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## Response of Maize Grown Under Water Deficit Conditions to Zeolite as a Soil Conditioner and Foliar Application of Abscisic Acid

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THE COMBINATION of zeolite as a soil conditioner and abscisic acid (ABA) as a foliar application represents a modern approach to mitigating the adverse effects of water deficit conditions on maize growth and performance. So, this study aimed to evaluate the effects of different irrigation regimes ($I_1$: 5500 $m^3$ $ha^{-1}$, $I_2$: 4400 $m^3$ $ha^{-1}$, $I_3$: 3300 $m^3$ $ha^{-1}$ as the main factor), zeolite rates ($Z_1$: 0 ton $ha^{-1}$, $Z_2$: 5 ton $ha^{-1}$, $Z_3$: 10 ton $ha^{-1}$ as sub-main factor), and ABA foliar treatments ($A_1$: 0 mmol, $A_2$: 5 mmol, $A_3$: 10 mmol as sub-sub factor) on maize yield and quality. Measurements taken 70 days after sowing included plant height, fresh and dry weights, leaf area, mineral constituents (N, P, K), chlorophyll content, proline, malondialdehyde (MDA), catalase (CAT), and peroxidase (POX). Harvest metrics comprised cob weight, cob length, number of seeds per cob, weight of 100 grains, grain and biological yields, harvest index, and quality parameters such as carbohydrates, protein, oil content, anthocyanins, and nutrient concentrations. Results indicated that the highest irrigation level ($I_1$) consistently produced the best results across all parameters. The application of zeolite at the highest rate ($Z_3$) significantly enhanced yield and quality metrics, while ABA at 10 mmol ($A_3$) provided the most substantial benefits. Moreover, interactions between treatments revealed a synergistic effect, with the combination of optimal irrigation, zeolite, and ABA leading to superior performance. On the other hand, the application of zeolite and ABA under water-deficit conditions ($I_2$ and $I_3$) markedly improved maize growth and yield. Finally, it is recommended that farmers incorporate zeolite into their soil management practices and utilize ABA foliar applications to optimize crop performance during drought. Future research should further investigate the synergistic effects of these treatments on various crops, contributing to sustainable agriculture in arid regions and enhancing food security through resource-efficient farming practices.

**Keywords**: Zeolite, Abscisic acid (ABA), Maize, Water Deficit.

## Introduction

Egypt currently faces significant challenges related to water scarcity, grappling with limited water resources and increasing demand due to population growth. These circumstances necessitate new thinking among researchers and practitioners in agriculture to find scientific methods that can reduce water consumption in crops compared to traditional practices. Thus, the search for innovative solutions aimed at improving water use efficiency and enhancing crop productivity becomes imperative **(Mostafa *et al.* 2024).** Maize (*Zea mays*) is an important crop that can be leveraged in studies related to water management, given its substantial nutritional and economic significance **(Abdelraof *et al.* 2023).** It serves as a staple food for both humans and livestock, in addition to being utilized in oil production and food processing industries. Maize is also known for its ability to withstand water deficit conditions, making it a suitable subject for research on water efficiency (**Elsherpiny, 2023)**.

Zeolite plays a vital role in improving soil properties by enhancing water retention and nutrient availability, contributing to better plant health and resilience against water stress (**Elawady *et al.* 2024**). The application of zeolite as a soil amendment can lead to notable improvements in crop yield **(Abd El-Azeiz *et al.* 2024).** Additionally, abscisic acid (ABA) is a key plant hormone that plays a crucial role in plants' responses to environmental stressors, including water deficiency **(Ali *et al.* 2020).** ABA helps regulate stomatal closure and promotes root growth, aiding plants in adapting to harsh water conditions and improving their water-use efficiency **(Muhammad-Aslam *et al.* 2022; Gao *et al*. 2024).**

The aim of this study is to evaluate the effects of zeolite and abscisic acid under water-deficit conditions on the yield and quality of maize. Through this research, we seek to develop effective strategies for optimizing water use in agriculture and enhancing food security in Egypt.

## 2. Material and Methods

A field experiment was conducted during two consecutive growing seasons (2023 and 2024) on a private farm located at Met Antar village, Talkha district, El-Dakahlia Governorate, Egypt (31°4'54"N, 31°24'4"E) to evaluate the effects of irrigation levels, zeolite application and foliar application of abscisic acid on maize (*Zea mays* L. cv. Yaqout single hybrid).

