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Yield and Quality of Sesame (*Sesamum indicum* L.) Improve by Water Preservative Materials under Normal and Deficit Irrigation in Birjand

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ABSTRACT

Crop production in dry areas is strongly affected by water shortage. In these regions, the application of water-absorbent materials is a useful strategy for sustainable crop production. Therefore, the aim of this study was to investigate the effect of two water preservative materials (WPM) on the growth and yield of sesame under two irrigation regimes. The experiment was carried out as factorial based on a randomized complete block design with three replications, during 2018 and 2019. Experimental factors were water availability levels (100 and 50% of sesame water requirement as normal and deficit irrigation, respectively) and application of WPM, including control (no-WPM), 125 kg ha^{-1} super absorbent polymer (SAP), 6200 kg ha^{-1} Zeolite (Z1), 11200 kg ha^{-1} Zeolite (Z2), SAP+Z1 and SAP+Z2. At the end of both growing seasons, vegetative growth parameters, yield components, seed and biological yields, water use efficiency and seed quality indices (oil and protein contents) were measured. The highest and the lowest amounts of vegetative parameters were obtained at SAP+Z2 under normal irrigation and control under deficit irrigation, respectively. Yield component indices were improved significantly by all WPM especially SAP+Z2 at both levels of irrigation. The highest seed yield was recorded by SAP+Z2 under normal irrigation (1304 and 1481 kg ha^{-1}, for the first and the second growing seasons, respectively). The highest oil yield (749 and 843 kg ha^{-1}, for the first and the second growing seasons, respectively) was gained at SAP+Z2 under normal irrigation, while its lowest value (125 and 136 kg ha^{-1}, for the first and the second growing seasons, respectively) was obtained with no- WPM under deficit irrigation. Similar trend was observed for protein yield. Overall, despite yield reduction, deficit irrigation improved water use efficiency. Moreover, WPMs were useful to improve growth and yield of sesame under both irrigation regimes.

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1. Introduction

In recent years, water resources are restricted for crop production worldwide, particularly in response to the indiscriminate harvesting of water reservoirs and climate change. Hence, there is an urgent need to explore water-saving strategies and to design more efficient irrigation systems in agriculture (Chang *et al.*, 2021; Mohebi, 2019; Satriani *et al.*, 2018). Most of the water shortage problems can be solved through increasing soil moisture holding capacity (Satriani *et al.*, 2018). Application of super absorbent polymers and zeolite, besides water deficit management, are surefire ways to achieve this aim (Tadayon and Karimzadeh Soureshjani, 2019; AbdAllah *et al.*, 2021). In addition, the selection of plants adapted to drought stress can also be beneficial. If a crop works well under water stress conditions, then it can be considered an appropriate choice for sustainable crop production in arid regions (Ebrahimian *et al.*, 2019). Sesame is one of these crops, which is commonly grown as a dry land crop (Pandey *et al.*, 2021).

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Sesame (*Sesamum indicum* L.) is one of the most important traditional oil seed crops in the world. It is considered the queen of oil seeds because it has a considerable amount (50-60%) of oil (Mushtaq *et al.*, 2020). This crop is well adapted to moisture stress and is mainly used by small holders in low-input agro-ecosystems as a well-suited option for different crop rotations (Lukurugu *et al*., 2023). It is widely cultivated in many parts of the world (over 50 countries) in more than 10 million ha cultivation area (Mushtaq *et al.*, 2020; Pourghasemian *et al*., 2020). This crop is widely used for edible oil, cake, flour, paste, and confectionary uses due to its stable oil, nutritious proteins and savory flavor (Mushtaq *et al.*, 2020).

Deficit irrigation, namely crop irrigation less than its full requirement, is a main strategy for water use optimization in irrigated lands (Asaadi *et al*., 2019). As a result, some of the plant yield is reduced, but the reduced yield could be compensated by profits obtained from reduced water consumption (Askari *et al.*, 2019). According to the results obtained from an experiment conducted in Kahramanmaras, Turkey, the irrigation interval of sesame under field conditions can be extended up to three weeks (Ucan and Killi, 2010). Although sesame is mainly grown in arid and semi-arid areas, as a drought-tolerant plant, deficit irrigation may lead to a decline in its growth and yield (Pourghasemian *et al.*, 2020). In a study on sesame, grain yield and harvest index decreased, while oil and grain water use efficiency increased, when drought stress (providing 50 and 70% of the plant's water requirement) was applied (Askari *et al*., 2019). Results of a previous study revealed that deficit irrigation in sesame increased root depth and root-to-shoot ratio (Ghasemi Hamedani *et al.*, 2020). In a study conducted on sesame, severe water stress (30 compared with 90% of field capacity) led to growth reduction through reducing stomata conductivity, chlorophyll content and photosynthetic rate (Pourghasemian *et al.*, 2020). Similarly, in another study on sesame severe drought stress (40% of potential evapotranspiration) considerably decreased seed oil percentage, while mild water stress (80% of potential evapotranspiration) had no negative impact on this index (Ebrahimian *et al.*, 2019). Observation of Ucan et al. (2007), also showed that Kcp =1 plant-pan coefficient is recommended to maximize sesame yield cultivated under field conditions, while irrigation intervals (7, 14 and 21 days) had no significant effect on the seed yield. Results of Fang et al. (2023) showed that drought stress reduced leaf relative water content, stomatal conductance, transpiration rate, photosynthetic rate, and actual quantum yield of PSII, thereby resulting in a decreased yield in contrast with well-watered sesame plants.

