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Utilization of Super Absorbent Polymer (SAP) Waste to Increase Water Absorption Rate in Zeoponic Plant Growth Media

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ABSTRACT
The quality of the plant growth medium (PGM) is crucial for the growth of horticultural plants, yet a common issue with PGM is its high electrical conductivity. Zeoponics, which uses zeolite as a base material often combined with compost, cocopeat, and fertilizers, helps mitigate this issue. However, Zeoponics still requires frequent watering due to limited water absorption. This research explores the incorporation of super absorbent polymer (SAP), known for absorbing 200 to 400 times its weight in water, to address this limitation. The study aimed to determine the optimal SAP quantity and assess plant survival duration with a new blend, termed zeoponic super absorbent (ZSA). Green mustard plants were used as indicators, with growth parameters such as height, fresh weight, and dry weight measured. Various ZSA blends were prepared with different SAP waste percentages (0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1%). Results indicate that increasing SAP concentration improves soil water retention and field capacity. The ZSA blend with 1% SAP content exhibited the highest air-dry moisture content (71.92%) and field capacity (205.5%), reducing the watering frequency to approximately once every 21 days. Additionally, optimal plant growth parameters, including height, leaf width, leaf length, and stem diameter, were observed at the 1% SAP concentration. The highest fresh weight (58.60 g) and dry weight (14.72 g) were observed at 1.0% SAP (ZSA5), indicating optimal biomass growth at this concentration. These findings suggest that integrating SAP into Zeoponics can significantly enhance water retention, improve plant growth, and increase drought resistance. This offers a practical solution for agricultural practices in water-stressed environments.

Keywords: Super absorbent polymer (SAP), waste, water absorption, zeoponic, zeoponic super absorben (ZSA)

INTRODUCTION
Plant growth medium (PGM) plays a crucial role in the productivity of horticultural plants, including flowers. A good PGM possesses suitable physical, chemical, and biological properties that aid in the optimal growth and development of plants (Widjaja *et al*., 2023). This is particularly important for high-value horticultural commodities driven by increasing demand. The quality of the PGM affects the availability of essential nutrients, water, and air to the roots, significantly impacting plant growth (Kazemi and Mohorko, 2017).

However, one of the common challenges in using PGMs is their high electrical conductivity (EC). Elevated EC levels can negatively affect nutrient and water absorption by plants, leading to reduced growth rates or stress (Cha *et al*., 2021; Ding *et al*., 2018). To address this issue, PGMs with higher cation exchange capacity (CEC), such as zeoponics, have been introduced. Zeoponics, a mixture of zeolite, compost, cocopeat, and fertilizers, offers improved nutrient retention (Suryaningtyas *et al*., 2023). Despite these benefits, zeoponics has limitations, particularly in its water absorption capacity, requiring frequent watering.

An innovative solution to this limitation is the incorporation of Super Absorbent Polymer (SAP) waste from the diaper industry. SAPs, including polyacrylic acid (PAA) and sodium polyacrylate (PNaA), can absorb 200 to 400 times their weight in water, enhancing the water retention of PGMs (Damiri *et al*., 2023). While modern diapers containing SAPs contribute to long-term environmental concerns due to their non-biodegradability, which can take up to 500 years to decompose, this material presents an opportunity for reuse in agricultural application (Castrillon *et al*., 2019).

By integrating SAP into zeoponics, the resultant "Zeoponic Super Absorbent" (ZSA) could offer improved water retention, effectively reducing the frequency of watering required. This integration has the potential to address one of the main limitations of zeoponics while simultaneously contributing to environmental sustainability and agricultural productivity (Chang *et al*., 2021). Furthermore, research by (Sojka and Entry, 2000) suggest that SAP waste provides no direct health or environmental dangers, making vegetables cultivated with polymer treatments safe to consume.

