK) refers to the rate at which a hydrogel can reabsorb water after being dried. It is a crucial property of hydrogels as it determines their reusability. The assessment of the re-swelling dynamics of crosslinked hydrogels at different time intervals is essential for gauging their ability to regain their original swollen state after dehydration. This property holds particular significance in applications where sustained water uptake and release are critical.

To assess the reswelling kinetics, CMH65, CMH60, and PA hydrogels were dried overnight at 50 °C in an oven until a constant weight was reached (W_d). Subsequently, these dried hydrogels were immersed in water for specific time intervals ranging from 10 to 180 min. After each time interval, the soaked hydrogels were removed from the water, excess water on the gel surface was carefully eliminated, and their wet weights (W_t) were measured. The W_t was recorded at intervals of 10, 20, 30, 60, 120, and 180 min. The wet hydrogels were then dried overnight at 50 °C in an oven until a constant weight was attained. This process of soaking (at predetermined intervals) and drying was repeated for a total of three cycles. The WRV of the hydrogels at each time frame was calculated using Equation (1).

Both WRV and RK are vital properties of hydrogels, but they assess different aspects of their interaction with water: WRV measures the equilibrium amount of water a hydrogel can hold, revealing its capacity for storing and releasing water over time. This is valuable for applications like soil conditioning, where sustained moisture release is crucial. Conversely, RK measures the rate at which a dehydrated hydrogel reabsorbs water, providing insights into water diffusion within its network. This property is key for controlled-release applications like pesticide or nutrient delivery, where precise timing is essential [32].

2.4. Assessment of hydrogels' impact on soil moisture and plant growth in potting soil

To investigate the effects of hydrogel amendment on moisture retention and chili plant growth in potting soil, four concentrations (0, 0.5, 1.0, and 2.0% (w/w)) of CMH65, CMH60, and PA hydrogels were mixed with Promix® potting soil. A total of ten treatments were established, including three hydrogels at three different concentrations, along with a control. Before adding the hydrogels, the soil was thoroughly saturated with water, and chili plants of the same age and approximately uniform height were carefully selected and placed in each pot. Observations were then recorded for moisture retention and plant growth parameters, such as plant height, leaf number, and root-to-shoot ratio (R:S ratio), for 16 days without the additional supplement of water.

The moisture retention (%) in the potting soil was determined by calculating the percentage decrease in pot weight after 16 days of plant growth compared to the initial pot weights on day 0. Additionally, the difference in moisture retention between consecutive days was calculated by subtracting the pot weight of each day from the pot weight of the previous day (data not shown).

The height of chili plants (in inches) was measured daily using a ruler. The increase in plant height (%) was calculated by subtracting the plant height on day 0 from the plant height on day 16. Leaf count was recorded daily, but for comparative analysis, the leaf count on the 16th day was utilized. To calculate the R:S ratio, the roots (below ground portion) and shoots (above ground portion) of each plant were separated on the 16th day of plant growth. The fresh weights of the roots and shoots for each plant were individually measured and recorded (data not shown). Subsequently, the fresh root and shoot materials were placed in separate brown bags and dried using a commercial dryer. The dried root and shoot materials were then weighed separately, and the data were recorded. A higher R:S ratio indicates a greater root density and root interception for nutrient uptake. The root-to-shoot ratio was calculated using Equation (2):

$$\text{Root Shoot Ratio (R : S Ratio)} = \text{root dry weight} \div \text{shoot dry weight} \tag{2}$$

2.5. Statistical analysis

Statistical analyses were conducted using Statistical Analysis System (SAS) software (version 9.4 by SAS Institute in Cary, NC, USA). A completely randomized design (CRD) with a factorial arrangement of treatments was employed for the experiments in this study. The sample size for measuring plant growth parameters, water retention values, and reswelling kinetics was six (6). Analysis of variance (ANOVA) was performed using the "proc mixed" and "proc GLM" procedures, with a significance level of 5%. Tukey's post hoc tests were conducted to compare treatment means, with a statistical significance threshold set at 0.05. The data were presented as mean ± standard error (SE). Box and whisker plots were generated using Excel software to compare the distribution of plant growth properties among different hydrogels and their concentrations.

3. Results and discussion

3.1. Water retention value (WRV) and reswelling kinetics (RK) of hydrogels

The analysis of variance indicated a significant ($p < 0.05$) difference in the average water retention value (%) among the three different hydrogel types. The mean WRV (%) values observed for PA, CMH65, and CMH60 hydrogels were 451.71 ± 3.49, 39.23 ± 3.10, and 33.16 ± 1.51, respectively (Fig. 2A and B). These findings align with a study conducted by Alam et al., 2019 [33], where CMH demonstrated lower WRV% compared to PA hydrogels. Despite having lower WRV (around 45%), CMH65 and CMH60 hydrogels are still preferred over PA hydrogels (exceeding 450%) due to their natural biodegradability, which eliminates the potential for environmental concerns associated with synthetic, non-biodegradable materials.

Despite lower initial water uptake, both CMH65 and CMH60 outperformed PA in maintaining moisture over three cycles of swelling and deswelling (Fig. 2A and B). PA hydrogels lost a substantial amount of their water-holding capacity, dropping by 46% from the first to the second cycle and a further 71% by the third. In contrast, CMH65 and CMH60 lost only 56.78% and 48.32% water in the first two cycles, respectively, and maintained better water retention even by the third cycle (38.92% and 52.84% loss). This suggests that CMH hydrogels offer a more reliable long-term water retention capability.

According to published reports, several factors are likely to contribute to these differences. PA hydrogels, being synthetic, can be engineered to have a highly hydrophilic surface and a dense, highly cross-linked structure, which maximizes water absorption [33,34]. On the other hand, CMHs have a fibrous and porous nature, which may limit their overall water uptake and retention compared to PA hydrogels [34].

