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Original Research

Improvement of Water Use Efficiency in Rice Cultivation Using Bio-Based Superabsorbent

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Abstract

The current water scarcity threatens the sustainable production of paddy fields. The application of superabsorbent (SAP) prepared by biodegradable materials is of significant importance. The main objective of this research is to consider the effect of starch-SAP (S-SAP) on water use efficiency for rice cultivation and compare that with commercial-SAP (C-SAP) in greenhouse conditions with a factorial completely randomized design with two factors. The first factor was drought stress at three levels and the second factor was SAP application at 11 levels. The S-SAP had high performance for water absorption and in turn the SEM, FT-IR and TGA results showed that the polyacrylic acid chain has been successfully bonded to the starch backbone leading the highly porous S-SAP. The greenhouse results significantly indicated that the drought stress, SAP (C-SAP and S-SAP) levels and interaction effects were effective on the water use efficiency. The application of 0.1% of the SAP improved the maximum water absorption capacity up to 42.96% enhancing the water use efficiency up to 11% compared with the control. Overall, the use of S-SAP was effective in elevating the water use efficiency in rice cultivation and the application of 4gr kg^{-1} N-enriched S-SAP was the optimum application rate for calcareous paddy fields.

Keywords: paddy fields, rice yields, starch polymer, water scarcity

Introduction

Rice is a cereal plant that has more than 20 species. It has spread in different ecosystem, climatic and geographical conditions. Rice has the most cultivation and consumption in the world after wheat [1]. In recent decades, rice production, has almost tripled [2]. The demand for rice is exponentially increasing [3]. Growing demand for food cannot be met at this speed due to the exploitation of agricultural land and changing the climate conditions [4]. Due to the changes in the annual rainfall patterns, the drought stress caused huge problems in Asian countries [5]. Drought stress is one of the most serious threats to rice production in the world which causes a significant reduction in rice yield [6]. About 3000 liters of water are needed to produce

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1 kg of rice. Therefore, drought stress can potentially reduce yields depending on the stage of plant growth [7]. The reduction of rice grain yields due to the drought stress and water shortage in some areas in Iran in recent years [8, 9]. This reduction can be mitigated by various programs supporting the farmers to maintain maximum rice production [7]. SAP as a soil amendment has good capabilities for high water absorption and water retention. They effectively improve the use of water in agriculture by maintaining soil moisture and reducing irrigation water use [10, 11].

The synthesis of SAP for agricultural application needs high water-absorption characteristics. Based on their origins, SAPs were classified into three groups: natural, synthetic and hybrid [12]. Natural SAPs consist of natural polymers such as starch, cellulose, chitin etc. The synthetic SAPs are made from chemical polymers such as acrylic acid, acrylamide, and methacrylic acid. The hybrid SAPs are prepared from both natural and synthetic polymers. As compared to synthetic SAPs, the hybrid SAPs always have superiority in water absorbency and biodegradability [13]. The starch-based synthesised SAP for application in agriculture have good ability for high water absorption in distilled water and salt water [14]. The starch synthesized SAP showed the renewable and antimicrobial properties as well [15].

A large number of hydrophilic groups on the chain of SAPs help to absorb water hundreds to thousands of times their own weight. In addition, the three-dimensional network with chemical cross-links or between chains guarantee strong water holding capacity even under abnormal conditions [16]. If the amount of super absorbent increases, the moisture retention capacity of soil will also increase causes humidity changes at the beginning and the end of the growing season [17]. Fazeli Rostampour [18] showed that the SAP has increased the yield in low irrigation treatments through the absorption of water and nutrients and their gradual release. Kenawy et al. [19] showed that SAP increased the yield of rice, maize and peanut under water stress condition. This study was carried out with the aim of increasing water productivity in rice cultivation using biological SAP. The main objective of this study were 1: to synthetize the biodegradable SAP and 2: to test the performance of SAPs for water use efficiency in rice cultivation.