The utilization of SAP waste in PGMs not only mitigates industrial waste issues but also enhances agricultural efficiency, especially in areas prone to water shortages or during periods of drought (Krasnopeeva *et al*., 2022). Furthermore, repurposing SAP waste into agricultural applications adds economic value by converting low-cost waste into high-value products (Gadtya *et al*., 2023).

In the context of innovation and sustainability, integrating waste management with agricultural development aligns with the goals of sustainable development. The use of SAP in plant media enhances water retention at the roots, which is crucial for water conservation, especially as droughts are projected to become more frequent due to climate change (Ostrand *et al*., 2020; Zohuriaan and Kabiri, 2008). Given the positive impact of increasing SAP concentration on water-holding capacity (Yu *et al*., 2017a), this study aims to identifying the optimal SAP quantity and its impact on the water retention duration within PGMs, aiming for measurable and practical outcomes that benefit both agricultural productivity and environmental sustainability.

MATERIALS AND METHODS

Location and experimental design

Research was conducted from February to July 2024, encompassing media preparation, planting, and analysis of media and plants. The planting experiment took place at the Cikabayan Experimental Garden Greenhouse, IPB University. Post-harvest media and plant analysis were carried out at the Land Physical Resources Development Laboratory and the Land Chemical and Fertility Laboratory, Faculty of Agriculture, IPB University.

Greenhouse equipment included 25 x 25 cm polybags, seed trays, name boards, watering cans, and shovels. The growth media consisted of zeoponic and zeoponic with SAP (ZSA), along with green mustard seeds. Measurement tools included rulers and digital calipers for tracking growth parameters, scales for precise weighing, an oven set at 60°C for 48 hours to determine dry weight, and instruments for assessing water content and field capacity.

The experimental design involved six different treatments, each combining varying quantities of Super Absorbent Polymer (SAP) with the zeoponic plant growth media. These treatments were labeled as follows: ZSA0 (zeoponic growth medium + SAP 0%), ZSA1 (zeoponic + SAP 0.2%), ZSA2 (zeoponic + SAP 0.4%), ZSA3 (zeoponic + SAP 0.6%), ZSA4 (zeoponic + SAP 0.8%), and ZSA5 (zeoponic + SAP 1%).

Preparation of plant Growth Media and Seedling

Preparation of the zeoponic plant growth media involved mixing zeolite, compost, and cocopeat in a 2:1:1 ratio, with the addition of 0.5 g/L NPK fertilizer and 5 mg/L micro-nutrient fertilizer (Suryaningtyas *et al*., 2023).

Seeding was conducted in trays with zeoponic media, ensuring the media remained moist without flooding, typically watered once a week. The environment was controlled for optimal sunlight and temperature, with seeding taking about 20 days.

Greenhouse preparation involved cleaning and setting up the necessary equipment. The greenhouse trial used a completely randomized design (CRD) with a single factor of media type, involving one plant species tested on six different media, including zeoponic and five ZSA variants, each planted in 25 x 25 cm polybags, replicated five times for a total of 30 pots. Transplanting from tray to polybag was done in the evening, selecting uniform seedlings. Polybags were arranged with 30 cm spacing for ease of watering**.** Maintenance included replanting within the first week and watering when plants approached wilting, based on media moisture content.

Measurement of water content and field capacity

First, samples of the plant growth media were weighed and then dried in an oven at 60°C for 24 hours to remove all moisture. After drying, the samples were weighed again to determine their dry weight. By comparing the initial weight with the dry weight, we calculated the moisture content and field capacity of the media.

Here is the formula for calculating water content (WC) and field capacity (FC):

$$\text{WC} = \left(\frac{Wd - Wod}{Wod}\right) \text{x } 100\% \quad (1)$$

Where:

W_d : the weight of the air-dried sample

W_{od} : the weight of the oven-dried sample

$$\text{FC} = \left(\frac{Ws - (100 - Wc)}{100 - Wc}\right) \text{x } 100\% \quad (2)$$

Where:

Ws : is the weight of saturated media

Wc : is the water content

Observing plant growth and harvesting

Observation of plant growth and harvesting involved weekly monitoring over a 4-week period following planting. Plant height was measured from the soil surface to the highest point using a ruler. Leaf width and leaf length were also measured using a ruler, while stem diameter was measured using a digital caliper. Green mustard plants were harvested 4 weeks after planting (WAP), cleaned, and weighed for fresh weight (including shoots and roots), then oven-dried at 60°C for 48 hours to determine dry weight.

