

Abscisic Acid Exogenous Spraying to Improve Sorghum (*Sorghum bicolor* (L.) Moench) Genotypes for Tolerance to Abiotic Stress

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ABSTRACT

Climate change poses significant challenges to agricultural production, particularly in semi-arid and arid regions, characterised by high temperatures and frequent drought conditions. Choosing appropriate crop genotypes and effective agronomical management practices for tolerance to abiotic stress becomes crucial for sustaining crop productivity under these conditions. This experiment aimed to determine the effect of exogenous abscisic acid spraying (distilled water only, 9 and 12 ppm) as the main factor on the performance of four sorghum genotypes (Bohooth, Giza, Al-Khair, and Warkaa) as sub-factors by using a split-plot design in RCBD repeated thrice. The study results showed that the interaction of abscisic acid spray at 12 ppm with the Giza and Al-Khair genotypes outperformed the control, recording the highest averages in most of the sorghum morphological indices. The abscisic acid spray had a significant positive impact on the sorghum genotypes, significantly enhancing growth parameters and grain yield, especially at 12 ppm concentrations. These findings suggest that ABA spraying has a potential priming influence to enhance sorghum grain filling capacity under heat stress during the grain filling stage, particularly by inhibiting the reactive oxygen system and increasing starch synthetase activities in sorghum grain.

Keywords: Abscisic acid, abiotic stress, genotypes, sorghum growth, yield component

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INTRODUCTION

Sorghum bicolor (L.) Moench belongs to the Poaceae family, globally positioned fifth among grain crops in terms of cultivated area and production, after wheat, rice, barley, and maize (Maaruf & Raheem, 2024). Sorghum grains are used in human and animal nutrition in poor countries.

They are used as human food when mixed with wheat flour at a rate of 50%. In developed countries, such as the United States, approximately 90% of the maize grains are used in human food industries, such as starch and its derivatives (Mouhamad & Fadhil, 2025) and are a crucial forage and biofuel energy crop (Yang et al., 2025).

Plant growth regulators are non-nutritive organic compounds that encourage, inhibit or modify plant biological processes and are formed at very low concentrations (Taha et al., 2025). Abscisic acid does not directly participate in cell division and expansion, but it works indirectly to regulate the growth of plants under the influence of stress by controlling the transpiration process, controlling the stomata opening and closing. In addition, other important effects that would keep the plant under the influence of biotic and abiotic stresses in good condition (Ali et al., 2020).

Climate change has significantly influenced world agricultural production, posing considerable challenges to food security, particularly in semi-arid and arid regions vulnerable to high temperatures and drought stress (IPCC, 2023). Salah Al-Din governorate in Central Iraq is highly susceptible to extreme heat events, with temperatures frequently reaching 45°C or more in July and August on some days with reduced relative humidity and high evaporation amount. These abiotic stresses severely affect crucial plant growth stages, notably flowering and grain formation stages, causing substantial yield reductions. Sorghum crop is recognised for its resilience to high-temperature stress and limited water availability, making it an essential crop for sustaining agricultural production under semi-arid conditions (Pradhan et al., 2022). A 26-34 °C air temperature is optimum for sorghum at the vegetative duration and 25-28 °C at the reproductive duration, as stated in Prasad et al. (2015). Remarkably high temperatures result in a decrease in yield. With increased day and night temperatures, flower initiation and floral primordial development are delayed. Spraying with abscisic acid is critical in minimising the adverse impacts of heat stress by improving the reactive oxygen system-scavenging ability to discourage the overaccumulation of reactive oxygen system and alleviate membrane injuries. Superinduction of the stress tolerance-related expression of genes under high temperature stress suggests that abscisic acid has a possible priming impact on the gene expression regulatory network for coping with heat stress factors (Liu et al., 2023). Additionally, with favourable climatic conditions, the crop genotypes significantly influence crop performance by promoting vegetative growth, reproductive development, and enhancing plant resistance to environmental stresses.

Climate change compels researchers to be concerned about food security. Hence, studying the phytohormones will assist in elucidating their accurate place and developing climate-resilient and high-yielding crop cultivars. The ABA role was confirmed against different stresses, chiefly abiotic stresses and in various physiological processes in crops. Abscisic acid (ABA) shares a critical part of its numerous functions during the fruit

development and ripening phases in crop plants (Gupta et al., 2022). Adverse abiotic ecological conditions, such as maximal temperature, severely affect crop growth and productivity. When crops are exposed to various ecological conditions, the ABA level increases significantly. Hence, for the plants' appropriate growth and development, the maintenance of a basal ABA level is paramount (Ali et al., 2020).

