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ORIGINAL PAPER

The Effects of Salicylic Acid and Silicon on Safflower Seed Yield, Oil Content, and Fatty Acids Composition under Salinity Stress

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Abstract

Soil and water salinization is a global treat for crop production and food security. Apply of phytohormones and nutrient management is a novel approach to reduce the negative impact of salinity. Hence the effects of salicylic acid (0, 600, 1200, and 1800 μM) and silicon (0, 1.5, and 2.5 mM) foliar application on safflower (*Carthamus tinctorius* L.) seed yield and quality were investigated under salt stress conditions (1.7, 7.5, and 15 dS m^{-1}). Salinity decreased capitulum number, seed number per capitulum, 100-seed weight, seed yield, oil percentage, oil yield, linoleic acid content, palmitic and linoleic acids yield, and seed potassium content. Application of salicylic acid (SA) and silicon (Si) increased biological and seed yield, oil content, oil yield, linoleic acid content, palmitic and linoleic acid yield but decreased stearic and oleic acid content and oleic acid yield. The harvest index (HI) was decreased with increasing salinity levels, indicating a stronger effect of salinity on seed yield more than biomass production. In contrast, SA and Si, whether alone or together, increased HI. The appropriate concentration of SA in saline and non-saline conditions was 1200 μM, but Si was different in salinity levels. Under non-stress and moderate stress conditions 2.5 mM Si showed better performance, while at severe salinity level, 1.5 mM Si showed an appropriate state. Oil content and quality improved by increasing linoleic acid and reducing stearic and palmitic acids by application of SA and Si. The content of seed elements with the application of salt, SA and Si showed different trends. Nitrogen content increased under salt stress, but potassium content decreased and sodium content did not change under saline and non-saline conditions. The application of SA and Si increased nitrogen and potassium content in stressed and non-stressed conditions, but had no significant effect on the amount of sodium.

Keywords Capitulum number · Harvest index · Linoleic acid · Oil yield · Seed protein · Stearic acid

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1 Introduction

Global agricultural productivity is seriously threatened by rising soil and water salinity. The issue is particularly prevalent in arid and semi-arid regions, such as Iran [1, 2]. Increased salinity risk has raised concerns about food security and the destruction of natural resources [3]. There are numerous reports of the detrimental effects of salinity on plant development, morphological, physiological, and biochemical processes, as well as quantitative and qualitative yield [2, 4, 5]. In the short term, salinity causes osmotic stress, while in the long term it leads to ionic toxicity and induces oxidative stress at the cellular level [4]. Sodium ions damage plant cells by inhibiting photosynthesis, impairing ionic homeostasis, and membrane lipid peroxidation, thereby adversely affecting plant growth and yield [1, 6, 7]. For example, in mustard (*Brassica juncea* L.), salinity caused detrimental effects on photosynthesis by reducing leaf area and chlorophyll content, bursting oxidative damage, and decreasing seed yield by reducing photosynthesis, the number of pods, seeds, and 100-seed weight [8]. In cotton (*Gossypium hirsutum* L.) [9], and safflower [2] salinity decreased leaf area, leaf water potential, and K, Ca, Mg, and N content while increased Na content. On the other hand, seed yield improvement has been reported because of the proper application of nutrients and plant growth regulators in the presence of saline and unconventional water sources and other adverse environmental conditions [8, 10].

To overcome environmental stresses, plants must be supplied with the optimal amount of micro- and macronutrients [10]. In this regard, one of the most important strategies to reduce the effects of stress and promote plant adaptation is the external supply of these elements to the plants [11]. Silicon (Si) is a quasi-essential element for plants and exists in the soil in the form of silicate or silicon oxide. Silicon application has shown significant effects on plant growth and development, either under stressful or optimal conditions [10, 12]. Silicon affects micro- and macronutrients uptake and distribution in plants [12]. Many studies report Si's beneficial effects on plant development and yield and its ability to mitigate the detrimental impacts of environmental stress [2, 5, 10, 11]. Silicon impacts plant growth by elevating osmolyte accumulation, nutrient absorption, photosynthesis rate, antioxidant activity, phenolic compounds and adjusting water status, and hormones regulation [11]. In a study, Si application increased safflower seed yield compared to control plants under stress conditions [13]. Also, Si treatment raised the growth of sunflower and sorghum [14] and safflower [2] grew under salinity stress.

Salicylic acid (SA), among other plant growth regulators (PGRs), is crucial for signaling network, plant growth, and tolerance to environmental stress [7, 8]. Salicylic acid is a phenolic molecule that acts as a phytohormone and has major impacts on a variety of physiological and biochemical processes, plant development, yield, and plant resilience to environmental stresses such as salinity [7, 15]. However, higher concentrations may cause plant toxicity and reduce yield [16, 17]. It has been reported that SA application under both non-stress and stress conditions reduced saturated fatty acids and increased linoleic acid and oleic acid content in *Cucurbita pepo* [18].

Silicon and SA can boost plant dry weight and yield stability by enhancing silicon and other nutrients absorption [17]. In a study, the combined application of SA and Si reduced the inhibitory effects of excess boron in chickpeas and helped increase plant tolerance to boron toxicity by preventing membranes oxidative damage [15]. With the simultaneous application of Si and SA in soybean and bean, it was found that SA foliar application increased leaf Si content which was accompanied by increased CO_2 uptake and stomatal opening [16]. Also, SA increased Si uptake and dry weight in peanuts, especially when combined with the Si foliar application [17]. It has been reported that the application of PGRs, such as SA and foliar application of elements, like Si improve the seed yield, oil and fatty acids in oilseed plants [13, 18, 19].

The increasing world population besides to climate change and soil degradation leads to use of arable lands with lower quality. Soil salinization is rapidly increasing on large scales, especially in countries located in arid and semi-arid regions. Therefore, it is essential to understand the mechanisms involved in salt tolerance and take measures to improve it. Safflower is an annual oilseed crop with a high economic value in edible oil production. Safflower has a robust root system and remarkable tolerance to salinity and drought [13]. The cultivated area of safflower in Iran is 3568 ha [20]. Due to its tolerance to environmental stresses and its production in dryland systems, this plant has the potential to be considered as a promising future crop for being cultivated in arid lands. Although safflower is a salt-tolerant crop [21, 22], its yield and oil quality reduce due to salt stress. Application of PGRs and nutrients may increase crop performance under stressful conditions. Although there is information about the separate effects of SA and Si on safflower, reports about the combined application of these substances on the performance and quality of safflower oil under salinity are limited. This study investigated the combined effect of SA and Si foliar application on seed yield and its components, oil yield, and changes in oil fatty acid profiles of safflower grown under salinity stress.

2 Materials and Methods

2.1 Experimental Design, Plant Materials and Treatments

This research was conducted in the research greenhouse of the University of Zanjan, Zanjan, Iran, in 2020. The experiment was performed as a factorial based on a randomized complete block design with three factors and three replications. Seeds were planted in plastic pots with a 30 cm top diameter and 35 cm height filled with sifted soil, sand, and manure with a ratio of 6:3:1. The soil was a clay loam type and contained pH 7.6, EC 1.74 dS m^{-1}, available P 16.8 mg kg^{-1}, available K 170 mg kg^{-1}, Na 18.86 mg kg^{-1}, Ca 14.4 mg kg^{-1}, total N 0.075%. Safflower seeds, cv. Goldasht were obtained from the Seed and Plant Improvement Institute, Oilseed Crops Research Department, Karaj, Iran. Salinity treatment consisted of three levels (1.7, 7.5, and 15 dS m^{-1}). The NaCl required for each pot was calculated and added to the pots after dissolving in water before sowing. In the growing season, the pots irrigated with purified tap water with a home water filtration system (Rad-Gostar Novin, Aqua Pro_67S1_RO, Iran). The tap water's EC after filtration was 0.36 dS m^{-1}. To keep the salinity concentration constant in the pot, the collected water in the saucer through the drainage was returned to the pot after irrigation. Salicylic acid treatment included four levels of foliar application (0, 600, 1200, and 1800 μM). Silicon treatment had three levels of foliar application (0, 1.5, and 2.5 mM) from potassium silicate (K_2SiO_3, Merck, Germany). Based on the weight ratio, the ratio of potassium to silicon was 2.79. The pH of the potassium silicate solution was adjusted to 7 using HCl (1 M) and NaOH (1 M).