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**Initial soil properties and characteristics of studied substances**

The physical and chemical properties of the initial soil and the zeolite used in this study were analyzed based on the standard methods of **Tandon (2005).** The zeolite, sourced from Alex Zeolite Company, a commercial supplier in Egypt, was selected for its high cation exchange capacity (CEC) of 160 cmol $kg^{-1}$, making it suitable for improving water retention and nutrient availability in water-deficient conditions. Its mineral composition included 64.75% $SiO_2$, 12.50% $Al_2O_3$, and 5.20% $K_2O$, providing essential elements for plant growth. Additionally, the zeolite contained 6.0% $Fe_2O_3$, 9.0% CaO, and 1.05% $P_2O_5$, further enhancing its role in improving soil fertility.

The initial soil used in the experiment was analyzed, showing a neutral to slightly alkaline pH of 8.2, with an electrical conductivity (EC) of 3.15 $dSm^{-1}$. Nutrient content in the soil included 25.3 mg $kg^{-1}$of available nitrogen, 7.48 mg $kg^{-1}$ of available phosphorus, and 175.9 mg $kg^{-1}$of available potassium. The soil texture was classified as clay, with a composition of 50% clay, 30% silt, and 20% sand, and an organic matter content of 1.15%.

In addition to the soil and zeolite, abscisic acid (ABA) was used as a foliar spray to modulate plant responses to water stress. Abscisic acid, a sesquiterpenoid plant hormone with the chemical formula $C_{15}H_{20}O_4$, was applied due to its well-documented role in regulating stomatal closure and enhancing drought tolerance in plants.

**Experimental design and treatments**

The experiment followed a split-split-plot design with three replications. Fig 1 shows the experimental flowchart.

Main plot factor: Irrigation treatments

1. $I_1$: (5500 $m^3$ $ha^{-1}$)
2. $I_2$: (4400 $m^3$ $ha^{-1}$)
3. $I_3$: (3300 $m^3$ $ha^{-1}$)

Sub-main plot factor: Zeolite application

1. $Z_1$: Without
2. $Z_2$: Zeolite (5 ton $ha^{-1}$)
3. $Z_3$: Zeolite (10 ton $ha^{-1}$)

Sub-sub main plot factor: Abscise acid foliar application

1. $A_1$: Without
2. $A_2$: Abscisic (5 mmol)
3. $A_3$: Abscisic (10 mmol)