The ABA phytohormone has high importance in the development of mechanisms and various stress responses to the environment when plants experience certain biotic or abiotic stresses, including extreme temperatures (Rehman et al., 2022). The extremely high temperatures, which result in heat stress, have become an intensely restrictive factor for crop production in the world. The sorghum growth duration largely occurs during the hot months of the summer season, resulting in intense heat stress that affects its growth and yield. Thus, a sorghum grain yield improvement under heat-stress environments is a major challenge for farmers in Iraq. Sorghum in the reproductive growth period is sensitive to heat stress because it causes a reduction in pollen vitality and affects the meiosis progression and development of sorghum heads, which causes a reduction in sorghum grain spikelets filled and a decrease in yield component traits. The grain-filling phase is the crucial stage for starch synthesis, grain filling and yield formation. Therefore, it is crucial to enhance the thermotolerance of sorghum during the grain-filling stage to achieve the highest possible yield under heat stress conditions. Abscisic acid, a phytohormone, is an efficient and effective way for crops to adapt to heat stress conditions. ABA is found to play a vital role in enabling rice to adapt to heat stress, conferring possibly improved stress tolerance on grains or seedlings pre-treated with abscisic acid, and its response to heat stress, and exogenous abscisic acid enhances thermo tolerance and yield in rice in heat stress conditions. Pre-treatment with abscisic acid has been shown to considerably toughen the abscisic acid signal in rice at heat stress (Liu et al., 2023).

Attention should be given to high-yielding Sorghum varieties, particularly newly introduced varieties, while taking into account the application of scientifically sound crop maintenance processes and adopting the necessary methods to achieve this using modern scientific methods and the introduction of new varieties. In the country, it is compared with the existing varieties, and then the best varieties are chosen to increase the productivity of this crop and improve its quality (Raheem et al., 2023). The differences in genetic composition among varieties show clear differences in growth and production characteristics (AL-Azee et al. 2023), and the interaction of genetic factors with the environment shows its effect on the phenotypic and production characteristics. All of these factors participate in determining the increase or decrease of these characteristics (Al-Rifai, 2017). Azawi (2023) observed during her study on five Sorghum cultivars (J, Giza, Enqaz, Rabeh and Li) that the Li cultivar was superior in leaf area, 4086.61 cm², while the J cultivar was superior in plant height, 177.48 cm. The Giza cultivar was superior

in most growth traits, including the number of leaves and chlorophyll a and b content; it produced 16.43 leaves plant⁻¹, 23.40- $\mu\text{g g}^{-1}$ and 19.83 $\mu\text{g g}^{-1}$, respectively.

Based on available information, ABA has not previously been used to prevent sorghum crop stress caused by high temperatures during early sowing. Therefore, the study aims to evaluate its effectiveness as an avoidance strategy by spraying with different concentrations to mitigate the effects of high temperatures in the field. This includes protecting plant growth, especially the reproductive organs during flowering and grain formation after pollination, to maximise grain yield. Abscisic acid is a growth regulator that is found in plants under various stresses. Unsuitable high temperatures at the sorghum crop flowering stage can significantly reduce productivity. Thus, this work seeks to assess the influence of ABA spraying in decreasing the negative heat stress effect and increasing sorghum grain production.

MATERIALS AND METHODS

Description of Experiment Location

To achieve the above goal, a field experiment was conducted on the 2024 summer growing season in the Al-Alam district of Salah Al-Din Governorate, located at 43.63 °E and 34.65 °N with 98 m MSL. Table 1 shows the climate elements description in Salah Al-Din Governorate during the experiment period, and Table 2 shows the most important experiment field which is physical and chemical soil characteristics at a depth of 30 cm.

Experimental Design and Studied Factors

The first factor included three levels of abscisic acid placed in the main plots, which were as follows: spraying with distilled water only, spraying with abscisic acid at 9 and 12 ppm, sprayed in two stages, at the eight-leaf stage and the pre-flowering stage. Abscisic acid solution was prepared according to Al-Jawaheri & Alogaidi's (2020) description. The brand of abscisic acid is A4906, which was produced by American Sigma-Aldrich Company in powder form and has a $\geq 98\%$ (HPLC) assay. The second factor included four Sorghum genotypes (Bohooth, Giza, Al-Khair, and Warkaa) placed in subplots. The source of the Sorghum genotypes' seed is Syria (Bohooth), Egypt (Giza) and Iraq (Al-Khair and Warkaa). The Randomised Complete Block in a split-plot design was used to carry out the field experiment and repeated three times.

