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Water-superabsorbent polymer improves seedling establishment in some warm-season plants

Un polímero superabsorbente de agua mejora el establecimiento de plántulas en algunas plantas de estación cálida

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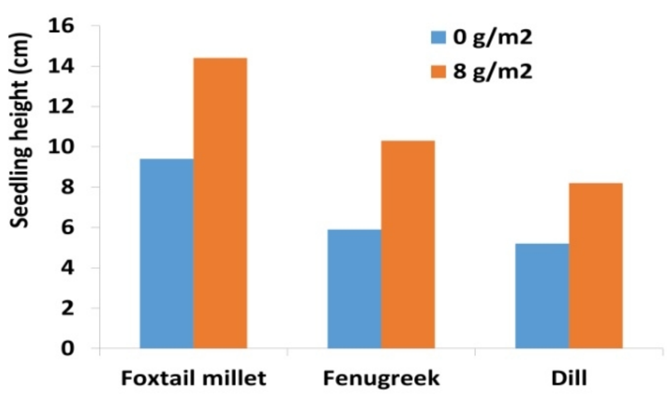

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ABSTRACT

Drought reduces plant establishment. Uneven and failed establishment causes crop loss. This experiment aimed at determining the effect of water-superabsorbent application rates (0, 2, 4, 6, and 8 g m^{-2}) on the plant establishment of foxtail millet, dill, and fenugreek. This field experiment was conducted in a semi-arid area. The used water-superabsorbent was synthetic and of acrylamide, acrylic acid and potassium acrylate type, which is able to absorb 220% moisture for its weight. The cycle of water absorption and drying of water-superabsorbent is repeatable. Mean comparisons showed that water-superabsorbent polymer improved seedling fresh weight, seedling dry weight, plant height, and seedling emergence percentage in all studied plants. Overall, except for foxtail millet, a water-superabsorbent rate of 8 g m^{-2} is recommended for high seedling emergence. For foxtail millet, a superabsorbent polymer rate of 6 g m^{-2} is sufficient.

Additional key words: dill; emergence percentage; fenugreek; foxtail millet; hydrogel.

RESUMEN

La sequía reduce el establecimiento de plantas. El establecimiento desigual y fallido provoca la pérdida de cultivos. Este experimento tuvo como objetivo determinar el efecto de las tasas de aplicación de superabsorbentes de agua (0, 2, 4, 6 y 8 g m^{-2}) en el establecimiento de plantas de mijo cola de zorra, eneldo y fenogreco. Este experimento de campo se realizó en una zona semiárida. El superabsorbente de agua utilizado fue sintético y del tipo acrilamida, ácido acrílico y acrilato de potasio, capaz de absorber un 220% de humedad por su peso. El ciclo de absorción de agua y secado del superabsorbente de agua es repetible. Las comparaciones de medias mostraron que el polímero superabsorbente de agua mejoró el peso fresco de las plántulas, el peso seco de las plántulas, la altura de las plantas y el porcentaje de emergencia de las plántulas en todas las plantas estudiadas. En general, a excepción del mijo cola de zorra, se recomienda una tasa de superabsorbente de agua de 8 g m^{-2} para una alta emergencia de plántulas. Para el mijo cola de zorra, una proporción de polímero superabsorbente de 6 g m^{-2} es suficiente.

Palabras clave adicionales: eneldo; porcentaje de emergencia; fenogreco; mijo cola de zorra; hidrogel.

INTRODUCTION

In dry and low water areas such as Iran, in addition to the fact that the water available for agriculture is not enough, this amount also does not exceed 3% of actual consumption, and the rest of the water is eliminated in some way (Alizadeh, 2005). In the wake of population growth, the phenomenon of desertification and declining agricultural lands, increasing demand for food is becoming more and more critical, with negative effects as soon as possible on all environmental, social, and economic contexts of life. The United Nations estimates that by the year 2030 more than five billion people in the world will somehow be involved with water scarcity (FAO, 2009).

Super absorbent polymer refers to a dry polymeric substance, usually sugar-like, with the ability to absorb aqueous solution several times its weight (eg. 10 to 120 times) and is capable of maintaining it. The super absorbent, after being added to the soil, releases the absorbed water gradually to the root of the plant, and thus the soil remains moist for a long time and without the need for watering (Khorram and Vasheghani-Farahani, 2003). Superabsorbents form three-dimensional polymer networks that do not dissolve in water but swell in an aqueous environment. Synthetic superabsorbent polymers are replacing natural polymers due to their high absorption capacity, availability and durability (Behera and Mahanwar, 2020). There are natural and synthetic types of water-superabsorbent polymers. Due to the biodegradable nature of natural polymers, their use is encouraged. One of the biodegradable polymers that can be produced from renewable sources is starch (Supare and Mahanwar, 2022). The moisture stored by the water-superabsorbent is gradually released and becomes available to the plant roots. The water-superabsorbent leads to an increase in the efficiency of water use, an increase in the irrigation interval, and the supply of soil nutrients. These compounds improve soil aeration and are suitable for controlled release of fertilizers (Oladosu *et al*., 2022).