The reswelling kinetics (RK) were significantly ($p < 0.05$) impacted by soaking times among the three hydrogels. In cycle one, all hydrogels reached their maximum wet weight (W_t) after 60 min of soaking, beyond which the percentage increase in their Wt value became minimal (Figs. 3–5). Similar to the trend observed in WRV, the reswelling kinetics (RK) values of the hydrogels also decreased

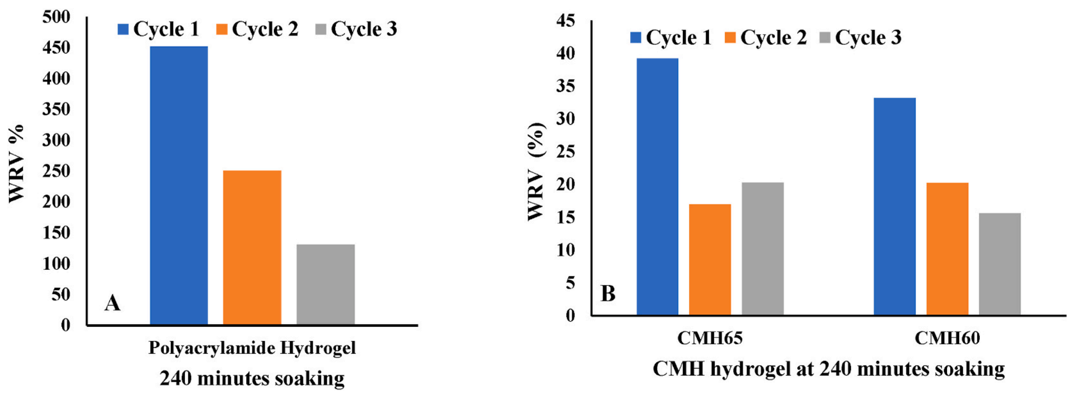

Fig. 2. A–B: Water retention values (%) of polyacrylamide (A) and cellulosic hydrogels, CMH65 and CMH60 (B), after soaking for 240 min in three repeated cycles.

from cycle one to cycle three (Figs. 3–5).

Interestingly, in cycle two, both CMH65 and CMH60 exhibited higher wet weight values at the 10-min and 20-min time frames, respectively, compared to the corresponding time frames in cycle one (Figs. 4 and 5). Incomplete recovery after drying and reswelling cycles is a known phenomenon in hydrogels, similar to the observations reported by Ceylan et al. (2004) where their hydrogels also reswelled quickly (within 1 min) but the final wet weight remained significantly lower than the initial state [35]. This behavior is observed in the CMH hydrogels in this study as well, and further investigation is needed to understand the underlying mechanisms.

It is generally acknowledged that the water-holding capacity of hydrogels is influenced by swelling and deswelling kinetics. In this study, the drying of wet gels from cycle 1 at an elevated temperature of 50 °C could have reversed the osmotic pressure difference, causing water to exit and resulting in shrinkage. The shrinkage process likely caused some loss of structural integrity, such as a less stable cross-linking network or reduced pore sizes, affecting water absorption. Upon reintroduction to water at room temperature, the osmotic pressure difference may have increased, leading to rapid water inflow and a faster swelling rate [36]. This accelerated water absorption could have contributed to the higher wet weight values observed in cycle 2.

Despite having a lower chitosan content (35%), the CMH65 hydrogel matched the water retention and reswelling performance of the CMH60 hydrogel (40% chitosan). This finding opens the door to optimizing chitosan content for efficient water management while potentially lowering production costs. However, published reports have indicated that hydrogels with higher cellulose to lower chitosan ratios tend to exhibit improved water retention and slower rehydration rates [37]. For instance, hydrogels crosslinked with 25% chitosan exhibited a WRV of approximately 600 g water/g material. When the chitosan content was increased to 35%, there was a decrease in the WRV. On the contrary, hydrogels prepared with 15% chitosan displayed an unstable physical appearance and were unable to retain water due to their less stable network structure [33].

3.2. Moisture retention (%) in potting soil

Moisture retention was evaluated by calculating the percentage reduction in pot weight between day 0 and after 16 days of plant growth. All pots displayed a noticeable weight decrease, indicating moisture loss during the 16-day period (Fig. 6A and B). The hydrogel-amended soils retained moisture more effectively than the control, as evidenced by their smaller weight reductions (Table 1 and Fig. 6A and B). This suggests that adding hydrogels can significantly reduce moisture loss in potted plants.

While this study observed no consistent pattern in moisture retention across the three hydrogel types and concentrations, research by Hafiz-Afham et al. (2023) [38] demonstrated that cotton-based hydrogels (40% hydrogel and 60% topsoil) effectively retain water, circulate it within the planting medium, and enhance water use efficiency in pepper crops without impacting plant growth. A study by Joseph (2020) [39] reinforced the potential of hydrogels and showed that they can significantly enhance plant growth. By retaining more moisture and nutrients within the soil, a minimal 0.2% hydrogel mix in soil was found to reduce water consumption by up to 50% compared to plants in normal soil without compromising crop yield [39]. For optimal CMH performance, careful consideration of factors like concentration, environment, and soil composition is crucial [32,40].

3.3. Plant height

In this study, the incorporation of CMHs as a potting soil supplement had a significant impact on chili plant growth and development, particularly in terms of height (Fig. 7). CMH60 hydrogel at concentrations of 0.5% (56.74 ± 2.51) and 2% (58.06 ± 3.02) resulted in higher average plant heights compared to the control and pots containing CMH65 or PA hydrogels. However, there were no significant differences in height increase between plants grown in the control soil and those with any of the three concentrations of PA hydrogels (Table 1). The lowest height increase was observed in pots with 1% CMH65 hydrogel. Our findings align with Hafiz-Afham et al. (2023) [38], who reported that soil enriched with 40% hydrogel exhibited the highest mean plant height (67.33 cm), followed by 60% hydrogel (62.22 cm). This suggests, as concluded by the authors that specific concentrations of CMH may create an ideal environment for efficient water and nutrient uptake, ultimately leading to enhanced plant growth [38]. The correlation between plant height and its ability to absorb water and nutrients effectively was highlighted [38]. This study demonstrates that incorporating 0.5% and 2% CMH60 effectively promotes chili plant height growth by optimizing water uptake and cell growth, likely resulting in

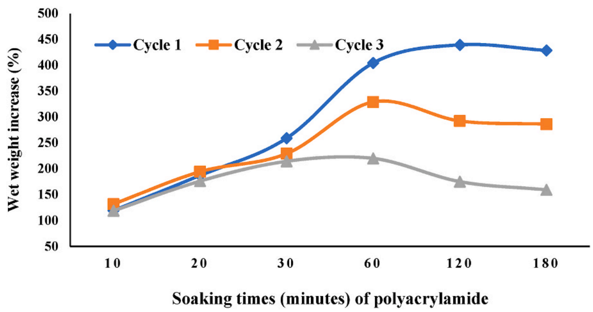

Fig. 3. Reswelling kinetics of polyacrylamide hydrogel (PA) measured as percent wet weight increase at 10 min–180 min soaking intervals, for three cycles.