2.2 Seed Sowing and Greenhouse Conditions

Twenty safflower seeds, disinfected with carboxin thiram fungicide, were planted at a depth of 3 cm in each pot. The first irrigation was done immediately after seeding, and the next irrigation rounds were performed at two-three days intervals. After emergence and thinning at the 3–4 leaf stage, five healthy plants were preserved in each pot. Abamectin was sprayed twice against two-spot mites, Benomyl was used once against powdery mildew, and Imidacloprid was applied once against aphids. The greenhouse light was provided by sunlight and artificial light. Lighting/darkness duration was 16/8 h. Radiation intensity was 900–1000 μM m^{-2} s^{-1}. The average relative humidity was 63%, and the maximum and minimum temperatures were 32/15°C day/night.

2.3 Foliar Application of Salicylic Acid and Silicon

After establishing the seedlings and at the 3–4 leaf stage, SA and Si foliar application was performed. Salicylic acid was sprayed first at 7 am; then Si was sprayed at 6 pm the following afternoon. The plants were harvested after maturity and when the plants turned yellow. The following traits were measured in all plants from each pot.

2.4 Phenotypic, Yield, Yield Components and Qualitative Trait Measurements

At harvest, plant height was measured from the soil surface to the tip of the plants. The plants were harvested from near the soil surface, dried in an oven at 70 °C and then weighed. The average weight of a plant was reported as biological yield in g per plant.

The capitula were separated and counted to report the capitulum number per plant. Then seeds were separated manually and counted to record the seed number per capitulum. 100 seeds were counted using a seed counter (Pfeuffer, Germany) and weighted by a digital scale (0.001 g accuracy). To calculate seed yield (g $plant^{-1}$), all capitula obtained from each pot were pounded by hand, and all seeds were weighed. The harvest index was calculated as the ratio of seed yield to biological yield and was expressed as a percentage.

Three g of seeds were grounded and packed in filter paper and their initial weight was obtained. The samples were placed in a Soxhlet device (BUCHI extraction system B-811, Germany) for 11 h to extract their oil with n-hexane solvent. The filter papers containing the sample were then placed in an oven at 50 °C for 2 h to remove the excess solvent. After 2 h, the samples were removed from the oven and transferred to a desiccator to prevent moisture absorption. Then, its secondary weight was immediately obtained by taking each sample from the desiccator. Finally, the oil content was calculated as a percentage with the following formula [23]:

$$\text{Oil } percentage = \left[(Initial\ weight - Secondary\ weight)/Initial\ weight\right] \times 100$$

Oil yield (g $plant^{-1}$) was obtained by multiplying the percentage of oil by seed yield per plant.

Fatty acids were identified using the gas chromatography method. The gas chromatograph-mass spectrometer (GC-MS) device included a gas chromatography model 7890B and a mass spectrometer (model 5977 A made by Agilent Company, USA). The GC/MS had a split/splitless injection system, an electron bombardment ionization model, and mass libraries related to the NIST and WILEY. The HP5-MS column with a 60 m length, a 0.25 mm inner diameter, and a 0.25 μm thickness was used. The fatty acid yield (mg $plant^{-1}$) was calculated by multiplying the percentage of each fatty acid by oil yield per plant.

The total seed nitrogen percentage was measured using the Kjeldahl method to calculate the seed protein percentage. The data was multiplied by a constant coefficient of 6.25 [24].

The wet digestion method was used to measure the seeds' potassium and sodium content according to the method of Walinga et al. [25]. Then the extract was used to measure the content of sodium and potassium by the method of flame measurement (flame photometry) using a flame photometer (Jenway, model PFP7/C, UK). Sodium and potassium contents were reported as a percentage.

2.5 Statistical Analysis

The normality of the data was confirmed by the normality test using SAS statistical software (SAS, Institute Inc. 2009). SAS statistical software (SAS, Institute Inc. 2009) was used for the analysis of variance. When the effects were significant ($P \leq 0.05$), differences between means were evaluated by using the least significant difference (LSD) test ($P \leq 0.05$).

3 Results

3.1 Growth and Yield Components

Salinity reduced plant height so that the tallest plants were found under non-stress conditions and sprayed with 1200 µM SA and 2.5 mM Si whilst the shortest plants belonged to the severe salinity level and non-treated plants. The separate and co-application of SA and Si increased plant height under salinity and non-salinity conditions. Under non-stress conditions and 7.5 dS m^{-1} salinity, the application of 1200 µM SA along with 2.5 mM Si increased plant height by 47% and 38%, respectively, compared to the non-application of these two compounds under the same conditions. At the 15 dS m^{-1} salinity, the application of 1200 µM SA and 1.5 mM Si elevated plant height by 39% compared to the non-application of these two compounds (Table 1).

Increased NaCl concentration decreased the capitulum number per plant and seed number per capitulum. Application of SA and Si increased the capitulum number per plant and seed number in the capitulum under both stress and non-stress conditions. The highest values of these traits were found in 1200 SA µM and all Si concentrations and lowest values were in the 15 dS m^{-1} and without applying SA and Si (Table 1). Application of 1200 µM SA along with 2.5 mM Si increased capitulum number by 60.8% and 61.2%, and seed number per capitulum by 22% and 22%, respectively, compared to the non-application of these two compounds under non-stress and 7.5 dS m^{-1} salinity conditions. While at 15 dS m^{-1} salinity, 1200 µM SA along with 1.5 mM Si increased capitulum number by 62%, and seed number per capitulum by 28% compared to the non-application of these two compounds (Table 1).

The 100-seed weight was affected only by salinity ($P \leq 0.001$) and the application of SA or Si had no significant effect on 100 seed weight. An increase in NaCl concentration reduced 100-seed weight. No significant difference was observed between salinity levels. Under salinity conditions, 100-seed weight showed a 12% reduction compared to the control conditions (Fig. 1).

3.2 Biological Yield, Seed Yield and Harvest Index

Foliar application of SA and Si reduced the damage caused by salinity stress and increased the biological and seed yield of safflower. In non-stress and 7.5 dS m^{-1} salinity conditions, 1200 µM SA along with 2.5 mM Si increased biological yield by 194% and 154% and seed yield by 129% and 96%, respectively, compared to the non-application of these two compounds at the same conditions. At the highest salinity level, the highest biological and seed yield was related to 1200 µM SA along with 1.5 mM Si, which caused a 158% and 107% increase respectively compared to the non-application of these two compounds at the same stress level (Table 1). Our results show that at the highest concentration of SA, biological and seed yield decreased in both stress and non-stress conditions regardless of the Si levels. It shows a negative effect of SA at this concentration in safflower. The harvest index decreased under salinity stress (Table 1). This reduction was sharp from non-stress conditions to 7.5 dS m^{-1}, but the reduction was slight from this level to the severe salinity stress level. These findings suggest that although salinity decreased the seed and biological yield, salinity had more effects on seed yield than biomass production. In contrast, the separate and combined treatments of SA and Si under stress and non-stress conditions increased HI. In the non-stress and 7.5 dS m^{-1} salinity conditions, 1200 µM SA along with 2.5 mM Si caused the highest HI, an increase of 18% and 28% compared to the non-application of these two compounds at the same stress levels, respectively. At 15 dS m^{-1} salinity, the highest HI was related to 1200 µM SA along with 1.5 mM Si treatment, which increased HI by 31% compared to the non-application of these two compounds (Table 1). It shows that spraying of SA and Si healing effects also increased with increasing salt levels.