Each replicate was divided into three main plots where abscisic acid was placed, and each main plot was divided into four subplots where the four Sorghum genotypes were planted. Each replication contained 12 experimental units, which included four lines of 3 m length, at a space between each line of 0.70 m and between each hole of 0.20 m. The field was fertilised with an amount of 200 kg N ha⁻¹ added in three equal doses at planting,

Table 1
The experiment location's climatic conditions (monthly averages)

Months	Max. Temp. (°C)	Min. Temp. (°C)	Avg. Temp. (°C)	Max. RH (%)	Min. RH (%)	Avg. RH (%)	ET (mm)
Jul.	43.55	29.75	36.65	29.33	8.30	18.82	10.53
Aug.	45.39	28.85	37.12	29.93	7.57	18.66	8.12
Sept.	40.20	24.73	32.47	35.31	11.90	23.58	6.56
Oct.	32.38	16.65	24.52	39.56	10.45	25.01	4.08
Nov.	22.59	10.42	16.51	95.40	37.30	65.50	1.89
Dec.	17.39	4.10	10.75	87.83	34.85	61.34	1.45

Note. Max. - Maximum; Min. - Minimum; Avg. - Average; Temp. - Temperature; RH - Relative Humidity; ET - Evaporation Amount

*Source: Agricultural Meteorology Centre, Salah al-Din Governorate - Tikrit Station, Ministry of Agriculture, Iraq (2024)

Table 2
Soil physical and chemical properties

Properties	pH	EC	Avail. N	Avail. P	Avail. K	O.M.	Sand	Clay	Silt	Texture
Values	7.3	1.71	6.5	9.7	100.3	0.7	494.20	160.30	345.50	Sandy
Measurement Unit	-	ds m ⁻¹	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	loam

Note. Soil samples were analysed at the Integrated Laboratories of the Department of Soil Resources and Water Sciences - College of Agriculture - Tikrit University, Salah al-Din, Iraq

during the elongation stage and the beginning of flowering. Phosphate 100 kg P₂O₅ ha⁻¹ and potassium 100 kg K₂O ha⁻¹ fertiliser were added in one dose before planting. The seeds were planted on July 1, at a depth of 2-3 cm, with 2-3 seeds put in each hole. The patching process was carried out one week after germination, and thinning was carried out three weeks after planting. One plant is left in each hole, and weeds are controlled according to need.

Data Collection

Data was collected on indices of plant height (cm) from the soil surface to the inflorescence node, plant leaves (leaf plant⁻¹) calculated at the head's appearance stage, plant leaf area (cm²) determined according to Elsahookie and Cheyed (2014), and leaf chlorophyll content (mg g⁻¹ fresh weight) estimated based on Mackinney's (1941) method. Head grains number (grains head⁻¹), head weight (g), 1000-grain weight (g), grain yield (t ha⁻¹), biological yield (t ha⁻¹) and harvest index (%) were calculated according to following formula: Grain yield (t ha⁻¹) / Biological yield (t ha⁻¹) × 100 (Ashraa Kalee & Raheem, 2024).

Statistical Analysis

The F-test was done on the collected data for all studied indices according to the design used at $\alpha = 0.05$ and 0.01, then Duncan's multiple range test was applied for treatment means comparison at $\alpha = 0.05$ by the SAS program V9-2002 (SAS Institute, 2004).

RESULTS AND DISCUSSION

ANOVA-Table (Fisher's Test)

Analysis of variance for the studied indices in Table 3 shows that the effect of abscisic acid concentrations was significant at $\alpha 0.01$ for all the studied indices except plant leaf number, which was significant at $\alpha 0.05$; chlorophyll content and harvest index were not significant. The genotype effect was significant at $\alpha 0.01$ for all the studied indices except the grain head⁻¹, which was not significant. The interaction effect of abscisic acid with genotypes was significant at $\alpha 0.01$ in total grain yield, moreover, at $\alpha 0.05$ in head weight, 1000-grain weight and harvest index, and not significant in plant height, plant leaves, leaves chlorophyll content, plant leaf area, grain head⁻¹ and biological yield.