Effects of water-superabsorbent in agriculture were studied in some research (Ritonga *et al*., 2019; Liu *et al*., 2020; Cao and Li 2021; Dhiman *et al*., 2021a; Tan *et al*., 2021). Langan and Christie (1985) and Kafi *et al.* (2005) reported that by increasing drought stress, the percentage of emergence in the studied plants was reduced and the use of water-absorbent compounds could play a major role in increasing the rate of emergence by improving access to water. They also reported that a water-absorbent composition is suitable for increasing the germination of seeds in semi-arid regions. Studies have also been done on the effect of some polymers on germination and plant growth. Polyacrylamide application increased wheat leaf length and width (*Triticum aestivum* L.), germination, seed dry weight, and seed yield (Jiang *et al*., 2010). Karimi and Naderi (2007) also reported that dry matter yield increased in maize (*Zea mays* L.) by increasing the application of superabsorbent. Rafiei (2010) reported that both superabsorbent and compost increased the emergence of black saxaul (*Haloxilon aphyllum* Minkw.) sapling and its establishment and improved measured traits compared to the control. Luo *et al.* (2009) studied the effect of octomycorrhizal fungi and hydrogel on the growth and yield of poplar (*Populus euphratica* Olive) under drought stress and observed that hydrogel was able to increase the available water of the plant by osmotic regulation and accumulation of small carbohydrate molecules and stimulated poplar growth. The concentration of metal in the planting medium may exceed the tolerance of metallophyte plants. Adding micron-size thiol-functional cross-linked acrylamide particles (X) to the waste rock culture medium increased the water storage capacity and water availability of the plant by 108%. Improving soil quality with X improved the establishment of the metallophyte plant Astrebla lappacea in the waste rock planting medium (Bigot *et al*., 2013). Water superabsorbent polymer (SAP) with wastewater (WW) and gasified biochar decreased potato (*Solanum tuberosum* L.) tuber yield but SAP + pyrolyzed biochar + WW increased spinach (*Spinacia oleracea* L.) yield. Therefore, the effect of soil amendment depends on the type of plant (Dhiman *et al*., 2021b).

Due to the low seedling establishment of small-seeded plants, especially in the warm seasons, the percentage of field emergence needs to be increased; the use of water-superabsorbents may be useful in this regard. There is research on the use of water-super absorbent to increase the performance of agricultural plants, but so far, no comprehensive research has been done on the use of water-superabsorbent to improve the emergence of seedlings and the establishment of small seeded plants, especially in the warm season. Therefore, this study aimed at determining the effect of water super absorbent application on the establishment of some warm-season plants.

MATERIALS AND METHODS

Treatments and agronomic operations

This research was carried out in a randomized complete block design with three replications at the Research Farm of Razi University (34°21'N, 47°9'E, altitude of 1,319 m). The average annual rainfall of the area is 450 mm and it has a temperate climate and is part of the semi-arid area. Some weather parameters during the cultivation period (Iran's Meteorological Organization, 2024) are given in table 1. Some characteristics of the soil of the test site are given in table 2. The studied factor was water-super absorbent polymer rates (0, 2, 4, 6, and 8 g m^{-2}). Effect of water superabsorbent was assessed on three warm-season crops including foxtail millet (*Setaria italica* L.), dill (*Anethum graveolens* L.), and fenugreek (*Trigonella foenum*-graecum L.).

Table 1. Some weather parameters during the cultivation period (Iran's Meteorological Organization, 2024).

Months	Temperature (°C)	Cumulated rainfall (mm)	Relative humidity (%)	Length of day light (h)
May	18.4	11.8	46	14
Jun	24.2	7.8	28	14.75

Table 2. Some characteristics of the soil of the test site.

K (ppm)	P (ppm)	N (%)	Field capacity (%)	OC (%)	E (ds/m)	pH	Texture
230	10	0.8	40.9	1.3	1.6	7.2	Clayey silt

Foxtail millet cv. KFM9 (produced in 2009) was obtained from Karaj Seed and Plant Improvement Institue. Dill cv. Varamin (produced in 2014), is widely cultivated in Kermanshah Province. Fenugreek was obtained from the local mass of Kermanshah (produced in 2014). Seeds of warm-season plants were cultivated on May 11, 2014.