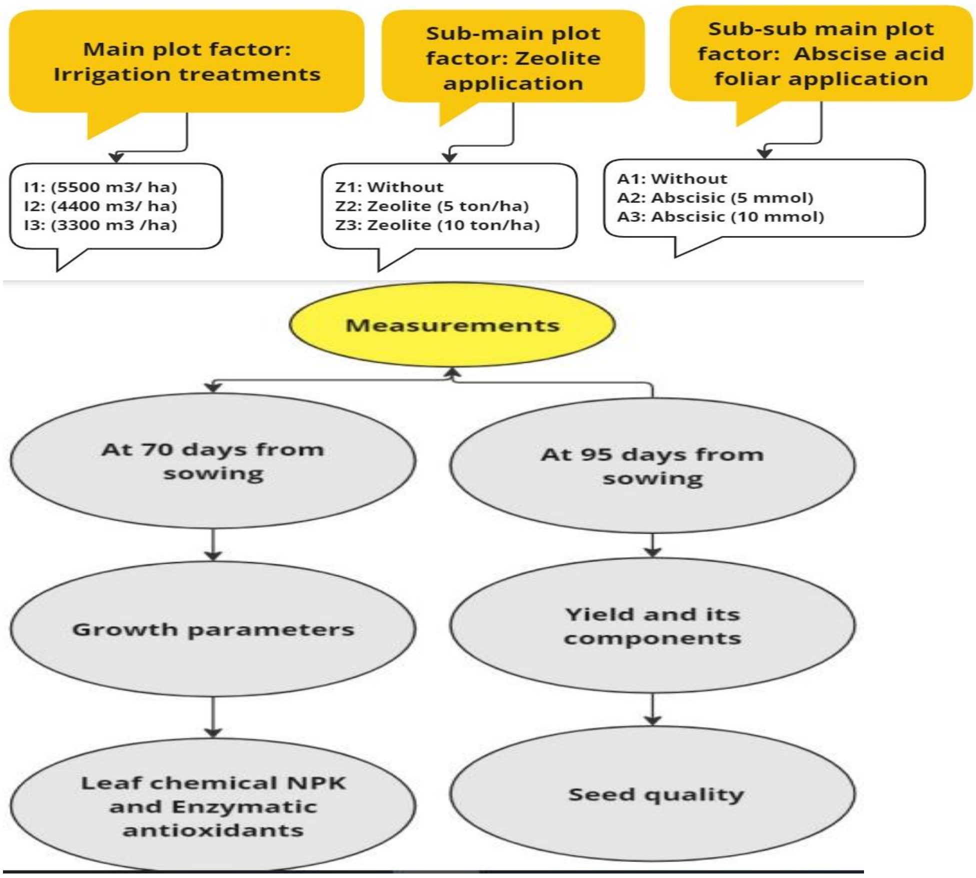


**Fig. 1. Experimental flowchart.**

**Cultivation and crop management**

Maize seeds (cv. Yaqout) were sown on 15th April in both studied seasons following the standard agronomic practices recommended by the Ministry of Agriculture and Soil Reclamation (MASR). Sub-sub plot area was 6.0 $m^2$. Zeolite was applied to the soil at the specified rates before sowing, ensuring uniform incorporation into the topsoil (0–20 cm). The experimental plots were irrigated using a drip irrigation system. Irrigation treatments were applied based on the total amount of water designated for each treatment ($I_1$, $I_2$, and $I_3$). A water meter was installed on the main irrigation line to measure the exact volume of water applied to each plot, ensuring precision in water application. Foliar sprays of abscisic acid were applied three times during the growing season: at 30, 45, and 60 days after sowing. The concentrations used were 5 mmol and 10 mmol as per the experimental design. The application was done using a handheld sprayer, ensuring uniform coverage of the plant with a volume of 1000 L $ha^{-1}$. Harvesting was implemented after 95 days from sowing.

**Data collection**

Data were collected at two stages: At 70 days after sowing: Initial growth measurements, leaves chemical constituents and antioxidant indicators were recorded (Table 1A). At harvest (95 days after sowing): Yield components and quality were measured (Table 1B).

**Statistical analyses**

All collected data were subjected to statistical analysis using analysis of variance (ANOVA) at a 5% probability level using Duncan letters **(Gomez and Gomez, 1984)** to determine the significance of the treatments**.**

**Table 1A. Measurements at 70 days from sowing.**

| Parameters | | Method | Reference |
|---|---|---|---|
| **Plant height ( cm), fresh and dry weights ( g plant$^{-1}$), leaf area (cm$^2$ plant$^{-1}$)** | | Manually | Direct measurement, **Pearce *et al.* (1975)** for leaf area |
| **Chlorophyll, SPAD reading** | | Measured using a chlorophyll meter (SPAD-502). | SPAD-502 meter |
| **Leaves digestion** | | Using a mixture of $HClO_4$ + $H_2SO_4$ | **Peterburgski (1968)** |
| **Leaf chemical NPK (DW)** | **N, %** | Micro-Kjeldahl | **Walinga *et al.* (2013)** |
| | **P, %** | Spectrophotometric | |
| | **K, %** | Flame photometer | |
| **Antioxidant indicator** | **Malondialdehyde MDA, µmol g$^{-1}$ F.W** | Spectrophotometrically | **Valenzuela (1991)** |
| **Enzymatic antioxidants (FW)** | **Catalase CAT, unit mg$^{-1}$ protein$^{-1}$** | | **Elavarthi and Martin, (2010)** |
| | Peroxidase **POX, unit mg$^{-1}$ protein$^{-}$** | | |
| **Non-Enzymatic antioxidants (FW)** | **Proline, µg.g$^{-1}$ F.W** | | **Ábrahám *et al.* (2010)** |

**Table 1B. Measurements at 95 days from sowing.**

| Parameters | | Method | Reference |
|---|---|---|---|
| **Weight of cob (g), cob length (cm), No. of seeds cob$^{-1}$, weight of 100 grain (g), grain and biological yields (Mgha$^{-1}$) and harvest index (%)** | | Manually | Direct measurement |
| **Seed quality** | **Carbohydrates, %** | *Via* Anthrone method | **AOAC (2000)** |
| | **Protein, %** | N (Kjeldahl) x 5.75 | |
| | **Oil, %** | Weight method | |
| | **Anthocyanin, mg100g$^{-1}$** | Spectrophotometrically | |
| **Seeds digestion** | | Using a mixture of $HClO_4$ + $H_2SO_4$ | **Peterburgski (1968)** |
| **Seeds chemical NPK (DW)** | **N, %** | Micro-Kjeldahl | **Walinga *et al.* (2013)** |
| | **P, %** | Spectrophotometric | |
| | **K, %** | Flame photometer | |

## 3. Results

### Growth criteria and leaves chemical constituents

The results presented in Tables 2 and 3 demonstrate the impact of various irrigation regimes, soil amendments (zeolite) and foliar applications of abscisic acid (ABA) on maize growth and chemical constituents during the 2023 and 2024 seasons at period of 70 days from sowing.