3.3 Seed Oil Quantity and Quality

Salt stress reduced seed oil content and oil yield per plant. Although seed oil content was reduced rapidly under moderate salt stress compared to non-stress conditions, this reduction was slight but significant between the salt levels (Table 1). The results showed that SA and Si could increase oil percentage and yield under stress and non-stress conditions. Under the non-stress conditions, the highest effect of SA and Si was found in 1200 µM SA along with 2.5 mM Si which enhanced seed oil content from 23.4 to 32.3%. Like to the non-stress conditions in 7.5 dS m^{-1} salt level, 1200 µM SA and 2.5 mM Si increased oil percentage and oil yield. Treated plants with 1200 µM SA and 1.5 mM Si showed the highest oil percentage and oil yield compared to the non-application of these two compounds at the highest level of salinity stress (Table 1).

The fatty acids profile showed that salinity caused a change in the oil quality. Salinity stress increased the content of palmitic, stearic, and oleic acids and decreased the amount of linoleic acid in safflower. At all salinity levels, the combination of SA and Si reduced the content of palmitic acid, stearic acid and oleic acid and increased the linoleic acid content (Table 2). For instance, in non-stress conditions linoleic acid content was increased from 64.8% in non-treated plants to 82.8% in application of 1200 µM SA

Table 1 Interaction of salicylic acid and silicon foliar application on height, biomass, number of capitulum per plant, number of seeds per capitulum, seed yield, harvest index, oil percentage, and oil yield at different salinity levels

Salt stress (dS m^{-1})	Salicylic acid (μM)	Silicon(mM)	Height (cm)	Biomass (g $plant^{-1}$)	Number of capitul per plant	Number of seed per capitul	Seed yield (g $plant^{-1}$)	Harvest index (%)	Oil percentage (%)	Oil yield (g $plant^{-1}$)
1.7 (control)	0	0	56.92 ± 1.39	7.23 ± 0.59	2.22 ± 0.12	17.72 ± 2.27	1.63 ± 0.114	22.6 ± 0.641	23.40 ± 1.44	0.385 ± 0.049
		1.5	67.80 ± 1.48	9.67 ± 0.2	2.41 ± 0.097	18.96 ± 1.31	2.26 ± 0.112	23.35 ± 0.679	25.03 ± 1.88	0.570 ± 0.069
		2.5	69.45 ± 0.91	10.42 ± 0.28	2.56 ± 0.13	19.74 ± 0.96	2.56 ± 0.093	24.54 ± 0.318	26.12 ± 1.82	0.671 ± 0.069
	600	0	71.91 ± 1.3	11.21 ± 0.34	2.58 ± 0.081	19.80 ± 0.99	2.78 ± 0.096	24.78 ± 0.121	26.29 ± 1.82	0.734 ± 0.076
		1.5	71.97 ± 0.61	11.71 ± 0.33	2.90 ± 0.052	20.01 ± 0.15	2.92 ± 0.126	24.96 ± 0.429	27.98 ± 1.48	0.822 ± 0.079
		2.5	74.03 ± 1.87	12.57 ± 0.42	2.91 ± 0.047	20.89 ± 0.43	3.18 ± 0.121	25.28 ± 0.451	28.60 ± 1.53	0.912 ± 0.083
	1200	0	76.31 ± 1.95	12.68 ± 0.18	3.13 ± 0.067	21.02 ± 0.35	3.28 ± 0.077	25.87 ± 0.295	29.24 ± 2.02	0.961 ± 0.083
		1.5	78.67 ± 3.4	13.74 ± 0.29	3.2 ± 0.12	21.27 ± 1.54	3.61 ± 0.112	26.25 ± 0.279	29.67 ± 2.17	1.075 ± 0.108
		2.5	83.90 ± 0.98	14.02 ± 0.44	3.57 ± 0.033	21.56 ± 1.09	3.73 ± 0.103	26.62 ± 0.108	32.30 ± 1.99	1.209 ± 0.106
	1800	0	69.06 ± 1.06	10.75 ± 0.31	2.69 ± 0.059	20.54 ± 0.67	2.48 ± 0.070	23.09 ± 0.147	26.04 ± 1.74	0.648 ± 0.061
		1.5	70.35 ± 0.92	11.13 ± 0.4	2.72 ± 0.053	20.62 ± 0.87	2.69 ± 0.122	24.18 ± 0.582	26.95 ± 1.36	0.729 ± 0.069
		2.5	68.24 ± 0.70	10.33 ± 0.33	2.44 ± 0.07	19.28 ± 0.18	2.32 ± 0.088	22.45 ± 0.477	25.41 ± 1.83	0.592 ± 0.065
7.5	0	0	50.73 ± 1.83	6.93 ± 0.51	1.83 ± 0.115	16.84 ± 1.32	1.31 ± 0.103	18.85 ± 0.49	21.92 ± 1.60	0.289 ± 0.043
		1.5	56 ± 1.07	7.67 ± 0.13	2.03 ± 0.102	16.96 ± 1.12	1.58 ± 0.011	20.57 ± 0.205	22.72 ± 1.86	0.359 ± 0.032
		2.5	58.86 ± 1.41	8.08 ± 0.24	2.17 ± 0.003	17.27 ± 1.82	1.68 ± 0.037	20.87 ± 0.169	23.55 ± 1.95	0.398 ± 0.042
	600	0	60.76 ± 1.62	8.29 ± 0.21	2.20 ± 0.063	17.91 ± 0.31	1.77 ± 0.072	21.27 ± 0.315	23.78 ± 1.89	0.422 ± 0.051
		1.5	62.75 ± 2.28	9.06 ± 0.13	2.38 ± 0.096	18.67 ± 0.45	2.00 ± 0.101	22.09 ± 0.807	24.26 ± 1.40	0.488 ± 0.051
		2.5	63.8 ± 0.13	9.48 ± 0.04	2.52 ± 0.023	19.33 ± 0.60	2.10 ± 0.055	22.12 ± 0.52	24.32 ± 1.86	0.512 ± 0.052
	1200	0	64.31 ± 1.32	9.68 ± 0.32	2.78 ± 0.036	19.79 ± 0.57	2.15 ± 0.096	22.17 ± 0.354	25.36 ± 1.94	0.548 ± 0.066
		1.5	68.02 ± 0.24	10.01 ± 0.55	2.84 ± 0.124	19.92 ± 70	2.29 ± 0.103	22.89 ± 0.466	25.41 ± 1.69	0.585 ± 0.064
		2.5	70.05 ± 0.81	10.67 ± 0.61	2.95 ± 0.047	20.58 ± 1.02	2.57 ± 0.159	24.09 ± 0.156	27.23 ± 1.95	0.706 ± 0.089
	1800	0	61.49 ± 0.7	8.64 ± 0.24	2.10 ± 0.053	19.14 ± 0.9	1.80 ± 0.061	20.87 ± 0.17	23.30 ± 1.86	0.423 ± 0.048
		1.5	62.87 ± 0.44	9.70 ± 0.37	2.32 ± 0.093	19.47 ± 1.09	2.04 ± 0.123	20.98 ± 0.486	24.16 ± 1.27	0.496 ± 0.055
		2.5	58.53 ± 1.86	8.55 ± 0.28	2.05 ± 0.047	18.97 ± 0.24	1.68 ± 0.069	19.66 ± 0.182	23.02 ± 1.41	0.389 ± 0.040
15	0	0	46.67 ± 1.2	5.83 ± 0.089	1.61 ± 0.057	14.83 ± 0.9	1.04 ± 0.031	17.78 ± 0.27	19.61 ± 1.66	0.204 ± 0.023
		1.5	53 ± 1.70	6.34 ± 0.36	1.71 ± 0.084	16.10 ± 0.29	1.17 ± 0.058	18.43 ± 0.406	21.29 ± 1.20	0.250 ± 0.026
		2.5	53.56 ± 1.44	6.76 ± 0.42	1.86 ± 0.084	16.26 ± 0.50	1.33 ± 0.068	19.62 ± 0.204	21.37 ± 1.64	0.285 ± 0.036
	600	0	56.16 ± 2.23	7.21 ± 0.35	1.92 ± 0.116	16.84 ± 0.79	1.45 ± 0.091	20.06 ± 0.525	21.48 ± 1.51	0.314 ± 0.041
		1.5	56.67 ± 2.03	7.54 ± 0.56	2.04 ± 0.104	17.62 ± 1.20	1.61 ± 0.098	21.46 ± 0.405	22.15 ± 1.32	0.360 ± 0.043
		2.5	60.83 ± 0.75	8.18 ± 0.84	2.11 ± 0.056	17.79 ± 1.70	1.78 ± 0.160	21.85 ± 0.33	23.05 ± 1.43	0.415 ± 0.061