Under deficit irrigation, strategies like the application of super absorbent polymers (SAP) are useful for nutrients and moisture maintenance in top soil to create a nutritious water reservoir around the rhizosphere. These hydrophilic polymers expand several times of their original dimensions when exposed to water. This will prevent the plant from quickly reaching the wilting point (Ji *et al.*, 2022). Results obtained from research conducted on cumin (*Cuminum cyminum* L.) revealed that SAP application (30 kg ha^{-1}) under deficit irrigation increased the seed and essential oil yields by 2.79 and 3.05 times, respectively (Samadzadeh *et al.*, 2016). Satriani et al. (2018) also found that the water use efficiency of bean (*Phaseolus vulgaris* L.) increased significantly with SAP under water deficit conditions. In a similar study on winter wheat (*Triticum aestivum* L.), it was concluded that SAP application promoted macro soil aggregates formation, soil bacterial abundance, soil water content as well as soil hygroscopic moisture, and finally improved the seed yield (Li *et al.*, 2014).

Besides SAP, zeolites also due to their water-holding ability are useful materials under deficit irrigation conditions (GhassemiSahebi *et al.*, 2020; Sun *et al.*, 2023). Zeolites are a large family of minerals and are among the most important microporosis material. In nature, when volcanic ash interacts with the high-pH water and high-salt content, zeolites are normally formed, causing a rapid crystal formation. Zeolites help the farmer cope with several problems, such as soil or water pollution, heavy metals contamination, loss of nutrients, and loss of water-use efficiency of dryland (Cataldo *et al.*, 2021). These materials, by selective absorption and controlled release of cations, can enhance the nutrient availability for the plants (Bahador and Tadayon, 2020). In a study on sunflower (*Helianthus annuus* L.) seed yield and protein content significantly improved, but nutrient leaching especially phosphorus decreased by the application of manure plus zeolite (Gholamhoseini *et al.*, 2013). Bahador and Bahador and Tadayon (2020) also observed that dry matter and oil yield of hemp (*Cannabis sativa* L.) increased through the regulation of antioxidant activities under mild water stress when 10 t ha^{-1} zeolite was used. Similarly, Zheng et al. (2018) found that the application of 15 t ha^{-1} zeolite in rice fields, reduced water usage and increased grain yield and quality. Dastbaz et al. (2023) also in research on corn (*Zea mays* L.) found that the effect of zeolite type and amount was significant on the yield. In a similar study, Alizadeh Forutan et al. (2022) found that zeolite had a positive effect on improving the growth and yield of corn.

This study aimed to investigate the possibility of sesame production with lower water consumption in dry areas. For this aim, the effect of SAP and zeolite application was investigated on the growth, yield and quality of obtained seeds under normal and deficit irrigation regimes.

2. Materials and methods

2.1. Experimental site

This research was conducted during two successive growing seasons (2018 and 2019) in the research field of the University of Birjand (32 °N and 59 °E, with 1491 masl), Iran. This region is characterized by a dry climate with ~130 mm annual long-term precipitation and 17°C annual mean air temperature. The main climatic parameters of the studied area during the research period are shown in Table 1. In addition, soil and water properties in the experimental site are presented in Table 2.

Table 1. Weather parameters of studied aria during the experimental period.

Month	Mean air temperature (°C)		Minimum air temperature (°C)		Maximum air temperature (°C)		Precipitation (mm)		Humidity (%)	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
April	20.08	23.91	12.44	10.57	27.70	29.2	15.5	22.01	34	40.01
May	26.39	29.57	17.80	13.52	34.98	32.9	0	19.04	17.30	28.91
June	28.42	34.31	20.89	16.83	35.97	39.9	0	0	13.46	17.05
July	27.23	38.09	19.10	21.99	35.37	40.6	0	0	18.72	13.90
August	22.68	34.81	12.74	17.06	32.60	43	0	0	14.30	13.8
September	16.74	34.95	7.52	14.77	25.97	37.5	1.6	0	25.33	13.82
October	13.20	26.87	6.24	8.21	20.17	33.10	23	3.24	45.97	27.10

Table 2. Some physical and chemical properties of soil and water used in the experiment.

Soil									
Soil texture	Bulk density (g. cm^{-3})	OM (%)	K	Na	Mg	Ca	SAR	EC (dS.m^{-1})	pH
			meq. l^{-1}						
Clay loam	1.37	0.34	2.11	10	4.2	6	4.85	6.8	7.6
Irrigation water									
Cl^-	HCO_3^-	SO_4^{2-}	K^+	Na^+	Mg^{2+}	Ca^{2+}	SAR	EC (dS.m^{-1})	pH
meq. l^{-1}									
8.5	4.8	6.7	0.05	13.2	2.6	3.4	7.2	1.3	7.5

2.2. Experimental treatments and design

The experiment was conducted as factorial based on a randomized complete block design (RCBD) with three replications. Experimental factors were water availability (WA: including 50 and 100% of sesame water requirement) and application of water preservative materials (WPM) [Control (no-WPM), 125 kg ha^{-1} super absorbent polymer (SAP), 6200 kg ha^{-1} Zeolite (Z1), 11200 kg ha^{-1} Zeolite (Z2), SAP+Z1 and SAP+Z2]. The levels of WAP were selected based on the results of several previous experiments, which are provided by Khashei Siuki and Ahmadi (2015). In this experiment, providing 100 and 50% of sesame water requirements were considered as full (normal) and deficit irrigation regimes, respectively. The properties of used zeolite and SAP (produced by ©Bolour-Ab Company, Iran) are presented in Table 3 and Table 4, respectively.