Abscisic Acid (ABA)

The data presented in Table 4 show that exogenous foliar spraying of ABA on sorghum plants under high temperature stress conditions revealed significant benefits, especially at the highest concentration, 12 ppm, which was the superior concentration in achieving the highest values of all studied indices compared with the 9 ppm and control treatment.

Table 3
ANOVA-Table represented by means of squares (M.S.)

S.O.V.	R	A	R*A	B	A*B	Error	CV (%)
d. f.	2	2	4	3	6	18	
Plant Height (cm)	783.12	338.48**	2.44	1078.03**	14.46 ^{N.S}	20.50	2.9
Plant Leaves (Leaf Plant ⁻¹)	12.13	1.96*	2.31	5.10**	0.30 ^{N.S}	0.40	6.1
Leaves Chlorophyll Content (mg g ⁻¹ fresh weight)	133.80	9.61 ^{N.S}	11.67	112.97**	5.97 ^{N.S}	6.87	5.9
Plant Leaf Area (cm ²)	67400.84	120691.68**	235.81	353203.18**	2663.73 ^{N.S}	3583.13	1.0
Grains Head ⁻¹	183642.69	60717.19**	6304.65	17848.66 ^{N.S}	3378.19 ^{N.S}	10057.85	4.2
Head Weight (g)	654.69	193068.77**	650.90	11608.62**	2510.70*	757.31	4.7
1000-grain Weight (g)	4.75	96.58**	3.58	7.21**	4.21*	1.37	3.9
Grain Yield (t h ⁻¹)	0.549	6.31**	0.21	6.64**	1.54**	0.272	8.6
Biological Yield (t ha ⁻¹)	13.44	16.42**	0.165	5.72**	0.081 ^{N.S}	0.425	4.0
Harvest Index (%)	14.34	46.35 ^{N.S}	7.93	189.75**	53.58*	15.76	10.7

Note. ** = Significant at α 0.01; * = Significant at α 0.05; N. S = Not significant; R = Replication; A= Abscisic acid; and B = Genotypes; C.V. = coefficient of variation; Total d. f. = 35

The concentration of 12 ppm ABA was superior in plant height and gave an average of 161.50 cm, while the control treatment was the lowest average, reaching 151.07 cm. This effect may be due to ABA's role in regulating responses to stress, especially under high temperature conditions, which helps the plant manage abiotic stresses by reducing transpiration and enhancing water-use efficiency. Moreover, it helps maintain stomata closure, decreasing water loss during transpiration and enhancing water-use efficiency. In addition, improving chlorophyll content enhances the photosynthesis process. This, in turn, supports better growth leading to increased plant height, as the plant growth regulators increase the plant's height. These findings are in agreement with those stated about a positive effect of ABA spraying on increasing plant height by Gomaa et al. (2023) in rice, Zulfiqar et al. (2024) in wheat and Abd El-Hady et al. (2025) in maize as compared to the control treatment. With concentrations of 9 and 12 ppm ABA, the highest averages of 10.53 and 10.67 leaf plant⁻¹ were recorded, respectively, with the control treatment recording the lowest plant leaves, reaching 9.91 leaf plant⁻¹.

This may be attributed to abscisic acid role in increasing plant height. These results indicate that ABA is effective in promoting leaf growth.

Kumar (2024) noticed similar results in wheat. The positive effect of ABA was clear on leaves' chlorophyll content; the concentration of 12 ppm of abscisic acid was superior, achieving an average of 45.67 mg gm⁻¹ fresh weight, while the control treatment recorded the minimum average, reaching 43.97 mg gm⁻¹ fresh weight. The increased chlorophyll content induced by ABA may be due to the protection of chloroplast pigments from harmful effects by increasing the activity of antioxidant enzymes. This was in line with those who found a positive role of ABA in leaf chlorophyll content enhancement in rice and wheat (Chen et al., 2022; Kumar, 2024). Similarly, the concentration of 12 ppm ABA was superior in plant leaf area, giving an average of 5880.53 cm² plant⁻¹, while the control treatment recorded the lowest average, reaching 5683.20 cm² plant⁻¹. The increase in the plant's leaf area is attributed to the ABA's role in increasing plant height and the number of leaves. The noticed results agree with those of Abd El-Hady et al. (2025).