Plots were divided into dimensions of 1×1 m. Sowing densities for foxtail millet, dill, and fenugreek were 20, 13, and 33 seeds/m^2, respectively. The plants were surface irrigated with an irrigation interval of 7 d. Samples were harvested before the competition between the bushes. The water super absorbent A-200 (Bojnourd Boulorab Company, Bojnurd, Iran) was a super

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absorbent material used in this study. The used water-superabsorbent was synthetic and of acrylamide, acrylic acid and potassium acrylate type, which is able to absorb 220% moisture for its weight. Water absorption leads to an increase in the diameter of the water-superabsorbent particles, and the water-superabsorbent provides the stored water to the plant. Therefore, this substance reduces the effects of drought stress on the plant. This material gives it back at the same speed as it absorbed water. The cycle of water absorption and drying of water-superabsorbent is repeatable and this material is able to maintain moisture for a long time (Karimi *et al*., 2009). The water-superabsorbent polymer was planted with seeds. Foxtail millet, dill, and fenugreek were cut after reaching stages 4, 5, and 5 leaves, respectively and the traits were measured.

Plant traits studied

The height of the plant was measured by a ruler with millimeter accuracy. To measure the fresh and dry weight of the seedlings, 5 plants per plot were taken. Then, the fresh seedlings were immediately weighed with digital scale, and then the envelopes containing the samples were placed in an oven at 75°C for 72 h to calculate the dry weight. The percentage of emergence was calculated by Eq. (1) (Ellis and Roberts, 1981):

$$FEP = \left(\frac{S}{T}\right) \times 100 \qquad (1)$$

where, *FEP* is the percentage of emergence, *S* is the number of emerged seeds and *T* is the total number of seeds.

Statistical analysis of data

The data related to each individual plant were subjected to analysis of variance and mean comparison. Each experiment consisted of five treatments and three repetitions. Considering that three plants were used, there were a total of 45 test plots or pots. First, the data were evaluated for outliers using Minitab (Ver. 11.12, Minitab, LLC, Pennsylvania) software, and then the normality test was performed. The data for each plant were analyzed using SAS (SAS Institute Inc., Cary, North Carolina, U.S.) software and compared with the Duncan test at the probability level of 5%.

RESULTS

Plant height

Water-superabsorbent polymer had a significant effect on plant height in all studied plants (Tab. 3). The use of a superabsorbent polymer rate of 8 g m^{-2} increased plant height by 54, 71 and 57% compared to non-use in foxtail millet, fenugreek, and dill, respectively (Tab. 4). According to the results, plant height increase with superabsorbent application in fenugreek was higher than that of foxtail millet and dill. The highest plant height was related to the treatment of foxtail millet with the water-superabsorbent rate of 8 g m^{-2} and the lowest plant height was related to the treatment of dill with the water-superabsorbent rate of 0 g m^{-2}.

Table 3. Analysis of variance (mean square) of the effect of super absorbent polymer (S) on some plants

Plant	Source of variation	df	Seedling fresh weight	Seedling dry weight	Plant height	Emergence percentage
Foxtail millet	Block	2	233*	3.8ns	1.61**	0.89**
	S	4	127442**	1622.5**	12.52**	47.07**
	Error	8	56	3.1	0.12	0.09
Fenugreek	Block	2	6.5ns	51.9**	0.125*	2.4ns
	S	4	414878.6**	27926.2**	8.537**	170.5**
	Error	8	4.3	5.5	0.035	1.3
Dill	Block	2	21.0**	10.8*	0.05**	4.0 ns
	S	4	7451.5**	585.2**	4.13**	0.67**
	Error	8	0.8	3.2	0.00	7.8

** and *= significant at a probability level of 1 and 5%, respectively. ns= insignificant.

Seedling fresh weight

Water-superabsorbent polymer had a significant effect on seedling fresh weight in all studied plants (Tab. 3). The use of water-super absorbent at the rate of 8 g m^{-2} increased seedling fresh weight of 101, 194 and 78% compared to non-use of water-super absorbent in foxtail millet, fenugreek, and dill, respectively (Tab. 4). According to the results, seedling fresh weight increase with superabsorbent application in dill was higher than that of foxtail millet and fenugreek. The highest seedling fresh weight was related to the treatment of fenugreek with the water-superabsorbent rate of 8 g m^{-2} and the lowest seedling fresh weight was related to the treatment of dill with the water-superabsorbent rate of 0 g m^{-2}.

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Table 4. Mean comparisons for effect of water-superabsorbent on some plant traits in three plants.