Table 1 (continued)

Salt stress (dS m^{-1})	Salicylic acid (μM)	Silicon(mM)	Height (cm)	Biomass (g $plant^{-1}$)	Number of capitul per plant	Number of seed per capitul	Seed yield (g $plant^{-1}$)	Harvest index (%)	Oil percentage (%)	Oil yield (g $plant^{-1}$)
	1200	0	62.69 ± 1.01	8.29 ± 0.41	2.31 ± 0.077	18.78 ± 0.57	1.86 ± 0.035	22.49 ± 0.72	23.57 ± 2.05	0.440 ± 0.046
		1.5	64.99 ± 0.94	9.24 ± 0.36	2.61 ± 0.15	18.93 ± 0.33	2.15 ± 0.082	23.25 ± 0.027	25.10 ± 2.05	0.543 ± 0.063
		2.5	63.28 ± 0.73	8.95 ± 0.21	2.34 ± 0.032	18.83 ± 0.47	2.05 ± 0.040	22.85 ± 0.298	22.55 ± 1.51	0.46 ± 0.039
	1800	0	53.74 ± 2.6	6.50 ± 0.4	1.88 ± 0.060	16.44 ± 0.14	1.36 ± 0.084	20.88 ± 0.051	21.09 ± 1.35	0.288 ± 0.035
		1.5	55.56 ± 1.13	7.15 ± 0.27	2.05 ± 0.090	17.08 ± 0.43	1.54 ± 0.039	21.52 ± 0.56	21.77 ± 1.44	0.335 ± 0.029
		2.5	51.66 ± 1.92	5.96 ± 0.032	1.70 ± 0.075	16.36 ± 0.35	1.20 ± 0.013	20.08 ± 0.137	20.68 ± 1.56	0.248 ± 0.021
LSD			3.035	0.555	0.158	2.49	0.122	1.13	0.923	0.064

Data represents the average of three replicates (n = 3) ± standard error. Differences between means were evaluated by using the least significant difference (LSD) test ($P \leq 0.05$)

and 2.5 mM Si. Also, the content of palmitic acid decreased in the non-stress and 7.5 dS m^{-1} salinity conditions, by mentioned SA and Si concentrations by 19% and 10%, respectively, compared to the non-treated plants at the same levels. A 13% reduction in palmitic acid content of was observed with the application of 1200 μM SA along with 1.5 mM Si compared to the non-application of these two compounds at the highest level of salinity stress (Table 2). Similarly, this situation was found for stearic and oleic acid.

Like the seed oil content, salinity stress decreased the yield of palmitic, stearic and linoleic acids and increased the yield of oleic acid in safflower. At all salinity levels, the application of SA and Si increased palmitic and linoleic acid yield (Table 2). Under non-stress conditions, the oleic acid yield was decreased due to the application of SA and Si, but surprisingly, it was increased under moderate and severe stress conditions (Table 3). The salted treatments sprayed with 1800 μM SA and all Si concentrations showed the highest oleic acid yield (Table 3). In the non-stress and 7.5 dS m^{-1} salinity conditions, the application of 1200 μM SA with 2.5 mM Si showed the most significant increase in the yield of palmitic and linoleic acids (Table 2). At the highest level of salinity stress, the treatment of 1200 μM SA and 1.5 mM Si caused an increase in the yield of palmitic acid and linoleic acids compared to the non-application of these two compounds (Table 2).

In general, the amount of stearic acid yield increased with applying SA and Si in stress and non-stress conditions. Foliar application of 2.5 mM Si without SA at non-stress conditions had the highest yield of stearic acid (49% increases) compared to the non-application of these two compounds at non-salinity conditions. The lowest yield of stearic acid was achieved in the non-application of these two compounds at 15 dS m^{-1} salinity level (Table 2).

3.4 Seed Protein Percentage, Seed Potassium and Sodium Contents

Salinity stress increased seed protein percentage in the seeds. An increasing trend in the seed protein percentage was observed with the application of SA and Si under saline and non-saline conditions. The highest protein content was found in severe salinity treatment and application of 1200 μM SA and 1.5 mM Si spraying. On the other hand, the lowest seed protein was in the non-treated plants grown under non-stress conditions. In the non-stress and 7.5 dS m^{-1} salinity conditions, the combined treatment of 1200 μM SA with 2.5 mM Si was the superior treatment in terms of increasing the seed protein percentage (Table 3). Separate application of Si and SA raised the seed protein percentage in safflower compared to the control treatment, but the co-application of these two compounds had more significant additive effect on the seed protein percentage.

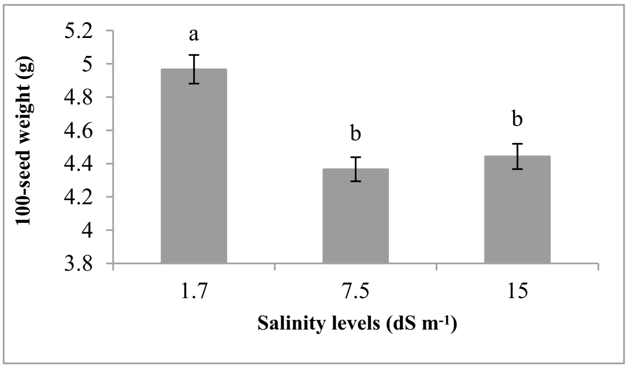

Fig. 1 Effect of salinity on the 100-seed weight of safflower. Columns with the same letters do not differ significantly (LSD test $P \leq 0.05$)

The seed sodium content was not affected by salinity, salicylic acid, silicon, and their interactions. In contrast, seed potassium content was affected by salinity and SA and Si application. Salinity reduced seed K content but separate and combined treatments of SA and Si increased it in stress and non-stress. Seed K content was increased up to 47.6% by spraying 1200 μM SA and 1.5 mM Si at 15 dS m^{-1} salinity compared to the non-application of them at the same salinity level (Table 3).

4 Discussions

High salt levels in soils can be toxic to plants, alter their morphology, and interfere with their physiological, biochemical, and molecular functions [1, 21]. Exogenous application of Si and SA can positively affect the quantitative and qualitative yield of plants by improving growth characteristics, increasing the uptake of essential elements, and decreasing the content of harmful elements in the shoot and root parts under environmental stresses, such as salinity [2, 15, 26].

Safflower height and biological yield were decreased by applying salinity. Increasing salt accumulation in the soil by reducing the potential of soil solution causes osmotic stress in plants [27]. The continuation of such conditions affects the plant tissues' water status. On the other hand, the production of toxic ions, oxidative damage, and nutritional disorders resulting from salinity stress affect plant water relations and reduce cell division and development, ultimately decreasing plant growth [1, 4, 6, 7]. Also, it is reported that all growth parameters decreased with increasing NaCl concentration in safflower [28, 29].

