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ORIGINAL PAPER

Nutritional Management Improved Sesame Performance and Soil Properties: a Function-Based Study on Sesame as Affected by Deficit Irrigation, Water Superabsorbent, and Salicylic Acid

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Abstract

To assess and investigate the effects of application of superabsorbent polymer (SAP) and salicylic acid (SA) on performance of drought-affected sesame (*Sesamum indicum* L.), soil characteristics, and water productivity of irrigation (WPi). A randomized complete block design with split-strip plot arrangement and three replications in two successive cropping years was arranged. Two levels of irrigation consisting of supplying 50% and 100% of the sesame water requirement (deficit irrigation, DI and full irrigation, FI, respectively) were allocated to the main plots, and application of SAP (80 kg ha^{-1}) was allocated to the subplots. Foliar application of SA (1 mM) and control was allocated to the strip plots. The results showed that the highest seed yield (SY) was obtained from DI, along with SAP and SA application. Under drought stress (DI), separate and simultaneous applications of SAP and SA increased WPi by 42% (SAP), 36% (SA), and 43% (SAP + SA), respectively, compared with control. The highest WPi was achieved through DI plus SAP application, which was 60% more than combination treatment of FI plus no-application of SAP. The results of principal component analysis (PCA) indicated that SY, seed weight per plant (SW), crop growth rate (CGR), and WPi were the effective variables of the first principal component (PC) and explained 67% of the total variance of the data. The nutritional management was effective in reducing drought stresses; moreover, the highest SY and biological yield (BY), CGR, the total amount of soil nitrogen (Soil N), and WPi were obtained in the simultaneous application of SAP and SA.

Keywords Agronomical management · Growth analysis · Drought stress · Principal component analysis · Ecological inputs

1 Introduction

Drought stress greatly affects function (Liu et al. 2010), structure (Zak et al. 2003), and production (Lal et al. 2013) of the agricultural ecosystems and poses a major threat to food security around the world (Kheir et al. 2021; Ding et al. 2021; Ali et al. 2020). In addition, drought stress leads to a number of social and economic negative consequences through reduced agricultural production and, consequently, reduces farm income (Deng et al. 2006). It is reported that to feed the projected population of 9 billion by 2050, more foods need to be produced, despite declining natural resources, harsh conditions, global warming and climate change, fragile environment, and abiotic stress including drought in particular; this seems a serious challenge faced to human beings, particularly considering the fact that today not only the amount of food produced is important, but also the sustainability of production and food security must be considered (Ding et al. 2021; Kheir et al. 2021; Ali

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et al. 2020; Hussain et al. 2018). Some researchers have suggested that through cross-talk between plant responses to these stresses, and discussing the potential management strategies, could regulate the mechanisms of plant tolerance to drought and/or chilling stresses (Hussain et al. 2018). Insufficient access to water in arid and semi-arid areas has raised water use efficiency (WUE) as one of the main challenges of sustainable agriculture in these areas. Hsiao et al. (2007) reported various causes that contribute to low WUE in agriculture which originates from environmental, biological, managerial, social, economic, and technological conditions. Oxidative damage as a consequence of severe drought stress in sesame has been fully described (Fazeli et al. 2007). It was reported that the increase in irrigation interval reduced sesame yield, also it was confirmed that applying five irrigations to sesame could save up to 1027 m^3 ha^{-1} with yield losses less than 2% (Tantawy et al. 2007). Increasing WUE in agriculture is the key to water scarcity and environmental problem reduction (Howell 2000). So far, many efforts have been made to reduce water consumption by crops, in other words, to produce more crops per water drops. Deficit irrigation (DI), as a valuable and sustainable strategy in dry areas, has been extensively investigated and employed. Several studies have confirmed that DI has succeeded in increasing water productivity (WP) for different crops, without seriously reducing yields (Geerts and Raes 2009). There are few successful reports indicating that the regulated DI in most orchards and vineyards not only improved WP but also increased farmers' incomes (Fereres and Soriano 2006). Ding et al. (2021) reported that application of DI up to 80% and 85% from soil available water resulted to the highest values of grain yield (7.5 t ha^{-1}) and WP (18.4 kg ha^{-1} mm^{-1}) respectively, provided that using higher rate of compost (12 t ha^{-1}). Deng et al. (2006) highlighted the DI, supplementary fertilization, and breeding new cultivars, as solutions to improve the WUE along with the biological storage mechanisms of water and economical irrigation technologies.

In recent years, there has been a lot of efforts to increase WUE (Ding et al. 2021; Ali et al. 2020), but only limited irrigation and application of ecofriendly inputs such as salicylic acid (SA) were considered as two main strategies for saving and optimizing water use (Islam et al. 2012). SA or ortho-hydroxy benzoic acid belongs to a group of phenolic compounds that can be widely found in plants and nowadays categorized as pseudo-hormonal substances (Kang and Wang 2003). This acid plays a role in regulating plant physiological processes, such as photosynthesis and chlorophyll content, stomata closure, ion absorption, antioxidant biosynthesis, respiration reduction, and increasing stress resistance (El-Tayeb 2005). El-Katony et al. (2019) reported that application of SA to maize, as foliar spray, induced stomatal closure and reduced rates of transpiration and photosynthesis under salinity stress conditions. Salinity increased concentrations of soluble sugars, proline, and Na^+ in the leaves, and decreased K^+ and phenolics concentrations. They suggested both salinity and SA reduced stomatal conductance and concentrations of phenolics, proline, and K^+ but increased Na^+ concentration of the shoot. It was concluded that SA alleviated the salt stress consequences particularly increased root/shoot ratio which in turn contributed to maize tolerance to salt stress. It was reported that exogenously application of SA (0.6 mM) under drought stress alleviated the stress effects and improved sesame traits including osmoregulation and SY (Yousefzadeh Najafabadi and Ehsanzadeh 2017). Athari and Talebi (2014) reported similar effects of drought stress on sesame yield and yield components, but it was indicated that application of 0.05 mM SA significantly increased SY, number of capsules per plant, 1000 seed weight, seed oil, and protein content under both the normal and deficit irrigation.

The superabsorbent polymers (SAP) absorb water and aqueous solution up to several times of their weight. These polymers improve soil aggregation and structure, decrease soil bulk density, and enhance growth conditions for plants, especially under drought stress. Among other advantages of superabsorbent, acceleration of plant emergence, lower number of required irrigations, uniform application of water for plant, higher fertilizer use efficiency, improvement of the beneficial soil microorganisms, and also higher porosity and stability of soil structure can be listed as well (Dabhi et al. 2013). SAP amendment to soils reduces the evapotranspiration rate of the plants. They induce a significantly higher growth rate in plants growing on SAP-amended soil. They mitigate the effects of salinity. The benefits of SAP amendment to soils substantially outweigh their costs (Huttermann et al. 2009). It has been reported that the highest sesame (*Sesamum indicum* L.) SY obtained when 80 kg ha^{-1} SAP, 6 kg ha^{-1} humic acid, and 50% of the sesame water requirement during the growing season were applied (Nassiri-Mahallati and Jahan 2020). The results of the meta-analysis performed on the published studies regarding the application of SAP in crop production in Iran indicate the positive effect of SAP on biomass production and grain yield of various crops across arid regions of the country (Jahan and Nassiri-Mahallati 2020).