Plant	Water-superabsorbent polymer rates (g m^{-2})	Plant height (cm)	Seedling fresh weight (mg)	Seedling dry weight (mg)	Emergence percentage (%)
Foxtail millet	0	9.4 ± 0.4 e	476.8 ± 2.7 e	50.5 ± 0.9 e	52.1 ± 0.3 e
	2	10.6 ± 0.8 d	605.2 ± 3.5 d	60.8 ± 1.5 d	55.3 ± 0.2 d
	4	12.0 ± 0.5 c	788.4 ± 3.9 c	79.5 ± 1.3 c	58.1 ± 0.4 c
	6	13.3 ± 0.2 b	917.2 ± 13.8 b	95.6 ± 1.7 b	60.0 ± 0.3 b
	8	14.4 ± 0.2 a	961.9 ± 2.2 a	106.3 ± 0.7 a	62.2 ± 0.5 a
Fenugreek	0	5.99 ± 0.01 e	416.27 ± 1.0 e	94.8 ± 3.2 d	57.4 ± 1.0 e
	2	7.21 ± 0.27 d	553.7 ± 1.8 d	152.7 ± 2.1 d	62.8 ± 0.8 d
	4	8.09 ± 0.13 c	1060.9 ± 0.8 c	270.9 ± 1.7 c	66.8 ± 1.0 c
	6	9.25 ± 0.21 b	1159.6 ± 0.9 b	300.4 ± 3.9 b	72.4 ± 0.6 b
	8	10.31 ± 0.04 a	1227.6 ± 2.5 a	310.2 ± 2.1 a	76.5 ± 1.0 a
Dill	0	5.24 ± 0.07 e	157.1 ± 1.6 e	38.4 ± 0.2 e	44.7 ± 0.3 b
	2	6.02 ± 0.07 d	193.9 ± 1.4 d	48.6 ± 2.7 d	46.9 ± 0.2 b
	4	6.74 ± 0.07 c	225.9 ± 1.7 c	57.1 ± 1.0 c	49.0 ± 0.4 b
	6	7.40 ± 0.07 b	259.5 ± 0.9 b	64.4 ± 1.9 b	49.6 ± 4.2 b
	8	8.26 ± 0.07 a	281.4 ± 2.0 a	74.6 ± 0.0 a	57.2 ± 0.3 a

Means followed by the same letter in each plant have no significant difference according to the Duncan's multiple range test ($P \leq 0.05$). Values show means ± standard error.

Seedling dry weight

Water-superabsorbent polymer had a significant effect on seedling dry weight in all studied plants (Tab. 3). The use of water-super absorbent at the rate of 8 g m^{-2} increased seedling dry weight of 110%, 227% and 94% compared to non-use of water-super absorbent in foxtail millet, fenugreek and dill, respectively (Tab. 4). According to the results, seedling dry weight increase with superabsorbent application in fenugreek was higher than that of foxtail millet and dill. The highest seedling dry weight was related to the treatment of fenugreek with the water-superabsorbent rate of 8 g m^{-2} and the lowest seedling dry weight was related to the treatment of dill with the water-superabsorbent rate of 0 g m^{-2}.

Seedling emergence percentage

Water-superabsorbent polymer had a significant effect on seedling emergence percentage in all studied plants (Tab. 3). The use of water-superabsorbent at the rate of 8 g m^{-2} increased seedling emergence percentage of 19, 33 and 27% compared to non-use of water-superabsorbent in foxtail millet, fenugreek and dill, respectively (Tab. 4). According to the results, the seedling emergence percentage increase with superabsorbent application in fenugreek was higher than that of foxtail millet and dill. The highest seedling emergence percentage was related to the treatment of fenugreek with the water-superabsorbent rate of 8 g m^{-2} and the lowest seedling emergence percentage was related to the treatment of dill with the water-superabsorbent rate of 0 g m^{-2}.

Leaf number

There was no variance between the rates of water- superabsorbent polymer used in this research in terms of the number of leaves. Foxtail millet, dill and fenugreek had 4, 5 and 5 leaves per plant, respectively.

DISCUSSION

The results of this study showed that with the increasing amount of water-super absorbent, the plant height increased significantly. Khashei Siuki *et al*. (2009) observed that using natural zeolite had a significant effect on maize plant height and yield. When polymers absorb and release water, the soil structure improves due to the expansion and contraction, and the pores containing air in the soil increase for root development, especially in fine tissue soils (Khorram and Vasheghani-Farahani, 2003). Water-super absorbent increases the growth and yield of plants by increasing water absorption and maintenance in the soil (Koupai *et al*., 2008; Narjary *et al*., 2012; Montesano *et al*., 2015). Prisa and Guerrini (2023) reported that with the increase in the use of hydrogel in the soil, the microbial activity increased, which was attributed to the increase in soil moisture storage with the polymer because more moisture intensifies the microbial activity in the rhizosphere. Intensification of microbial activity is important in the decomposition of organic matter in the soil and the release of nutrients for the plant. Hydrogel increased the mass of spearmint (*Mentha spicata*) in clay and sandy soil. The hydrogel also improved the germination of radish (*Raphanus sativus*) seeds, which was due to loosening the soil and increasing the soil moisture reserve (Peyrusson, 2021). Hydrogel increased the water use efficiency and the growth of maize plants, and hydrogel 0.5% was the best application rate (Albalasmeh *et al*., 2022).