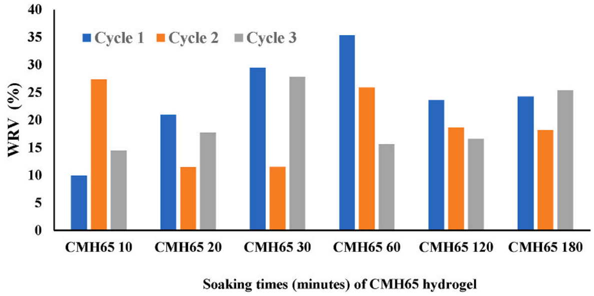

Fig. 4. Water retention values (%) of CMH65 hydrogel at different soaking intervals from 10 min to 180 min, repeated for three cycles.

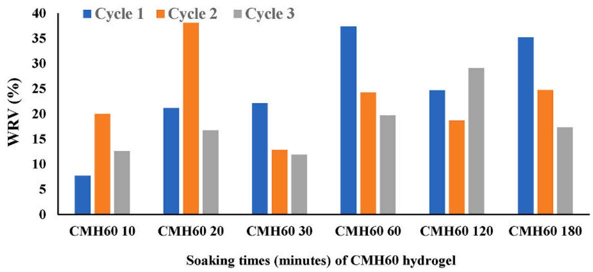

Fig. 5. Water retention values (%) of CMH60 hydrogel at different soaking intervals from 10 min to 180 min, repeated for three cycles.

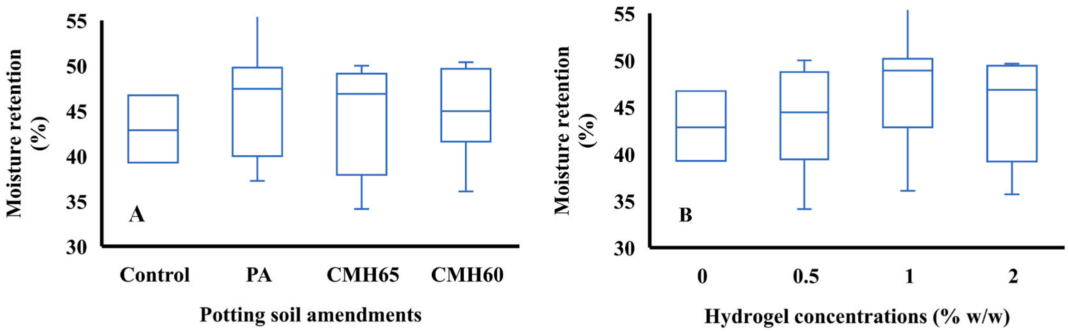

Fig. 6. A–B: Moisture retention (%) from potting soils amended with PA, CMH65, and CMH60 hydrogels (A) at doses 0, 0.5, 1, and 2% (w/w) (B), after 16 d plant growth.

Table 1
Effects of hydrogel amendment in potting soil on moisture retention, plant height, leaf count, and root-to-shoot ratio in chili plant growth over a 16-day period*.

hydrogels		moisture retention	plant height	leaf count	R:S ratio
type	conc. (% w/w)	mean ± se	mean ± se	mean ± se	mean ± se
CMH65	0.5	41.43 ± 4.63^{a}	49.47 ± 1.27^{ab}	14.00 ± 0.58^{ab}	22.27 ± 1.35^{ab}
	1.0	46.99 ± 1.33^{a}	32.51 ± 3.48^{c}	13.33 ± 0.88^{ab}	17.98 ± 4.10^{ab}
	2.0	43.96 ± 4.18^{a}	38.95 ± 3.79^{bc}	18.33 ± 1.20^{ab}	17.08 ± 0.90^{ab}
CMH60	0.5	45.09 ± 1.8^{a}	56.74 ± 2.51^{a}	15.67 ± 2.33^{ab}	20.12 ± 1.03^{ab}
	1.0	45.38 ± 4.64^{a}	43.86 ± 3.02^{abc}	11.33 ± 0.88^{b}	24.21 ± 1.19^{a}
	2.0	44.44 ± 2.64^{a}	58.06 ± 3.02^{a}	18.67 ± 1.86^{a}	20.55 ± 3.13^{ab}
PA	0.5	44.15 ± 3.03^{a}	40.60 ± 4.21^{bc}	14.33 ± 1.76^{ab}	12.95 ± 1.19^{b}
	1.0	49.00 ± 4.20^{a}	45.62 ± 2.07^{abc}	15.67 ± 1.86^{ab}	20.69 ± 1.95^{ab}
	2.0	44.77 ± 3.80^{a}	38.87 ± 2.86^{bc}	15.00 ± 1.00^{ab}	14.77 ± 1.46^{ab}
control		42.96 ± 2.15^{a}	40.90 ± 1.39^{bc}	12.67 ± 0.88^{ab}	19.57 ± 1.70^{ab}

*[a, b, c] Any two means with the same superscript are not significantly different at the five (5) percent level of probability using Tukey's post hoc test. SE = Stard Error. PA = Polyacrylamide. R:S ratio = root-to-shoot ratio.

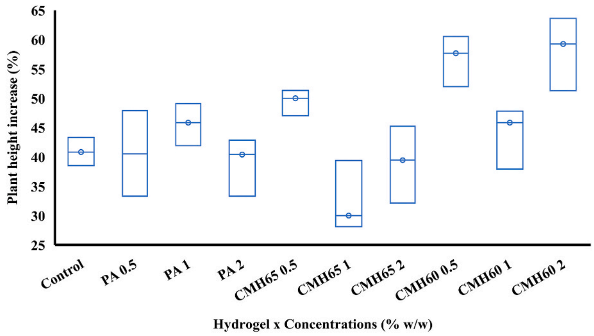

Fig. 7. Distribution of chili height increase (%) after 16–day growth in potting soils amended with PA, CMH65, and CMH60 hydrogels at concentrations 0, 0.5, 1, and 2% (w/w).

significantly increased plant height compared to the control and other concentrations.