Data analysis

The experiment was designed using a randomized complete block design (RCBD) with six levels of SAP concentration (0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%) with three replications. The data were analyzed using Analysis of Variance (ANOVA) to evaluate how different SAP concentrations affected plant growth parameters, such as plant height, leaf width, and leaf length. To identify which treatments were significantly different, post-hoc tests were done using Tukey's Honest Significant Difference (HSD) at a 5% significance level. All statistical analyses were performed using Minitab 19 software.

RESULTS AND DISCUSSION

Effect of Superabsorbent Polymers (SAP) on physical properties of ZSA

Table 1 presents the effects of different SAP concentrations on soil water content and field capacity. As SAP concentration increases from 0% to 1.0%, there is a clear trend of improved water retention capacity. In the absence of SAP (0%), the PGM's water content is 50.40%, with a field capacity of 133.0%. When SAP is applied at concentrations between 0.2% and 0.6%, both water content and field capacity significantly increase, with water content ranging from 66.83% to 70.30% and field capacity from 138.1% to 147.1%. The highest values are observed at 1.0% SAP, where water content reaches 71.92% and field capacity peaks at 205.5%. This demonstrates that SAP significantly enhances the soil's water retention ability, which is particularly beneficial for agricultural operations in water-limited environments by reducing water requirements and supporting crop growth.

Table 1. Effect of SAP concentration on air dry moisture content and field capacity

Treatment	Amount of SAP (%)	Air Dry Moisture Content (%)	Field Capacity (%)
ZSA0	0	50.40	133.0
ZSA1	0.2	66.83	138.1
ZSA2	0.4	62.48	121.8
ZSA3	0.6	70.30	147.1
ZSA4	0.8	61.68	147.5
ZSA5	1.0	71.92	205.5

In comparison to other soil amendments, SAP shows clear superiority in enhancing water retention. For instance, Razzaghi *et al*. (2020) reviewed the effects of biochar on soil density and water retention, demonstrating that biochar significantly increased water content at field capacity in coarse-textured soils. However, biochar's effectiveness diminished with increasing soil fineness, limiting its applicability across a range of soil types. In contrast, SAP consistently improves water retention regardless of soil texture, making it particularly advantageous in both coarse- and fine-textured soils where water availability is a critical factor.

Similarly, Li *et al*. (2017) investigated the use of vermiculite to improve water and fertilizer retention in plant growing applications. Their study found that incorporating 20% vermiculite into sulphoaluminate cement (SAC) increased the water absorption rate by 95.3% and improved water retention by 13% over 120 hours. However, while these results show that vermiculite can enhance water retention, its impact is limited to specific material-based systems like SAC.

Kallenbach *et al*. (2019) explored the use of lactobionate (LB), a hydrophilic compound derived from dairy industry byproducts, as a potential soil amendment to enhance soil moisture retention and soil organic carbon (SOC). Their study showed that LB increased soil water content by 37% and microbial biomass by 70 times, with the K^+-stabilized form raising water content by 100–600% compared to unamended soils. While LB enhances both water retention and soil organic carbon (SOC), its effects are short-term (up to two months) and may require frequent reapplications.

SAPs function as hydrogels in agricultural settings, acting as soil amendments capable of absorbing and retaining hundreds of times their weight in water. They gradually release this stored water over time, which aids in improving plant growth and drought resistance. SAP incorporation also positively influences key soil properties, such as permeability, density, structure, and infiltration rates, while mitigating nutrient loss (Hakiem *et al*., 2022; Dingley *et* *al*., 2024; Supare and Mahanwar, 2022). Studies have shown that SAPs significantly enhance the water-holding capacity of growing media and improve soil porosity by 0.26–6.91%, along with water holding capacity increases of 5.68–17.90% (Malik *et al*., 2023).