### Irrigation regime's effect

According to the data of Table 2 (growth criteria), the highest irrigation regime ($I_1$: 5500 $m^3$ $ha^{-1}$) consistently produced the best results in terms of plant height, fresh weight, dry weight, and leaf area across both seasons. For example, the plant height in the first season under $I_1$ was 317.32 cm, significantly higher than under lower irrigation regimes ($I_2$ and $I_3$), indicating the importance of sufficient water for optimal maize growth. Conversely, the lowest irrigation regime ($I_3$: 3300 $m^3$ $ha^{-1}$) resulted in the lowest performance across all growth metrics, suggesting that water stress limits the growth of maize. With respect to the chemical constituents (N,P,K) and chlorophyll content (Table 3), the highest values for chlorophyll readings (SPAD), along with N, P, and K contents, were observed under the $I_1$ irrigation regime, followed by $I_2$ and $I_3$.

### Zeolite's effect

Increasing the zeolite application rate enhanced growth performance. The highest rate ($Z_3$: 10 ton $ha^{-1}$) resulted in the highest plant height (311.31 cm in the first season), fresh weight (1070.67 g $plant^{-1}$), and dry weight (190.26 g $plant^{-1}$).The control treatment without zeolite ($Z_1$) consistently had the lowest growth values, indicating that zeolite is effective in improving maize growth, likely due to its capacity to enhance water retention and nutrient availability (Table 2). The application of zeolite notably enhanced chlorophyll content, with $Z_3$ (10 tons $ha^{-1}$) recording the highest value (41.82 SPAD) compared to the control ($Z_1$). Additionally, zeolite at 10 tons $ha^{-1}$ ($Z_3$) resulted in the highest levels of nitrogen, phosphorus, and potassium in maize leaves, further highlighting its effectiveness in improving nutrient retention and availability (Table 3).

### Abscisic acid's effect

Abscisic acid at a concentration of 10 mmol ($A_3$) led to the highest growth parameters, including fresh and dry weights. In the first season, A3 achieved a fresh weight of 1030.19 g $plant^{-1}$ and a dry weight of 182.70 g $plant^{-1}$, surpassing all other treatments. In contrast, the treatment without ABA ($A_1$) exhibited the lowest growth performance, demonstrating that foliar application of ABA, particularly at higher concentrations, effectively mitigates the effects of water stress on maize growth. Additionally, abscisic acid application improved chlorophyll content, with $A_3$ (10 mmol) showing the best results (40.70 SPAD). The foliar application of ABA at 10 mmol ($A_3$) also led to the highest N, P, and K concentrations, indicating its role in enhancing nutrient absorption under varying water regimes.

### Interaction effects

The interaction between irrigation regimes, zeolite, and ABA treatments showed significant effects on both growth performance and chemical constituents. For example, the combination of the highest irrigation regime ($I_1$), zeolite at 10 ton $ha^{-1}$ ($Z_3$), and 10 mmol ABA ($A_3$) led to the best overall performance, indicating a synergistic effect of these treatments on enhancing maize growth and nutrient uptake. On the other hand, it was observed that the combined treatment of zeolite at 10 tons $ha^{-1}$ (Z3) and 10 mmol ABA ($A_3$) under the water deficit condition of $I_2$ (4400 $m^3$ $ha^{-1}$) produced better results than plants grown under the traditional irrigation regime ($I_1$, 5500 $m^3$ $ha^{-1}$) without the combined application of zeolite and abscisic acid ($I_1Z_1A_1$).

**Table 2. Impact of different irrigation regimes, varying zeolite rates and foliar application of abscisic acid at different concentrations on the growth performance of maize during the 2023 and 2024 seasons.**