Principal component analysis (PCA) is a multivariate statistical method that is often used to examine a group of correlated variables. One of the most important applications of this approach is multivariate analysis, measurement and recognition of complex structures, indexing and reducing of data dimensions (Manly and Navarro Alberto 2016). In fact, in this method, fewer variables as the principal components (PC) will be extracted from the early variables; thus, less significant information will be removed. The first extracted PC takes the largest amount of data dispersion from the entire data set. The best result will be achieved when the initial variables have a strong positive or negative correlation. In this case, displaying a large number of initial variables will be possible by two or three of the PCs. Therefore, PCs can be of interest as criteria for revealing the intrinsic aspects of the data (Manly and Navarro Alberto 2016). Ercan et al. (2002) applied PCA and cluster analysis to characterize Turkish sesame landraces using agronomic and morphologic descriptors. Li et al. (2008) applied PCA to study sesame oil adulteration. El-Sherif (2016) reported that the results of path analysis revealed that the sesame plant height (H) followed by SY per plant and harvest index exhibited high positive direct effects on SY. Masoudi (2019) reported that the results of PCA showed that 6 components comprised 82.8% of the total variation in 91 sesame genotypes. In the first component, BY, SY, capsule weight, number of capsules in the branches, and number of capsules per plant had high positive coefficients. Similar results confirmed by other studies (Tanwar and Bisen 2017; Baraki et al. 2015).

Increasing decline in water resources has oriented many studies to find solutions for increasing WUE, particularly in dry and semi-arid regions, and to conduct extensive studies to assess the effects of various levels of irrigation and fertilizers on different crop performances. Employing of DI management in growing crops tolerant of the semi-arid conditions in the Northeast of Iran may save irrigation without significant yield penalties. There are many studies that have been performed in relation to DI, SAP, SA, and their useful application in agriculture; however, there is still a lack of its applied definition on many crops in particular neglected and underutilized crops including sesame which is widely cultivated mainly by poor farmers across arid regions around the world.

Based on empirical evidences, it is hypothesized that the application of nutritional management in such conditions, through improved the plant physiological characteristics including CGR and drought resistance, also soil properties, not only improve plant growth and yield, but also when employed simultaneously with DI as a management strategy in consumption less water, could increase WPi. Therefore, the objectives of this study were, first to assess and investigate the effects of application of SAP and SA as nutrition management on sesame performance, soil properties, and WPi to answer a question as whether the combined application of SAP and SA is effective in enhancing the WPi or not, and if so, which sesame characteristics would be affected by SAP and SA, using a multivariate analysis approach. The second, to explore and determine the effective factors on WPi of sesame as the most important cash-crop in low input cropping systems.

2 Materials and Methods

2.1 General Information and Experimental Design

Field studies were conducted in 2016 and 2017 at the Research Farm of Agriculture Faculty, Ferdowsi University of Mashhad, Iran (latitude: 36°15′N; longitude: 59°28′E; elevation: 985 m above sea level). The experiment station was located in Kashaf river watershed in the northeast part of the country, in a semi-arid region with mean annual precipitation of 252 mm and temperature of 15 °C. Soil samples were taken from 0- to 15- and 15- to 30-cm depths and analyzed for some physiochemical properties before conducting the experiment (Table 1). The soil type was Typic Haplocalcids (Soil Survey Staff 2014).

A split strip plot arrangement based on the randomized complete block design (RCBD) design with three replications was conducted during each cropping years. The two levels of irrigation including (1) supplying 50% of the sesame water requirement as DI and (2) supplying 100% of the sesame water requirement as FI were allocated to the main plots. Application of SAP (80 kg ha^{-1}) into the soil and control (no application of SAP) was allocated to the sub plots. Foliar application of SA (1 mM) and control (no application of SA) was allocated to the strip plots. The characteristics of applied SAP (AQUASORB®: SNF Co. Ltd, UK) and SA (Salicylic Acid®: Alta Laboratories Ltd, India) are presented in Table 2.

Table 1 Soil properties of the experimental field (mean of 2 years)

Soil properties	0–15 cm	15–30 cm
Total N (mg kg^{-1})	740	690
Available P (ppm)	10	13
Available K (ppm)	417	400
C/N	11.9	11.4
pH (saturation extract)	7.2	7.1
EC (dS m^{-1})	0.91	0.90
Bulk density (g cm^{-3})	1.43	1.41
Organic matter (%)	1.12	1.10
$CaCO_3$ (g 100 g^{-1} soil)	16	16.50
Texture grade	Silty-loam	Silty-loam
Soil type	Haplocalcids	Haplocalcids
Water content at FC (vol%) (?)	27.5 ± 1.3(SD)	29.1 ± 0.9(SD)
Available water (vol%)	13.4 ± 1.1(SD)	15.2 ± 0.7(SD)

EC, soil electrical conductivity**;** *FC*, field capacity; *SD*, standard deviation

Table 2 Characteristics of used superabsorbent polymer (SAP) and salicylic acid (SA)

Superabsorbent polymer (SAP)		Salicylic acid (SA)	
Appearance	White powder	Chemical formulation	$C_7H_6O_3$
Moisture content	< 5	Molar mass (g.mol^{-1})	138.12
Odor and toxicity	0	Density	1.44
Mass density (g.cm^{-3})	0.8	Melting temperature (158.6 °C)	158
pH	9.81	Boiling point (°C)	211
		Soluble in water	
		IUPAC name	

2.2 Planting and Management

Main plots as 6 m × 3 m were separated with a distance of 1 m between to avoid nutrients mixing due to irrigation. Each plot consists of 6 rows of plant. Each main plot was divided into two equal parts and SAP fine granules were properly mixed with the soil immediately before sowing. Using CropWat ® software (FAO 2016, 1998), the sesame volume of water requirement was estimated as 200 m^3 ha^{-1} for each irrigation time to supply 100% of the water requirement (FI), considering the local conditions, daily evapotranspiration, and the length of sesame growing season.

SAP was added to the soil and mixed to depth of 30 cm using a spade. The sowing dates (May 20, 2016–May 20, 17) were the same for both years of the experiment. Sesame seed (*Sesamum indicum* L. var. Darab 1) was sown on rows 50 cm apart and with 10 cm within row distance. In order to avoid water movement from one plot to the other ones, for each block and each plot, the irrigation piping was separately installed. In order to reach the plant density of 30 plant m^{-2}, the thinning was performed when plants have 4 leaves. Plots were immediately irrigated after sowing and then irrigation continued by 7-day intervals. Irrigated water was recorded by the counter. Different levels of SA were applied on leaves at 6 to 7 leaf stage in the corresponding plots.

The experiment sites were different for the 2 years of the experiment, but adjacent, and underwent fallow during the year before this experiment. Weeds were controlled by hand 3 times during the growing season (15, 30, and 45 days after planting). The most important weeds in the field were *Chenopodium album* L., *Convolvulus arvensis* L., *Descurainia sophia* L., and *Sisymbrium officinale* L. During the growing season, no herbicides, pesticides, and chemical fungicides were used.

2.3 Measurements, Calculations, and Studied Crop Characteristics

Each plot was divided into two sections, one for SY and its components and the other one for destructive sampling during the crop growth period. Measuring of leaf area and BY was started from June 6 and continued 5 times (every 2 weeks) up to the end of growing season in an area of 0.5 m^2. The leaf area was measured with the leaf area meter, LI-3100C, LI-COR, Inc. Lincoln, NE, USA. Leaf area index (LAI) was calculated by dividing each leaf area value into unit ground surface area. At the end of the growing season, the H was measured. While considering the marginal effect, plants in a 1 m^2 of each plot area were harvested to determine the BY, SW, and SY (14% moisture content). The oven-dried plants (at 80 °C for 48 h) were weighed for each sampling and final harvest.