Further research supports these results, Ostrand *et al*. (2020) found that SAP application not only increases water content (WC) and water-holding capacity (WHC), but also positively affects soil pH, electrical conductivity (EC), and cation exchange capacity (CEC). These effects depend on the SAP type, application timing, and the soil's buffering capacity. Additionally, Yang *et al*. (2020) observed that SAP applications enhance soil moisture retention, reduce temperature fluctuations during the day, and extend the period favorable for photosynthesis in maize leaves.

In agricultural trials, hydrogels have been shown to increase soil moisture at field capacity by up to 400% compared to untreated soils. For instance, adding hydrogel to perlite boosted container capacity by 28% (with 1% hydrogel) and 48% (with 2% hydrogel) without reducing air capacity (Montesano *et al*., 2015). Importantly, phytotoxicity testing indicated no harmful effects, and trials with cucumber and sweet basil demonstrated improved plant growth and quality. However, further research is necessary to evaluate the cost-effectiveness of large-scale agricultural applications of SAPs.

Effect of SAP on plant growth parameters

The data in **Table 2** shows the effect of different concentrations of SAP on the growth parameters of plants at 4 weeks after planting (WAP). The plant heights ranged from 27.17 cm to 39.77 cm. The treatment with 1.0% SAP (ZSA5) resulted in the highest average plant height (39.77 cm), while the control (ZSA0) had the lowest (27.17 cm). The differences in plant height between the control and treatments ZSA2 (37.77 cm) and ZSA5 (39.77 cm) were statistically significant ($p < 0.05$). Leaf width varied significantly with the application of SAP. The widest leaves were observed in the 1.0% SAP treatment (ZSA5) with an average width of 11.20 cm, significantly higher than the control (8.17 cm) and other treatments. The treatment ZSA5 resulted in the longest leaves, with an average length of 17.90 cm, showing statistically significant differences from the control. This indicates a positive response to increasing SAP concentration. Overall, the application of SAP positively influenced plant growth parameters, with the highest concentration of 1.0% SAP (ZSA5) achieving the largest values for plant height, leaf width, and leaf length.

Table 2. Effect of SAP concentration on the growth parameters at 4 WAP

Treatment	Amount of SAP (%)	Plant height (cm)	Leaf width (cm)	Leaf length (cm)
ZSA0	0	27.17 b	8.17 c	13.17 b
ZSA1	0.2	34.17 ab	10.57 ab	16.97 ab
ZSA2	0.4	37.77 a	10.13 abc	17.67 a
ZSA3	0.6	35.37 ab	8.97 bc	16.47 ab
ZSA4	0.8	32.37 ab	9.60 abc	14.57 ab
ZSA5	1.0	39.77 a	11.20 a	17.90 a

Note: *Different letters in the same column indicate significant differences at $p < 0.05$*

In comparison, Yeboah *et al*. (2020) examined the use of biochar as a soil amendment to enhance plant growth and nutrient uptake. Their study found that biochar, especially when applied using spot and ring methods, significantly improved growth parameters, including plant height, girth, biomass, and grain yield, in cowpea. However, the effectiveness of biochar was highly dependent on the application method, with broadcasting methods showing less improvement.

Similarly, Dai *et al*. (2020) shown that by enhancing the pH, cation exchange capacity (CEC), and structure of the soil, biochar may greatly increase plant growth by increasing nutrient availability and water retention. Treatments with high-ash biochar work best on sandy or acidic soils. Its influence is dependent on the particular soil conditions as well as the qualities of the biochar, therefore its universal applicability is limited. As a result, the effectiveness varies greatly.