Table 3. Properties of zeolite used in the experiment (*Ahmadee et al.*, 2014).

P_2O_5	MgO	K_2O	Na_2O	CaO	SiO_2	Al_2O_3	Fe_2O_3
%							
0.013	0.62	3.68	3	2.21	70.95	7.88	1.31
Cr	Zn	Cu	Sr	Ba	So3	Cl	L.O.I
Ppm							
7	12	54	399	1154	1.34	3504	8.13

Table 4. Properties of nano-composite super-absorbent used in the experiment.

Type	Appearance	Humidity content (%)	Smell and toxicity	Density (g cm^3)	pH of Aqueous solution
Synthetic	Brown powder	<5	No	0.8	6-7
Particle size (µm)	Maximum durability in soil (year)	PAC* for distilled water (g g^{-1})	PAC for NaCl solution with concentration of 1000 ppm	PAC in soil under 2200 pa pressure	Time to reach 60% of maximum absorption (min)
200-400	5-7	500	260	190	15-20

PAC= Practical absorption capacity

2.3. Agronomic practices

Experimental plots (each 6 m^2 area: 3×2 m) were created manually after soil preparation (including plowing, disk and leveling). The distance between plots in each replicate was 0.5 m, while 2.5 m was considered as the distance between blocks. In each plot, there were 8 planting rows, in which the sesame seeds (Birjand landrace) were manually sown at a depth of 2 cm, in 10th June of both studied years. Zeolite was mixed evenly with the soil of each related plot up to the depth of 30 cm, before seed sowing, while SAP was used below the planting rows at the depth of 15 cm. Hand weeding was done one time, a month after plant emergence. There was no fertilization and chemical controlling of pests and diseases during the plant growth.

Sesame water requirement was determined according to the results of Fallah Ghalhari et al. (2016), who estimated its water requirement using the CROPWAT model. Based on that data, 20 times irrigation with weekly intervals was used during the growing season. The total volume of consumed water during all irrigation times was 2300 and 4600 m^3 ha^{-1}, providing 50 and 100% of the sesame water requirement, respectively. A pump and volume meter (contour with an accuracy of 0.0001 m^3) were used for precise controlling of the amount of water consumed per plot. In this study, the amount of water storage in the root zone was first calculated using Eq. 1. Then, the sesame water requirement was calculated using Eq. 2, and the amount of irrigation water during constant irrigation intervals of 7 days was calculated and delivered to plots by volumetric contour.

$$I = (\theta fc - \theta pwp)MAD \times Drz \quad (1)$$

$$ET_c = ET_o \times K_c \quad (2)$$

In above equations: $\theta fc - \theta pwp$= total useable water in soil; MAD= moisture loss coefficient or moisture allowable discharge and Drz= root depth

2.4. Measured parameters

During both growing seasons, after deleting the margin effect (two side planting rows and 25 cm from the beginning and the end of each plot), the remained area was divided into two parts, one part for measurement of vegetative parameters and yield components and the other part for determination of biological and seed yields. Sesame harvesting was done around mid-October, 4 months after seed planting. Vegetative indices were plant height and dry weight (aerial parts), leaf weight and leaf area index (LAI: area of leaves per one m^2 of land) and number of lateral branches per plant. The study of root growth indices in this study could bring useful data for the interpretation of the results. However, due to the difficulty of root measurement in the soil bed under field conditions, conducting similar research in a controlled environment to study the root indices can be useful. In addition, the number of capsules per plant, seed number per capsule and 1000-seed weight were yield component parameters, which were measured only at the end of the second growing season. SPAD (chlorophyll index) also was determined using SPAD meter model 502 plus Konica, in the flowering stage of the second year. After measuring the yields of the plant, harvest index (HI) and water use efficiency (WUE) were determined using Eq. 3 and 4.

$$\mathrm{HI} = \frac{\text{Seed yield}}{\text{Biological yield}} \times 100 \quad (3)$$

$$\mathrm{WUE} = \frac{\text{Seed yield (kg.ha}^{-1}\text{)}}{\text{Consumed water (m}^{-3}\text{.ha}^{-1}\text{)}} \quad (4)$$

The oil percentage of the obtained seed from each plot was determined using a soxhlet extractor (Soxtec 2050 model, Switzerland). Moreover, to determine the protein percentage of seeds the Kjeldahl method was used (Kjeltec 8100, Foss Company, Denmark). Finally, for calculation of oil and protein yields the equations of 5 and 6 were used.

Oil yield= seed yield ×oil percentage (5)

Protein yield= seed yield ×protein percentage (6)

2.5. Data analysis

Data obtained from each growing season were separately analyzed as factorial based on an RCBD design using SAS 9.1. Means were compared by the FLSD test at a 5% level of probability.