In the case of the grain head⁻¹ indices, the concentration of 12 ppm ABA was also superior, yielding an average of 2472.67 grains head⁻¹, the lowest average recorded by the control treatment, reaching 2330.58 grains head⁻¹. This work highlighted the important role of increasing grain head⁻¹ and the importance of ABA in the flowering process.

These findings align with Hwaidi (2023), who found that ABA enhances flowers' resistance to heat and promotes high levels of pollination and double fertilisation. Moreover, it has a role in regulating the inner plant water content (Al-Jawaheri & Alogaidi, 2020).

Table 4
Abscisic acid effect on the studied indices

Indices	Abscisic Acid Concentrations (ppm)		
	0	9	12
Plant Height (cm)	151.07 c	158.02 b	161.50 a
Plant Leaves (Leaf Plant ⁻¹)	9.91 b	10.53 a	10.67 a
Leaves Chlorophyll Content (mg g ⁻¹ Fresh Weight)	43.97 c	44.34 b	45.67 a
Plant Leaf Area (cm ²)	5683.20 c	5750.78 b	5880.53 a
Grains Head ⁻¹	2330.58 b	2395.42 ab	2472.67 a
Head Weight (g)	481.08 c	558.08 b	728.92 a
1000-grain Weight (g)	27.75 b	29.67 b	33.33 a
Grain Yield (t h ⁻¹)	5.35 c	6.04 b	6.80 a
Biological Yield (t ha ⁻¹)	15.04 c	16.69 b	17.30 a
Harvest Index (%)	34.69 b	36.28 ab	39.35 a

Note. In the same row, similar letters do not differ significantly

In addition, spraying sorghum plants with abscisic acid contributed to increasing leaf area and stimulating carbon metabolism, which led to an increase in the grain head⁻¹. Al-Fayyadh and Hwaidi (2022) and Abd El-Hady et al. (2025) stated similar findings in maize. Concerning head weight, the concentration of 12 ppm ABA outperformed, yielding the heaviest head weight of 728.92 g, while the control treatment had a lighter head weight of 481.08 g. This is attributed to the fact that the abscisic acid treatment at this stage contributed to increased pollen fertility and activity, which led to an increase in grain head⁻¹ and then an increase in head weight. A positive role of exogenous ABA was found in increasing sunflower capitulum weight (Hwaidi, 2023) and in rice panicle weight (Liu et al., 2023).

Moreover, the concentration of 12 ppm ABA is superior in 1000-grain weight, with an average of 33.33 g, while the lowest average recorded by the control treatment is 27.75 g. The spraying of ABA may encourage root growth, absorb more nutrients and water, and then support photosynthesis with the required nutrients, increasing the mobile carbon produced substances from metabolism processes that supply the key source of grain filling. Also, it facilitates the transfer of photosynthetic products from the source (leaves) to the sink (grains) and then increases grain weight. Similar findings were obtained by Al-Fayyadh and Hwaidi (2022) in maize and Wang et al. (2025) in rice.

For final yields, the concentration of 12 ppm of ABA was superior, yielding the highest grain yield of 6.80 t ha⁻¹, whereas the lowest yield was recorded by the control treatment of 5.35 t ha⁻¹. This may be attributed to the abscisic acid role in the yield components increasing (Table 4), which positively affected the total grain yield. These results were in line with those of Hwaidi (2023), Ahmed and Al-Tameemi (2025) for sunflowers, and Abd El-Hady et al. (2025) for maize. Similarly, the concentration of 12 ppm ABA outperformed in biological yield, yielding 17.30 t ha⁻¹, while the control treatment recorded the lowest 15.04 t ha⁻¹. This is due to the beneficial effect of abscisic acid in increasing crop growth and grain yield (Table 4). This information agrees with that indicated by Abd El-Hady et al. (2025). The concentration of 12 ppm ABA was superior in the harvest index with 39.35%, while the control treatment recorded the least at 34.69%. The superior harvest index with ABA spraying confirms its effective role in increasing the ratio of grain yield to total plant biological yield. This suggests that ABA may better improve overall plant efficiency and productivity. The higher seed yield resulted in improved harvest index (Table 4). Kumar (2024) and Zulfiqar et al. (2024) in wheat and Abd El-Hady et al. (2025) in maize, stated similar findings that correspond with our results.

Sorghum Genotypes

Significant differences among sorghum genotypes in all studied indices except the grain head⁻¹ are shown in Table 5. The Bohooth genotype had significantly taller plants, 172.64 cm.