The 2% CMH60 treatment likely facilitated optimal cell expansion and elongation, promoting greater height development. Sasmal and Patra (2020) [41] reported that the quantity of water retained in the soil increased significantly with CMH inclusion, resulting in controlled water release under dry conditions. This observation aligns with Azeem et al. (2023) [42], who attributed plant growth to CMH's effective water retention and gradual release capabilities, ensuring a consistent and controlled moisture supply to plant roots. Similarly, Prisa and Guerrini (2022) [43] reported increased *Solanum lycopersicum* plant height, vegetative growth, seed germination, and microbial colonization of the substrate with two or three hydrogel (Hydro Start) capsules under drip irrigation. Importantly, these reports observed no differences in substrate pH between the control and hydrogel-amended soils. In contrast to our findings, Fernández et al. (2017) [44] reported that five pre-hydrated gel doses (0.5, 1.0, 1.5, 2.0, and 2.5 g/plant) did not significantly ($p > 0.05$) affect *Capsicum annuum* plant height, although the numerical values varied. However, the authors report that CMH hydrogels, like those used in our study, were safe for promoting plant growth and did not negatively impact plant height [44].

3.4. Total leaf count

The results indicated that both the type and concentration of hydrogel in the soil had an impact on the total leaf count of chili plants (Table 1). Among the three dosages tested, CMH60 at a 2% concentration exhibited the highest mean leaf count (18.67 ± 1.86). On the other hand, the lowest mean leaf count was observed in soils mixed with 1% CMH60 (11.33 ± 0.88) (Fig. 8A and B). Notably, the total leaf count was consistently higher in soils amended with CMHs compared to synthetic PA hydrogels.

Hafiz-Afham et al. (2023) [38] reported similar findings, with soil containing 40% hydrogel exhibiting the highest mean leaf number (73.77 ± 2.43), followed by 60% hydrogel (64.33 ± 3.03). Interestingly, the 100% hydrogel treatment resulted in the lowest mean leaf count (28.44 ± 2.24). This study aligns with Ekebafe et al. (2013) [45], who observed significant increases in okra plant height, stem diameter, leaf area, and biomass accumulation when soils mixed with hydrogels. In their study, authors identified the optimal application rate as 6.0 kg ha^{-1}, as it maximized growth while maintaining proper soil nutrient balance [45]. Similarly, Diógenes et al. (2022) [46] concluded that employing an appropriate hydrogel concentration can significantly enhance water availability for plants, leading to improved growth parameters like leaf count and height. Peyrusson's (2021) [47] study using cellulose-based hydrogels further underscored this, with spearmint biomass more than doubling (110% increase) in clay-rich soils and increasing by 78% in sandier soils, highlighting the significant potential of hydrogels for enhancing plant growth even in challenging soil conditions.

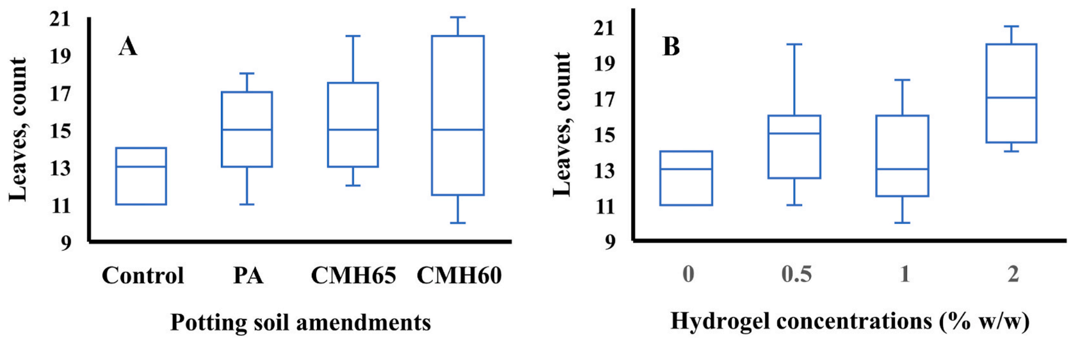

Fig. 8. A–B: The leaf count on chili plants after 16-day growth in potting soils amended with PA, CMH65, and CMH60 hydrogels (A) at concentrations (%) of 0, 0.5, 1, and 2 (B).

3.5. Root-to-shoot ratio (R:S ratio)

The results indicated a clear trend in root-to-shoot ratios (R:S) across different hydrogel treatments (Table 1, Fig. 9A). Plants grown in PA hydrogel-amended soils displayed the lowest R:S values, indicating less root development relative to shoot growth. Conversely, plants treated with CMH60 hydrogel exhibited the highest R:S ratios, suggesting an enhanced root system compared to the control and CMH65 treatments. Interestingly, within each hydrogel type, the 1% concentration yielded a higher R:S ratio than the 2% concentration (Fig. 9B). This observation hints at a potential threshold effect, where lower hydrogel concentrations promote enhanced root development relative to shoot growth, suggesting the need for further investigation to optimize concentrations for balanced growth. Notably, the lowest R:S ratio (12.95 $\pm$ 1.19) occurred in plants grown with 0.5% PA hydrogel, while the highest value (24.21 $\pm$ 1.19) was observed in those soils mixed with 1% CMH60 hydrogel.

The observed variations in R:S may be a consequence of the diverse ways hydrogels enhance root development, including alleviating water stress and promoting root respiration. Acting as tiny reservoirs [15,40], these hydrogels provide readily accessible water, minimizing the need for plants to invest energy in excessive root growth and allowing them to prioritize shoot development. Patra et al. (2022) [48] further highlights the role of porous structures in hydrogels- promoting healthy root respiration and building a stronger system to support increased shoot growth through improved soil-air circulation. Contributing to this, Yangyuoru et al. (2009) [49] report on the direct water uptake from hydrogel particles by plants when required, while Mu et al. (2021) [50] emphasize the hydrogels' ability to buffer soil conditions during stress, further supporting the function of both roots and shoots [51].

Additionally, cellulose-based hydrogels (CMHs) have been shown to stimulate beneficial microbial activity [52], leading to enhanced nutrient decomposition and availability for plants [53]. This improved nutrient acquisition, likely due to better root-to-soil contact facilitated by CMHs [53], benefits both root and shoot development. Supporting this explanation, Thomas (2005) [54] found that hydrogels enhance moisture and root-soil contact, improving eucalypt seedling survival. Similarly, Kalaleh (2018) [55] observed a positive correlation between hydrogel use and higher root-to-shoot ratios (R:S), indicating improved overall onion plant health. These findings suggest that CMHs hold promise for promoting balanced and vigorous plant growth by both optimizing nutrient absorption and enhancing root-soil interactions [56].