Exogenous application of SA at optimal concentrations has shown beneficial effects on plant growth and development grown under both normal and stressful conditions [7, 30]. Numerous studies have reported improvement in plant growth with SA treatment, especially under stress. For example, height and biomass in cotton [9] and dry weight in peanut [17] and mung bean [31] increased with SA application under salinity. Salicylic acid modulates cell division and expansion by regulating the transcription of critical genes, such as cell cycle-related genes and cell wall-loosening genes [32]. The positive effect of SA on chlorophyll content is due to the stimulation of mineral assimilation and the inhibition of free radical synthesis [7, 33]. Ethylene affects stomatal closure in plants, and SA limits ethylene production by inhibiting the activity of 1-aminocyclopropane-1-carboxylic acid synthase. On the other hand, decreased potassium content stimulates ethylene formation while potassium accumulation due to SA treatment inhibits ethylene formation. It is reported; SA improved the stomatal density and conductance notably under stress [34]. Salicylic acid affects some metabolic factors in carbon fixation including Rubisco enzyme concentration and activity, and/or photosynthetic carbon reduction cycle [35]. Also, SA treatment may affect the SOS (salt over sensitive) pathway, notably SOS4 and SOS5 and regulate sodium and potassium homeostasis [34]. Also, this hormone enhances the absorption of essential elements and water by improving root growth [30]. Finally, improvement of biological yield with SA treatment can be due to the incremental effects on cell division and development, height, chlorophyll, leaf area, photosynthesis, and the content of K, N, Ca, and Mg as well as its reducing effect on Na content [9, 30].

Silicon increase the chlorophyll content by improving the uptake of essential elements for chlorophyll biosynthesis, such as nitrogen and iron. On the other hand, silicon raises the stomatal conductance by increasing the stomatal density and aperture size. Finally, by increasing the chlorophyll content and stomatal conductance, silicon increases the photosynthetic rate and as a result plant growth [36, 37]. Silicon-treated plants under environmental stress showed increased biomass production and improved tolerance due to the adequate uptake of Si [38, 39]. This increase was associated with increased in chlorophyll and photosynthesis and a reduction in oxidative damage by increasing gene expression and activity of antioxidant enzymes [5, 34, 40]. As well as an increment in the relative water content and water absorption by improving root hydraulic conductivity [41]. It has been reported that the shoot's dry weight increased with the application of Si in the peanut [17] and safflower [2], and this increase was effective due to the increment of Si accumulation in the shoot. Under salinity stress, Si application improved plant height, leaf area, and consequently plant biomass via increasing photosynthesis and associated traits and RWC [2, 40].

In this study, the synergistic effect of SA and Si was observed on growth, seed yield, and quantity and quality of oil in safflower. Silicon and SA separately have positive

Table 2 Interaction of salicylic acid and silicon foliar application on palmitic acid, stearic acid, linoleic acid yield and oleic acid percentage, |palmitic acid, stearic acid and linoleic acid at different salinity levels

Salt stress (dS m^{-1})	Salicylic acid (μM)	Silicon (mM)	Palmitic acid (%)	Stearic acid (%)	Linoleic acid (%)	Oleic acid (%)	Palmitic acid yield (mg $plant^{-1}$)	Stearic acid yield (mg $plant^{-1}$)	Linoleic acid yield (mg $plant^{-1}$)
1.7 (control)	0	0	12.88 ± 0.88	12.65 ± 0.35	64.82 ± 0.85	5.48 ± 0.94	50.02 ± 9.05	48.88 ± 7.28	249.4 ± 32.86
		1.5	12.43 ± 0.68	11.56 ± 0.35	67.73 ± 0.39	4.26 ± 0.54	71.40 ± 11.82	66.16 ± 9.54	386.05 ± 47.62
		2.5	12.08 ± 0.42	10.83 ± 0.41	70.02 ± 1.03	0.64 ± 0.071	81.26 ± 9.85	72.80 ± 8.75	469.11 ± 44.43
	600	0	11.87 ± 0.42	8.13 ± 0.38	72.88 ± 1.48	0.53 ± 0.043	87.61 ± 11.68	59.86 ± 7.73	534.63 ± 52.89
		1.5	11.83 ± 0.36	7.88 ± 0.39	75.31 ± 1.54	0.46 ± 0.041	97.76 ± 12.32	65.00 ± 8.3	617.9 ± 53.77
		2.5	11.56 ± 0.21	7.72 ± 0.22	77.31 ± 0.62	0.36 ± 0.047	105.78 ± 11.34	70.54 ± 7.39	704.65 ± 59.52
	1200	0	11.55 ± 0.28	4.72 ± 0.37	79.95 ± 0.99	0.3 ± 0.047	111.41 ± 11.97	45.52 ± 6.2	767.84 ± 62.64
		1.5	11.52 ± 0.31	4.54 ± 0.31	80.84 ± 1.2	0.22 ± 0.050	124.19 ± 14.77	48.94 ± 6.82	867.83 ± 81.88
		2.5	10.4 ± 0.24	4.29 ± 0.25	82.81 ± 1	0.16 ± 0.012	126.12 ± 13.12	52.11 ± 6.62	1000.43 ± 81.2
	1800	0	12.24 ± 0.1	8.88 ± 0.48	71.66 ± 0.98	0.9 ± 0.22	79.45 ± 8.07	57.83 ± 7.69	463.43 ± 40.29
		1.5	12.07 ± 0.24	8.64 ± 0.98	73.72 ± 1.25	0.78 ± 0.131	88.10 ± 9.46	63.91 ± 12.79	535.61 ± 42.3
		2.5	12.39 ± 0.27	11.24 ± 0.33	69.42 ± 1.09	1 ± 0.076	73.66 ± 9.47	66.94 ± 9.19	410.16 ± 39.76
7.5	0	0	13.12 ± 0.25	14.68 ± 0.24	61.39 ± 0.42	9.3 ± 0.12	38.11 ± 6.36	42.61 ± 6.99	177.25 ± 25.57
		1.5	12.92 ± 1.02	13.53 ± 0.53	63.76 ± 1.14	6.74 ± 0.13	46.77 ± 7.3	48.7 ± 5.52	228.43 ± 18.11
		2.5	12.82 ± 0.24	12.69 ± 0.87	64.18 ± 128	6.51 ± 0.14	51.22 ± 6.25	51.13 ± 8.63	254.86 ± 23.4
	600	0	12.67 ± 0.28	11.03 ± 0.24	67.56 ± 0.72	6.14 ± 0.99	53.60 ± 6.92	46.67 ± 6.07	284.89 ± 31.6
		1.5	12.48 ± 0.47	10.51 ± 0.51	67.92 ± 0.41	3.64 ± 0.68	61.08 ± 7.5	51.43 ± 6.54	331.5 ± 33.11
		2.5	12.42 ± 0.34	9.98 ± 0.47	68.39 ± 0.49	3.02 ± 0.69	63.77 ± 7.53	51.34 ± 6.84	350.11 ± 34.43
	1200	0	12.11 ± 0.28	8.48 ± 0.32	69.45 ± 0.34	2.68 ± 0.64	66.67 ± 9.32	46.67 ± 6.7	380.59 ± 44.56
		1.5	11.98 ± 0.25	7.95 ± 0.25	71.11 ± 0.58	2.21 ± 0.35	70.30 ± 9.07	46.6 ± 5.98	415.06 ± 42.47
		2.5	11.86 ± 0.31	5.51 ± 0.25	73.87 ± 0.57	2.09 ± 0.41	83.95 ± 11.95	38.91 ± 5.54	520.2 ± 62.07
	1800	0	12.58 ± 0.65	10.98 ± 0.37	64.16 ± 0.86	6.24 ± 0.157	53.56 ± 8.41	46.56 ± 6.33	270.38 ± 27.38
		1.5	12 ± 0.31	9.34 ± 0.33	65.69 ± 0.57	6.06 ± 0.137	59.69 ± 7.66	46.42 ± 5.96	325.4 ± 34.35
		2.5	12.11 ± 0.48	9.89 ± 0.28	65.54 ± 0.99	6.72 ± 0.55	47.42 ± 6.47	38.61 ± 4.66	254.52 ± 22.79
15	0	0	14.36 ± 0.46	16.7 ± 0.36	55.26 ± 1.26	12.16 ± 0.33	29.5 ± 4.13	34.17 ± 4.19	112.58 ± 11.11
		1.5	13.9 ± 0.28	15.76 ± 1.04	57.67 ± 1.21	11.68 ± 0.06	34.82 ± 4.28	39.61 ± 6.12	143.64 ± 13.47
		2.5	13.87 ± 0.44	14.71 ± 0.53	60.23 ± 1.04	9.84 ± 0.34	39.75 ± 5.89	42.07 ± 6.03	171.5 ± 20.13
	600	0	12.98 ± 0.2	14.33 ± 0.66	62.24 ± 0.68	8.17 ± 0.23	40.82 ± 5.82	45.15 ± 7.18	194.84 ± 24.01
		1.5	12.78 ± 0.93	13.92 ± 0.61	62.94 ± 1.23	6.62 ± 0.38	46.5 ± 8.31	50.35 ± 7.41	226.12 ± 24.46
		2.5	12.59 ± 0.5	13.69 ± 0.25	64.15 ± 0.88	6.23 ± 0.27	52.69 ± 9.29	56.92 ± 8.7	265.79 ± 36.55
	1200	0	12.46 ± 0.23	12.93 ± 0.22	66.24 ± 0.32	6.17 ± 0.18	54.93 ± 6.55	56.92 ± 6.45	290.94 ± 29.05
		1.5	12.5 ± 0.55	11.94 ± 0.81	67.08 ± 1.59	6.14 ± 0.25	68.25 ± 10.3	65.17 ± 10.55	263.04 ± 38.61
		2.5	12.9 ± 0.47	10.3 ± 0.28	70.17 ± 0.91	4.11 ± 0.70	59.86 ± 6.74	47.79 ± 5.17	323.88 ± 24.36
	1800	0	13.01 ± 0.55	14.78 ± 0.31	60.79 ± 1.37	9.55 ± 0.27	37.73 ± 5.82	42.65 ± 5.59	174.69 ± 19.14
		1.5	12.82 ± 0.46	12.71 ± 0.32	62.6 ± 1.11	8.61 ± 0.42	43.17 ± 4.96	42.74 ± 4.49	209.69 ± 16.73
		2.5	13.87 ± 0.81	16.47 ± 0.23	57.76 ± 1.19	10.18 ± 0.49	34.54 ± 4.39	40.86 ± 3.75	142.91 ± 10.6
LSD			0.660	0.641	1.537	0.972	8.191	5.82	52.44

