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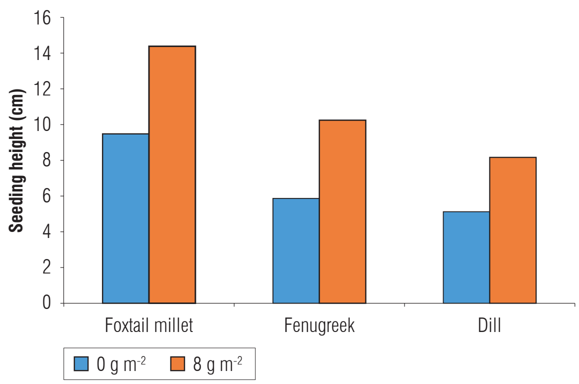
Water-superabsorbent polymer improves seedling establishment in some warm-season plants

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



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Water- superabsorbent polymer improved seedling height in some warm season plants.

Source: H. Heidari

ABSTRACT

Drought reduces plant establishment. Uneven and failed establishment causes crop loss. This experiment aimed to determine 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 water-superabsorbent used was synthetic and composed of acrylamide, acrylic acid and potassium acrylate (type), which can absorb up to 220% of its own weight in moisture. The cycle of water absorption and drying of water-superabsorbent is repeatable. Mean comparisons showed that the water-superabsorbent polymer improved seedling fresh weight, seedling dry weight, plant height, and seedling emergence percentage in all the 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: water use; hydrogel; dill; fenugreek; foxtail millet; emergence percentage.

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RESUMEN

La sequía reduce el establecimiento de las plantas. El establecimiento desigual y fallido causa 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 llevó a cabo en un área semiárida. El superabsorbente de agua utilizado fue sintético y estaba compuesto de un tipo de acrilamida, ácido acrílico y acrilato de potasio, que puede absorber hasta el 220% de su propio peso en humedad. 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 las plántulas. Para el mijo cola de zorra, una tasa de polímero superabsorbente de 6 g m^{-2} es suficiente.

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

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INTRODUCTION

In dry and low-water areas such as Iran, in addition to the fact that the water available for agriculture is insufficient, this amount represents less than 3% of actual consumption, and the rest of the water is lost in various ways (Alizadeh, 2005). Due to population growth, desertification, and the reduction of agricultural lands, the increasing demand for food is becoming increasingly critical, with negative effects on all environmental, social, and economic aspects of life. The United Nations estimates that by 2030, more than five billion people worldwide will face water scarcity (FAO, 2009).

A super absorbent polymer refers to a dry polymeric substance, usually resembling sugar granules, with the ability to absorb an aqueous solution several times its weight (e.g., 10 to 120 times) and retain it. Once added to the soil, the super absorbent gradually releases the absorbed water to the plant roots, maintaining soil moisture for extended periods without requiring additional watering (Khorram and Vasheghani-Farahani, 2003). Superabsorbents form three-dimensional polymer networks that, while swelling in aqueous environments, do not dissolve in water. Synthetic superabsorbent polymers are replacing natural polymers due to their high absorption capacity, availability, and durability (Behera and Mahanwar, 2020).

Superabsorbent polymers exist in natural and synthetic forms. Due to the biodegradable nature of natural polymers, their use is encouraged. Starch, a biodegradable polymer produced from renewable sources, is one example (Supare and Mahanwar, 2022). The moisture retained by superabsorbents is gradually released, becoming available to plant roots. These compounds enhance water-use efficiency, extend irrigation intervals, and supply soil nutrients. They also improve soil aeration and are suitable for controlled fertilizer release (Oladosu *et al*., 2022).

The impact of superabsorbents in agriculture has been studied in several works (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 increasing drought stress reduced the emergence rate of plants studied; however, the application of water-absorbent compounds improved water accessibility and enhanced emergence rates. These authors also suggested that water-absorbent compositions increase seed germination in semi-arid regions.