| Treatments | | | Plant height, cm | | Fresh weight, g plant$^{-1}$ | | Dry weight, g plant$^{-1}$ | | Leaf area, cm$^2$/plant | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season |
| **Main factor: Irrigation treatments** | | | | | | | | | | |
| **I $_1$** (5500 m$^3$ ha$^{-1}$) | | | 317.32a | 321.28a | 1114.74a | 1128.00a | 198.00a | 201.19a | 995.41a | 1018.59a |
| **I $_2$** (4400 m$^3$ ha$^{-1}$) | | | 305.56b | 309.43b | 1044.78b | 1057.48b | 185.04b | 187.63b | 957.96b | 979.26b |
| **I $_3$** (3300 m$^3$ ha$^{-1}$) | | | 283.79c | 286.87c | 894.70c | 907.19c | 157.30c | 159.89c | 872.30c | 890.33c |
| **Sub main factor: Soil addition treatments** | | | | | | | | | | |
| **Z$_1$:** Without | | | 292.14c | 295.84c | 951.26c | 963.81c | 166.56c | 169.04c | 902.48c | 921.30c |
| **Z$_2$:** Zeolite (5 ton ha$^{-1}$) | | | 303.23b | 307.11b | 1032.30b | 1044.85b | 183.52b | 186.48b | 951.30b | 971.59b |
| **Z$_3$:** Zeolite (10 ton ha$^{-1}$) | | | 311.31a | 314.62a | 1070.67a | 1084.00a | 190.26a | 193.19a | 971.89a | 995.30a |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | | | |
| **A$_1$:** Without | | | 300.43b | 304.28b | 1005.41c | 1018.00c | 177.44b | 180.11c | 934.59c | 955.07c |
| **A$_2$:** Abscisic (5 mmol) | | | 301.75b | 305.35b | 1018.63b | 1031.48b | 180.19ab | 182.93b | 942.19b | 961.89b |
| **A$_3$:** Abscisic (10 mmol) | | | 304.50a | 307.94a | 1030.19a | 1043.19a | 182.70a | 185.67a | 948.89a | 971.22a |
| **Interaction** | | | | | | | | | | |
| **I $_1$** | **Z$_1$** | **A$_1$** | 299.92 | 303.10 | 1000.67 | 1015.33 | 177.00 | 179.67 | 931.33 | 949.33 |
| | | **A$_2$** | 302.97 | 306.35 | 1024.33 | 1036.00 | 181.67 | 185.00 | 943.33 | 963.67 |
| | | **A$_3$** | 303.36 | 307.80 | 1036.33 | 1048.67 | 183.67 | 186.67 | 948.67 | 971.33 |
| | **Z$_2$** | **A$_1$** | 317.27 | 321.92 | 1128.00 | 1139.33 | 201.00 | 204.00 | 1007.33 | 1027.00 |
| | | **A$_2$** | 317.66 | 321.43 | 1143.33 | 1154.00 | 203.00 | 206.67 | 1012.00 | 1035.00 |
| | | **A$_3$** | 325.07 | 329.26 | 1155.33 | 1167.33 | 204.67 | 209.00 | 1018.67 | 1039.00 |
| | **Z$_3$** | **A$_1$** | 329.41 | 333.48 | 1170.67 | 1184.00 | 208.00 | 211.00 | 1026.00 | 1056.33 |
| | | **A$_2$** | 329.21 | 333.55 | 1180.00 | 1200.00 | 210.00 | 213.00 | 1032.33 | 1059.00 |
| | | **A$_3$** | 331.06 | 334.59 | 1194.00 | 1207.33 | 213.00 | 215.67 | 1039.00 | 1066.67 |
| **I $_2$** | **Z$_1$** | **A$_1$** | 296.89 | 301.31 | 958.33 | 972.00 | 170.00 | 171.67 | 908.00 | 929.33 |
| | | **A$_2$** | 297.50 | 300.78 | 977.00 | 989.67 | 170.67 | 173.00 | 917.67 | 938.00 |
| | | **A$_3$** | 298.71 | 302.01 | 989.00 | 1003.00 | 173.00 | 175.67 | 923.00 | 946.33 |
| | **Z$_2$** | **A$_1$** | 304.93 | 309.48 | 1050.33 | 1065.33 | 186.67 | 190.00 | 960.00 | 983.00 |
| | | **A$_2$** | 305.23 | 309.61 | 1061.33 | 1073.33 | 189.00 | 190.67 | 968.00 | 988.33 |
| | | **A$_3$** | 307.22 | 311.27 | 1073.33 | 1090.00 | 191.67 | 194.67 | 978.00 | 999.00 |
| | **Z$_3$** | **A$_1$** | 309.83 | 313.78 | 1086.00 | 1096.33 | 192.67 | 195.67 | 981.33 | 1004.00 |
| | | **A$_2$** | 312.39 | 315.81 | 1098.33 | 1106.67 | 194.67 | 197.67 | 988.67 | 1008.00 |
| | | **A$_3$** | 317.35 | 320.82 | 1109.33 | 1121.00 | 197.00 | 199.67 | 997.00 | 1017.33 |
| **I $_3$** | **Z$_1$** | **A$_1$** | 274.76 | 278.32 | 850.33 | 858.67 | 141.67 | 143.67 | 842.33 | 854.67 |
| | | **A$_2$** | 277.37 | 281.50 | 859.67 | 870.33 | 148.67 | 151.00 | 849.33 | 859.00 |
| | | **A$_3$** | 277.78 | 281.44 | 865.67 | 880.67 | 152.67 | 155.00 | 858.67 | 880.00 |
| | **Z$_2$** | **A$_1$** | 282.14 | 285.79 | 881.33 | 894.00 | 156.00 | 158.67 | 867.00 | 883.67 |
| | | **A$_2$** | 284.24 | 287.94 | 892.33 | 904.00 | 158.00 | 160.67 | 873.00 | 893.00 |
| | | **A$_3$** | 285.35 | 287.27 | 905.33 | 916.33 | 161.67 | 164.00 | 877.67 | 896.33 |
| | **Z$_3$** | **A$_1$** | 288.70 | 291.35 | 923.00 | 937.00 | 164.00 | 166.67 | 888.00 | 908.33 |
| | | **A$_2$** | 289.16 | 291.19 | 931.33 | 949.33 | 166.00 | 168.67 | 895.33 | 913.00 |
| | | **A$_3$** | 294.64 | 297.00 | 943.33 | 954.33 | 167.00 | 170.67 | 899.33 | 925.00 |
| **LSD at 5%** | | | **6.55** | **6.53** | **7.04** | **19.44** | **8.26** | **3.04** | **17.51** | **18.21** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