In this study, incorporating CMHs into the planting media likely alleviated water stress in chili plants through several mechanisms. As proposed by Wang and Geng (2019) [57], the hydrogel may have enhanced cell membrane stability, increased relative water content in leaves, and reduced blockage in the xylem and phloem, ultimately facilitating efficient water and nutrient translocation. This suggests that CMHs can not only improve nutrient uptake but also help chili plants manage water stress more effectively, leading to optimal growth and yield.

This research explored the impact of incorporating cellulose-based hydrogels (CMHs) and a synthetic counterpart (PA) into potting soil on chili pepper growth and development. Key findings reveal the promising potential of CMHs, particularly CMH60, in optimizing water management and promoting robust plant growth. Cellulose based hydrogels, despite absorbing less water initially (in cycle 1) compared to PA hydrogels, exhibited remarkable resilience across three cycles of swelling and deswelling, losing significantly less water (38.92%–52.84% vs. 71% for PA). This suggests a more stable, sustained water-holding capacity, likely due to their fibrous, porous structure [52]. This finding aligns with previous studies, highlighting the suitability of CMHs for long-term irrigation strategies [17]. Interestingly, both CMH hydrogels exhibited a surprising surge in water absorption (within 10–20 min) during the second cycle, surpassing their initial values of cycle 1. This phenomenon, attributed to potential structural changes during the drying process, underlines the dynamic nature of hydrogels and their ability to adapt to repeated wetting and drying cycles [48,58]. Additionally, chitosan content within CMHs seems to play a crucial role in WRV, with optimal water retention observed at 35% chitosan in CMH65. However, exceeding this level can diminish water-holding capacity [33].

In relation to plant growth, CMH60, at specific concentrations (0.5% and 2%), emerged as the leader in promoting chili plant growth. This hydrogel facilitated optimal water availability and potentially cell expansion/elongation, leading to a significant increase in plant height compared to the control and CMH65. Similar trends were observed for leaf count, with CMH60 at 2% promoting the highest leaf production, highlighting its potential for enhanced photosynthesis and biomass production [17].

In this study, CMH60, with a higher chitosan ratio (40% compared to 35% in CMH65), exhibited superior water absorption and retention. This advantage stems from both the increased percentage of chitosan and its unique properties, including abundant amine groups that attract and bind water [9,35], a more porous network for enhanced absorption, additional ionic interactions with cellulose (cationic chitosan with anionic cellulose) for improved water retention, and viscoelasticity that forms a gel-like barrier, further slowing water loss [33,34]. Collectively, these properties are known to promote plant growth, making CMH60 an efficient water reservoir for plants and ensuring an ample water supply even under harsh conditions.

Additionally, the results in this study show variability in plant responses based on different concentrations of hydrogels, indicating that the effectiveness of hydrogel applications may be dose dependent. This highlights the importance of optimizing hydrogel concentration for specific plant species and growth conditions. Furthermore, CMHs offer a sustainable alternative to synthetic PA hydrogels due to their biodegradability, minimizing environmental concerns associated with biomass bagasse and synthetic waste [59,60]. The integrated analysis underscores the relevance of these insights for optimizing agricultural practices and resource management.

4. Conclusions

This study establishes that hydrogels produced from energy cane bagasse cellulose microfibers have promising applications in water conservation and plant growth. A comprehensive analysis of WRV, RK, soil moisture retention, plant height, total leaf count, and

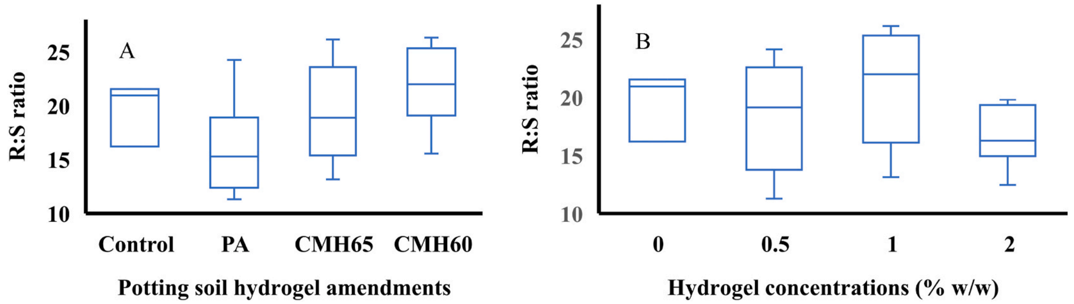

Fig. 9. A–B: The root-to-shoot ratios (R:S ratio) of chili plants after 16 days of growth in potting soils supplemented with PA, CMH65, and CMH60 hydrogels (A) at concentrations (%) of 0, 0.5, 1, and 2 (B).

root-to-shoot ratio (R:S) in the context of CMHs (CMH60, CMH65) provides valuable insights with both scientific and practical implications.

The study's key findings on WRV highlight the environmentally friendly nature of CMHs compared to synthetic PA hydrogels. Despite lower initial WRV, CMHs exhibit remarkable long-term water retention, making them a reliable alternative for sustainable applications. Furthermore, the dynamic patterns observed in RK shed light on the intricate interplay between soaking times and the reswelling process. This contributes to our understanding of hydrogel structural changes during deswelling, influencing water absorption and providing a foundation for further research into optimizing chitosan content for efficient water management.

The effectiveness of hydrogel-amended soils in moisture retention, as evidenced by reduced weight reductions in potted plants, underlines the practical application of CMHs in agriculture. However, the inconsistent moisture retention patterns across hydrogel types and concentrations suggest the need for careful consideration of various factors, including environment and soil composition, to achieve optimal performance. The substantial impact of CMHs on chili plant growth, particularly in terms of height and leaf count, signifies their potential as effective soil supplements. Notably, the study identifies specific concentrations (0.5% and 2% CMH60) that effectively promote plant growth, offering practical guidance for agricultural practices.

The observed variations in R:S ratios across different hydrogel treatments suggest a potential threshold effect, urging further investigation into the optimal concentrations for balancing root and shoot development. Additionally, evaluating the long-term effects of CMH60 and CMH65 hydrogels on soil properties and microbial activity is crucial. Investigating the applicability of CMHs to other crops under diverse environmental conditions, like arid regions or different soil types, would broaden its potential impact. Exploring the combined use of CMHs with other sustainable practices like organic fertilizers could further enhance agricultural efficiency and resource conservation.

Overall, this study makes significant contributions to sustainable agriculture by providing valuable insights into the effectiveness of CMHs in promoting chili plant growth and water use efficiency. Addressing limitations and pursuing future research directions will further strengthen the scientific value of this work and pave the way for the wider adoption of hydrogel technology in agricultural practices.