Data represents the average of three replicates (n = 3) ± standard error. Differences between means were evaluated by using the least significant difference (LSD) test ($P \leq 0.05$)

effects on the physiological characteristics, photosynthesis, relative water content, soluble sugar content, Mg, Ca, and K uptake, and growth of plants. Also, Si application increases the endogenous SA level, notably under stress. On the other hand, a combination of Si and SA can alleviate environmental stresses in plants by increasing the compatible solutes, raising K uptake, decreasing Na and Cl ionic toxicity, and increasing the antioxidant defense system that this causes to retain the balance of reactive oxygen species and malondialdehyde content. These complex interactions improve plant growth, development, and yield traits [39]. However, the exact mechanism of the synergistic effect of silicone and salicylic acid has not been clearly defined yet. In some studies, the synergistic effect of SA and Si on plant growth

Table 3 Interaction of salicylic acid and silicon foliar application on oleic acid yield, seed protein and seed potassium percent at different salinity levels

Salt stress (dS m^{-1})	Salicylic acid (μM)	Silicon (mM)	Oleic acid yield (mg $plant^{-1}$)	Seed protein (%)	Seed potassium (%)
1.7 (control)	0	0	20.6 ± 3.45	13.04 ± 3.2	0.201 ± 0.0075
		1.5	24.49 ± 4.49	15.06 ± 4.06	0.2047 ± 0.0043
		2.5	4.38 ± 0.90	16 ± 1.62	0.2093 ± 0.0096
	600	0	3.85 ± 0.42	17.29 ± 3.07	0.2183 ± 0.0022
		1.5	3.84 ± 0.66	17.75 ± 2.53	0.2242 ± 0.0062
		2.5	3.31 ± 0.63	17.81 ± 2.35	0.2286 ± 0.0038
	1200	0	2.93 ± 0.67	18.63 ± 3.5	0.2307 ± 0.0039
		1.5	2.44 ± 0.78	19.23 ± 2.01	0.2342 ± 0.0038
		2.5	1.941 ± 0.25	20.69 ± 2.53	0.2436 ± 0.0058
	1800	0	5.98 ± 1.89	15.61 ± 4.55	0.2156 ± 0.0015
		1.5	5.85 ± 1.55	16.31 ± 1.44	0.2201 ± 0.0061
		2.5	5.93 ± 0.761	14.94 ± 1.44	0.2119 ± 0.0032
7.5	0	0	26.99 ± 4.41	16.27 ± 2.49	0.1845 ± 0.0015
		1.5	24.13 ± 1.93	18.77 ± 5.48	0.189 ± 0.0034
		2.5	26.04 ± 3.30	21.63 ± 1.62	0.1906 ± 0.0036
	600	0	26.54 ± 7	21.81 ± 1.08	0.1984 ± 0.0034
		1.5	18.15 ± 4.83	23.38 ± 2.17	0.2114 ± 0.0037
		2.5	15.90 ± 5.00	24.98 ± 1.77	0.2159 ± 0.0021
	1200	0	15.3 ± 5.32	25.56 ± 2.53	0.2167 ± 0.0037
		1.5	13.22 ± 3.40	26.38 ± 3.43	0.2239 ± 0.0031
		2.5	15.08 ± 4.45	28.81 ± 2.46	0.2280 ± 0.0058
	1800	0	26.45 ± 3.34	22.88 ± 1.98	0.1997 ± 0.0028
		1.5	30.21 ± 3.95	24.63 ± 3.14	0.2155 ± 0.0063
		2.5	26.48 ± 4.69	19.94 ± 2.78	0.1925 ± 0.005
15	0	0	24.95 ± 3.37	17.88 ± 2.44	0.1421 ± 0.015
		1.5	29.2 ± 3.23	21.83 ± 2.26	0.1713 ± 0.0068
		2.5	28.23 ± 4.28	24.79 ± 1.14	0.1835 ± 0.0016
	600	0	25.75 ± 3.95	25.88 ± 1.26	0.1836 ± 0.0044
		1.5	24.09 ± 4.09	27.37 ± 0.902	0.1901 ± 0.007
		2.5	26.06 ± 4.63	27.44 ± 2.53	0.1967 ± 0.0019
	1200	0	27.25 ± 3.52	29.94 ± 5.23	0.1988 ± 0.0021
		1.5	33.52 ± 4.98	31.92 ± 2.44	0.2097 ± 0.0077
		2.5	19.34 ± 4.69	27.69 ± 4.7	0.2004 ± 0.0004
	1800	0	27.57 ± 3.7	24.75 ± 5.77	0.1826 ± 0.0024
		1.5	29.01 ± 3.58	25.82 ± 1.59	0.1859 ± 0.001
		2.5	25.37 ± 3.16	20.37 ± 3.9	0.1756 ± 0.0027
LSD			6.08	3.57	0.0136