3. Results and discussion

3.1. Vegetative growth

The interaction effect of irrigation management and application of different water preservative materials (WPM) was significant on almost all vegetative growth parameters of sesame (Table 5). In both levels of water availability, the highest values of plant height, number of lateral branches, plant dry weight, leaf weight and leaf area index were obtained with SAP+ Z2, while their lowest amounts were gained in control (no-WPM) treatment. Among all 12 combined treatments, the highest values of all vegetative parameters were obtained in SAP+ Z2 under a normal irrigation regime (Table 6). On average, water deficit reduced the values of plant height, plant weight, leaf weight and the number of lateral branches by 22, 108, 77 and 46%, respectively; while SAP+Z2 improved them by 32, 130, 101 and 54%, respectively, compared with the control treatment. It has been reported that in drought stress conditions, more photosynthetic materials allocate to the root system of sesame to be developed for more water absorption (Askari *et al.*, 2019), which probably makes lower allocation of photo-assimilate for the growth of aerial organs. In support of this theory, Ghasemi Hamedani et al. (2020) observed that root to shoot ratio of sesame increased in response to deficit irrigation. They stated that it is a survival strategy for sesame under limited water conditions. In a similar study on sesame, it was concluded that disruption in growth parameters under low soil water content is due to a decrease in chlorophyll pigments and florescence, stomata conductivity and photosynthetic rate (Pourghasemian *et al.*, 2020).

Table 5. Mean squares for the effect of irrigation management and application of water preservative materials on growth, yield and quality of sesame.

S.O.V	df	Plant Height	Number of lateral branches per plant	Plant dry weight	Leaf dry weight	Leaf are index		SPAD	Number of capsules per plant	Number of seeds per capsule	1000-grain weight	Water use efficiency
		2019	2019	2019	2019	2018	2019	2019	2019	2019	2019	2019
Replication	2	3.62^{ns}	0.027^{ns}	123.8^{ns}	2.33^{ns}	25.7^{**}	0.05^{ns}	0.75^{ns}	0.77^{ns}	0.52^{ns}	0.0003^{ns}	0.0014^{ns}
IM*	1	1297.3^{**}	20.25^{**}	25974.6^{**}	1248.4^{**}	5445^{**}	33.11^{**}	555.78^{**}	1586^{**}	4400.1^{**}	7.047^{**}	0.0003^{ns}
WPM	5	231.0^{**}	2.29^{**}	3159.8^{**}	188.6^{**}	4.56^{**}	4.58^{**}	57.59^{**}	153.8^{**}	85.5^{**}	0.43^{**}	0.0133^{**}
IM* WPM	5	105.8^{**}	0.25^{*}	1111.4^{**}	71.24^{**}	0.000^{ns}	1.79^{**}	5.82^{**}	26.6^{**}	1.17^{ns}	0.033^{**}	0.0049^{**}
Error	22	6.72	0.088	244.9	4.24	0.0033	0.11	0.71	1.11	1.07	0.0025	0.0010
C.V (%)	-	4.29	7.48	20.14	9.80	2.30	10.13	3.29	4.16	2.22	1.90	17.89

S.O.V	df	Biological yield		Seed yield		Harvest index	Oil percentage	Protein percentage	Oil yield		Protein Yield	
		2019	2018	2018	2019	2019	2019	2019	2018	2019	2018	2019
Replication	2	1623^{ns}	58800^{**}	14241^{ns}	22610^{ns}	9.2^{ns}	0.077^{ns}	0.15^{ns}	6340^{ns}	7046^{ns}	330^{ns}	820^{ns}
IM	1	12900481^{**}	23328900^{**}	1145613^{**}	1428786^{**}	227.2^{**}	961.29^{**}	14.49^{**}	412017^{**}	611166^{**}	40592^{**}	35750^{**}
WPM	5	849816^{**}	102900^{**}	169304^{**}	224493^{**}	51.0^{**}	46.18^{**}	2.55^{**}	68129^{**}	86970^{**}	6096^{**}	6249^{**}
IM* WPM	5	49436^{**}	2101^{**}	100926^{**}	136172^{**}	41.0^{**}	0.72^{ns}	0.57^{*}	38718^{**}	50280^{**}	3412^{**}	3667^{**}
Error	22	9841	109.09	14542	22620	7.0	0.53	0.19	6527	8113	364.3	854.6
C.V (%)	-	2.51	0.34	21.59	24.06	17.43	1.54	3.32	28.62	28.92	22.69	34.04

ns, ** and *: no-significant and significant at 1 and 5% probability levels, respectively.

*IM=Irrigation management; WPM= water preservative materials

Leaf area index as the main parameter that shows the photosynthetic potential of the plant, decreased by 80 and 83% under deficit irrigation during the first and the second growing seasons, respectively; while again SAP+Z2 increased it by 5.5 (first growing season) and 94% (second growing season) compared with no-WPM application (Table 6). Similar results were obtained by Zheng et al. (2018) on rice. The decline in sesame leaf area, under water deficit is due to loss in turgor pressure and commonly results in the decline of cell expansion (Pourghasemian *et al.*, 2020). Overall, all vegetative growth indices of sesame were improved by more water availability and application of WPM. However, the effect of both levels of zeolite was more than SAP, as well as combined application of zeolite and SAP was more effective than their single utilization in improving plant vegetative growth (Table 6). In similar studies, the positive effects of zeolite and SAP on the vegetative growth of corn and sorghum (Najafinezhad *et al.*, 2015), cotton (Fallahi *et al.*, 2015) and cumin (Samadzadeh *et al.*, 2016) were reported earlier. The beneficial effect of zeolite and SAP on plant growth is related to the ability of selective absorption, water and nutrients availability enhancement, controlled release of cations and improvement of soil physical properties (Samadzadeh *et al.*, 2016; Bahador and Tadayon, 2020).