The increased fresh and dry weight of the seedling with the superabsorbent application was probably due to increased absorption and maintenance of water in the soil and increased ventilation. Johnson and Leah (1990) and Rifat and Safdar (2004) reported that fresh and dry weights were increased significantly by increasing the concentration of absorbent polymer. Increasing biomass and seedling establishment due to the application of soil hydrogels were reported by many researchers (Thomas, 2008; Orikiriza *et al.,* 2009; Zareian *et al.,* 2018). The prediction of emergence time, the selection of suitable planting dates, and the rapid and complete establishment of seedlings are necessary for successful cultivation, and these are strongly influenced by environmental factors such as temperature and soil moisture (Jacobsen and Bach, 1998; Seefeldet *et al*., 2002; Madsen *et al*., 2016). Increasing the percentage of emergence by increasing the amount of water-super absorbent is probably due to the long-term availability of seeds to moisture with the use of water-super absorbent in the soil. Application of zeolite in drought stress conditions led to an increase in emergence percentage, average daily emergence, and plant establishment (Armandpisheh *et al*., 2011). With increasing the concentration of nanocomposite in the culture medium, the growth of shoot and root of tomato (*Lycopersicon esculentum* Mill.) under mild and severe drought stress increased (Nassaj-Bokharaei *et al*., 2021).

The reason for the superiority of dry weight, plant height, and emergence percentage of fenugreek seedlings over foxtail millet and dill may be the large fenugreek seeds, which have resulted in stronger seedlings and ultimately more seedling dry weight. In maize, seed size did not affect seed germination and seedling length, but it affected seedling fresh weight and seedling dry weight (Akinyosoye *et al*., 2014).

Makino *et al*. (1996) proposed a model for the erosion kinetics of a water-superabsorbent matrix. α and β are the starting and ending coefficients of water-superabsorbent erosion. Water-superabsorbent starts to swell in contact with water. The swelling continues until the weight of water ($W(t)$) in the water-superabsorbent reaches the weight of the polymer in the water-superabsorbent ($\alpha P(t)$). Erosion or release of polymer and water from the water-superabsorbent starts when $W(t) = \alpha P(t)$. When the weight of water in the water-superabsorbent decreases to $\beta P(t)$, erosion ends. Swelling and erosion continue repeatedly, until all the polymer molecules are removed from the hydrogen matrix.

The mechanism of water absorption and release in water-superabsorbent is as follows. First, water slowly diffuses inside the polymer matrix. Then water interacts with the functional groups in the polymer matrix and causes chain expansion. Water is also held by the capillary force of the pores inside the polymer matrix. Then the water is slowly released from the polymer network and the pore structure. Finally, the water is removed and the polymer keeps its shape (Zowada and Foudazi, 2023).

In forward osmosis (FO) process, water is transferred through a semi-permeable membrane from the side where the chemical potential of water is higher to the other side where the chemical potential of water is lower. From the point of view of thermodynamics, there is also FO process in water-superabsorbent polymer. The water-superabsorbent swells in water, which is due to the lower chemical potential of the water in the water-superabsorbent compared to the surrounding water. Swelling pressure results from polymer-water mixing, network elastic reaction force and osmotic pressure of ionizable groups. Swollen water-superabsorbent polymer is actually a solution. Water-superabsorbent polymer plays many roles such as solute, osmotic membrane and pressure generating device (Wang *et al*., 2014).

Water-superabsorbent degradation depends on the composition of Water-superabsorbent and the mechanism of degradation and is characterized by degradation products and swelling behavior of Water-superabsorbent (Meyvis *et al*., 2000). Water-superabsorbent degradation has different mechanisms such as hydrolytic degradation, non-cellular enzymatic degradation and cellular degradation (Mazzeo *et al*., 2019).

The water-superabsorbent polymer studied in this research is destroyed by microorganisms after 3 to 5 years, depending on the type of soil, and therefore do not cause environmental pollution (Qanadzadeh *et al*., 2015). Some types of hydrogels are very durable, for example, potassium acrylate, if high-quality water is used, it can grow up to 150 times (Otorres and Soto, 2017). Therefore, these compounds remain in the soil for several years and maintain their properties.

One of the limitations of this irrigation method and this research was the application rate of the water-superabsorbent polymer. Because there was little information about the effect of hydrogel on seedling establishment, therefore, 8 g m^{-2} was considered the highest application rate. If more values were considered, the saturation point would probably be obtained. Another limitation of this study is the range of studied plants. If a wider spectrum was studied, more information would be obtained.