In contrast, the Giza and Warkaa genotypes had shorter plants, 149.04 and 149.93 cm, respectively. These differences in plant height among sorghum genotypes may be due to differences in their genotype in genetic makeup among the genotypes that determine the number of internodes and stem height, and thus, differences appear in the height of the plant and their ability to respond to environmental conditions, with their impact on increased cell division and elongation. These results are similar to the results of Azawi (2023), Maaruf & Raheem (2024) and Abas et al. (2025). The Bohooth, Giza, and Al-Khair genotypes outperformed in the highest plant leaves 11.00, 10.41 and 10.77 leaves plant⁻¹, respectively, while the Warkaa genotype had the lowest number of plant leaves 9.30 leaves plant⁻¹. The reason for the variation among genotypes may be due to differences in their genetic makeup. A particular composition may have the ability to express itself better under the influence of environmental factors, while other cultivars cannot. The plant's number of leaves are closely related to the amount of light captured and the CO₂ absorbed by the plants for photosynthesis. The more light received, the more photosynthesis is produced to support plant growth. Photosynthesis is considered one of the most significant methods to increase crop yield. The more leaves there are, the higher the photosynthesis. The result of photosynthesis is then translocated to other plant parts to produce high biomass (Kusumawardana et al., 2025). These results agreed with what was reported by Sharif et al. (2024) and Haque et al. (2025).

The Khair genotype was superior in chlorophyll content in leaves with 49.77 mg g⁻¹ fresh weight. In contrast, the Warkaa genotype was the lowest, reaching 41.71 mg g⁻¹ fresh weight.

Table 5
Sorghum genotypes' effect on the studied indices

Indices	Sorghum genotypes			
	Bohooth	Giza	Al-Khair	Warkaa
Plant Height (cm)	172.64 a	149.04 c	155.82 b	149.93 c
Plant Leaves (Leaf Plant ⁻¹)	11.00 a	10.41 a	10.77 a	9.30 b
Leaves Chlorophyll Content (mg g ⁻¹ Fresh Weight)	44.10 b	43.06 b	49.77 a	41.71 c
Plant Leaf Area (cm ²)	5683.76 c	6028.73 a	5808.21 b	5565.30 d
Grains Head ⁻¹	2430.89 a	2437.56 a	2388.56 a	2341.22 a
Head Weight (g)	560.89 b	612.22 a	627.67 a	556.67 b
1000-grain Weight (g)	31.22 a	29.67 bc	30.78 ab	29.33 c
Grain Yield (t h ⁻¹)	5.03 c	6.90 a	6.62 a	5.70 b
Biological Yield (t ha ⁻¹)	16.52 b	17.20 a	16.38 b	15.28 c
Harvest Index (%)	30.51 b	40.29 a	40.18 a	37.45 a

Note. In the same row, similar letters do not differ significantly

The difference among genotypes in chlorophyll content in their leaves may be primarily due to genetic variation among them and their different responses to surrounding growth factors. These results agree with the results of Mouhamad and Fadhil (2025), who reported that the sorghum genotypes varied in leaf chlorophyll content. The Giza genotype excelled in plant leaf area with the highest value of 6028.73 cm² plant⁻¹, while the Warkaa genotype had the lowest value of 5565.30 cm² plant⁻¹. This difference among Sorghum genotypes is due to genetic differences in canopy structure and leaf development potential, with their differences in growth speed before reaching maximum leaf area. These results are consistent with those of Maaruf & Raheem (2024) and El-Sheikh et al (2025). The grain head⁻¹ was not significantly affected by Sorghum genotypes, whereas the Khair and Giza genotypes outperformed in head weight with 627.67 and 612.22 g, respectively; conversely, the Warkaa genotype had the lowest with 556.67 g. The difference between cultivars may be due to the genetic makeup of genotypes and the way each utilises the environmental conditions surrounding growth. The number of grains per head is linked to genetic factors, which are greatly affected by environmental conditions. This is similar to the results of Al-Shakarchy and Altaweel (2021). On the other hand, the Bohooth genotype outperformed with the high weight of 1000 grains, 31.22 g. In contrast, the Warkaa genotype had the lowest weight, reaching 29.33 g. This may be due to differences in the genetic material of each genotype that cause differences in the grain size and weight. Similar findings are reported by Raheem et al. (2024), Begna (2025) and Bajhir et al. (2025). The Khair and Giza genotypes produced maximum grain yield, 6.62 and 6.90 t ha⁻¹, respectively, whereas the Bohooth genotype yielded the lowest 5.03 t ha⁻¹. This was caused by differences in yield components among the sorghum genotypes (Table 5), consistent with the findings of Li et al. (2025) and Haque et al. (2025). Furthermore, in biological yield, the Giza genotype was superior with 17.20 t ha⁻¹. In contrast, the Warkaa genotype yielded the lowest at 15.28 t ha⁻¹. This happened because of the significant superiority of the Giza genotype in plant leaves, leaf area and grain yield (Table 5). This result is consistent with those of Raheem et al. (2023). Finally, only the Bohooth genotype differed significantly from the other genotypes by the lowest harvest index, 30.51%, while the other genotypes outperformed, with no significant differences among them. This is contributing to variations in genetic composition affecting grain yield and biological yield. A genotype may have a high yield, but its biological yield is low, which increases the harvest index. These results are followed by those observed by Raheem et al. (2023) in maize.