Water productivity of irrigation (WPi) (kg seed ha^{-1}/m^3 water ha^{-1}) that is defined as ratio between the marketable yield produced by a crop along the growing season and the irrigation water applied in the same period is calculated using Eq. 1. (Fernandez et al. 2020):

$$\mathrm{WPi} = \mathrm{Ys}/\,\mathrm{IWU} \tag{1}$$

where Ys is seed yield (kg ha^{-1}), and IWU is the irrigation water used (m^3 ha^{-1}).

CGR (g (dry matter) m^{-2} day^{-1})) is calculated using Eq. 2 (Hunt 1990):

$$\mathrm{CGR} = \left(\mathrm{W}_2 - \mathrm{W}_1\right)/\left(\mathrm{T}_2 - \mathrm{T}_1\right) \times 1/\mathrm{GA} \tag{2}$$

where W_1 is plant dry matter weight in the first sampling (g m^2), W_2 is plant dry matter weight in the second sampling (g m^2), T_1 is the first sampling time (day), T_2 is the second sampling time (day), and GA is ground area per plant (m^2). In order to calculate CGR, randomized destructive sampling was done from the area of 0.25 m^2 every 15 days, starting 15 days after emergence, and considering marginal effect. At the end of the growing season, soil samples were taken from 0- to 15- and 15- to 30-cm soil depth and the total amount of soil nitrogen (Soil N) was determined using Kjeldahl's method (AOAC official method 968.06 [4.2.04]) (Horwitz and Latimer 2005). The procedure is as follows:

(1) Weigh 1 g of soil sample. Place in a Kjeldahl flask. (2) Add 0.7 g of copper sulfate, 1.5 g of K_2SO_4 and 30 ml

of H_2SO_4. (3) Heat gently until frothing ceases. If necessary, add a small amount of paraffin or glass beads to reduce frothing. (4) Boil briskly until the solution is clear and then continue digestion for at least 30 min. (5) Remove the flask from the heater and cool, add 50 ml of water, and transfer to a distilling flask. (6) Place accurately 20–25 ml of standard acid (0.1 M HCl or 0.05 M H_2SO_4) in the receiving conical flask so that there will be an excess of at least 5 ml of the acid. Add 2–3 drops of methyl red indicator. Add enough water to cover the end of the condenser outlet tubes. (7) Run tap-water through the condenser. (8) Add 30 ml of 35-percent NaOH in the distilling flask in such a way that the contents do not mix. (9) Heat the contents to distill the ammonia for about 30–40 min. (10) Remove the receiving flask and rinse the outlet tube into the receiving flask with a small amount of distilled water. (11) Titrate excess acid in the distillate with 0.1 M NaOH. (12) Determine blank on reagents using the same quantity of standard acid in a receiving conical flask. The calculation is:

$$\text{Percent } N = 1.401[(V1M1 - V2M2) - (V3M1 - V4M2)]/W \times df$$

where $V1$ is the milliliters of standard acid put in receiving flask for samples; $V2$ is the milliliters of standard NaOH used in titration; $V3$ is the milliliters of standard acid put in receiving flask for blank; $V4$ is the milliliters of standard NaOH used in titrating blank; $M1$ is the molarity of standard acid; $M2$ is the molarity of standard NaOH; W is the weight of sample taken (1 g); and df is the dilution factor of sample (if 1 g was taken for estimation, the dilution factor will be 100).

To determine the soil available phosphorus (Soil P), the Olsen's method was employed (Page et al., 1982). With the Olsen method, P is extracted from soil using a 0.5 M sodium bicarbonate ($NaHCO_3$) solution by shaking at 180 rpm for 30 min. The extractant was filtered (150 mm MN 619 G filter paper), after which P concentration of the extract was determined using Spectrophotometers (Jenway, Model 6705, UV/Visible Spectors, UK).

Soil pH and soil electrical conductivity (Soil EC) were determined according to FAO guideline (Motsara and Roy 2008). Soil texture was identified using Hydrometer method according to FAO guideline. Soil organic matter was determined using Colorimetric method (Datta et al. 1962). Calcium carbonate in soil sample was determined using Calcimeter Bernard method in which percentage of calcium carbonate, $CaCO_3$ (%), is defined as the total carbonates which is contained in 100 g of dry soil (Lamas et al. 2005).

2.4 Analyzing, Calculations, and Model Fitting

To determine the effect of SAP and SA application on the studied traits, data were subjected to analysis of variance (ANOVA) using Minitab ® Statistical Software Ver. 17. A normality test was performed. Transformation was also performed for numerical data where needed. To ensure the uniformity of treatment variances, the Bartlett's test was used. Since there was no statistical difference between both years of data, the mean value of each trait was reported. Data analysis and graph plotting were done, using the Minitab® Statistical Software Ver. 17.1, IBM® SPSS® Ver. 23 and Microsoft Excel Ver. 14. Comparisons of the means were done using Duncan's multiple range test (DMRT) and at the 5% probability level.

Principle components analysis is carried out through various steps (Manly and Navarro Alberto 2016): (1) The variables X_1, X_2… and X_p are standardized to have a mean of zero and variance of one. (2) The covariance matrix C is calculated. If the first step is performed, the covariance matrix will be the solidarity matrix. (3) The Eigenvalues of λ_1, λ_2… and λ_3 and the corresponding Eigenvectors a_1, a_2… and a_3 are calculated. Therefore, the coefficients of the ith component are represented by a_i and its variance is λ_i. (4) Components that only represent a small part of the data changes are deleted.

Logistic peak regression models were fitted to LAI, CGR, and WPi (Eq. 3). Sigmoidal model was fitted to dry matter accumulation (Eq. 4) (Soltani et al. 2006):

$$y = a_0 + a_1 \times 4 \times (\exp(-(x - a_2)/a_3))/(1 + \exp(-(x - a_2)/a_3))^2 \tag{3}$$

$$y = a_0 + a_1/(1 + \exp(-(x - a_2)/a_3)) \tag{4}$$

where a_0 is the intercept, a_1 is the rate of leaf area production, a_2 is the time to achieve the maximum leaf area index, and a_3 is the rate of leaf area decreasing.

3 Results

3.1 ANOVA of the Experimental Factors

3.1.1 Irrigation

The ANOVA revealed that the effects of irrigation levels, SAP, and SA application on many sesame traits also soil properties were significant (data not shown). BY and SY at irrigation level of 100% was 22.5% and 9% higher compared to when only 50% irrigation was applied, respectively (Table 3). Increasing irrigation from 50 to 100% increased H, LAI, CGR, and Soil EC by 2, 36, 61, and 10%, respectively; however, SW and Soil N decreased by 4 and 45%, respectively (Table 3). WPi at two levels of irrigation was not significantly different, although at 50% irrigation level, it was 26% higher than100% irrigation.