Other studies have investigated the effect of specific polymers on germination and plant growth. For example, polyacrylamide application increased wheat (*Triticum aestivum* L.) leaf length and width, germination rate, seed dry weight, and seed yield (Jiang *et al*., 2010). Karimi and Naderi (2007) observed increased dry matter yield in maize (*Zea mays* L.) with higher superabsorbent application rates. Rafiei (2010) noted that both superabsorbent and compost improved the emergence of black saxaul (*Haloxilon aphyllum* Minkw.) seedlings, enhancing their establishment and traits compared to controls.

The benefits of combining polymers with other treatments have also been documented. Luo *et al*. (2009) examined the effect of ectomycorrhizal fungi and hydrogel on the growth and yield of poplar (*Populus euphratica* Oliv.) under drought stress and observed that hydrogel enhanced the available water for the plant by osmotic regulation and accumulation of small carbohydrate molecules, thereby stimulating poplar growth. The concentration of metals in the planting medium may exceed the tolerance levels of metallophyte plants. Adding micron-size thiol-functional crosslinked acrylamide particles (SAP X) to the waste rock culture medium increased the water storage capacity and water availability to the plant by 108%. Improving soil quality with SAP X facilitated the establishment of the metallophyte plant *Astrebla lappacea* in the waste rock planting medium (Bigot *et al*., 2013).

A combination of water superabsorbent polymer (SAP) with wastewater (WW) and gasified biochar reduced potato (*Solanum tuberosum* L.) tuber yield, but the application of SAP + pyrolyzed biochar + WW enhanced spinach (*Spinacia oleracea* L.) yield. Therefore, the effect of a soil amendment depends on the type of plant (Dhiman *et al*., 2021b).

Due to the low seedling establishment rate of small-seeded plants, especially in warm seasons, the percentage of field emergence must be increased; the use of water-superabsorbents may be useful in this regard. Although there is research on the use of water-superabsorbents to increase the performance of agricultural plants, no comprehensive studies have been conducted on their use to improve the emergence of seedlings and the establishment of small-seeded plants, especially in warm seasons. Therefore, this study aimed to determine the effect of water-superabsorbent 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 that is part of the semi-arid region. 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 the rate of water-super absorbent polymer (0, 2, 4, 6, and 8 g m^{-2}). The effect of water-superabsorbent polymer was assessed on three warm-season crops, including foxtail millet (*Setaria italica* L.), dill (*Anethum graveolens* L.), and fenugreek (*Trigonella foenum*-graecum L.).

Foxtail millet cv. KFM9 (produced in 2009) was obtained from the Karaj Seed and Plant Improvement Institute. Dill cv. Varamin (produced in 2014), is a variety widely cultivated in Kermanshah Province.

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

Months	Temperature (°C)	Cumulated rainfall (mm)	Relative humidity (%)	Length of daylight (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 (mg kg^{-1})	P (mg kg^{-1})	N (%)	Field capacity (%)	OC (%)	EC (dS m^{-1})	pH	Texture
230	10	0.8	40.9	1.3	1.6	7.2	Clayey silt

Fenugreek seeds were obtained from the local seed stock 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 superabsorbent A-200 (Bojnourd Boulorab Company, Bojnurd, Iran) was used in this study as a superabsorbent material. The water superabsorbent was synthetic and composed of acrylamide, acrylic acid and potassium acrylate type, which can absorb up to 220% of its weight in moisture. This absorption process causes an increase in the diameter of the water-superabsorbent particles, and the material releases the stored water to the plant when needed. Therefore, this substance mitigates the effects of drought stress on the plant. Additionally, it releases water at the same rate as it absorbs it. The cycle of water absorption and drying is repeatable, allowing the material to maintain moisture for extended periods (Karimi *et al*., 2009). The water-superabsorbent polymer was sown along with the seeds. Foxtail millet, dill, and fenugreek were cut after reaching of 4, 5, and 5 leaves, respectively, and the traits were measured.