ABA × Genotypes Interaction

Table 6 shows that the Exogenous foliar spray of ABA exhibited significant differences due to the differences among sorghum genotypes. ABA improved the growth quality

and yield of sorghum genotypes in general. The interaction between 12 and 9 ppm ABA spraying and the Bohooth genotype was superior, giving the tallest plant a height of 176.00 cm and more plant leaves (11.67 leaves plant⁻¹). In contrast, the control treatment with the Warkaa genotype recorded the lowest height at 141.69 cm and plant leaf count of 9.10 leaves plant⁻¹. The average across the Al-Khair genotype, exogenous spraying of 12 ppm ABA increased the maximum leaf chlorophyll content, reaching 51.51 mg gm⁻¹ FW; control conditions caused a reduction across the Warkaa genotype (40.31 mg gm⁻¹ FW). The leaf area and grain head⁻¹ of the Giza genotype showed an important increase at 12 ppm ABA spraying, reaching 6141.52 cm² and 2535.33 grain head⁻¹, respectively, relative to the control treatment of the Warkaa genotype, which recorded values of 5468.55 cm² and 2279.00 grain head⁻¹. On the other hand, a combination of 12 ppm ABA spraying with the Al-Khair and Giza genotypes showed a significant improvement in maximum head weights of 762.67 and 758.67 g, respectively, while decreasing the head weight of the Bohooth genotype under control conditions to 415.67 g. Moreover, the concentration of 12 ppm of ABA with the Bohooth genotype outperformed and yielded the highest 1000-grain weight, 36.00 g. In contrast, the control treatment with the Warkaa genotype recorded the lowest average, reaching 27.00 g. ABA plays an effective role in enhancing grain filling features, accelerating starch build-up by raising related enzyme activities, and regulating levels of grain endogenous hormones, consequently contributing to adequate grain filling (Yu et al., 2024).

The spraying of 12 ppm ABA significantly affected the grain yield in Al-Khair and Giza genotypes, with maximum yields of 8.11 and 8.12 t ha⁻¹, respectively, when compared to the control treatment and the Bohooth genotype, which had the lowest yield, reaching 4.77 t ha⁻¹. Exogenous spraying of 12 ppm ABA for the Giza genotype positively and significantly increased biological yield by an average of 18.19 t ha⁻¹, over the control treatment with the Warkaa genotype, which had the lowest 14.15 t ha⁻¹. In addition, the harvest index was significantly affected by the interaction of exogenous ABA spraying and sorghum genotypes. The interaction between 12 ppm ABA spraying and the Khair genotype significantly registered a maximum harvest index of 47.05%, while the control treatment with the Bohooth genotype registered a minimum of 29.15%. The above results agree with Al-Jawaheri and Alogaidi (2020), who observed a beneficial interaction between ABA concentrations and rice varieties in grain panicle⁻¹, weight of 1000 grains and total grain yield. Yu et al. (2024) found that maize hybrids reveal a significant increase in weight of 1000 grains and grain yield after following ABA treatment over the control. Naqqash et al. (2024) obtained a positive and significant interaction with exogenous spraying of ABA on canola (*Brassica napus* L.) cultivars, which resulted in an increased number of seeds silique⁻¹, weight of 1000 grains, seed yield and biological yield as compared to the control treatment.