Table 6. Interaction effects of water availability level and application of water preservative materials on vegetative growth of sesame.

water availability	WPM	Plant Height (cm)	Number of lateral branches per plant	Plant dry weight (g)	Leaf dry weight (g plant^{-1})	Leaf area index		SPAD index
		2019	2019	2019	2019	2018	2019	2019
50% of sesame water requirement	Control*	50.2^{h}	2.34^{e}	34.0^{g}	11.0^{i}	1.73^{f}	1.85^{h}	16.35^{i}
	SAP	53.3^{gh}	3.01^{d}	45.0^{fg}	13.6^{hi}	1.75^{ef}	2.06^{h}	19.16^{h}
	Z1	53.9^{gh}	3.00^{d}	48.3^{fg}	15.0^{gh}	1.78^{ef}	2.21^{gh}	21.16^{g}
	Z2	55.1^{fg}	3.00^{d}	53.3^{fg}	15.5^{gh}	1.81^{def}	2.31^{fgh}	23.61^{f}
	SAP+ Z1	56.5^{efg}	4.02^{c}	60.4^{efg}	17.0^{fgh}	1.84^{de}	2.69^{efg}	24.61^{ef}
	SAP+ Z2	57.4^{d-g}	4.00^{c}	64.0^{ef}	18.3^{efg}	1.86^{d}	2.80^{ef}	25.46^{d}
100% of sesame water requirement	Control	58.7^{def}	4.00^{c}	68.3^{def}	19.7^{def}	3.15^{c}	3.10^{de}	26.60^{cd}
	SAP	59.9^{cde}	4.00^{c}	81.0^{cde}	20.7^{de}	3.18^{bc}	3.26^{de}	27.51^{c}
	Z1	61.0^{cd}	4.70^{b}	94.5^{bcd}	22.6^{cd}	3.20^{abc}	3.57^{cd}	29.01^{b}
	Z2	63.4^{c}	5.00^{b}	100.6^{bc}	24.3^{c}	3.23^{abc}	3.83^{c}	29.05^{b}
	SAP+ Z1	69.4^{b}	5.00^{b}	111.0^{b}	30.6^{b}	3.26^{ab}	4.83^{b}	30.31^{b}
	SAP+ Z2	85.9^{a}	5.67^{a}	171.5^{a}	43.4^{a}	3.28^{a}	6.83^{a}	35.03^{a}
LSD		4.39	0.50	26.50	3.48	0.09	0.56	1.43

In each column means with at least one similar letter had no significant difference based on the FLSD test.
*WPM= water preservative materials, Control (no-WPM), SAP=125 kg ha^{-1} super absorbent polymer, Z1= 6200 kg ha^{-1} Zeolite, Z2=11200 kg ha^{-1} Zeolite.

3.2. Yield components

Simple effects of the irrigation regime and WPM application were significant on all three yield components of sesame, while their interaction effect was significant on the number of capsules per plant and 1000-grain weight (Table 5). Seed number per capsule for control, SAP, Z1, Z2, SAP+Z1 and SAP+Z2 were 19.5, 21.5, 23.1, 25.0, 30.1 and 32.5, respectively. In addition, the number of seeds per capsule for normal and deficit irrigation was 57 and 35, respectively, which shows a 63% reduction with low water availability. Ebrahimian et al. (2019) reported that although sesame is relatively tolerant to drought stress, water limitation over 60-80% of its potential evapotranspiration reduces its yield components. However, they stated that there is a high genetic variation among the genotypes of sesame, which makes it possible to identify drought-tolerant genotypes to be used in deficit irrigation programs. It has been reported that the sensitivity of sesame to drought stress increases during flowering and seed-filling stages (Ucan and Killi, 2010). Therefore, if instead of uniform irrigation of the plant during the whole growing season, we applied extra irrigation at the late stages of growth, the yield components would probably be less reduced.

Application of all WPMs increased significantly the number of capsules per plant under both irrigation regimes, compared with the control treatment (no-WPM). The best treatment of WPM was SAP+Z2, which improved this parameter by 68 and 66%, under deficit and normal irrigation, respectively (Table 7). 1000-grain weight also was higher with WPM application and normal irrigation regime. The highest and the lowest values of this index were observed at SAP+Z2 under normal irrigation and no- WPM (control) under deficit irrigation managements, respectively, with about 92% difference. The increasing effect of WPMs on 1000-grain weight under deficit irrigation was more than their effects under normal irrigation. For example, SAP+Z2 increased this index up to 18 and 52% compared with no-WPM, when normal and deficit irrigations were applied, respectively (Table 7). Overall, it was concluded that WPMs had an improving role for sesame yield components particularly when deficit irrigation was applied. Najafinezhad et al. (2015) stated that zeolite can absorb water up to around 60% of its weight and accordingly it is an appropriate material for improving the reproductive traits of plants under deficit irrigation. In addition, trapped nutrient in zeolite pores provides proper plant nutrition and thus improves its growth and development (Bahador and Tadayon, 2020). SAP application also leads to an increase in leaf area index and leaf area duration, which are essential for more photo-assimilate production to be stored in seeds (Salavati *et al.*, 2018).