Table 3 Mean comparisons of some sesame characteristics and soil properties affected by different irrigation levels (DI, FI), superabsorbent (SAP) application, and salicylic acid (SA) spraying

	SY (kg ha^{-1})	BY (kg ha^{-1})	SW (g)	H (cm)	LAI	CGR (g m^{-2} day^{-1})	Soil N (%)	Soil P (%)	EC (dS m^{-1})	pH	WPi (kg seed ha m^{-3} water ha^{-1})
Irrigation level											
DI	1278.54a	11,956.58b	20.72a	66.24a	4.32b	12.31b	0.11a	0.0051a	0.82a	8.00a	0.76a
FI	1413.96a	12,521.69a	19.75a	67.61a	5.20a	16.04a	0.06b	0.0058a	0.73b	7.93a	0.56b
SAP											
Application	1623a	13426a	25.20a	87.3a	6.04a	17.01a	0.07b	0.0072a	0.60b	9.48a	0.76a
Non-application	1057b	11902b	15.32b	56.0b	4.48b	13.78b	0.06b	0.0041b	0.79a	7.47b	0.54b
SA											
Application	1461.17a	12,232.74a	22.87a	75.14a	5.65a	15.25a	0.13a	0.0060a	0.89a	7.45a	0.73a
Non-application	1243.84b	11,395.79b	17.57b	49.28b	3.36b	13.66a	0.10b	0.0044b	0.84b	7.47a	0.62b

In each column and for each factor, means followed by the same letters are not significantly different at 5% probability level

DI, deficit irrigation; *FI*, full irrigation; *SAP*, superabsorbent polymer; *SA*, salicylic acid; *SY*, seed yield; *BY*, biological yield; *SW*, seed weight per plant; *LAI*, leaf area index; *H*, plant height; *CGR*, crop growth rate; *Soil N*, the total amount of soil nitrogen; *Soil P*, the soil available phosphorus; *Soil EC*, soil electrical conductivity; *pH*, soil pH; *WPi*, water productivity of irrigation

3.1.2 The Effect of SAP Application

Sesame SY and BY increased by 10 and 44%, respectively, as a result of SAP application (Table 3). SW, H, LAI, and CGR were also 39, 36, 48, and 46% higher than the control. The application of SAP significantly improved soil properties, and Soil N, Soil P, and pH increased by 14, 43, and 21%, respectively (Table 3). SAP application reduced Soil EC significantly from 0.79 to 0.66 dS m^{-1} (Table 3). Application of SAP resulted in 29% higher WPi (Table 3).

3.1.3 The Effect of SA Spraying

SA spraying, compare to no SA application, improved all the studied traits except for CGR and Soil pH, so that the SY, BY, SW, H, LAI, Soil N, Soil P, and WPi were higher by 15, 38, 23, 34, 41, 23, 27, and 15%, respectively,

3.1.4 Interaction of Irrigation and SAP Levels

The highest SY was obtained for irrigation level of 100% plus SAP application (Table 4). It seems that SAP application effectively reduced drought stress consequences on SY, for example, using SAP under drought stress conditions (supplying 50% of water requirement) increased SY by 42.2% compared with non-application of SAP (Table 4).

At both irrigation levels, the highest BY was obtained when SAP was applied (Table 4). SAP application under drought stress conditions (50% irrigation) resulted in 23.5, 30, 32, 59, 20, 44, and 16.5% increase in SW, H, LAI, CGR, Soil N, Soil P, and pH compared with control (treatment of 50% irrigation and no application of SAP) (Table 4). The lowest Soil EC was obtained under treatment of 100% irrigation and SAP application (Table 4). An interesting result was that the highest WPi was realized when only 50% of the water requirement was supplied and simultaneously the SAP was applied, which was 60% more than 100% irrigation and no application of SAP (Table 4).

3.1.5 Interaction of Irrigation and SA

Interaction of irrigation and spraying levels of SA was significant on most of studied traits. The highest SY (1686 kg ha^{-1}), SW (24 g per plant), Soil N (0.14%), Soil P (0.0062%), and WPi (0.84 kg m^{3}) resulted from irrigation level of 50% and SA spraying, and the highest BY (12,382 kg ha^{-1}), H (85 cm), LAI (7.02), and CGR (16.89 g m^{-2} day^{-1}) obtained from 100% irrigation level and SA spraying interaction (Table 4).

Table 4 Mean comparisons of sesame characteristics and soil properties affected by different irrigation levels (DI, FI), superabsorbent (SAP) application, and salicylic acid (SA) spraying

Treatments	SY (kg ha^{-1})	BY (kg ha^{-1})	SW (g)	H (cm)	LAI	CGR (g m^{-2} day^{-1})	Soil N (%)	Soil P (%)	EC (dS m^{-1})	pH	WP$_i$(kg seed ha m^{-3} water ha^{-1})
Interaction of irrigation levels and SAP											
DI × SAP	1486b	13238a	22.17b	91a	9.70a	16.58b	0.101a	0.0063b	0.77a	9.32a	0.96a
DI × non-SAP	860d	11265c	16.95c	64b	6.56c	12.68d	0.081b	0.0035d	0.90a	7.78b	0.70b
FI × SAP	1759a	13614a	28.22a	83b	7.39	17.43a	0.048c	0.0082a	0.43b	9.65a	0.55c
FI × non-SAP	1255c	12540b	13.70d	47c	2.41d	14.88c	0.040 s	0.0047c	0.68ab	7.16c	0.38d
Interaction of irrigation levels and SA											
DI × SA	1686.22a	12,083.34b	24.08a	65.09b	4.29b	13.61c	0.14a	0.0062a	0.89a	7.48a	0.84a
DI × non-SA	1081.94c	11,240.97d	19.69b	44.09d	2.74c	12.38d	0.12b	0.0040b	0.75a	7.44a	0.54c
FI × SA	1236.11c	12,382.15a	21.65b	85.19a	7.02a	16.89a	0.11c	0.0059a	0.89a	7.42a	0.61c
FI × non-SA	1405.74b	11,550.62c	15.45c	54.47c	3.97c	14.95b	0.08d	0.0048b	0.93a	7.50a	0.70b
Interaction of SAP and SA											
Non-SAP × SA	1476b	12738ab	16.69b	85b	6.22b	17.03a	0.28a	0.0047b	0.61b	9.84a	0.56b
SAP × SA	1563a	13113a	21.76a	95a	7.39a	16.82a	0.25a	0.0151a	0.81a	9.57a	0.69a
Non-SAP × non-SA	1091d	12479b	14.25c	60c	4.02c	13.76c	0.04b	0.0043b	0.60b	8.85ab	0.39d
SAP × non-SA	1305c	12752ab	13.69c	72d	6.56b	14.47b	0.08b	0.0085b	0.45c	8.85b	0.48c

In each column and for each treatment group, means followed by the same letters are not significantly different at 5% probability level

DI, deficit irrigation; *FI*, full irrigation; *SAP*, superabsorbent polymer; *SA*, salicylic acid; *SY*, seed yield; *BY*, biological yield; *SW*, seed weight per plant; *LAI*, leaf area index; *H*, plant height; *CGR*, crop growth rate; *Soil N*, the total amount of soil nitrogen; *Soil P*, the soil available phosphorus; *Soil EC*, soil electrical conductivity; *pH*, soil pH; *WPi*, water productivity of irrigation

3.1.6 Interaction of SAP and SA

The highest amounts of SY, BY, SW, H, LAI, Soil P, and WPi were obtained as a result of combined application of SAP and SA (Table 4). It seems that the use of ecological inputs was effective in reducing Soil EC, so the simultaneous application of SAP and SA resulted in a 72% reduction in Soil EC compared with the control.