Data represents the average of three replicates (n = 3) ± standard error. Differences between means were evaluated by using the least significant difference (LSD) test ($P \leq 0.05$)

and environmental stress tolerance has been identified too. Combined foliar application of SA and Si in mung bean and spinach plants reduced sodium uptake and increased RWC, stomatal conductance, chlorophyll index, leaf area index, potassium uptake, biomass, and seed yield by improving root growth in saline conditions. This indicates that the accumulation of sodium ions in roots somehow helped to decrease the concentration of accumulated sodium ions in shoots [29, 42]. Also, these researchers reported that during salinity stress, an increment in water uptake by improving root growth due to the combined application of SA and Si increased RWC in leaves, leading to stomatal opening and increasing stomatal conductance and photosynthetic rate finally growth and yield [42]. In wheat, the separate application of Si and SA increased RWC, soluble sugars, soluble protein, the content of K, Ca, and Mg, antioxidant enzyme activity, and biological yield but the co-application of these two compounds had a more significant additive effect on the above traits and drought tolerance [41]. In chickpea plants exposed to boron toxicity, the co-application of SA and Si raised the fresh and dry biomass of the shoot by increasing the antioxidant defense system and the content of chlorophyll and carotenoids [15]. The application of SA, especially when combined with the foliar application of Si, increased the dry weight of the peanut plant [17]. Contrary to the above studies, it has been reported that the foliar application of Si and SA or their separate application had no significant effect on increasing resistance to nitrogen deficiency stress in rice [38]. Also, the co-application of Si and SA in soybean improved photosynthesis, while in beans it had the opposite effect [16]. Based on this, it seems that the interaction of Si and SA varies depending on the plant species, plant age, and Si and SA concentrations at the time of application.

Salinity reduced seed yield, yield components, oil content, and oil yield in safflower, consistent with other researchers' results [19, 43]. It has been reported that the high salinity concentration in soil and water can reduce the quantitative and qualitative yield of the plant by causing toxicity in the plant [7]. Data showed that both seed yield and oil percent were reduced under salt stress conditions, but the oil yield was more related to seed yield than seed oil percent. In other word, a direct relationship was observed between seed yield and oil yield. Despite the increase in oil content under salinity stress in soybean, the oil yield is also reduced with decreasing seed yield [44].

One factor that reduces the yield of safflower under salinity stress can be a decrease in the lateral branches and capitulum number, which occurred due to a decrease in the number of flowers and the loss of capitula. Hussain and Al-Dakheel [29] declared a similar report on the safflower under salinity stress. The reduction in oil percentage may be due to the participation of some fatty acids, such as linoleic acid in cellular hardening. In salinity stress, fatty acids produce certain enzymes, such as lipoxygenase, to increase salinity tolerance [45]. Reduced oil content and oil yield in safflower due to salinity were in line with the study of Flagella et al. [46] on sunflower.

An increase in safflower seed yield with SA is due to its positive role on flowering, the number of capitula per plant and the number of seeds per capitulum (Table 1). This result was consistent with the results of Lotfi et al. [31] who reported that the number of pods per plant, the number of seeds per plant, and seed yield increased with the application of SA in mung beans. Despite reducing the oil percentage, application of SA in soybean plants increased oil yield due to increased seed yield [44]. The results of this study about the positive effects of SA on the quantitative and qualitative yield of safflower, especially under saline conditions, agreed with the above results. It has been reported that improving root growth and water and nutrient uptake by applying SA at salinity stress can lead to improved plant growth and quantitative and qualitative yield [7, 30]. Raised seed yield in chickpeas with SA treatment has been attributed to an increase in root length, photosynthetic rate, stomatal conductance, number of pods, and 100-seed weight due to this hormone [47].

In the present study, a positive effect of Si on the growth and quantitative and qualitative yield of safflower was observed under salinity stress (Tables 1, 2 and 3). Previous research has indicated that plants treated with Si under environmental stresses show an increase in seed yield due to adequate Si uptake [38, 39]. Si increased some physiological traits and capitulum number in safflower and, in this way, led to an increase in safflower seed yield [13]. It has been reported that the application of Si in sesame increased the number of capsules per plant, the number of seeds per capsule, 1000-seed weight, seed yield, and oil content [48]. The results of this study about the increase in seed yield, yield components, and oil content with the application of Si under salinity stress were consistent with the results of the above studies. This increase can be attributed to the positive role of Si in improving chlorophyll, water content, and photosynthesis, which leads to an increment in flowering and seed formation as well as the availability of more photosynthetic assimilates for the developing seeds.

This study showed a synergistic effect of SA and Si on safflower's seed yield and yield components. In this regard, it has been reported that in saline conditions, the co-application of SA and Si improved the seed yield of mung beans via reducing Na uptake and increasing chlorophyll index, leaf area index, and K content [42]. Also, the co-application of SA and Si had a more significant incremental effect on the number of seeds per spike, 1000-grain weight, and seed yield in wheat [41] and pod formation in peanut [17] compared to the separate application of Si and SA. It seems that the synergistic effect of SA and Si can be attributed to the crucial roles of these compounds in the morphophysiological, and biochemical processes of plants and the uptake of water and nutrients.

The positive effect of the interaction of Si and SA in safflower under salinity stress could be due to the effect of these two compounds on gene expression. In this regard, it has been reported that in stressful environments, both Si and SA positively regulate critical genes involved in rhizosphere acidification, antioxidant defense, SA biosynthesis, and Si uptake in plants and inhibit the expression of genes responsible for the biosynthesis of abscisic acid in the roots and shoots [39]. On the other hand, it has been specified that Si together with SA can reduce the polymerization reactions of Si to help its uptake [17]. This indicates that the co-application of these two compounds helps provide silicon for oilseed crops with limited root uptake for Si.

Salinity stress reduced the harvest index in safflower plants. Although both seed yield and biological yield decreased under stress conditions, seed yield showed a more significant decrease than to biological yield. Reduction of HI under salinity stress was associated with a more significant reduction in seed yield compared to biological yield in salinity conditions. In contrast, the improvement of HI with the application of SA and Si showed an incremental effect of them on the seed yield compared to the biological yield. The results of this study about the reduction of HI in safflower under salinity stress were in line with the study by Hussain and Al-Dakheel [29], who stated that HI in safflower decreased with increasing NaCl concentration. In the mung bean, HI also increased with the application of SA [31]. The results of this study about the positive effect of Si on the HI were in accordance with the results of the study by Manaf et al. [48], who declared that the application of Si in sesame increased seed yield and HI. In our study, the observed synergistic effect between SA and Si on the HI was consistent with the results of the study by Maghsoudi et al. [41] in wheat and Lotfi et al. [31] in mung bean, who stated that the co-application of Si and SA raised the HI.

Fatty acids content and quality are quantitative traits that are affected by genetic and environmental factors [18, 49]. Changes in the amount and composition of seed fatty acids due to salinity stress have been reported in several studies. For example, the content of palmitic and oleic acids decreased in safflower under salinity conditions, while the amount of stearic, linoleic, and linolenic acids increased [19]. Salinity in soybean decreased the amount of linoleic acid and the yield of palmitic, stearic, oleic, and linoleic acids and increased the amount of palmitic, stearic, and oleic acids [44], which was in line with the results of our study. Decreased linoleic acid and increased oleic acid content have been reported in sunflower under salinity stress [46]. The significant change in the percentage of fatty acids under salinity stress indicates that safflower seeds' saturated and unsaturated fatty acids of have been affected by changes in environmental conditions. The water deficit under salinity stress can shorten the lipid accumulation stage, damaging all desaturase enzymes [46, 50]. Increased oleic acid percentage and decreased linoleic acid percentage in salinity conditions can be due to the rapid lipid accumulation and limited activity of all enzymes, such as the 12Δ desaturase enzyme (responsible for the unsaturation of oleic acid to linoleic acid) because sodium and chloride ions can inactivate these enzymes. These conditions can be harmful to lipid metabolism [46]. Oleic acid synthesis occurs by C18: 1 formation in plastids and unsaturation location to C18: 2 and C18: 3 in the cytosol. Since environmental stresses, such as salinity limit the transfer of oleic acid to the cytosol, thus, the percentage of oleic acid increases, and the percentage of linoleic acid decreases [51]. There was a direct relationship between the yield of fatty acids and seed yield, which indicates that the decrease in the yield of fatty acids at salinity could be due to reduced seed yield and the percentage of oil accumulated in the seed.