Table 6
Interaction of abscisic acid (ABA) with sorghum genotypes on the studied indices

ABA (ppm) × Genotypes	Plant Height (cm)	Plant Leaves (Leaf Plant ⁻¹)	Leaves		Plant Leaf Area (cm ²)	Grains Head ⁻¹	Head Weight (g)	1000-grain Weight (g)	Grain Yield (t h ⁻¹)	Biological Yield (t ha ⁻¹)	Harvest Index (%)
			Chlorophyll Content (mg g ⁻¹ Fresh Weight)	Chlorophyll Content (mg g ⁻¹ Fresh Weight)							
0×Bohooth	169.40 ab	10.20 bcd	43.78 c	43.78 c	5578.41 ef	2360.00 abc	415.67 e	27.67 f	4.77 d	14.97 fg	29.15 f
0×Giza	145.00 fg	9.93 bcd	42.15 cd	42.15 cd	5934.47 b	2337.33 abc	504.00 d	27.33 f	5.86 bc	15.87 def	37.28 cde
0×Al-Khair	148.18 efg	10.40 bc	48.64 ab	48.64 ab	5751.35 cd	2346.00 abc	548.67 cd	29.00 ef	5.10 cd	15.17 fg	33.56 c-f
0×Warkaa	141.69 g	9.10 d	40.31 d	40.31 d	5468.55 g	2279.00 c	476.00 d	27.00 f	5.67 cd	14.15 g	40.07 abc
9×Bohooth	172.53 a	11.67 a	43.59 c	43.59 c	5685.56 cde	2432.00 abc	540.67 cd	30.00 cde	5.19 cd	17.00 a-d	30.53 ef
9×Giza	149.67 d-g	10.40 bc	42.39 cd	42.39 cd	6010.21 b	2440.00 abc	574.00 c	28.67 ef	6.72 b	17.54 ab	38.70 bcd
9× Al-Khair	157.58 cd	10.80 ab	49.15 ab	49.15 ab	5739.27 cd	2405.00 abc	571.67 c	31.00 bcd	6.66 b	16.71 b-e	39.92 abc
9× Warkaa	152.30 def	9.27 cd	42.22 cd	42.22 cd	5568.07 fg	2304.67 bc	546.00 cd	29.00 def	5.59 cd	15.52 ef	35.97 c-f
12×Bohooth	176.00 a	11.13 ab	44.92 bc	44.92 bc	5787.32 c	2500.67 ab	726.33 a	36.00 a	5.12 cd	17.61 ab	31.85 def
12×Giza	152.47 def	10.90 ab	45.65 bc	45.65 bc	6141.52 a	2535.33 a	758.67 a	33.00 b	8.12 a	18.19 a	44.91 ab
12× Al-Khair	161.72 bc	11.10 ab	51.51 a	51.51 a	5934.02 b	2414.67 abc	762.67 a	32.33 b	8.11 a	17.26 abc	47.05 a
12× Warkaa	155.80 cde	9.53 cd	42.61 cd	42.61 cd	5659.27 def	2440.00 abc	668.00 b	32.00 bc	5.85 bc	16.15 c-f	36.30 c-f

Note. In the same column, similar letters do not differ significantly

CONCLUSION

The obtained results confirm that the positive effects of ABA, particularly 12 ppm concentration under high temperature conditions, meaningfully improved the capability of the sorghum plants to tolerate the bad effects of abiotic stress and improved their growth and yield. So, it can be concluded that the foliar spraying of abscisic acid significantly improves sorghum growth performance and yield attributes, effectively mitigates abiotic stress responses, which leads to better growth and productivity compared with not spraying. Moreover, foliar spray of exogenous abscisic acid exhibited differences due to the different sorghum genotypes. Increasing the sorghum genotype growth and yield is mainly related to the enhancement of plant leaves, leaf area, leaf chlorophyll content and then photosynthesis in leaves. The sorghum genotypes exhibited highly significant performance across all studied indices; the findings indicated that the impact of exogenous ABA on the plants mainly depended on the sorghum genotypes. Both genotypes, Khair and Giza, significantly outperformed in most of the studied indices, while the binary interaction of 12 ppm ABA with the Giza genotype recorded the highest grain yield. Therefore, it can be considered the best treatment proposed in this study. Future studies should explore the impacts of these treatments across different crops to promote the agricultural sustainability of semi-arid regions.

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