Data availability statement

Data will be made available upon request.

CRediT authorship contribution statement

Jaabili S. Gosukonda: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Investigation. **Venkata N. Degala:** Methodology, Investigation, Formal analysis. **Hari P. Singh:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture, [Evans-Allen, GEOX 9001].

Notations

CMH Cellulosic microfiber hydrogels
CMH65 Cellulosic microfiber hydrogel with 65% cellulose and 35% chitosan
CMH60 Cellulosic microfiber hydrogel with 60% cellulose and 40% chitosan
CONH Amide group (Carbonyl group attached to a nitrogen
−OH Hydroxyl group
SO_3H Sulfonic acid
W_d Dry weight of the hydrogel
W_t Wet weight of the wet hydrogel at time t
RK Reswelling kinetics
R:S Root-to-shoot ratio
PA Polyacrylamide
WRV Water retention value

References

[1] O.V. Carvalho-Netto, J.A. Bressiani, H.L. Soriano, C.S. Fiori, J.M. Santos, G.V.S. Barbosa, M.A. Xavier, M.G.A. Landell, G.A.G. Pereira, The potential of the energy cane as the main biomass crop for the cellulosic industry, Chem. Biol. Technol. Agric. 1 (20) (2014) 1–8, https://doi.org/10.1186/s40538-014-0020-2.
[2] D. Scordia, S.L. Cosentino, T.W. Jeffries, Second generation bioethanol production from *Saccharum spontaneum* L. ssp. aegyptiacum (Willd.) Hack, Bioresour. Technol. 101 (2010) 5358–5365, https://doi.org/10.1016/j.biortech.2010.02.036.
[3] J.E. Knoll, W.F. Anderson, Vegetative propagation of napiergrass and energy cane for biomass production in the southeast USA, Agron. J. 104 (2012) 518–522, https://doi.org/10.2134/agronj2011.0301.
[4] E.O. Ajala, J.O. Ighalo, M.A. Ajala, A.G. Adeniyi, A.M. Ayanshola, Sugarcane bagasse: a biomass sufficiently applied for improving global energy, environment and economic sustainability, Bioresour. Bioprocess. 8 (2021) 87, https://doi.org/10.1186/s40643-021-00440-z.
[5] B.N. Boschiero, G.Q. Sérgio Castro, L.P. Cruz, J.L.N. Carvalho, S.R. Silva, J.A. Bressiani, O.T. Kölln, Biomass yield, nutrient removal, and chemical composition of energy cane genotypes in Southeast Brazil, Ind. Crops Prod. 191 (2023) 115993, https://doi.org/10.1016/j.indcrop.2022.115993. Part B.
[6] N. Tripathi, C.D. Hills, R.S. Singh, C.J. Atkinson, Biomass waste utilisation in low-carbon products: harnessing a major potential resource, npj Clim. Atmos. Sci. 2 (2023) 35, https://doi.org/10.1038/s41612-019-0093-5.
[7] J. Chen, C. Li, Z. Ristovski, A. Milic, Y. Gu, M.S. Islam, S. Wang, J. Hao, H. Zhang, C. He, H. Guo, H. Fu, B. Miljevic, L. Morawska, P. Thai, Y.F. Lam, G. Pereira, A. Ding, X. Huang, U.C. Dumka, A review of biomass burning: emissions and impacts on air quality, health and climate in China, Sci. Total Environ. 579 (2017) 1000–1034, https://doi.org/10.1016/j.scitotenv.2016.11.025.
[8] R.M. Rowell, R.M. Rowell (Eds.), Handbook of Wood Chemistry and Wood Composites, first ed., CRC Press, Boca Raton, FL, 2005 https://doi.org/10.1201/9780203492437.
[9] S.M.F. Kabir, P.P. Sikdar, B. Haque, M.A.R. Bhuiyan, A. Ali, M.N. Islam, Cellulose-based hydrogel materials: chemistry, properties and their prospective applications, Prog. Biomater. 7 (2018) 153–174, https://doi.org/10.1007/s40204-018-0095-0.
[10] H.P. Singh, Q.L. Woodford, V.N. Degala, Preparation of hydrogels from energy cane bagasse cellulose fibers, Int. J. Adv. Sci. Eng. Technol. 7 (2019) 15–17.
[11] M. Kim, F.D. Day, Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills, J. Ind. Microbiol. Biotechnol. 38 (2011) 803–807, https://doi.org/10.1007/s10295-010-0812-8.
[12] O.V. Carvalho-Netto, J.A. Bressiani, H.L. Soriano, C.S. Fiori, J.M. Santos, G.V.S. Barbosa, M.A. Xavier, M.G.A. Landell, G.A.G. Pereira, The potential of the energy cane as the main biomass crop for the cellulosic industry, Chem. Biol. Technol. Agric. 1 (2014) 20, https://doi.org/10.1186/s40538-014-0020-2.
[13] A.M.A. Hasan, M.E.S. Abdel-Raouf, Cellulose-based superabsorbent hydrogels, in: M.I.H. Mondal (Ed.), Cellulose-Based Superabsorbent Hydrogels, Polymers and Polymeric Composites: A Reference Series, Springer, Cham, 2018, https://doi.org/10.1007/978-3-319-76573-0_11-1.
[14] S. Bashir, M. Hina, J. Iqbal, A.H. Rajpar, M.A. Mujtaba, N.A. Alghamdi, S. Wageh, K. Ramesh, S. Ramesh, Fundamental concepts of hydrogels: synthesis, properties, and their applications, Polymers 12 (2020) 2702, https://doi.org/10.3390/polym12112702.
[15] C. Demitri, F. Scalera, M. Madaghiele, A. Sannino, A. Maffezzoli, Potential of cellulose-based superabsorbent hydrogels as water reservoir in agriculture, Int. J. Polym. Sci. 12 (2013) 1–6, https://doi.org/10.1155/2013/435073.
[16] R. Kundu, P. Mahada, B. Chhirang, B. Das, Cellulose hydrogels: green and sustainable soft biomaterials, Curr. Res. Green Sustain. Chem. 5 (2022) 100252, https://doi.org/10.1016/j.crgsc.2021.100252.
[17] V. Miljkovi′c, I. Gaji′c, L. Nikoli′c, Waste materials as a resource for production of CMC superabsorbent hydrogel for sustainable agriculture, Polymers 13 (2021) 4115, https://doi.org/10.3390/polym13234115.
[18] N. Chandel, K. Jain, A. Jain, T. Raj, A.K. Patel, Y. Yang, S.K. Bhatia, The versatile world of cellulose-based materials in healthcare: from production to applications, Ind. Crops Prod. 201 (2023) 116929, https://doi.org/10.1016/j.indcrop.2023.116929.
[19] E. Caló, V.V. Khutoryanskiy, Biomedical applications of hydrogels: a review of patents and commercial products, Eur. Polym. J. 65 (2015) 252–267, https://doi.org/10.1016/j.eurpolymj.2014.11.024.
[20] M.R. Guilherme, F.A. Aouada, A.R. Fajardo, A.F. Martins, A.T. Paulino, M.F.T. Davi, A.F. Rubira, E.C. Muniz, Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: a review, Eur. Polym. J. 72 (2015) 365–385, https://doi.org/10.1016/j.eurpolymj.2015.04.017.
[21] S. Watcharamul, S. Lerddamrongchai, T. Siripongpreda, C. Rodtassana, R. Nuisin, S. Kiatkamjornwong, Effects of carboxymethyl cellulose/nano-calcium carbonate hydrogel amendment of loamy sand soil for maize growth, ACS Agric. Sci. 2 (2022) 1071–1080, https://doi.org/10.1021/acsagscitech.2c00185.
[22] A.A. Shaikh, O. Rehman, M. Rashid, S. Alvi, A. Raza, A. Waheed, M. Irfan, S. Saleem, M. Iqbal, G. Mujtaba, Potentials of hydrogels in rainfed soil to conserve soil moisture and fertility to maximize the wheat yield, Soil Environ. 39 (2020) 204–210, https://doi.org/10.25252/SE/2020/162339.
[23] W.A. Laftah, S. Hashim, Synthesis, optimization, characterization, and potential agricultural application of polymer hydrogel composites based on cotton microfiber, Chem. Pap. 68 (2014) 798–808, https://doi.org/10.2478/s11696-013-0507-5.
[24] S.K. Das, G.K. Ghosh, Hydrogel-biochar composite for agricultural applications and controlled release fertilizer: a step towards pollution free environment, Energy 242 (2021) 122977, https://doi.org/10.1016/j.energy.2021.122977.
[25] F.F. Montesano, A. Parente, P. Santamaria, A. Sannino, F. Serio, Biodegradable superabsorbent hydrogel increases water retention properties of growing media and plant growth, Agric. Agric. Sci. Procedia 4 (2015) 451–458, https://doi.org/10.1016/j.aaspro.2015.03.052.
[26] R. Ramli, Slow release fertilizer hydrogel: a review, Polym. Chem. 10 (2019) 6073–6090, https://doi.org/10.1039/C9PY01036J.
[27] M.N. Alam, L.P. Christopher, Natural cellulose-chitosan cross-linked superabsorbent hydrogels with superior swelling properties, ACS Sustain. Chem. Eng. 6 (2018) 8736–8742, https://doi.org/10.1021/acssuschemeng.8b01062.