Improvement of fatty acid profiles with SA has been reported in several studies. The exogenous application of SA under salinity stress has increased oleic acid and decreased palmitic, stearic, linoleic, and linolenic acids [19]. Under drought stress, spraying plants with SA increased the amount of oleic and linoleic fatty acids and decreased palmitic and stearic acids in *Cucurbita pepo* L. [18]. Under salinity stress, the application of SA in soybean increased the amount of linoleic acid and the yield of palmitic, stearic, oleic, and linoleic acids and decreased the amount of palmitic, stearic, and oleic acids [44], which was in line with the results of this research. Decreased oleic acid percentage and increased linoleic acid percentage with the application of SA can be attributed to the increased fluidity of lipid membranes and the activity of the oleoyl-phosphatidylcholine D12 desaturase enzyme [52]. The decrease in stearic acid percentage can be due to a negative correlation with linoleic acid. It has also been reported that SA can play a role in reducing the detrimental effect of stresses on fatty acid metabolism in safflower so that the expression level of unsaturation genes of fatty acid (*FAD3* and *FAD7*) increased in SA treatments compared to the control group after 72 h [53]. Increased yield of fatty acids due to SA treatment was associated with raised seed and oil yield.

Silicon application has been proven not only to increase the growth and yield of plants, but also to improve their quality, such as fatty acids, proteins, sugars, and vitamins [54]. The results of this study about the positive effect of Si on the quality of fatty acids in the oil were in line with the results of the study by Manaf et al. [48], who stated that the application of Si in sesame increased the percentage of linoleic acid and decreased the percentage of stearic and palmitic acids. Improving the quality of fatty acids by Si treatment can be due to the role of Si in the increased uptake of required elements in their biosynthesis pathway by improving the root system [12] and also the increment of photosynthetic assimilation by improving photosynthesis [40]. Increased yield of fatty acids with Si treatment can be attributed to increased seed yield and oil yield by Si foliar application. Also, the synergistic effect of Si and SA on the quality of fatty acids in safflower under salinity stress can be because of these two compounds on the uptake of elements and gene expression. It has been reported that in stressful environments, both Si and SA positively regulate genes involved in antioxidant defense, nutrient uptake, growth, yield, and tolerance in plants [39].

Salinity stress increased seed protein percentage and decreased seed potassium content. In this regard, it has been reported that increased salinity stress may activate mechanisms for dealing with oxidative stress to prevent the degradation of structural and functional proteins. Also, increased protein content under salinity conditions can be due to increased synthesis of de novo-induced proteins from salinity or decreased activity of proteolytic enzymes [55]. Mervat et al. [43] reported that the seed protein percentage in sunflower increased due to irrigation with saline water, which is consistent with the results of our study. The application of SA increased the seed protein content of chickpeas and wheat [47, 56]. In this context, it has been reported that phytohormones increase the sink size at the level of seeds and direct the flow of metabolites into the growing seeds, thereby increasing the seed protein content and improving seed yield per plant [57]. This increase in seed protein content may be due to increased nitrate reductase activity with the application of SA [56]. The results of our study about the positive effect of Si on seed protein were in line with the study by Manaf et al. [48], who declared that the application of Si increased the protein percentage in sesame. Si can improve seed protein by increasing the uptake of necessary nutrients in the protein biosynthesis pathway [12] and by raising photosynthesis, and photosynthetic assimilates [40]. The synergistic effect of Si and SA on the amount of seed protein in safflower can be considered due to the important roles of these two compounds in photosynthesis and the uptake of water and nutrients involved in protein production.

In many glycophytes, a negative correlation exist between plant growth and shoot sodium concentration. These plants usually exhibit excluder behavior and limit sodium levels in the shoot in two ways: (1) reduction of loading through the xylem and (2) return of sodium from the shoot to the root through the phloem [58]. Also, one of the mechanisms of plant tolerance to salinity is to increase potassium absorption and prevent sodium entry into the roots and its transfer to various organs of the plant [4]. The non-significant differences in seed sodium concentration between salinity and non-stress treatments can be due to the prevention of sodium transfer to shoots and seeds. Decreased potassium content has been reported in various organs of plants under salinity stress [7, 9]. In wheat, the amount of sodium in leaves, stems, roots, spikes, and seeds increased and the potassium content decreased with increasing salinity. The decrease in seed potassium content was attributed to the inhibition of potassium uptake and accumulation via the root system by high sodium concentrations [59]. Sodium competes with potassium because of a similar ionic radius. High sodium levels in the rhizosphere cause sodium to be absorbed by root cells through potassium transporters, which ultimately inhibits potassium uptake in the plant [4]. Increasing the uptake of potassium and calcium and decreasing the uptake of sodium in different organs of plants with the separate application of SA [9] and Si [14] and their combined application [41] has been reported, which was in line with the results of our study. Researchers reported that the total K content in wheat seeds was higher in SA-treated plants under stress conditions [56]. Si application increased the amount of potassium in rice grain and straw [60], which was consistent with the results of the present study. It has been specified that Si increases H^+-ATPase activity in cell membranes to increase cellular potassium uptake [61]. Also, due to the role of SA and Si in regulating the uptake processes of various elements, such as K, N, and Ca [9, 14], the combined application of SA and Si can have a more significant effect on increasing the uptake of essential elements and reducing harmful elements, such as sodium.

5 Conclusion

The results showed that although safflower is a salt-tolerant plant, a significant reduction was observed in this crop's performance under salt stress. Our findings show that the application of SA and Si could increase safflower quantity and quality under stress and non-stress conditions. Salinity reduced plant height, biomass, seed yield and yield components, seed oil quantity and quality and seed K^+ content. At the same time, the application of SA and Si increased these traits under the same conditions. Salinity increased oleic acid and decreased linoleic acid content. In contrast, foliar application of SA increased seed oil content and oil yield, and improved the oil quality of safflower seeds by increasing linoleic acid. Also, application of Si and SA reduced the amount of palmitic acid compared to the control. The co-application of these two compounds showed a more significant effect than the separate application. For instance, co-application of SA and Si showed more significant reduction effect on palmitic acid. At the highest salinity level, the combined treatment of 1200 µM SA and 1.5 mM Si increased the oil percentage, seed potassium content, and seed yield. The higher concentration of SA could not show this positive effect. Our experiment results showed that the application of 1200 µM SA and 1.5 mM Si was the best treatment to reduce the risk of salinity in safflower.

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Author contribution Bahareh Jamshidi Jam: Greenhouse management, plants husbandry, data collecting in greenhouse and laboratory, statistical data analyses, initial draft preparation. Farid Shekari: conceptualization, methodology, formal analysis, writing and review of initial draft preparation, project administration. Babak Andalibi: Material preparation, review manuscript. Reza Fotovat: Statistical analyses of data. Reza Fotovat and Vahab Jafarian: Methodology, scientific advisory. Aria Dolatabadian: Review and editing of the manuscript. All authors listed on the title page have read the manuscript, attest to the validity and legitimacy of the data and its interpretation, and agree to its submission to the online "Silicon" Journal. The contents of this manuscript will not be copyrighted, submitted, or published elsewhere, while acceptance by the Journal is under consideration.

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Data Availability The datasets and materials used and/or analyzed during the current study are available from the authors on reasonable request.

Declarations

Research Involving Human Participants and/or Animals Not applicable.

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare that they have no conflict of interest.

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