CONCLUSION

Overall, water-super absorbent increased the seedling weight and the percentage of seedling emergence. According to the results of this study, for the high seedling establishment of the studied plants, except for foxtail millet, 8 g m^{-2} of super absorbent is recommended. For foxtail millet, 6 g m^{-2} is suggested. Assessing the effect of super absorbent on seedling establishment in drought conditions should be considered in future research.

Conflict of interests: The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts at risk the validity of the presented results.

Author's contributions: A. Hosseini conducted the experiment and analyzed the data. H. Heidari designed and translated manuscript. I. Nosratti and M. Khoramivafa revised the manuscript.

BIBLIOGRAPHIC REFERENCES

Akinyosoye, S.T., J.A. Adetumbi, O.D. Amusa, M.O. Olowolafe, and J.O. Olasoji. 2014. Effect of seed size on *in vitro* seed germination, seedling growth, embryogenic callus induction and plantlet regeneration from embryo of maize (*Zea mays* L.) seed. Niger. J. Genet. 28(2), 1-7. Doi: https://doi.org/10.1016/j.nigjg.2015.06.001

Albalasmeh, A.A., O. Mohawesh, M.A. Gharaibeh, A.G. Alghamdi, M.A. Alajlouni, and A.M. Alqudah. 2022. Effect of hydrogel on corn growth, water use efficiency, and soil properties in a semi-arid region. J. Saudi Soc. Agric. Sci. 21(8), 518-524. Doi: https://doi.org/10.1016/j.jssas.2022.03.001

Alizadeh, A. 2005. Soil, water-plant relationship. 4th ed. Emam Reza university; Astan Ghods Razavi Publication, Mashhad, Iran.

Armandpisheh, O., A.H. Shirani Rad, I. Allahdadi, A. Ebadi, and A.A. Koliaei. 2011. The reduction of unpleasant effects of drought stress with the application of zeolite the canola (*Brassica napus* L.) seeds characteristics. Plant and Ecosystem, 6(24), 67-75.

Behera, S. and P.A. Mahanwar. 2020. Superabsorbent polymers in agriculture and other applications: a review. Polym.-Plast. Technol. Mater. 59(4), 341-356. Doi: https://doi.org/10.1080/25740881.2019.1647239

Bigot, M., J. Guterres, L. Rossato, A. Pudmenzky, D. Doley, M. Whittaker, U. Pillai-McGarry, and S. Schmidt. 2013. Metal-binding hydrogel particles alleviate soil toxicity and facilitate healthy plant establishment of the native metallophyte grass *Astrebla lappacea* in mine waste rock and tailings. J. Hazard. Mater. 248-249, 424-434. Doi: https://doi.org/10.1016/j.jhazmat.2013.01.025

Cao, L. and N. Li. 2021. Activated-carbon-filled agarose hydrogel as a natural medium for seed germination and seedling growth. Int. J. Biol. Macromol. 177, 383-391. Doi: https://doi.org/10.1016/j.ijbiomac.2021.02.097

Dhiman, J., S.O. Prasher, E. ElSayed, R.M. Patel, C. Nzediegwu, and A. Mawof. 2021a. Effect of hydrogel based soil amendments on heavy metal uptake by spinach grown with wastewater irrigation. J. Clean. Prod. 311, 127644. Doi: https://doi.org/10.1016/j.jclepro.2021.127644

Dhiman, J., S.O. Prasher, E. ElSayed, R.M. Patel, C. Nzediegwu, and A. Mawof, 2021b. Effect of hydrogel based soil amendments on yield and growth of wastewater irrigated potato and spinach grown in a sandy soil. Environ. Technol. Innov. 23, 101730. Doi: https://doi.org/10.1016/j.eti.2021.101730

Ellis, R.A. and E.H. Roberts. 1981. The quantification of ageing and survival in orthodox seeds. Seed Sci. Technol. 9, 373-409.

FAO. 2009. Crop production statistics. In: http://www.fao.org/docrep/010/ah864e/ah864e00.htm; consulted: June, 2024.

Iran's Meteorological Organization. 2024. Meteorological data. In: https://www.irimo.ir/index.php?newlang=eng; consulted: July, 2024.

Jacobsen, S.E. and A.P. Bach. 1998. The influence of temperature on seed germination rate in quinoa) *Chenopodium quinoa* Willd). Seed Sci. Technol. 26, 515-523.