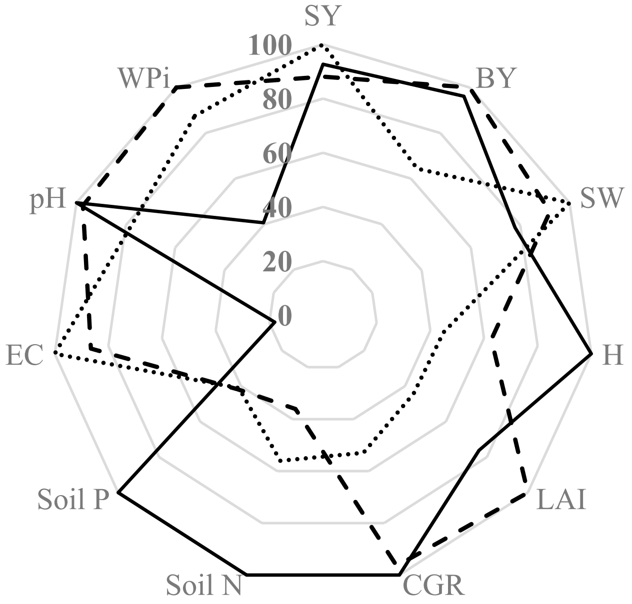


Fig. 1 Relative comparison of sesame characteristics and soil properties under conditions of the following: application of SAP+DI (cut line), application of SA+DI (dotted line), and application of SAP+SA (solid line). (DI, deficit irrigation; FI, full irrigation; SAP, superabsorbent polymer; SA, salicylic acid; SY, seed yield; BY, biological yield; SW, seed weight per plant; LAI, leaf area index; H, plant height; CGR, crop growth rate; Soil N, the total amount of soil nitrogen; Soil P, the soil available phosphorus; Soil EC, soil electrical conductivity; pH, soil pH; WPi, water productivity of irrigation)

3.2 Relative Comparison of the Effects of SAP and SA Application

Interaction effects of SAP and SA at 50% irrigation level (drought stress) on sesame growth characteristics and some soil properties are shown in Fig. 1. Simultaneous application of two inputs on some characteristics, including CGR, Soil N, Soil P, H, and Soil pH, was quite beneficial.

3.3 Correlation Between Studied Properties

The correlation between BY and SY of sesame with SW ($r=0.64^{**}$), H ($r=0.74^{**}$), LAI ($r=0.88^{**}$), CGR ($r=0.83^{**}$), Soil P ($r=0.88^{**}$), and pH ($r=0.39^{*}$) was positive and significant (Table 5). SW was positively correlated with Soil N ($r=0.58^{*}$) and Soil P ($r=0.71^{**}$), so increasing Soil N and Soil P would improve SW. Sesame H was significantly and positively correlated with LAI ($r=0.91^{**}$), CGR ($r=0.71^{**}$), and Soil P ($r=0.72^{**}$) (Table 5). Sesame LAI showed a positive and significant correlation with CGR ($r=0.63^{**}$) and Soil P ($r=0.52^{*}$), while there was a positive and significant correlation between Soil P and WPi (Table 5).

3.4 Growth Analysis and WPi

As it shown in Fig. 2a, LAI values during the growing period were estimated by fitting the logistic peak regression model

Table 5 Coefficients of correlation (*r*) between sesame characteristics and soil properties affected by different irrigation levels (DI, FI), superabsorbent (SAP) application, and salicylic acid (SA) spraying

Traits	SY	BY	SW	H	LAI	CGR	Soil N	Soil P	EC	pH
BY	0.68**									
SW	0.56**	0.64**								
H	0.36*	0.74**	0.61**							
LAI	0.18 ns	0.58*	0.46*	0.91**						
CGR	0.48*	0.83**	0.34*	0.71**	0.63*					
Soil N	0.02 ns	0.05 ns	0.58*	0.31*	0.37*	−0.26				
Soil P	0.77**	0.88**	0.71**	0.72**	0.52*	0.76**	0.09 ns			
EC	−0.12 ns	0.13 ns	−0.19 ns	0.09 ns	0.12 ns	−0.11 ns	0.13 ns	−0.16 ns		
pH	0.40*	0.39*	0.44*	0.37*	0.25*	0.37*	0.1 ns	0.37*	−0.15 ns	
WPi	0.50 ns	0.22 ns	0.32*	0.45*	0.45*	0.05 ns	0.59**	0.32*	0.38 ns	0.28 ns

*, **, and ns represent significance at 5, 1% of probability level, and non-significant

DI, deficit irrigation; *FI*, full irrigation; *SAP*, superabsorbent polymer; *SA*, salicylic acid; *SY*, seed yield; *BY*, biological yield; *SW*, seed weight per plant; *LAI*, leaf area index; *H*, plant height; *CGR*, crop growth rate; *Soil N*, the total amount of soil nitrogen; *Soil P*, the soil available phosphorus; *Soil EC*, soil electrical conductivity; *pH*, soil pH; *WPi*, water productivity of irrigation