[28] X. Zhang, Y. Wang, C. Lu, W. Zhang, Cellulose hydrogels prepared from micron-sized bamboo cellulose fibers, Carbohydr. Polym. 114 (2014) 166–169, https://doi.org/10.1016/j.carbpol.2014.08.012.
[29] D. Bruneel, E. Schacht, Chemical modification of pullulan: 1. periodate oxidation, Polymer 34 (1993) 2628–2632, https://doi.org/10.1016/0032-3861(93)90600-F.
[30] M. Pagliaro, Autocatalytic oxidations of primary hydroxyl groups of cellulose in phosphoric acid with halogen oxides, Carbohydr. Res. 308 (1998) 311–317, https://doi.org/10.1016/S0008-6215(98)00090-1.
[31] H. Yang, A. Sheikhi, T.G.M. van de Ven, Reusable green aerogels from cross-linked hairy nanocrystalline cellulose and modified chitosan for dye removal, Langmuir 32 (2016) 11771–11779, https://doi.org/10.1021/acs.langmuir.6b03084.
[32] S.D. Palanivelu, N.A.Z. Armir, A. Zulkifli, A.H.A. Hair, K.M. Salleh, K. Lindsey, M.H. Che-Othman, S. Zakaria, Hydrogel application in urban farming: potentials and limitations-a review, Polymers 14 (2022) 2590, https://doi.org/10.3390/polym14132590.
[33] M.N. Alam, M.S. Islam, L.P. Christopher, Sustainable production of cellulose-based hydrogels with superb absorbing potential in physiological saline, ACS Omega 4 (2019) 9419–9426, https://doi.org/10.1021/acsomega.9b00651.
[34] A.H. Karoyo, L.D. Wilson, A Review on the design and hydration properties of natural polymer-based hydrogels, Materials 14 (2021) 1095, https://doi.org/10.3390/ma14051095.
[35] D. Ceylan, M. Ozmen, O. Okay, Swelling-deswelling kinetics of ionic poly (acrylamide) hydrogels and cryogels, J. Appl. Polym. Sci. 99 (2006) 319–325, https://doi.org/10.1002/app.22023.
[36] R.A. Rather, M.A. Bhat, A.H. Shalla, An insight into synthetic and physiological aspects of superabsorbent hydrogels based on carbohydrate type polymers for various applications: a review, Carbohydr. Polym. Technol. Appl. 3 (2022) 100202, https://doi.org/10.1016/j.carpta.2022.100202.
[37] Y.W. Chen, S.H. Binti Hassan, M. Yahya, H.V. Lee, Novel superabsorbent cellulose-based hydrogels: present status, synthesis, characterization, and application prospects, in: M. Mondal (Ed.), Cellulose-Based Superabsorbent Hydrogels. Polymers and Polymeric Composites: A Reference Series, Springer, Cham, 2019, pp. 155–195, https://doi.org/10.1007/978-3-319-77830-3_9.
[38] K. Hafiz-Afham, N.A. Hasan, M.Y. Rafi, N.J. Sidik, The growth impact of *Capsicum annum* in hydrogel incorporated media, IOP Conf. Ser. Earth Environ. Sci. 1155 (2023) 012031, https://doi.org/10.1088/1755-1315/1155/1/012031.
[39] A. Joseph, A.A. George, A. Prakash, M.J.A. Gowri, M. Mathew, Study on the effect of hydrogel on plant growth, in: P.C. Thomas, V.J. Mathai, G. Titus (Eds.), Emerging Technologies for Sustainability, Proc. Ann. Intl. Conf. Emer. Res. Area., Kerala CRC Press, Kottayam, 2019, https://doi.org/10.1201/9780429353628, 11–17 July 18-20.
[40] S.K. Das, E.K. Bhujel, Developing low cost hydrogel technology for improving soil moisture and agricultural productivity, Bio. Res, Today Off. 3 (2021) 534–537.
[41] P. Sasmal, S. Patra, Effect in growth of corn plant from cellulose-based hydrogel derived from Wheat Straw, J. Inst. Eng. 103 (2020) 41–46, https://doi.org/10.1007/s40034-020-00180-3.
[42] M.K. Azeem, A. Islam, R.U. Khan, A. Rasool, M.A.R. Qureshi, M. Rizwan, F. Sher, T. Rasheed, Eco-friendly three-dimensional hydrogels for sustainable agricultural applications: current and future scenarios, Polym. Adv. Technol. 34 (2023) 3046–3062, https://doi.org/10.1002/pat.6122.
[43] D. Prisa, G. Guerrini, Hydrogel application in the germination and growth of *Zea mays* and *Solanum lycopersicum* seedlings, GSC Adv. Res. Rev. 12 (2022) 26–32, https://doi.org/10.30574/gscarr.2022.12.3.0233.
[44] R.D.R. Fernández, F.R. Jarama, F.M. Gallo, D.A.M. Intriago, Hydrogel for improving water use efficiency of *Capsicum annuum* crops in Fluvisol soil, Rev. FCA UNCUYO. 50 (2018) 23–31.