Materials and Methods

A very simple and low-cost method was introduced in this study for the synthesis of the SAP. All needed materials were polymerized in one step in one container. Potassium hydroxide solution 4.5 M added to the 0.34 M starch solution until it becomes completely jelly. After that, 3.3 M urea solution was added and stirred for 30 minutes. Later on, N,N-methylbisacrylamide (connector) 0.032 M and acrylic acid (monomer) 6.8 M and ammonium persulfate (initiator) 0.11 M were added and stirred for 10 minutes. The resulting mixture was placed in an oven at 65ºC for 5 hours. The obtained gel was washed with methanol and put in the oven at a temperature of 75ºC for a dry. Then, they were crushed into smaller pieces as outlined by Liu et al. [20].

Functional groups and bonds in molecules was determined by the Fourier transform infrared spectrometer (FT-IR) made by Shimadzu company model IRTracer-100 with four resolutions within the wavelength ranges between 1500 to 4000 cm. To study the thermal stability and evaluate the stability of S-SAP compounds, the thermogravimetric analysis (TGA) with a Perkin Elmer device was used in the temperature range of 30 to 650ºC with a temperature speed of 10ºC/min in a dry air. A ZIAM Nova NanoSEM 650 scanning electron microscope with electron acceleration voltage kv10 was used for surface morphological characteristics.

0.05 grams of S-SAP with a diameter of 0.3 to 0.6 mm was poured into a beaker containing different water solutions i.e. miliq water, tap water, salt water and 0.9% sodium chloride. Following 5, 10, 20, 30, 60, 120 minutes and 12 hours, the contents of the beaker were passed through a sieve to remove the excess water solutions. The excess water around the SAP was removed with filter paper and then weighed. The water absorption capacity of the SAPs was calculated by the following equation:

$$q= \frac{w_1 - w_0}{w_0}$$

where, the q, w_1, w_0 are the water absorbency, the swollen SAP and the dry SAP, respectively.

In order to estimate the maximum soil water absorption capacity, a certain amount of dry soil was passed through a 2 mm sieve and treated with amounts of 0.1, 0.2 and 0.3 percent of S-SAP with diameter sizes of 100 to 150 µm. Small holes were made in the bottom of plastic containers and covered with a filter paper. The treated soil was poured into plastic containers. A soil sample without S-SAP was considered as a control. The samples were placed in a water bath for 12 hours. Then, they were weighed and the weight of the permeated water was obtained by subtracting the weight of the empty container, filter paper and soil [11].

The greenhouse experiment was done in pots in Sari University of Agricultural Sciences and Natural Resources, Sari, Iran. The studied soil was prepared from paddy fields. Some soil properties were measured and shown in Table 1. A cubic plastic pots were used with a diameter and height of 25 and 40 cm, respectively.

This experiment was carried out as a factorial completely randomized design with three replications. The first factor was drought stress at three levels and the second factor was SAP at 11 levels as tabulated in Table 2.

Table 1. Some physical and chemical properties of studied soils.

Electrical Conductivity (dS m^{-1})	K	P	pH	OC	$CaCO_3$	Total N	Clay	Silt	Sand	Soil Texture
	mg kg^{-1}			%						
1.54	138	9.3	7.3	2.18	31.15	0.22	25	49	26	Loam

Table 2. The experimental treatments of the study.

Factors	Abbreviation signs	Description
Water stress (main factor)	d_1	No stress (Full saturation)
	d_2	30% depletion of total available water and then irrigated until saturation
	d_3	60% depletion of total available water and then irrigated until saturation
Superabsorbent (sub-factors)	h_1	Without application of SAP+ fertilisation based on soil test
	h_2	2 gr kg^{-1} C-SAP A200+ fertilisation based on soil test
	h_3	4 gr kg^{-1} C-SAP A200+ fertilisation based on soil test
	h_4	2 gr kg^{-1} S-SAP without N+ fertilisation based on soil test
	h_5	4 gr kg^{-1} S-SAP without N+ fertilisation based on soil test
	h_6	2 gr kg^{-1} N-enriched S-SAP+ fertilisation based on soil test
	h_7	4 gr kg^{-1} N-enriched S-SAP+ fertilisation based on soil test
	h_8	N-enriched S-SAP in the amount of 100% fertilizer recommendation
	h_9	N-enriched S-SAP in the amount of 75% nitrogen fertilizer recommendation
	h_{10}	N-enriched S-SAP in the amount of 50% nitrogen fertilizer recommendation
	h_{11}	N-enriched S-SAP in the amount of 25% nitrogen fertilizer recommendation