According to Bai *et al*. (2022), vermiculite (5% and 10%) significantly increased microbial diversity, enhanced photosynthesis, and promoted plant growth in sediments. It also promoted plant growth by releasing essential nutrients and fostering beneficial bacteria. However, the study did not address potential limitations regarding the long-term effectiveness of vermiculite or its broader ecological impacts. Additionally, there is limited information on its applicability across different aquatic environments beyond the specific conditions tested.

Recent research by Seven *et al*. (2024) found that SAP had no significant effect on shoot height under various drought conditions or SAP doses compared to control plants. However, an upward trend in shoot height was observed with increased SAP doses within an 80% irrigation regime, suggesting that SAP's benefits may become more pronounced at higher doses and under moderate irrigation conditions.

These findings collectively highlight the critical role of SAP in enhancing plant growth and development. The significant increase in plant height, leaf width, and leaf length with higher SAP concentrations underscores its efficacy in improving overall plant vigor and biomass. The variation in growth parameters observed across different SAP concentrations indicates that optimal SAP application rates can vary depending on specific crop needs and environmental conditions.

Moreover, the insights from Seven *et al*. (2024) suggest that while SAP's impact on shoot height might not be immediately evident under certain conditions, its benefits could become more pronounced with appropriate irrigation regimes and higher doses. This reinforces the importance of tailored SAP applications to maximize agricultural productivity.

The integration of SAP into soil management practices offers a promising strategy for optimizing plant growth and water use efficiency. The ability of SAP to extend watering intervals and enhance biomass production positions it as a valuable tool for sustainable agriculture, particularly in water-scarce regions.

The observed improvements in plant growth parameters at higher SAP concentrations, combined with the potential for significant increases in shoot biomass under specific conditions, highlight the multifaceted benefits of SAP. As agriculture faces increasing challenges from climate change and water scarcity, leveraging SAP technology could play a crucial role in maintaining crop productivity and ensuring food security. Future research should continue to explore the optimal conditions for SAP application, taking into account crop type, environmental factors, and irrigation practices to fully harness its potential in sustainable agriculture.

In Zeoponic Super Absorbent (ZSA), the integration of zeolite, compost, cocopeat, and SAP forms a highly effective plant growth medium. Zeolite improves nutrient retention and cation exchange capacity, compost supplies essential organic matter and nutrients, and cocopeat enhances aeration and water-holding capacity (Suwardi et al. 2023). SAP plays a key role by significantly increasing water retention, absorbing and gradually releasing moisture. This combination optimizes water and nutrient availability, making the ZSA an ideal growth medium for maximizing plant growth, especially in water-limited environments or under challenging conditions.

Figure 1. Green mustard plants after 4 weeks after planting (WAP)

Effect of SAP concentration on green mustard yield

The fresh and dry weights of ZSA plants change with different SAP concentrations but do not follow a clear pattern of increasing or decreasing (**Table 3**). The data shows that at 1.0% SAP (ZSA5), the fresh weight significantly increases to 58.60 g, indicating optimal biomass growth at this concentration. This increase is statistically significant compared to other treatments, as denoted by different letters in the same column. Similarly, dry weights show variability across treatments. The highest dry weight is observed at 1.0% SAP (ZSA5), with 14.72 g, which is significantly higher than the other concentrations. These findings suggest that while the general trend of fresh and dry weight changes with varying SAP concentrations is not linear, there is a clear optimum at 1.0% SAP, highlighting the concentration's efficacy in promoting plant biomass under the given experimental conditions.

Supporting these findings, a study by Seven *et al*. (2024) demonstrated that shoot dry matter production linearly increased with higher doses of SAP under all drought regimes. Specifically, an 18.2% ($p=0.0256$) and 24.0% ($p=0.0344$) increase in shoot dry matter was observed in plants treated with 0.1 g and 1 g SAP under low drought conditions (3 days; 80% irrigation), respectively. This indicates that SAP application can enhance shoot biomass production by up to 24%, depending on the dose, under low drought conditions. The positive impact of SAP on biomass production, particularly under stress conditions, underscores its potential in improving plant growth and resilience, making it a valuable tool for agricultural water management and productivity enhancement.