Table 7. Interaction effects of water availability level and application of water preservative materials on yield components of sesame.

water availability	WPM	Number of capsules per plant	Number of seeds per capsule	1000-grain weight (g)
50% of sesame water requirement (deficit irrigation)	Control*	13.70^{i}	31.33^{i}	1.727^{k}
	SAP	16.33^{h}	32.66^{i}	1.928^{j}
	Z1	18.00^{h}	34.66^{h}	2.224^{i}
	Z2	20.00^{g}	36.33^{gh}	2.353^{h}
	SAP+ Z1	21.00^{g}	38.00^{g}	2.494^{g}
	SAP+ Z2	23.00^{f}	40.33^{f}	2.627^{f}
100% of sesame water requirement (normal irrigation)	Control	25.33^{e}	52.33^{e}	2.795^{e}
	SAP	26.66^{de}	54.33^{d}	2.942^{d}
	Z1	28.33^{cd}	56.66^{c}	3.164^{c}
	Z2	30.00^{c}	58.33^{c}	3.192^{bc}
	SAP+ Z1	39.33^{b}	60.33^{b}	3.258^{ab}
	SAP+ Z2	42.00^{a}	64.00^{a}	3.308^{a}
LSD		1.78	1.75	0.086

In each column means with at least one similar letter had no significant difference based on the FLSD test.
*WPM= water preservative materials, Control (no-WPM), SAP=125 kg ha^{-1} super absorbent polymer, Z1= 6200 kg ha^{-1} Zeolite, Z2=11200 kg ha^{-1} Zeolite.

3.3. Plant yield and water use efficiency

Interaction effects of WPM application and irrigation management were significant on sesame yield, harvest index and water use efficiency during both growing seasons (Table 5). Means comparison results revealed that the biological yield of sesame was higher under normal irrigation and WPM application. Although WPM improved biological yield under both levels of irrigation, its positive effect was some higher when deficit irrigation was applied (Table 8). Reduction in biological yield under low water availability is due to a reduction in cell division and elongation as well as the reduction in translocation of photoassimilates (Sehgal *et al.*, 2018). However, zeolite is able to absorb and retain water and nutrients in its small pores for long periods and therefore improves the biological yield of plants, especially under drought stress conditions (Hazrati *et al.*, 2022). Applying of SAP also improves soil water-holding capacity, consequently reducing the adverse effects of drought stress on plant growth and yield (Malik *et al.*, 2022).

More water availability and single or combined application of both WPM types improved seed yield, during both successive growing seasons. On average, the seed yield of sesame was 736 and 380 kg ha^{-1}, at the end of the first growing season and 824 and 425 kg ha^{-1} at the end of the second one, when 100 and 50% of plant water requirement was provided, respectively (Table 8). Due to the thermophilicity of sesame, the relative increase in seed yield in the second study year is probably related to warmer ambient air in this season (Table 1). An increase in seed yield arises from the improving yield component (capsule per plant, seed per capsule and grain weight) in plants treated with a normal irrigation regime. These results are similar to those reported by Askari et al. (2019). Ebrahimian et al. (2019) also reported that yield reduction in sesame under drought stress is mainly due to a reduction in seed number in capsule and seed weight. The same authors also stated that reduction in chlorophyll content and photosynthesis is the main reason for yield reduction under deficit irrigation. Fang et al. (2023) also found that yield reduction of sesame under drought stress is due to a reduction in leaf relative water content, stomatal conductance, transpiration rate, and photosynthetic rate.

Among all WPMs, SAP+Z2 was the best treatment for increasing the seed yield, so it increased this index by 151 (first year) and 158% (second year) in comparison with the control (no-WPM) under full irrigation, and by 41 (first year) and 37% (second year) under deficit irrigation regime (Table 8). The beneficial effect of WPMs on seed yield arises mainly from providing proper soil moisture conditions for plants. As Li et al. (2019) showed that SAP utilization improved the water absorption and water retention property of the soil. The reducing effect of drought stress on biological yield was lower than seed yield, where the differences of seed yield between two irrigation management for both growing seasons was ~ 94%, while for biological yield was 73 (first growing season) and 35% (second growing season). Similarly, Askari et al. (2019)

reported that drought stress exerted more negative effects on reproductive organs than vegetative ones.

The harvest index significantly increased by combined consumption of WPM (SAP+Z1 and SAP+Z2) under high water availability, while there was no significant difference between other treatments (Table 8). In good agreement with these results, Askari et al. (2019) also reported that the harvest index of sesame was 29 and 24%, when 100 and 50% of plant water requirements were provided, respectively. They stated that both more leaf area expansion (source) and stronger sinks (seeds) under a normal irrigation regime, lead to optimal usage of solar radiation, which finally increases the harvest index. Bahador and Tadayon (2020) also found that zeolite adjusts the conditions of moisture shortage, then more nutrients can be used for seed production to improve the harvest index.