According to the soil test, phosphorus and potassium fertilizers and one third of nitrogen fertilizer were mixed with the soil before planting. One third of the nitrogen fertilizer was added in the form of liquid at the maximum tillering stage and one third at the flowering stage. A solution of 5% Vitavax Thiram was used to disinfect the seeds of Tarem Hashemi variety. Following the seeds reached the three-leaf stage, three rice seedlings were planted in each pot. After the complete establishment of the plant (two weeks after planting), the dry treatments were applied. During the growth of the plant, weeding, fighting against pests and diseases was done uniformly in all pots. The amount of water used for each pot during the growth period of the plant was recorded at each watering time. The yield was calculated when the plant was fully matured. The efficiency of water use (E) was obtained by the following equation:

$$E = \frac{Y}{V}$$

where Y and V were the yield and the volume of water used, respectively.

The normal distribution test was performed by the Kolmogorov-Smirnov test. All data in this study was normally distributed. The statistically significant differences among the treatments were analysed by ANOVA using SAS software and the comparison of means was tested with the least significant difference test (LSD) at 5% level.

Results and Discussion

SAP Synthesized Characteristics

The pure and grafted starch (S-SAP) contain an absorption peaks between 3750 and 3300 cm^{-1}, which is a main characteristic of the starch structure (Fig. 1). The absorption peak in regions of 1700 cm^{-1} in both polyacrylic acid and S-SAP are attributed to carbonyl groups. The absorption peaks in regions of 930 cm^{-1}, 856 cm^{-1} and 577 cm^{-1} are related to C-OH, C-O-C and pyranose, respectively, being smaller after polymerization. These findings indicate that the copolymerization between acrylic acid monomer and starch molecule has successfully occurred [20, 21].

The thermal behaviour of starch is divided into three stages (Fig. 2). The first stage has been attributed

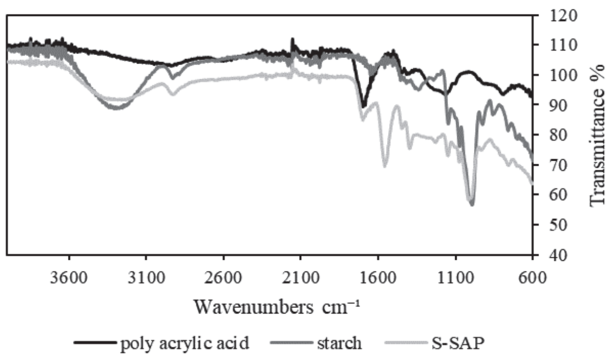

Fig. 1. The FTIR spectra of pure poly acrylic acid, starch and S-SAP.

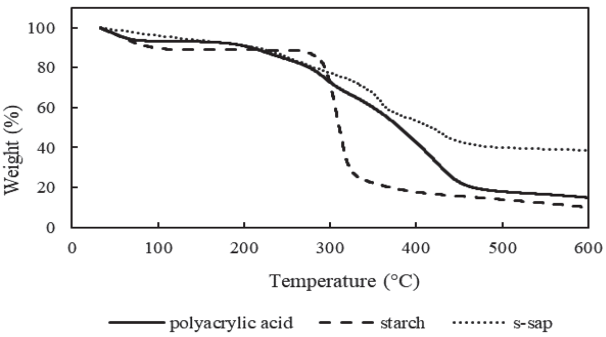

Fig. 2. The TGA curves of pure polyacrylic acid, starch and S-SAP.

to the evaporation of free water and boundary water. A specific weight loss is observed in the second stage with the highest degree of destruction at 250-350ºC. This stage of degradation implies the depolymerisation and the breaking of the molecular chain of starch. The weight of the sample in the third stage slowly decreases indicating the complete destruction of glucose residues. The thermal behaviour of polyacrylic acid and S-SAP shows that in all stages, the weight of the sample slowly decreased. Polyacrylic acid after bonding with starch has the same thermal properties as its pure state. At a temperature higher than 300ºC, the starch molecular chain weakens the dependence of polyacrylic acid with water, the weight loss in the S-SAP is less than polyacrylic acid. The reduction in the weight of the S-SAP compared to starch and polyacrylic acid indicates a higher thermal stability in the S-SAP [20, 21].