**Table 3. Impact of different irrigation regimes, varying zeolite rates and foliar application of abscisic acid at different concentrations on the chlorophyll content and leaves chemical constituents (NPK) of maize during the 2023 and 2024 seasons.**

| Treatments | | | Chlorophyll, SPAD reading | | N, % | | P, % | | K, % | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor: Irrigation treatments** | | | | | | | | | | |
| **I 1** (5500 $m^3$ $ha^{-1}$) | | | 43.27a | 43.90a | 3.36a | 3.40a | 0.395a | 0.410a | 3.18a | 3.28a |
| **I 2** (4400 $m^3$ $ha^{-1}$) | | | 41.54b | 42.19b | 3.15b | 3.20b | 0.370b | 0.385b | 2.99b | 3.06b |
| **I 3** (3300 $m^3$ $ha^{-1}$) | | | 36.18c | 36.86c | 2.67c | 2.72c | 0.318c | 0.331c | 2.55c | 2.69c |
| **Sub main factor: Soil addition treatments** | | | | | | | | | | |
| **$Z_1$:** Without | | | 38.54c | 39.09c | 2.85c | 2.88c | 0.338c | 0.351c | 2.71c | 2.82c |
| **$Z_2$:** Zeolite (5 ton $ha^{-1}$) | | | 40.63b | 41.30b | 3.11b | 3.15b | 0.366b | 0.381b | 2.95b | 3.04b |
| **$Z_3$:** Zeolite (10 ton $ha^{-1}$) | | | 41.82a | 42.54a | 3.23a | 3.28a | 0.379a | 0.394a | 3.07a | 3.17a |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | | | |
| **$A_1$:** Without | | | 39.91c | 40.58b | 3.01c | 3.05c | 0.356c | 0.370c | 2.87b | 2.96c |
| **$A_2$:** Abscisic (5 mmol) | | | 40.38b | 41.04a | 3.06b | 3.11b | 0.361b | 0.376b | 2.91a | 3.01b |
| **$A_3$:** Abscisic (10 mmol) | | | 40.70a | 41.32a | 3.10a | 3.16a | 0.37a | 0.380a | 2.95a | 3.06a |
| **Interaction** | | | | | | | | | | |
| **I 1** | **$Z_1$** | **$A_1$** | 40.63 | 41.21 | 3.00 | 3.03 | 0.355 | 0.369 | 2.87 | 3.01 |
| | | **$A_2$** | 41.34 | 41.82 | 3.08 | 3.12 | 0.363 | 0.377 | 2.93 | 3.07 |
| | | **$A_3$** | 41.37 | 41.95 | 3.12 | 3.15 | 0.366 | 0.380 | 2.96 | 3.11 |
| | **$Z_2$** | **$A_1$** | 43.80 | 44.51 | 3.41 | 3.45 | 0.400 | 0.416 | 3.23 | 3.34 |
| | | **$A_2$** | 43.82 | 44.51 | 3.43 | 3.47 | 0.406 | 0.423 | 3.28 | 3.35 |
| | | **$A_3$** | 44.21 | 44.78 | 3.49 | 3.53 | 0.410 | 0.426 | 3.29 | 3.37 |
| | **$Z_3$** | **$A_1$** | 44.27 | 44.93 | 3.51 | 3.57 | 0.414 | 0.431 | 3.34 | 3.41 |
| | | **$A_2$** | 44.65 | 45.29 | 3.55 | 3.63 | 0.418 | 0.435 | 3.37 | 3.45 |
| | | **$A_3$** | 45.35 | 46.04 | 3.61 | 3.67 | 0.421 | 0.438 | 3.40 | 3.46 |
| **I 2** | **$Z_1$** | **$A_1$** | 39.39 | 39.91 | 2.87 | 2.90 | 0.341 | 0.354 | 2.76 | 2.82 |
| | | **$A_2$** | 39.33 | 40.03 | 2.94 | 2.98 | 0.348 | 0.361 | 2.80 | 2.87 |
| | | **$A_3$** | 40.06 | 40.58 | 2.97 | 3.01 | 0.350 | 0.364 | 2.83 | 2.90 |
| | **$Z_2$** | **$A_1$** | 41.85 | 42.60 | 3.16 | 3.19 | 0.372 | 0.387 | 3.00 | 3.06 |
| | | **$A_2$** | 41.97 | 42.61 | 3.21 | 3.25 | 0.376 | 0.391 | 3.04 | 3.10 |
| | | **$A_3$** | 42.25 | 43.00 | 3.25 | 3.29 | 0.381 | 0.397 | 3.05 | 3.12 |
| | **$Z_3$** | **$A_1$** | 42.36 | 43.06 | 3.29 | 3.33 | 0.385 | 0.400 | 3.10 | 3.17 |
| | | **$A_2$** | 43.18 | 43.80 | 3.34 | 3.39 | 0.389 | 0.404 | 3.13 | 3.20 |
| | | **$A_3$** | 43.43 | 44.12 | 3.37 | 3.46 | 0.393 | 0.408 | 3.18 | 3.34 |
| **I 3** | **$Z_1$** | **$A_1$** | 34.74 | 35.31 | 2.51 | 2.51 | 0.302 | 0.314 | 2.33 | 2.44 |
| | | **$A_2$** | 34.94 | 35.50 | 2.54 | 2.61 | 0.305 | 0.317 | 2.42 | 2.54 |
| | | **$A_3$** | 35.07 | 35.53 | 2.59 | 2.65 | 0.309 | 0.322 | 2.49 | 2.62 |
| | **$Z_2$** | **$A_1$** | 35.36 | 36.09 | 2.62 | 2.69 | 0.313 | 0.326 | 2.52 | 2.65 |
| | | **$A_2$** | 36.06 | 36.86 | 2.68 | 2.74 | 0.318 | 0.331 | 2.56 | 2.69 |
| | | **$A_3$** | 36.37 | 36.78 | 2.73 | 2.77 | 0.322 | 0.336 | 2.60 | 2.73 |
| | **$Z_3$** | **$A_1$** | 36.82 | 37.59 | 2.75 | 2.80 | 0.325 | 0.339 | 2.66 | 2.79 |
| | | **$A_2$** | 38.11 | 38.91 | 2.79 | 2.83 | 0.331 | 0.345 | 2.70 | 2.84 |
| | | **$A_3$** | 38.20 | 39.13 | 2.83 | 2.88 | 0.336 | 0.349 | 2.73 | 2.87 |
| **LSD at 5%** | | | **0.85** | **0.67** | **0.07** | **0.07** | **0.006** | **0.006** | **0.13** | **0.16** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