Water use efficiency was higher under deficit irrigation than the corresponding treatments in the full irrigation regime. There was only one exception, where providing 100% of sesame water requirement combined with SAP+Z2 (as the best among all 12 treatments) resulted in more water use efficiency than its corresponding treatment when 50% of plant water requirement was provided (Table 8). The positive effects of zeolite (Hazrati *et al.*, 2022) and SAP (Malik *et al.*, 2022) on improving water use efficiency have been previously reported on other plants. This is due to the fact that WPMs application into the soil leads to a considerable increase in water retention capacity (Ai *et al.*, 2021). On average, water use efficiency for full and deficit irrigation regimes was almost equal and calculated as ~0.18 kg m^{-3} (Table 8). In the study of Askari et al. (2019), it was concluded that severe and mild water stress management enhanced the water uses efficiency of sesame by 18 and 13.5%, respectively, compared to optimum irrigation. Considering the values of water use efficiency in the present study, which were not increased significantly by deficit irrigation, it seems that providing of 50% plant water requirement is not suitable for the studied region, and probably better results will gain if sesame irrigates with about 75% of its water requirement. In support of this hypothesis, Ebrahimian et al. (2019), found that mild water stress availability (80 and 60% of potential evapotranspiration) did not affect severely sesame (4.5 and 13.5% reduction in yield), but severe drought stress (40% of potential evapotranspiration) significantly reduced its seed yield by 29%.

It was also found that seed and biological yields of sesame during both growing seasons had a similar trend in response to water availability and WPM (Table 7). However, the yields were higher during the second growing season compared with the first year, which may be related to climatic factors such as more precipitation and humidity changes (Table 1).

Table 8. Interaction effects of water availability level and application of water preservative materials on the yield and water use efficiency of sesame.

water availability	WPM	Biological yield (kg ha^{-1})		Seed yield (kg ha^{-1})		Harvest index (%)	Water use efficiency (kg seed per m^3 water)**
		2018	2019	2018	2019	2019	2019
50% of sesame water requirement (deficit irrigation)	Control*	2040^{l}	2709^{i}	309.0^{g}	348.1^{f}	12.87^{c}	0.151^{def}
	SAP	2100^{k}	3182^{h}	345.3^{fg}	385.6^{ef}	12.11^{c}	0.167^{b-f}
	Z1	2160^{j}	3377^{g}	375.0^{efg}	418.4^{def}	12.39^{c}	0.181^{b-e}
	Z2	2220^{i}	3487^{fg}	383.3^{d-g}	432.3^{def}	12.39^{c}	0.187^{b-e}
	SAP+ Z1	2280^{h}	3612^{ef}	432.3^{d-g}	481.4^{c-f}	13.32^{c}	0.209^{bc}
	SAP+ Z2	2340^{g}	3709^{e}	434.7^{d-g}	478.8^{c-f}	13.15^{c}	0.212^{b}
100% of sesame water requirement (normal irrigation)	Control	3600^{f}	4061^{d}	519.0^{c-f}	574.0^{c-f}	14.13^{c}	0.124^{f}
	SAP	3680^{e}	4212^{d}	557.0^{cde}	620.3^{cde}	14.72^{bc}	0.134^{ef}
	Z1	3760^{d}	4416^{c}	585.6^{cd}	648.1^{cd}	14.67^{bc}	0.140^{ef}
	Z2	3840^{c}	4561^{c}	644.3^{bc}	712.9^{bc}	15.62^{bc}	0.154^{c-f}
	SAP+ Z1	3920^{b}	4833^{b}	811.0^{b}	907.4^{b}	18.75^{b}	0.197^{bcd}
	SAP+ Z2	4000^{a}	5175^{a}	1304.0^{a}	1481.4^{a}	28.48^{a}	0.322^{a}
LSD		17.68	167.98	204.2	254.68	2.07	0.055

In each column, means with at least one similar letter had no significant difference based on FLSD test.

*WPM= water preservative materials, Control (no-WPM), SAP=125 kg ha^{-1} super absorbent polymer, Z1= 6200 kg ha^{-1} Zeolite, Z2=11200 kg ha^{-1} Zeolite.

**The denominator in the equation of water use efficiency (Eq. 4) is a measure of consumed water, which is stable for each irrigation treatment. Therefore, the variability in water use efficiency is due to the variability in seed yield (the numerator) between experimental treatments.

3.4. Seed quality

Analysis of variance revealed that single effects of irrigation management and WPM application were significant on seed oil percentage, while their interaction effects were significant on protein percentage and oil and protein yields during both studied years (Table 5). Oil percentages for full and deficit irrigations were 52.6 and 42.3% and for control, SAP, Z1, Z2, SAP+Z1 and SAP+Z2 were 43.9, 45.2, 46.6, 47.8, 49.6 and 51.3%, respectively. These findings are in parallel to the observations of Bahador and Tadayon (2020) on hemp, who reported that zeolite increased oil percentage and yield under water deficit and helped plants to tolerate drought stress. According to the results obtained by Elferjani et al. (2018) on canola, the decrease in oil content to water deficit was most probably due to reduced photosynthesis and poor remobilization of photoassimilates.