The electron microscope images of starch, polyacrylic acid, and S-SAP (Fig. 3) show that there is a distinct difference between their surface structures. The surface of starch is smooth, soft and granular, while poly-acrylic acid has a rough, dense and non-porous surface. On the surface of the S-SAP, there are lumpy parts that are very porous with irregular pores. These observations show that the polymerization bond between the polyacrylic and starch has fairly occurred. The results herein showed that the procedure used in this study was fairly good leading to the formation of highly porous S-SAP materials [22].

As the ions in the solution increased, the absorption of water by the S-SAP is decreased consequently (Fig. 4). The highest swelling of S-SAP occurred in water purified using a millipore Milli-Q lab water system. The presence of ions in the absorption environment has a pronounced effect on the absorption behaviour of the S-SAP as shown in Fig. 3. Many theories have been expressed to find out the reason for the swelling behaviour of S-SAP in saline environment. One of the simplest theories is the Donnan equilibrium theory. Accordingly, the electrostatic interactions (ion swelling pressure) cause the difference in the osmotic pressure of freely mobile ions in the S-SAP gel and in the salt solution. Osmotic pressure is the driving force for S-SAP swelling. Increasing the concentration of mobile ions between the gel and the external environment reduces the volume of the gel and its swelling ability decreases [21].

The Capacity of Water Absorption by S-SAP in Soils

The presence of the S-SAP in soils dramatically changed the soil water absorption capacity as shown in Fig. 5. The small amounts of applied S-SAP can improve the maximum water absorption capacity in the soil. The maximum absorption capacity in the control

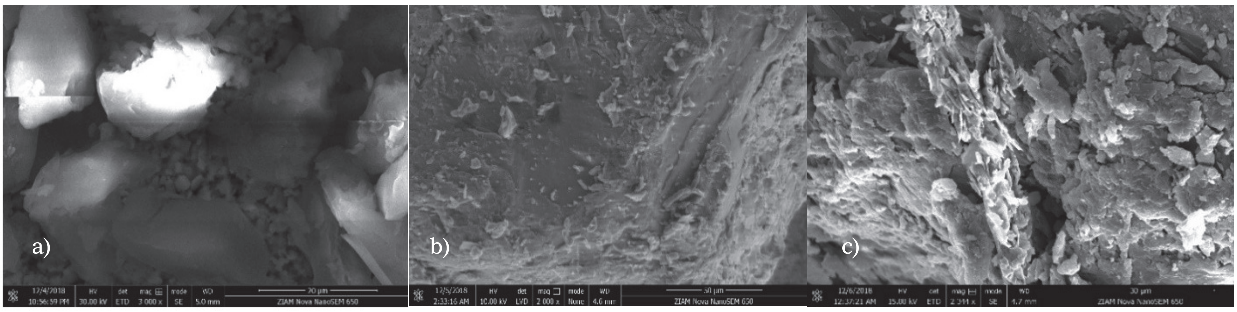

Fig. 3. The SEM micrographs of a) starch, b) poly acrylic acid and c) S-SAP.

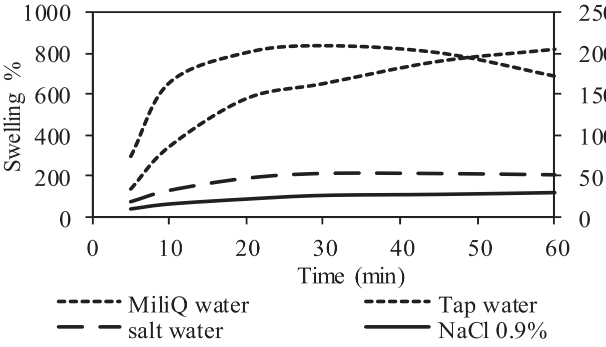

Fig. 4. The absorption capacity of SAP in water solutions with different salinities.