**Oxidative activity**

Data in Table 4 reveal significant variations in antioxidant indicators, including proline, malondialdehyde (MDA), catalase (CAT), and peroxidase (POX) in maize leaves under different irrigation regimes, zeolite applications, and foliar treatments with abscisic acid (ABA) across the 2023 and 2024 growing seasons at period of 70 days from sowing.

**Irrigation regime's effect**

The highest irrigation treatment ($I_1$: 5500 $m^3$ $ha^{-1}$) resulted in the lowest levels of proline, MDA, catalase (CAT) and peroxidase (POX) across both seasons, indicating less water stress and oxidative damage. In contrast, the lowest irrigation treatment ($I_3$: 3300 $m^3$ $ha^{-1}$) showed the highest values. Specifically, the elevated MDA levels under water deficit conditions suggest increased lipid peroxidation, reflecting oxidative stress in maize plants.

**Zeolite's effect**

The application of zeolite demonstrated a notable impact on antioxidant indicators. The control treatment ($Z_1$: without zeolite) showed the highest levels of proline, malondialdehyde (MDA), catalase (CAT) and peroxidase (POX), suggesting that the absence of zeolite may result in increased stress responses. In contrast, higher rates of zeolite ($Z_2$ and $Z_3$) led to lower levels of proline, malondialdehyde (MDA), catalase (CAT) and peroxidase (POX), indicating improved moisture retention and nutrient availability, which could alleviate oxidative stress.

**Abscisic acid's effect**

Foliar application of ABA significantly influenced enzymatic antioxidants. The treatment without ABA ($A_1$) resulted in higher levels of proline, malondialdehyde (MDA), catalase (CAT) and peroxidase (POX) compared to treatments with ABA. Specifically, the application of 10 mmol ABA ($A_3$) led to a reduction in proline, malondialdehyde (MDA), catalase (CAT) and peroxidase (POX), suggesting that ABA helps in managing stress and reducing oxidative damage.