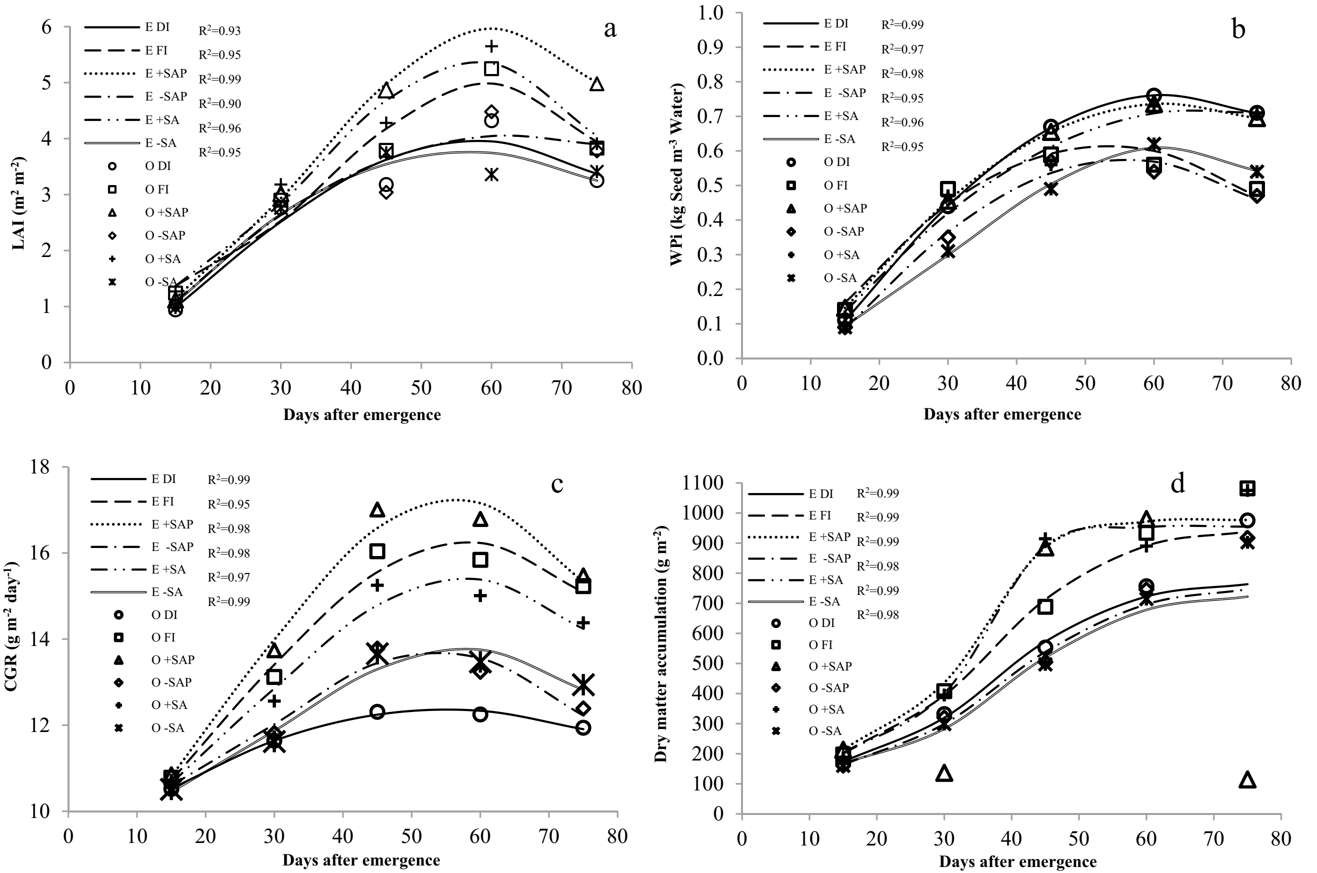


Fig. 2 The fitting of logistic peak function to leaf area index data (**a**), crop growth rate (**b**), irrigation water productivity (**c**), and fitting of sigmoidal function to dry matter accumulation (**d**) of sesame affected by irrigation levels, application of SAP, and SA spraying. In all figures, R^2 represents coefficient of determination for the estimated curves. (E, estimated; O, observed; DI, deficit irrigation (solid line); FI, full irrigation (dash line); + SAP, superabsorbent polymer application (dotted line); − SAP, non-superabsorbent application (dash-dotted line); + SA, salicylic acid application (dash-dotted-dotted line); − SAP, non-salicylic acid application (double line))

to measured data. Sixty days after emergence, LAI was at its maximum value, as a result of SAP application; moreover, FI ranked second related this trait. It seems that reduction of sesame LAI at the end of the growing season could be related to natural leaf abscission and high temperature at that time (data not shown).

The same trend was observed for CGR (Fig. 2b). The observed trend for CGR changes was completely in accordance with LAI changes (Fig. 2a, b).

The highest WPi was observed for 50% irrigation, SAP application, and SA spraying, and showed significant differences with other treatments at 75 days after emergence (Fig. 2c). In the above treatments, WPi showed a significant difference with other treatments (Fig. 2c), considering LAI and CGR reduction at 75 days after emergence (Fig. 2a, b). It seems that the higher WPi resulted in higher accumulation of sesame dry matter under these three treatments compared with the other treatments. As shown in Fig. 2a and Fig. 2b, the higher slope of LAI and CGR curve in SAP application was clearly revealed in higher slope of dry matter accumulation of SAP application (Fig. 2d). This association is completely accordance with ecophysiological basis of crop growth (Hunt 1990).

Dry matter accumulation during the growing period was estimated by fitting the sigmoidal regression model to measured data which showed that from 30 to 60 days after emergence, dry matter accumulation in all treatments, except SAP, was continued with a relatively steep slope (Fig. 2d). It seems that SAP application accelerated maximum dry matter achievement (Fig. 2d). Under SAP treatment, dry matter was stable at 45 days after emergence and it continued with a relatively steep slope until at 60 days after emergence. Under FI, dry matter accumulation was continued up to 75 days after emergence, and stayed the same point with SAP application (Fig. 2d).

3.5 PCA and Effective Variables on WPi

Eigenvalues and corresponding variances of the principal components and eigenvectors of the first two principal components of the sesame WPi in response to irrigation levels, SAP application, and SA spraying are shown in Tables 6 and 7 accordingly. The variables were analyzed into two principal components. The first and the second principal components explained 66.97 and 15.3% of the total variance of the initial variables, respectively (Table 6). The comparison of the variances of the principal components (eigenvalues) with the variances of the initial variables shows the relative importance of the principal components. After standardizing the initial variables, all of them would have a variance equal one. Therefore, the variance of the first principal component in sesame seeds is 7.3 times of the initial variables.

As shown in Fig. 3, SY, SW, CGR, Soil N, Soil P, Soil EC (with negative coefficient), and WPi, on the first component, were the highest effective ones, so this component can be an indicator of sesame yield. Four related variables including BY, H, LAI, and Soil pH were placed on the second component (Fig. 3). It seems that this component is partially descriptive of the spatial geometric arrangement of the plant (high values of coefficients of H and LAI on this component).

Drawing the dendrogram of cluster analysis (Fig. 4) largely confirmed the results of the PCA.

Equations 5 and 6 show the linear combination of the first and second principal components, respectively. Investigating the coefficients of each of the variables studied in the experiment on the first component extracted after data standardization (with mean zero and variance 1) revealed that the coefficients of SY, BY, SW, H, LAI, CGR, pH, and Soil P were positive and significant (Eq. 5). Therefore, any management to improve these variables would result in improved SY and ultimately improved WPi.

$$
\begin{aligned}
PC1 =\ & 0.34(SY) + 0.33(BY) + 0.35(SW) \\
& + 0.33(H) + 0.26(LAI) + 0.35(CGR) \\
& + 0.05(\text{Soil N}) + 0.36(\text{Soil P}) - 0.21(\text{Soil EC}) \\
& + 0.36(\text{Soil pH}) + 0.14(WPi)
\end{aligned} \tag{5}
$$

Table 7 Coefficient of eigenvectors of the first two principal components (PC) of sesame characteristics and soil properties affected by different irrigation levels (DI, FI), superabsorbent polymer (SAP) application, and salicylic acid (SA) spraying

Variables	Principle component	
	PC1	PC2
SY	0.68	0.71
BY	0.13	0.62
SW	0.74	0.57
pH	0.67	0.69
EC	-0.47	-0.77
Soil N	0.69	0.68
H	0.86	0.39
CGR	0.80	0.19
LAI	0.70	0.60
Soil P	0.02	0.82
WPi	0.83	-0.51

SY, seed yield; *BY*, biological yield; *SW*, seed weight per plant; *LAI*, leaf area index; *H*, plant height; *CGR*, crop growth rate; *Soil N*, the total amount of soil nitrogen; *Soil P*, the soil available phosphorus; *Soil EC*, soil electrical conductivity; *pH*, soil pH; *WPi*, water productivity of irrigation

$$
\begin{aligned}
PC2 =\ & 0.71(SY) + 0.62(BY) + 0.57(SW) \\
& + 0.39(H) + 0.60(LAI) + 0.19(CGR) \\
& + 0.68(\text{Soil N}) + 0.82(\text{Soil P}) - 0.77(\text{Soil EC}) \\
& + 0.69(\text{Soil pH}) - 0.51(WPi)
\end{aligned} \tag{6}
$$

4 Discussion

The results showed that WPi increased by 26% in DI compared with FI. Improving WUE in various crops as a result of limited irrigation has been reported by many researchers. Pereira et al. (2017) reported that 698-mm irrigation depth (equal to 130% of ETc) provided the highest sesame yield and oil content and 305-mm irrigation depth (equal to 40% of ETc) resulted in the highest WUE. Umar et al. (2015) reported that scheduling irrigation at 0.4 bar compared with 0.8 bar produced the highest grain yield of

Table 6 Eigenvalues and corresponding variance of principle components (PC) of sesame characteristics and soil properties affected by different irrigation level (DI, FI), superabsorbent polymer (SAP) application, and salicylic acid (SA) spraying

Component	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11
Eigenvalues	7.36	1.69	1.08	0.44	0.16	0.12	0.05	0.03	0.02	0.007	0.005
Proportion	66.97	15.37	9.83	4.01	1.51	1.13	0.50	0.32	0.21	0.06	0.04
Cumulative	66.97	82.35	92.18	96.19	97.71	98.85	99.35	99.68	99.89	99.95	100