At both levels of water availability, SAP+Z2 was the best treatment of WPMs, in terms of seed protein percentage. In addition, full irrigation improved the seed protein content under all treatments of WPM (Table 9). Oil yield as the main qualitative parameter in sesame seeds improved significantly by more water availability and application of WPM. The oil yield of sesame is connected with seed yield and oil content of produced seeds, and we observed that normal irrigation improved both of these parameters (Tables 8 and 9). In a study on sesame mild water stress (providing 80% of potential evapotranspiration) had no significant reducing effect on seed yield, but slightly improved oil percentage and therefore oil yield for normal and mild stress was finally 583 and 573 kg ha^{-1}, respectively (Ebrahimian *et al.*, 2019). The same authors stated that under mild drought stress, sesame probably induces a specific defense mechanism by fatty acid production for osmotic regulation. Mushtaq et al. (2020) said that sesame as a drought-tolerant plant, is usually cultivated in regions with annual precipitation of 625-1100 mm. In the present study, there was no rainfall during the sesame growing season (Table 1) and besides that the amount of consumed water through irrigation was 230 and 460 mm (2300 and 4600 m^3 ha^{-1}), under full and normal irrigation regimes, respectively. Therefore, it can be concluded that the oil yield obtained in our study is very acceptable.

In addition, higher oil yield was obtained by the combined application of SAP and zeolite in comparison with their single consumption. The highest and the lowest values of oil yields were obtained from full irrigation with SAP+Z2 and deficit irrigation with no-WPM, respectively. So, the differences between these treatments were 498 and 520% for the first and the second growing seasons, respectively (Table 9). Similar results were obtained about the protein yield, where during both studied years SAP+Z2 was the best WPM, particularly with providing 100% of sesame water requirement, while no-WPM was the worst treatment, especially under deficit irrigation (Table 9). Gholamhoseini et al. (2013) also in a study concluded that the oil content of sunflower increased by natural zeolite application, more likely due to trapping and exchanging valuable nutrients which reduces nutrient leaching.

Table 9. Interaction effects of water availability level and application of water preservative materials on seed quality of sesame.

water availability	WPM*	Oil percentage	Protein percentage	Oil yield (kg ha^{-1})		Protein yield (kg ha^{-1})	
		2019	2019	2018	2019	2018	2019
50% of sesame water requirement (deficit irrigation)	Control	39.10^{j}	11.20^{f}	125.2^{f}	136.1^{f}	36.76^{g}	39.0^{d}
	SAP	40.52^{i}	12.20^{e}	144.2^{ef}	156.2^{f}	42.64^{fg}	47.0^{d}
	Z1	41.54^{hi}	12.83^{de}	175.8^{def}	173.8^{ef}	49.01^{fg}	53.7^{cd}
	Z2	42.31^{h}	13.15^{cd}	183.3^{def}	182.9^{ef}	52.16^{efg}	56.8^{cd}
	SAP+ Z1	44.14^{g}	13.28^{cd}	209.2$^{c\text{-}f}$	212.4^{def}	60.57$^{d\text{-}g}$	63.9^{cd}
	SAP+ Z2	46.06^{f}	13.42^{bcd}	213.8$^{c\text{-}f}$	224.7^{def}	61.94$^{d\text{-}g}$	65.5^{cd}
100% of sesame water requirement (normal irrigation)	Control	48.72^{e}	13.51^{bcd}	257.1$^{c\text{-}f}$	280.1$^{c\text{-}f}$	74.56$^{c\text{-}f}$	77.6^{cd}
	SAP	49.95^{e}	13.55^{bcd}	278.6^{cde}	309.9^{cde}	81.98^{cde}	84.1^{bcd}
	Z1	51.79^{d}	13.62^{bc}	297.1^{bcd}	335.7^{cd}	90.95^{cd}	88.2^{bcd}
	Z2	53.38^{c}	13.84^{bc}	331.6^{bc}	380.6^{bc}	103.69^{bc}	98.7^{bc}
	SAP+ Z1	55.13^{b}	14.16^{b}	421.8^{b}	500.2^{b}	131.71^{b}	128.5^{b}
	SAP+ Z2	56.71^{a}	15.01^{a}	748.9^{a}	843.3^{a}	223.13^{a}	226.9^{a}
LSD		1.24	0.74	136.8	152.5	32.32	49.50

In each column, means with at least one similar letter had no significant difference based on FLSD test.

*WPM= water preservative materials, Control (no-WPM), SAP=125 kg ha^{-1} super absorbent polymer, Z1= 6200 kg ha^{-1} Zeolite, Z2=11200 kg ha^{-1} Zeolite.

4. Conclusion

Results of two successive studies on sesame revealed that reducing water availability in sesame cultivation although reduced significantly seed and oil yields, except in the case of SAP+Z2, water use efficiency increased when 50% of water requirement was provided (0.178 and 0.184 kg seed per m^3 water, in 100 and 50% water availability levels, respectively). Overall, providing of 50% water requirement caused severe drought stress on sesame. The seed yield in 100 and 50% water availability levels was 736.8 and 380.0 kg. ha^{-1} in the first growing season, and 824.0 and 424.1 kg. ha^{-1} in the second growing season, respectively. This experiment also showed that particularly combined application of water preservative materials (super absorbent polymer and zeolite) considerably improved vegetative growth, yield components, seed yield (924 kg. ha^{-1} in SAP+ Z2 compared with 438 kg. ha^{-1} in control) as well as seed oil and protein contents of sesame. Due to the water crisis in many parts of dry regions of the world and considering the positive effects of these substances over many years, it seems that their application is an appropriate strategy for crop production in those areas.

Abbreviation

WPM: water-preservative materials, SAP: super absorbent polymer

Conflict of Interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No human or animals were used in the present research.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed Consent

The authors declare not to use any patients in this research.

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