Plant traits studied

The height of the plant was measured using a ruler with millimeter accuracy. To measure the fresh and dry weight of the seedlings, 5 plants per plot were sampled. The fresh seedlings were immediately weighed using a digital scale, and 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 using Eq. (1) (Ellis and Roberts, 1981):

$$FEP = \frac{S}{T} \times 100 \tag{1}$$

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

Statistical analysis of data

The data collected from each individual crop were subjected to an analysis of variance and mean comparisons. Each experiment consisted of five treatments and three repetitions. Since three plants were used, there were a total of 45 test plots or pots. Initially, the data were evaluated for outliers using Minitab (Ver. 11.12, Minitab, LLC, Pennsylvania) software. Subsequently, the normality test was performed. The data for each crop were analyzed using SAS (SAS Institute Inc., Cary, North Carolina, U.S.) software and were compared using the Duncan test at a 5% probability level.

RESULTS

Plant height

The application of a water-superabsorbent polymer had a significant effect on plant height in all studied

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*	3.8^{ns}	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	6.5^{ns}	51.9**	0.125*	2.4^{ns}
	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.

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, the increase in plant height with superabsorbent application in fenugreek was higher than that observed in foxtail millet and dill. The highest plant height was observed in the treatment of foxtail millet with the water-superabsorbent rate of 8 g m^{-2}, and the lowest plant height occurred in the treatment of dill with the water-superabsorbent rate of 0 g m^{-2}.

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 in foxtail millet and fenugreek. The highest seedling fresh weight was observed in the treatment of fenugreek with the water-superabsorbent rate of 8 g m^{-2}, while the lowest seedling fresh weight was recorded in the treatment of dill with the water-superabsorbent rate of 0 g m^{-2}.

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 by 110, 227 and 94% compared to the non-use of water-superabsorbent in foxtail millet, fenugreek and dill, respectively (Tab. 4). According to the results, the seedling dry weight increase with superabsorbent application in fenugreek was higher than that in foxtail millet and dill. The highest seedling dry weight was observed in the treatment of fenugreek with the water-superabsorbent rate of 8 g m^{-2}, while the lowest seedling dry weight was recorded in 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

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

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	1,060.9±0.8 c	270.9±1.7 c	66.8±1.0 c
	6	9.25±0.21 b	1,159.6±0.9 b	300.4±3.9 b	72.4±0.6 b
	8	10.31±0.04 a	1,227.6±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 Duncan's multiple range test ($P \leq 0.05$). Values show means ± standard error.

the rate of 8 g m^{-2} increased seedling emergence percentage by 19, 33 and 27% compared to the 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 in foxtail millet and dill. The highest seedling emergence percentage was observed in the treatment of fenugreek with the water-superabsorbent rate of 8 g m^{-2}, while the lowest seedling emergence percentage was recorded in 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-superabsorbent, 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 textured soils (Khorram and Vasheghani-Farahani, 2003). Water-superabsorbent increases the growth and yield of plants by increasing water absorption and retention in the soil (Koupai *et al*., 2008; Narjary *et al*., 2012; Montesano *et al*., 2015). Prisa and Guerrini (2023) reported that with the increased in the use of hydrogel in the soil, the microbial activity increased, which was attributed to the increase in soil moisture storage caused by 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 soil loosening and increasing the soil moisture reserve (Peyrusson, 2021). Hydrogel increased water-use efficiency and the growth of maize plants, and hydrogel at 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 retention of water in the soil and increased ventilation. Johnson and Leah (1990) and Rifat and Safdar (2004) reported that fresh and dry weights significantly increased with higher concentrations 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-superabsorbent is probably due to the long-term availability of seeds to moisture provided by the 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 increased concentration of nanocomposite in the culture medium, the growth of shoot and root of tomato (*Solanum lycopersicum* L.) 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 lie in the larger 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 did affect 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 (αP(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 βP(t), erosion ends. Swelling and erosion continue repeatedly until all the polymer molecules are removed from the hydrogel 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 retains its shape (Zowada and Foudazi, 2023).

In the 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 polymers. 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. A 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 the polymer and the mechanism of degradation and is characterized by degradation products and swelling behavior of the polymer (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 does 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, 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 higher rates 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-superabsorbent 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 water-superabsorbent is recommended. For foxtail millet, 6 g m^{-2} is suggested. Assessing the effect of water-superabsorbent 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 the manuscript. I. Nosratti and M. Khoramivafa revised the manuscript.

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