PCi denotes the number of principle component, $i = 1, 2, 3, ..11$

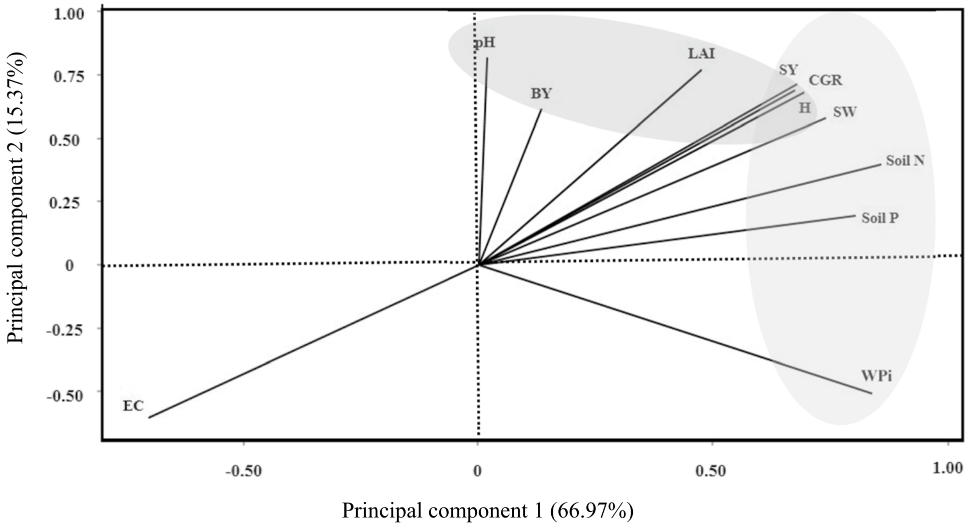
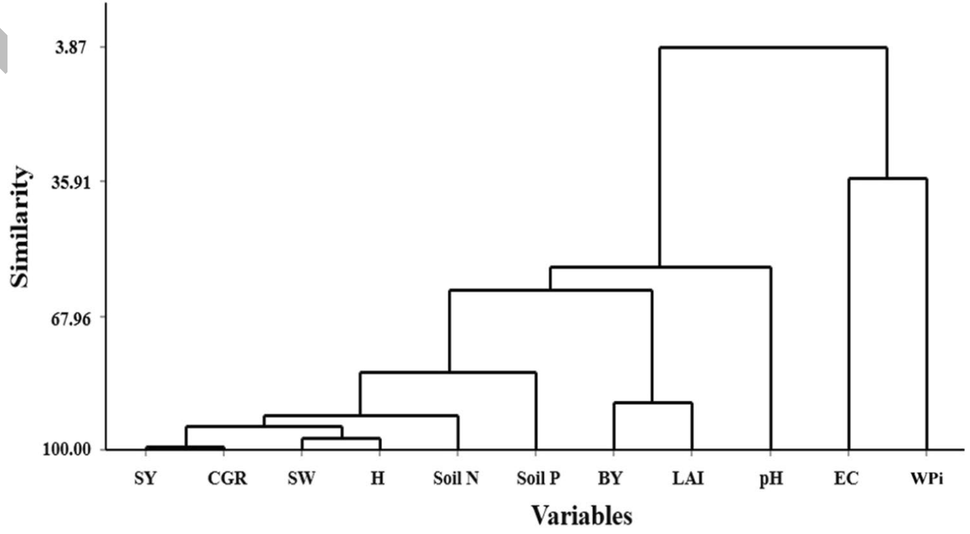


Fig. 3 Biplot of the two principal component analysis (PCA) showing the loading of studied sesame characteristics and soil properties (solid lines) on principal components (PC1, PC2). The length of the solid lines approximates the variance of the variables, whereas the angles between them (cosine) approximate their correlations. Variables close together correspond to observations that have similar loads on the PCA components. The biplot shows that SY, SW, CGR, Soil N, P, and WPi are strongly positively correlated to PC1 and each other, while EC is strongly negatively correlated to PC1. BY, H, LAI, and pH have strongly correlated to PC2. (SY, seed yield; BY, biological yield; SW, seed weight per plant; LAI, leaf area index; H, plant height; CGR, crop growth rate; Soil N, the total amount of soil nitrogen; Soil P, the soil available phosphorus; Soil EC, soil electrical conductivity; pH, soil pH; WPi, water productivity of irrigation)

sesame crop. Eskandari et al. (2009) reported that severe water stress (300-mm evaporation from class-A pan) reduced biological and grain yield, oil, and protein yield of sesame significantly. The results of the study conducted by Ali et al. (2015) revealed that the maximum values of H, leaf number per plant, and stover yield resulted from the simple effect of irrigating at 9-day interval compared with 18- and 27-day intervals, and triple interaction of irrigating at 9 days, conventional tillage method (compared with deep and shallow tillage), and application of 60 kg P ha^{-1} (compared with 0, 30, and 90 kg P ha^{-1}).

Some growth characteristics of sesame were reduced due to the simple effect of DI. Drought-induced yield reduction has been reported in many crop species, which depends upon the severity and duration of the stress period (Farooq et al. 2009). Oxidative damage as a consequence of severe drought stress in sesame has been fully described (Fazeli et al. 2007). It has been proved that drought stress, especially in three stages of emergence and flower formation,

Fig. 4 Dendrogram of hierarchical agglomerative cluster analysis (using similarity index; variance method: Ward's method) based on all measured variables in soil and sesame samples affected by different irrigation levels, superabsorbent application, and salicylic acid spraying. Dotted line represents 75% similarity level. (SY, seed yield; BY, biological yield; SW, seed weight per plant; LAI, leaf area index; H, plant height; CGR, crop growth rate; Soil N, the total amount of soil nitrogen; Soil P, soil phosphorous content; Soil EC, soil electrical conductivity; pH, soil pH; WPi, water productivity of irrigation)



pollination, fertilization, and seed formation, has severe negative effects. Drought stress prevents the emergence of stem fundamental cells. Drought during pollination and fertilization stage reduces the number of seeds due to the desiccation of pollens, and the wilting of the stigma prevents pollen tube growth. In the stage of seed filling, plants under stress use assimilates to cope with stress instead of allocating it to seeds. As a result, SW and subsequent SY are affected by negative effects of drought stress (Taiz and Zeiger 2006). Jouyban et al. (2016) reported that increased irrigation intervals from 6 to 18 days for sesame crop resulted in significant SY, oil yield, and protein yield loss by 44.5, 44.5, and 39.7%, respectively. They also found that SAP should be applied exactly under the planting rows to realize the positive effects of its utilization. It was reported (Tantawy et al. 2007) that increasing irrigation interval reduced sesame yield. They recommended to apply five irrigation to sesame could save up to 1027 m^3 ha^{-1} with yield losses less than 2%. It was reported that drought stress decreased the protein and proline oxidase content, total leaf area, H, whole plant fresh weight, whole plant dry weight, weight of seeds per pod, number of pods, and increased the amino acid, proline and glycine betaine content of sesame, and root length, but the treatment of Paclobutrazol and abscisic acid enhanced this parameters under drought stress and partially ameliorated the drought induced growth inhibition by increasing osmoregulation significantly (Abraham et al. 2008).