Jiang, T., L. Teng, S. Wei, L. Deng, Z. Luo, Y. Chen, and D.C. Flanagan. 2010. Application of polyacrylamide to reduce phosphorus losses from a Chinese purple soil: laboratory and field investigation. J. Environ. Manage. 91(7), 1437-1445. Doi: https://doi.org/10.1016/j.jenvman.2010.02.006

Johnson, M.S. and R.T. Leah. 1990. Effect of superabsorbent polyacrylamides on efficiency of water use by crop seeding. J. Sci. Food Agr. 52(3), 431-434. Doi: https://doi.org/10.1002/jsfa.2740520316

Kafi, M., A. Nezami, H. Hosseini, and A. Masoumi. 2005. Physiological effects of drought stress by polyethylene glycol on germination of lentil (*Lens culinaris* Medik.) genotypes. Iran. J. Field Crops Res. 3(1), 69-81.

Karimi, A. and M. Naderi. 2007. Yield and water use efficiency of forage corn as influenced by superabsorbent polymer application in soils with different textures. Agric. Res. 7(3), 187-198.

Karimi, A., M. Noshadi, and M. Ahmadzadeh. 2009. Effects of super absorbent polymer (Igeta) on crop, soil water and irrigation interval. J. Water Soil Sci. 12(46), 403-414.

Khashei Siuki, A., M. Koochakzadeh, and M. Shahabifar. 2009. Effect of natural zeolite application and soil moisture on yield components of corn (*Zea mays* L.). Iran. J. Soil Res. 22(2), 235-241. Doi: https://doi.org/10.22092/ijsr.2009.127006

Khorram, M. and E. Vasheghani-Farahani. 2003. Fast responsive thermosensitive hydrogels as drug delivery systems. Iran. Polymer J. 12(4), 316-322.

Koupai, J.A., S.S. Eslamian, and J.A. Kazemi. 2008. Enhancing the available water content in unsaturated soil zone using hydrogel, to improve plant growth indices. Ecohydrol. Hydrobiol. 8(1), 67-75. Doi: https://doi.org/10.2478/v10104-009-0005-0

Langan, E.C. and H.W. Christie. 1985. Seed coating composition and method. Patent US4493162A.

Liu, C., F. Lei, P. Li, J. Jiang, and K. Wang. 2020. Borax crosslinked fenugreek galactomannan hydrogel as potential water-retaining agent in agriculture. Carbohydr. Polym. 236, 116100. Doi: https://doi.org/10.1016/j.carbpol.2020.116100

Luo, Z.-B. K. Li, X. Jiang, and A. Polle. 2009. Ectomycorrhizal fungus (*Paxillus involutus*) and hydrogels affect performance of *Populus euphratica* exposed to drought stress. Ann. Forest Sci. 66(1), 106-114. Doi: https://doi.org/10.1051/forest:2008073

Oladosu, Y., M.Y. Rafii, F. Arolu, S.C. Chukwu, M.A. Salisu, I.K. Fagbohun, T.K. Muftaudeen, S. Swaray, and B.S. Haliru. 2022. Superabsorbent polymer hydrogels for sustainable agriculture: a review. Horticulturae 8(7), 605. Doi: https://doi.org/10.3390/horticulturae8070605

Madsen, M.D., K.W. Davies, C.S. Boyd, D. Kerby, and T.J. JSvejcar. 2016. Emerging seed enhancement technologies for overcoming barriers to restoration. Restor. Ecol. 24(Suppl. 2), 77-84. Doi: https://doi.org/10.1111/rec.12332

Makino, K., R. Idenuma, and H. Ohshima. 1996. A model for erosion kinetics of a hydrogel matrix. Colloids Surf. B Biointerfaces 8(1-2), 93-100. Doi: https://doi.org/10.1016/S0927-7765(96)01313-6

Mazzeo, M.S., T. Chai, M. Daviran, and K.M. Schultz. 2019. Characterization of the kinetics and mechanism of degradation of human mesenchymal stem cell-laden poly(ethylene glycol) hydrogels. ACS Appl. Bio Mater. 2(1), 81-92. Doi: https://doi.org/10.1021/acsabm.8b00390

Meyvis, T.K.L., S.C. De Smedt, J. Demeester, and W.E. Hennink. 2000. Influence of the degradation mechanism of hydrogels on their elastic and swelling properties during degradation. Macromolecules 33(13), 4717-4725. Doi: https://doi.org/10.1021/ma992131u

Montesano, F.F., A. Parente, P. Santamaria, A. Sannino, and F. Serio. 2015. Biodegradable superabsorbent hydrogel increases water retention properties of growing media and plant growth. Agric. Agric. Sci. Proc. 4, 451-458. Doi: https://doi.org/10.1016/j.aaspro.2015.03.052

Narjary, B., P. Aggarwal, A. Singh, D. Chakraborty, and R. Singh. 2012. Water availability in different soils in relation to hydrogel application. Geoderma 187-188, 94-101. Doi: https://doi.org/10.1016/j.geoderma.2012.03.002