Integrating these insights, the combined effects of SAP on extending watering intervals and enhancing plant biomass highlight the multifaceted benefits of SAP in agriculture. By improving soil water retention and promoting biomass growth, SAPs provide a dual advantage of conserving water and boosting crop yields. These advantages are particularly significant in the context of global water scarcity and the need for sustainable agricultural practices. Optimizing SAP concentrations can lead to more efficient water use and increased agricultural output, thus supporting food security and environmental sustainability. The variability in fresh and dry weights with different SAP concentrations also suggests the importance of precise SAP application tailored to specific crop needs and environmental conditions, ensuring maximum benefits from this innovative soil amendment technology.

Table 3. Effect of SAP Concentration on Fresh Weight and Dry Weight of Green Mustard at 4 WAP

Treatment	Amount of SAP (%)	Fresh weight (g)	Dry weight (g)
ZSA0	0	13.38 b	3.36
ZSA1	0.2	32.18 ab	8.08
ZSA2	0.4	45.70 ab	11.48
ZSA3	0.6	26.22 ab	6.59
ZSA4	0.8	29.86 ab	7.50
ZSA5	1.0	58.60 a	14.72

Note: *Different letters in the same column indicate significant differences at $p < 0.05$*

In a study by Başak (2020), a 10 g SAP treatment significantly increased the height and stem fresh weight of tomato plants compared to the control ($P \leq 0.05$). The highest plant height (387.9 cm) and stem fresh weight (3493 g) were recorded in the 10 g SAP-treated slabs. This finding aligns with the observations in this study where SAP positively influenced plant growth parameters at specific concentrations, although the optimal concentrations and effects varied between plant species and conditions.

SAP increases crop yield and water productivity by 12.8% and 17.2%, respectively, with vegetable crops showing the greatest economic advantages (Zheng *et al*., 2023). Additionally, SAPs promote the germination and growth of plant seeds, significantly increasing the yield of crops such as grain, cotton, vegetables, and fruits. However, their agricultural application is still in the small-scale experimental demonstration stage (Ai *et al*., 2021).

Effect of SAP concentration on watering intervals

The graph illustrates the relationship between the watering interval and the concentration of SAP in soil (**Figure 2**). As the concentration of SAP increases from 0% to 1.0%, there is a noticeable extension in both the minimum and maximum watering intervals. Initially, at 0% SAP, plants need watering every 2 to 6 days, highlighting a high frequency of moisture requirement. This frequent need indicates that the soil has a limited capacity to retain water, leading to rapid depletion and necessitating frequent irrigation to support plant growth.

When the SAP concentration reaches 1.0%, the watering interval significantly extends, with the minimum interval stretching to 18 days and the maximum interval reaching 21 days. This substantial increase in watering intervals demonstrates SAP's ability to improve soil water retention properties. By absorbing and gradually releasing water, SAPs reduce the necessity for frequent watering, thereby sustaining plant hydration over longer periods. This capability is particularly beneficial in regions with limited water availability or in agricultural practices aiming to minimize water usage without compromising crop productivity.

This finding is supported by studies like Kargar *et al*. (2017), which showed that frequent watering could negatively impact the growth of silver maple (*Acer saccharinum*) due to root respiration constraints. Similarly, Elhadi *et al*. (2013) observed that saplings watered less frequently (every nine days) grew taller than those watered every three or six days, indicating that frequent irrigation can hinder root growth and nutrient uptake, ultimately stunting growth.

Yu *et al*. (2017b) investigated how Super Absorbent Polymers (SAPs) affect water absorption and retention across different soil textures and SAP concentrations. They found that SAPs significantly improved soil water retention, particularly in soils with lower clay content. During drying, SAPs continued to absorb water from the soil, reducing moisture loss and supporting plant hydration.