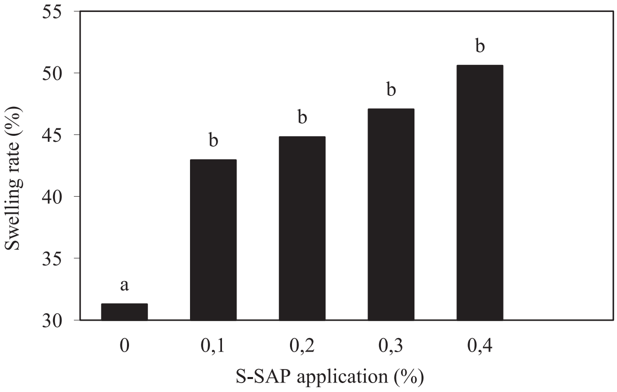

Fig. 5. The maximum capacity of the water absorption by S-SAP in soils.

soil is 31.1% (v/v). An increase of 0.1% of the S-SAP can improve the maximum water absorption capacity up to 42.96%, which is 37.25% more than the control. Similarly, the increase of 0.2, 0.3 and 0.4% of S-SAP has improved the maximum absorption capacity in soil up to 44.82%, 47.06% and 50.59% which was 43.21%, 50.36% and 61.63% more than the control, respectively. The increase of water absorption capacity by application of superabsorbent treatment has a linear trend. This result indicated that, the maximum water absorption capacity increase with increasing the amount of superabsorbent to the soil preventing the water loss by drainage and subsequently have a significant impact on the reduction of potential sources of groundwater pollution due to percolation phenomena of fertilizer solutions in areas of intense agricultural activity.

Water Consumption

All dataset was normally distributed in this study. Therefore, based on the results of analysis of variance (Table 3), the different levels of water stress and doses of applied SAP affected the water consumption and in turn, had a statistically significant difference at the level of 1%. The highest and lowest amounts of water consumption were observed at treatments of fully saturated (d_1) and 60% depletion of soil available water (d_3) (Table 4). Ebrahimi-Rad et al. [23] outlined that along with the reduction of water consumption by soil amendments, the efficiency of water-use also showed an increasing trend. The effect of different levels of SAP on the water consumption showed that the highest amount was in treatment without application of SAP (h_1), which had a significant difference with other treatments. The lowest water consumption was observed to the treatment with 4gr kg^{-1} application of S-SAP (h_7), which had a significant difference with others (Table 4). The results showed that with the increase in the application dose of SAP, the water consumed has decreased.

The interaction effects of different levels of dryness and SAP showed that the highest water consumption was related to d_1h_1 treatment (Table 3 and 4) followed by d_1h_{11}, d_1h_2, d_1h_4 and d_1h_6 treatments with no significant difference. Compared with control, the hydrogel was effective for water consumption and led to the further decreases for water consumption. Aghayari et al. [24] concluded that the application of SAP saved irrigation water by 13.4% during the growth period of the corn crop. This suggests that treatment with hydrogel could improve root growth condition, compensating for any damage of root from a shortage of water. The hydrogel application along with other mitigation approaches could combat with drought events and climate changes.

Table 3. Results of analysis of variance (mean square) of the amount of water consumed, water use efficiency and yield of rice

Source	Degrees of Freedom	Water Consumption (m^3 ha^{-1})	Water Use Efficiency (kg m^{-3})	Yield (kg ha^{-1})
Dryness levels	2	19087884.091**	0.317**	35135894.101**
SAP levels	10	1943666.566**	0.174**	556918.828**
Dryness levels× SAP levels	20	107107.935**	0.009**	60394.101**
Error %	66	22642.818	0.002	12485.010
Coefficient of Variation %		3.36	4.66	2.98

**significance at the 1 level.

Table 4. The comparison means of the water consumption, water use efficiency and the yield of rice.