Nassaj-Bokharaei, S., B. Motesharezedeh, H. Etesami, and E. Motamedi. 2021. Effect of hydrogel composite reinforced with natural char nanoparticles on improvement of soil biological properties and the growth of water deficit-stressed tomato plant. Ecotoxicol. Environ. Saf. 223, 112576. Doi: https://doi.org/10.1016/j.ecoenv.2021.112576

Orikiriza, L.J.B., H. Agaba, M. Tweheyo, G. Eilu, J.D. Kabasa, and A.J. Hüttermann. 2009. Amending soils with hydrogels increases the biomass of nine tree species under non-water stress conditions. Clean Soil Air Water 37(8), 615-620. Doi: https://doi.org/10.1002/clen.200900128

Otorres, A. and G.M. Soto. 2017. Potassium acrylate: a novelty in hydroponic substrates. pp. 1-8. In: XIII International Engineering Congress (CONIIN). Santiago de Queretaro, Mexico. Doi: https://doi.org/10.1109/CONIIN.2017.7968177

Peyrusson, F. 2021. Hydrogels improve plant growth in mars analog conditions. Front. Astron. Space Sci. 8, 729278. Doi: https://doi.org/10.3389/fspas.2021.729278

Prisa, D. and G. Guerrini. 2023. Innovative hydrogels use in the germination and growth of tree species *Paulownia tomentosa* and *Cupressus sempervirens*. GSC Adv. Res. Rev. 14(2), 121-128. Doi: https://doi.org/10.30574/gscarr.2023.14.2.0058

Qanadzadeh, M., A. Faridhosseini, N. Sadaqat, S. Javidi, and H. Barzegar. 2015. The effect of superabsorbent polymer on the physical properties of three types of soil texture (sand, loam, clay). In: National Congress of Irrigation and Drainage of Iran. Ferdowsi University of Mashhad, Mashhad, Iran.

Rafiei, Z. 2010. Comparing effect of hydrogel and compost on establishment and growth properties of Haloxilon aphyllum. MSc thesis. College of Natural Resources, University of Tehran.

Rifat, H. and A. Safdar. 2004. Water absorption by synthetic polymer (Aquasorb) and its effect on soil properties and tomato yield. J. Agric. Biol. 6, 998-1002.

Ritonga, H., A. Nurfadillah, F.S. Rembon, L.O.A.N. Ramadhan, and M. Nurdin. 2019. Preparation of chitosan-EDTA hydrogel as soil conditioner for soybean plant (*Glycine max*). Groundw. Sustain. Dev. 9, 100277. Doi: https://doi.org/10.1016/j.gsd.2019.100277

Seefeldet, S.S., K.K. Kidwell, and J.E. Waller. 2002. Base growth temperature, germination rates and growth response of contemporary spring wheat (*Triticum aestivum* L.) cultivars from the USA Pacific North West. Field Crops Res. 75(1), 47-52. Doi: https://doi.org/10.1016/S0378-4290(02)00007-2

Supare, K. and P.A. Mahanwar. 2022. Starch-derived superabsorbent polymers in agriculture applications: an overview. Polym. Bull. 79, 5795-5824. Doi: https://doi.org/10.1007/s00289-021-03842-3

Tan, W.K., J. Zhu, J.Y. Lim, Z. Gao, C.S. Loh, J. Li, and C.N. Ong. 2021. Use of okara-derived hydrogel for enhancing growth of plants by minimizing leaching and locking nutrients and water in growing substrate. Ecol. Eng. 159, 106122. Doi: https://doi.org/10.1016/j.ecoleng.2020.106122

Thomas, D.S. 2008. Hydrogel applied to the root plug of subtropical eucalypt seedlings halves transplant death following planting. Forest Ecol Manage. 255(3-4), 1305-1314. Doi: https://doi.org/10.1016/j.foreco.2007.10.035

Wang, H., J. Wei, and G.P. Simon. 2014. Response to osmotic pressure versus swelling pressure: comment on “bifunctional polymer hydrogel layers as forward osmosis draw agents for continuous production of fresh water using solar energy”. Environ. Sci. Technol. 48(7), 4214-4215. Doi: https://doi.org/10.1021/es5011016

Zareian, F., M. Jafari, S.A. Javadi, and A. Tavili. 2018. Application of zeolite and geohumus superabsorbent on establishment and some growth indices of *Nitraria schoberi* L. Acta Ecol. Sin. 38(4), 296-301. Doi: https://doi.org/10.1016/j.chnaes.2017.12.005

Zowada, R. and R. Foudazi. 2023. Macroporous hydrogels for soil water retention in arid and semi-arid regions. RSC Appl. Polym. 1(2), 243-253. Doi: https://doi.org/10.1039/D3LP00117B