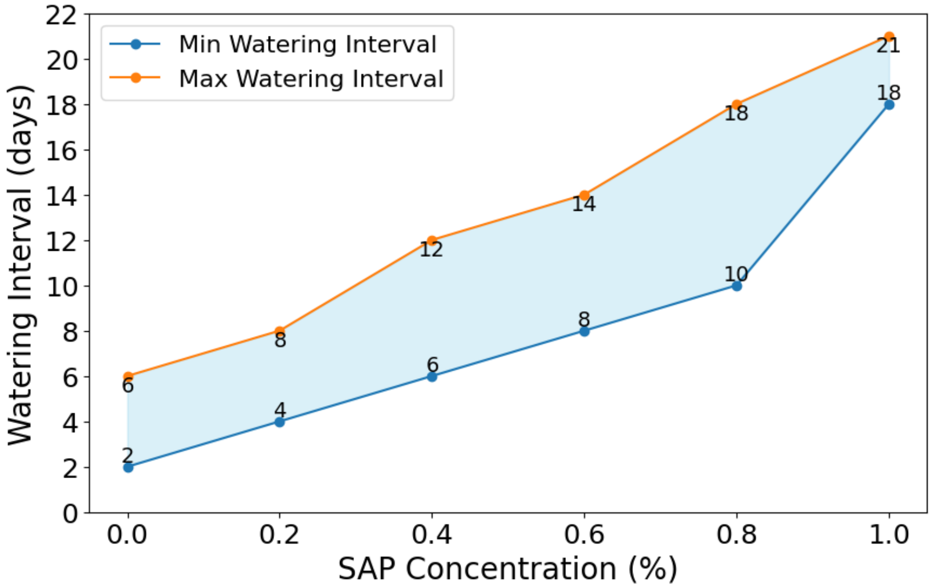

Figure 2. Watering Intervals Based on SAP Concentration

In comparison to other soil amendments, like peat moss, Nugrahaeningtyas and Park (2024) found that Sphagnum hyaline cells in peat moss can absorb 16–25 times their dry weight in water, enhancing moisture retention. However, Super Absorbent Polymers (SAPs) are far more effective in terms of water-holding capacity, absorbing and retaining up to 300 times their weight. While peat moss is beneficial for moisture retention, it falls short of SAPs in terms of the volume of water retained. Additionally, peat moss is often considered environmentally unsustainable, making SAPs a more efficient and eco-friendly option for improving soil moisture retention in agricultural practices.

These findings are pivotal for enhancing water management strategies in agriculture. By incorporating SAP into soil, farmers can optimize irrigation schedules, potentially leading to significant water conservation. This not only supports sustainable agricultural practices but also ensures consistent crop growth even under variable environmental conditions. Understanding the impact of SAP on watering intervals aids in developing targeted approaches to irrigation, which are crucial for maintaining agricultural productivity while addressing global water resource challenges.

CONCLUSION

The SAP at 1.0% concentration is the most effective treatment, increasing air dry moisture content to 71.92% and field capacity to 205.5%. This concentration also optimizes green mustard plant growth parameters including plant height, leaf width, leaf length, and stem diameter. Additionally, it results in the highest fresh weight (58.60 g) and dry weight (14.72 g), indicating optimal biomass growth. Furthermore, SAP at 1.0% increases the minimum watering interval to 18 days, with a maximum of 21 days, improving soil water retention and promoting sustainable agriculture practices. This research underscores SAP’s potential for improving water efficiency in agriculture, especially under water-scarce conditions. Future studies should examine long-term impacts on soil health and effectiveness across various soil types and climates to scale SAP use sustainably. This study was conducted using a specific plant-growing medium called zeoponic, a mix of zeolite, compost, and cocopeat with added SAP. Results may vary with different growing media, and further research is needed to assess the long-term effects of SAP within this particular medium and its environmental impact.

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