SA spraying reduces the effects of drought stress through effects on catalase and peroxidase enzymes and other osmotic regulators such as proline, glycine, and betaine (Farooq et al. 2009; El-Tayeb 2005; Horvath et al. 2002). Drought stress with dysfunction of stomata and photosynthetic system, degradation of proteins and enzymes, decreasing leaf area, and dropping of flowers and fruits reduces the crop yields (Doupis et al. 2013). It has been reported that foliar application of SA (0.5 and 1.0 mM) improved fennel (*Foeniculum vulgare* Mill.) physiological characteristics including antioxidant enzymes, water potential, leaf osmolytes, chlorophyll and carotenoids, and seed oil content mainly through alleviated drought effects (Askari and Ehsanzadeh 2015b).

Da Silva et al. (2017) reported that application of SA at 10–5 M induced tolerance to drought stress in sesame during germination and initial developmental stages. Khatiby et al. (2017) reported that the effects of different concentration of salicylic acid (0, 1.5, 2.25 mM) application were not significant on sesame studied traits, but water stress (irrigation cut at flowering and seed producing stages) significantly reduced sesame H, number of branches, and number of capsules per plant. Askari and Ehsanzadeh (2015a) reported that SY, oil content, and root growth of six fennel genotypes plants were improved when exposed to salicylic acid spray. It was also indicated that the interaction of drought (deficit water condition) and SA application significantly increased chlorophyll, carotenoid, and leaf osmolyte content in fennel (Askari and Ehsanzadeh 2015b). Feitosa et al. (2016) reported that application of SA (12 mg L^{-1}) on sesame ameliorated the negative effects of drought stress (water suspension for 8 days) by alteration of the behavior of net photosynthesis, stomatal conductance, transpiration, and leaf temperature. It was reported that the application of a concentration of 0.6 mM SA enhanced sesame resistance to drought stress which in turn resulted to increased seed yield (Yousefzadeh Najafabadi and Ehsanzadeh 2017). It has been reported that fennel growth characteristics, yield, and oil yield were improved by foliar application of SA under deficit water conditions (Askari and Ehsanzadeh 2015a). Agami et al. (2019) reported that addition of SA or proline notably increased WUE and mitigated the stress created by field DI; moreover, SA was the more efficient in mitigating field DI stress than proline. They concluded that SA, as a growth regulator, could be used to alleviate the negative effect of limited water availability in soil on wheat as well as improving the growth and yield of the crop.

It has been reported (Nassiri-Mahallati and Jahan 2020) that high temperatures at early and mid-summer (June–July) reduced sesame leaf area. Sinclair et al. (2003) reported that in seed crops, nitrogen is remobilized from leaves to seeds, also leaf aging is accelerated by seed filling period and growth.

It has been suggested (Huttermann et al. 2009) that SAP amendment to soils reduces the evapotranspiration rate of the plants. They concluded a significantly higher growth rate in plants growing on SAP-amended soil. Drought tolerance of crops has been mainly considered as a result of SAP application is related to water retention and slow-release properties of SAP (Huttermann et al. 2009). El-Katony et al. (2019) suggested that foliar spraying of SA on maize under stress resulted in reduced stomatal conductance and concentrations of phenolics, proline, and $K+$ but increased $Na+$ concentration of the shoot. They suggested that SA improved maize growth conditions through altering root/shoot ratio.

Fitting the functions for growth analysis and WPi during the growth period made it possible to study the effect of experimental treatments more accurately. Considering the major difference between the two treatments at 30 and 60 days after emergence, it seems that using SAP caused higher slope of accumulation of sesame dry matter at 30 days after emergence as compared with the other treatments, thus helped sesame with to confront limiting hot weather (which may coincide in June–July). This suggests that the history of local weather conditions determines how sesame would be grown considering its agronomic management and preference for SAP application to avoid summer heat.

Ding et al. (2021) modeled the combined impacts of deficit irrigation, rising temperature, and compost application on wheat yield and water productivity. They reported that higher compost rates may be used to mitigate the effect of deficit irrigation on wheat yield and water productivity, but not compatible with mitigation of climate change in arid and semi-arid regions. It has been reported that SAP application reduced prolonged irrigation effects on pepper (*Capsicum annuum* L.) by increasing growth rate, yield, leaf chlorophyll content, relative water content, electrolyte leakage, and proline accumulation (Sayyari and Ghanbari 2012). It was concluded that SAP can store and absorb considerable water and reduce negative effects of water shortage on plants. Mohebi (2019) reported that SAP significantly affected uptake of mineral nutrients and consequently resulted in a raise in date palm seedling establishment under water DI. It was reported that eco-environmental scenario had more advantages than economic and environmental scenarios in wheat production mainly due to higher relative water content (Jahan and Amiri 2018). Kareem et al. (2019) reported that SA application improved the final wheat biomass and yield components. It was reported that foliar application of SA (0.5 and 1.0 mM) resulted in increased root growth, yield and yield component, oil content of fennel, and irrigation WUE under control and water-deficit conditions (Askari and Ehsanzadeh 2015a). Semida et al. (2017) reported that foliar application of SA (1 and 2 mM) enhanced drought stress tolerance in onion plants by improving photosynthetic efficiency and plant water status as evaluated by membrane stability index and relative water content. They suggested that SA application may, in future, find application as a potential growth regulator for improving plant growth and yield under deficit irrigation by 20–40%.

The main purpose of PCA application is to summarize the main aspects of the variations in the variables by a smaller number of linear combinations or non-intercorrelated components (Manly and Navarro Alberto 2016). In other words, there is no correlation between the components. Employing principal component analysis (Baraki et al. 2015) for grain yield and oil content of thirteen sesame genotypes, it was found that a large part of variability in grain yield, oil content, length of capsule, bearing zone, and number of capsules accounted by the first three principal components explained 88.49% of the total variance. Similar results were reported by Tanwar and Bisen (2017). They concluded that sesame characters including H, number of capsules, number of primary branches per plant, oil content, days to maturity, and SY per plant consist the highest principal component values. It was suggested that mechanisms of plant tolerance to chilling and drought stresses can be regulated through developing tolerant plant genotypes, genetic modifications, seed treatments, application of plant growth regulators and compatible solutes, and use of plant mineral nutrients, which have the potential to be applied as the management strategies (Hussain et al. 2018).

5 Conclusions

The nutritional management was effective in reducing drought stress; moreover, the highest SY and BY, CGR, Soil N, and WPi were obtained in the simultaneous application of SAP and SA. Fitting regression model revealed that the highest amount of sesame dry matter accumulation resulted from SAP application and under this treatment, maximum dry matter was achieved 15 days earlier compared with other treatments. This is very important in avoiding drought and high temperature at the end of the growing season which coincides with the middle of summer. The high correlation between the variables within each component, and the placement of WPi along with variables affecting yield, variables such as CGR, Soil N, Soil P, and Soil EC in one component, indicate that any improvement in these variables will result in an increase in WPi and could minimize the damage caused by drought and dehydration. These findings can be useful when developing or re-assessing guidelines for optimal agronomic practices involving non-traditional crops under reduced irrigation also may help to revise the agronomical management practices (i.e., to determine the best sowing date, limited irrigation, application of natural nutritional inputs) to achieve optimum yield along with increasing WPi and crop nutrition in arid and semi-arid regions.

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is acknowledged.

Availability of Data and Materials Additional data may be available on request to the authors; please contact the corresponding author. We are legally responsible for information, data, used methods, and results.

Code Availability All used and created codes are available on demand.

Declarations

Ethics Approval This research meets all the ethical guidelines, including adherence to the legal requirements of our country.

Consent to Participate The authors voluntarily agree to participate in this research study.

Consent for Publication The authors confirm no conflict of interest and agree with the submission of the manuscript to *Journal of Soil Science and Plant Nutrition.*

Conflict of Interest The authors declare no competing interests.

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