[45] L.O. Ekebafe, J.A. Idiaghe, M.O. Ekebafe, Effect of delignified native bamboo (*Bambusa vulgaris*) cellulosic–g-poly (acrylonitrile) hydrogel on the growth indices of okra (*Abelmoschus esculentus*) seedlings, Casp. J. Appl. Sci. Res. 2 (2013) 67–75.
[46] M.F.S. Diógenes, V. Mendonça, L.F. De Medeiros Mendonça, E.A. De Moura, K. Da Silva Lima Reges, L.M. De Oliveira, A.M.F. De Oliveira, Use of hydrogel in the irrigation management of white pitaya (*Hylocereus undatus*) seedlings: biometrics and accumulation of organic and inorganic solutes, Semin. Agrar. 43 (2022) 491–508, https://doi.org/10.5433/1679-0359.2022v43n2p491.
[47] F. Peyrusson, Hydrogels improve plant growth in mars analog conditions, Front. Astron. Space Sci. 8 (2021) 729278, https://doi.org/10.3389/fspas.2021.729278.
[48] S.K. Patra, R. Poddar, M. Brestic, P.U. Acharjee, P. Bhattacharya, S. Sengupta, P. Pal, N. Bam, B. Biswas, V. Barek, P. Ondrisik, M. Skalicky, A. Hossain, Prospects of hydrogels in agriculture for enhancing crop and water productivity under water deficit condition, Int. J. Poly. Sci. (2022) 4914836, https://doi.org/10.1155/2022/4914836.
[49] M. Yangyuoru, E. Boateng, S.G.K. Adiku, D. Acquah, T.A. Adjadeh, F. Mawunya, Effects of natural and synthetic soil conditioners on soil moisture retention and maize yield, J. Appl. Ecol. 9 (2009) 73–81. https://api.semanticscholar.org/CorpusID:94788102.
[50] M. Mu, M.G. De Kauwe, A.M. Ukkola, A.J. Pitman, W. Guo, S. Hobeichi, P.R. Briggs, Exploring how groundwater buffers the influence of heatwaves on vegetation function during multi-year droughts, Earth Sys. Dyn. 12 (2021) 919–938. https://esd.copernicus.org/articles/12/919/2021/.
[51] M.Z. Karipçin, Hydrogels improved parsley (*Petroselinium crispum* (Mill.) Nyman) growth and development under water deficit stress, PeerJ 11 (2023) e15105, https://doi.org/10.7717/peerj.15105.
[52] W. Abobatta, Impact of hydrogel polymer in agricultural sector, Adv. Agr. Environ. Sci. 1 (2018) 59–64, https://doi.org/10.30881/aaeoa.00011.
[53] S. Li, G. Chen, Agricultural waste-derived superabsorbent hydrogels: preparation, performance, and socioeconomic impacts, J. Clean. Prod. 251 (2020) 119669, https://doi.org/10.1016/j.jclepro.2019.119669.
[54] D.S. Thomas, Hydrogel applied to the root plug of subtropical eucalypt seedlings halves transplant death following planting, For. Ecol. Manag. 255 (2008) 1305–1314, https://doi.org/10.1016/j.foreco.2007.10.035.
[55] H. Kalaleh, Y. Atassi, Up-scalable synthesis of high porous superabsorbent polymer via alkaline hydrolysis of acrylamide using microwave irradiation: application in agriculture, J. Mater. Environ. Sci. 9 (2018) 955–963, https://doi.org/10.26872/jmes.9.3.106.
[56] A.K. Verma, S.S. Sindhu, P. Anand, A. Singh, V.B.S. Chauhan, S.K. Verma, Vermi products and biodegradable superabsorbent polymer improve physiological activities and leaf nutrient contents of gerbera, Res. J. Biotechnol. 13 (2018) 8–18.
[57] Z. Wang, Y. Geng, T. Liang, Optimization of reduced chemical fertilizer use in tea gardens based on the assessment of related environmental and economic benefits, Sci. Total Environ. 713 (2020) 136439, https://doi.org/10.1016/j.scitotenv.2019.136439.
[58] R. Kratochvílová, M. Kráčalík, M. Smilková, P. Sedláček, M. Pekař, E. Bradt, J. Smilek, P. Závodská, M. Klučáková, Functional hydrogels for agricultural application, Gels 9 (2023) 590, https://doi.org/10.3390/gels9070590.
[59] S.K. Das, E.K. Bhujel, A. Roy, R. Laha, V.K. Mishra, Design, development and evaluation of pine resin-based hydrogel for soil application in water stress condition: an innovative technology, Indian J. Hill Far. 36 (2023) 15–22.
[60] G. El-Aziz, A. Ibrahim, A. Fahmy, Using environmentally friendly hydrogels to alleviate the negative impact of drought on plant, Open J. Appl. Sci. 12 (2022) 111–133, https://doi.org/10.4236/ojapps.2022.121009.