Treatments	Water Consumed (m^3 ha^{-1})	Water Use Efficiency (kg m^{-3})	Yield (kg ha^{-1})
d_1	4309^{a}	0.91^{a}	4782^{a}
d_2	3672^{b}	0.89^{a}	3765^{b}
d_3	3179^{c}	0.73^{b}	2719^{c}
h_1	5472^{a}	0.6^{h}	3233^{g}
h_2	4627^{c}	0.8^{f}	3750^{cde}
h_3	4250^{f}	0.85^{d}	3659^{ef}
h_4	4464^{d}	0.84^{de}	3800^{cd}
h_5	4076^{g}	0.97^{b}	4000^{b}
h_6	4304^{ef}	0.92^{c}	3900^{b}
h_7	3759^{h}	1.11^{a}	4167^{a}
h_8	4235^{f}	0.89^{c}	3820^{c}
h_9	4402^{de}	0.8^{ef}	3600^{f}
h_{10}	4672^{c}	0.78^{f}	3700^{def}
h_{11}	5014^{b}	0.71^{g}	3600^{f}
d_1h_1	6509^{a}	0.722^{mn}	4700^{de}
d_1h_2	5579^{b}	0.852^{hijk}	4750^{de}
d_1h_3	4934^{ghi}	0.933^{efg}	4604^{e}
d_1h_4	5492^{bc}	0.875^{fghij}	4800^{cd}
d_1h_5	4795^{hij}	1.044^{b}	5000^{ab}
d_1h_6	5412^{bcd}	0.921^{fgh}	4980^{abc}
d_1h_7	4778^{hij}	1.057^{b}	5050^{a}
d_1h_8	5138^{efg}	0.938^{defg}	4820^{bcd}
d_1h_9	4913^{ghi}	0.937^{efg}	4600^{e}
d_1h_{10}	5253^{cde}	0.895^{fghi}	4700^{de}
d_1h_{11}	5593^{b}	0.823^{ijkl}	4600^{e}
d_2h_1	5203^{def}	0.578^{p}	3000^{kl}
d_2h_2	4400^{lm}	0.852^{hijk}	3750^{ij}
d_2h_3	4158^{mn}	0.910^{fgh}	3769^{ij}
d_2h_4	4200^{mn}	0.905^{fgh}	3800^{hi}
d_2h_5	3967^{no}	1.01^{bcd}	4000^{g}
d_2h_6	4000^{no}	0.996^{bcde}	3980^{gh}
d_2h_7	3500^{q}	1.258^{a}	4400^{f}
d_2h_8	4033^{no}	0.947^{cdef}	3820^{ghi}
d_2h_9	4397^{lm}	0.819^{jkl}	3600^{j}
d_2h_{10}	4631^{jkl}	0.799^{kl}	3700^{ij}
d_2h_{11}	4975^{fgh}	0.724^{mn}	3600^{j}
d_3h_1	4703^{ijk}	0.426^{q}	2000^{p}
d_3h_2	3900^{op}	0.705^{mn}	2750^{no}
d_3h_3	3657^{pq}	0.714^{mn}	2604^{o}
d_3h_4	3700^{pq}	0.757^{lm}	2800^{mn}
d_3h_5	3467^{q}	0.867^{ghijk}	3000^{kl}
d_3h_6	3500^{q}	0.852^{hijk}	2980^{klm}
d_3h_7	3000^{r}	1.017^{bc}	3050^{k}
d_3h_8	3533^{q}	0.798^{kl}	2820^{lmn}
d_3h_9	3897^{op}	0.667^{n}	2600^{o}
d_3h_{10}	4131^{no}	0.654^{no}	2700^{no}
d_3h_{11}	4474^{kl}	0.581^{op}	2600^{o}

Means with the same letter are not significantly different. Saturation with no water stress (d_1), 30% depletion of available water and then irrigated until saturation (d_2), 60% depletion of available water and then irrigated until saturation (d_3). without SAP+ fertilization based on soil test (h_1), 2 and 4 gr kg^{-1} C-SAP A200+ fertilization based on soil test (h_2, h_3), 2 and 4 gr kg^{-1} S-SAP without N+ fertilization based on soil test (h_4, h_5), 2 and 4 gr kg^{-1} N-enriched S-SAP+ fertilization based on soil test (h_6, h_7), N-enriched S-SAP in the amount of 100, 75, 50 and 25% nitrogen fertilizer recommendation (h_8, h_9, h_{10}, h_{11}).

Water Use Efficiency

The effect of SAP treatments on water consumption efficiency was significant in this study. The water use efficiency was affected by different levels of dryness and SAP as shown in Table 3 and Table 4. The highest and lowest values of water use efficiency were belonged to d_1 and d_3 treatments, respectively. The water use efficiency in d_2 treatment was less than d_1 treatment but they did not have significant difference. The highest water use efficiency was observed in h_7 treatment. Treatment of h_5 was in the next rank and had significant difference with other treatments.

The highest water use efficiency in the interaction effects belonged to the treatment of d_2h_7 showing a significant difference with other treatments (Table 4). Treatment of d_1h_5, d_1h_7, d_2h_5 and d_3h_7 are in the next order. With increasing of SAP application, the water use efficiency was increased. The SAP has increased the efficiency of water use by storing water and nutrients effectively, which prevents the wastage of water and nutrients and ultimately prevents the significant reduction of yield and the subsequent water use efficiency [17]. Satriani et al. [25] stated that the highest efficiency of water consumption was observed to the soil treated with SAP under low irrigation conditions in bean crop. Dehkordi et al. [17] mentioned that if the amount of SAP increases, the moisture retention capacity of the soil also increase causing changes in humidity at the beginning and end of the growing season. By increase in the severity of drought stress, the efficiency of water consumption decreased drastically, which could be attributed to the significant increase in yield performance in full irrigation treatments compared to severe drought stress at 60% depletion of available water. The effect of conservation tillage methods and different amounts of SAP on soil physical properties and water use efficiency were significant effect on corn yield and irrigation water use efficiency [26].

Rice Yields

The results showed that the rice yield was significantly affected by different levels of dryness and SAP (Table 4). At different levels of dryness, the highest and lowest yields were observed to treatments of fully saturated (d1) and 60% depletion of soil available water (d_3), respectively (Table 4). Unsurprisingly, the yield decreased with the increase of water stress. Environmental stresses cause a decrease in yield and the most important of that is the lack of water [27]. Yousefian et al. [28] and Moradi et al. [27] have been reported that permanent flooding treatment in paddy had the highest yield in rice. The findings of Yang et al. [29] showed that water stress caused a decrease in grain yield by high adverse impact on flowering stage.

At different levels of SAP, the treatment with 4 gr kg^{-1} application of S-SAP (h_7) showed the highest grain yield with significant differences with other treatments. The high level of grain yield in d1 treatment was accompanied by less water consumption and higher water-use efficiency. The lowest yield belonged to h_1 treatment, which was significantly different from other treatments. The C-SAP (h_3 treatment) and S-SAP (h_5 treatment) showed significant difference with each other. Overall, the yield has increased with the increase in the amount of applied SAP.

Based on the interaction effects of SAP levels and dryness (Table 4), the results showed that d_1h_7 treatment had the highest yield value demonstrating the increasing of SAP up to 4 gr kg^{-1} can enhance the yield. Afterward, d_1h_5 and d_1h_6 treatments had the highest yields that showed the significant difference with other treatments. The treatments of C-SAP have not shown the significant differences with the control, but they showed significant difference with S-SAP treatments. The S-SAP has best positive effects on rice yields in water stress conditions. The lowest yield is belonged to d_3h_1 treatment, which had a significant difference with other treatment. Drought stress leads to a decrease in yield through the reduction of the leaf surface and disturbance in the absorption and transfer of nutrients. The S-SAP application has a supporting effective on the water storing in soils and the nutrient uptake in drought stress conditions preventing the reduction of yield [17]. Fazli Rostampour [18] showed that dry matter yield was not affected by SAP in 100% irrigation treatment. The C-SAP was only able to have a small effect on the yield of dry matter by absorbing nutrients and preventing them from being washed away. In deficit irrigation treatments, it has increased the yield through the absorption of water and nutrients and their slow release of water. Increasing the SAP application to the soil, increased the yield of rice plants under normal conditions and under stress compared to the control plants [19]. The increased yield under stress conditions in soils treated with S-SAP can be explained by the ability of SAP to slowly release water and nutrients [30]. These effects in paddy can be attributed to several factors improved by hydrogel application such as root zone moisture retention and the reduced leaching of soil nutrients surrounding the roots.

Conclusions

The SAP was synthesized successfully with easy and feasible procedure that were effective in paddy fields. The current fast and simple methodology for synthesizing the S-SAP indicated the best outcome and was more effective compared with C-SAP treatments. The bio-based S-SAP can be useful for high water demand plant as a promising approach. By increasing the drought stress both yield and water use efficiency decreased that significantly mitigated by S-SAP application in paddy soils. These results indicate the positive effect of SAP in drought conditions on rice plants. By increasing the amount of SAP, the yield and water use efficiency increased significantly. At dryness condition, the water consumption can be drastically decreased by application of bio-synthesized superabsorbent without any need for fully submerging in paddy fields. Overall, the SAP application can help to combat the climate changes and drought stresses as a promising approach for sustainable agricultural production.

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Conflict of Interest

The authors declare no conflict of interest.

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