**Interaction effects**

The interaction between irrigation regimes, zeolite rates, and ABA applications revealed that combined treatments significantly improved the antioxidant profile of maize leaves. For instance, the combination of the lowest irrigation ($I_2$) with the highest zeolite rate ($Z_3$) and 10 mmol ABA ($A_3$) resulted in lower levels of proline, malondialdehyde (MDA), catalase (CAT) and peroxidase (POX) compared to the plants grown under traditional irrigation (I1) without both zeolite and ABA.

**Yield and quality parameters**

Data presented in Tables 5 and 6 illustrate the impact of various irrigation regimes, zeolite applications and foliar treatments with abscisic acid (ABA) on maize yield and quality at harvest during the 2023 and 2024 seasons. The harvest measurements included cob weight (g), cob length (cm), number of seeds per cob, weight of 100 grains (g), grain yield (Mg $ha^{-1}$, **Fig 2**), biological yield (Mg $ha^{-1}$) and harvest index (%) (Table 5). Additionally, Table 6 includes analyses of carbohydrates, protein, oil content (%), anthocyanins (mg/100g) and nutrient concentrations of nitrogen, phosphorus, and potassium (%).

**Irrigation regime's effect**

The irrigation regime significantly influenced the yield and quality parameters. The highest irrigation level ($I_1$: 5500 $m^3$ $ha^{-1}$) consistently produced the best results, including greater cob weight (g), cob length (cm), number of seeds per cob, weight of 100 grains (g), grain and biological yields ($Mgha^{-1}$) , harvest index (%), carbohydrates, protein, oil content (%), anthocyanins (mg/100g) and nutrient concentrations of nitrogen, phosphorus and potassium (%). The irrigation level of $I_1$ (4400 $m^3$ $ha^{-1}$ came in the second order, while the lowest values were achieved under the irrigation level of $I_3$ (3300 $m^3$ $ha^{-1}$).

**Zeolite's effect**

The addition of zeolite also played a crucial role. Higher zeolite rates ($Z_3$: 10 ton $ha^{-1}$) resulted in improved yield and quality metrics compared to lower rate ($Z_2$: 5 ton $ha^{-1}$), which came in the second order. The control group (without zeolite) possessed the lowest values of cob weight (g), cob length (cm), number of seeds per cob, weight of 100 grains (g), grain and biological yields ($Mgha^{-1}$) , harvest index (%), carbohydrates, protein, oil content (%), anthocyanins (mg/100g), nitrogen, phosphorus and potassium (%).

**Abscisic acid's effect**

Foliar application of abscisic acid showed significant benefits, particularly at the highest concentration ($A_3$: 10 mmol), which was the superior treatment in obtaining the maximum values of cob weight (g), cob length (cm), number of seeds per cob, weight of 100 grains (g), grain and biological yields ($Mgha^{-1}$) , harvest index (%), carbohydrates, protein, oil content (%), anthocyanins (mg/100g) and nutrient concentrations of nitrogen, phosphorus, and potassium (%).

**Table 4. Impact of different irrigation regimes, varying zeolite rates and foliar application of abscisic acid at different concentrations on the antioxidant indicators in leaves of maize during the 2023 and 2024 seasons.**

| Treatments | | | Proline, µg $g^{-1}$ F.W | | MDA, µmol $g^{-1}$ F.W | | CAT (Unit $mg^{-1}$ $protein^{-1}$) | | POX (Unit $mg^{-1}$ $protein^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| **Main factor: Irrigation treatments** | | | | | | | | | | |
| **$I_1$** (5500 $m^3$ $ha^{-1}$) | | | 7.06c | 6.54c | 11.20c | 10.38c | 184.66c | 187.71c | 67.61c | 69.76c |
| **$I_2$** (4400 $m^3$ $ha^{-1}$) | | | 7.36b | 6.79b | 12.18b | 11.24b | 202.87b | 205.87b | 72.54b | 75.09b |
| **$I_3$** (3300 $m^3$ $ha^{-1}$) | | | 8.59a | 7.92a | 14.71a | 13.57a | 243.05a | 247.54a | 83.14a | 86.22a |
| **Sub main factor: Soil addition treatments** | | | | | | | | | | |
| **$Z_1$:** Without | | | 8.31a | 7.67a | 13.78a | 12.74a | 229.65a | 233.08a | 79.69a | 82.43a |
| **$Z_2$:** Zeolite (5 ton $ha^{-1}$) | | | 7.44b | 6.88b | 12.43b | 11.49b | 205.58b | 209.18b | 73.23b | 75.77b |
| **$Z_3$:** Zeolite (10 ton $ha^{-1}$ | | | 7.26c | 6.70c | 11.89c | 10.96c | 195.35c | 198.86c | 70.36c | 72.88c |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | | | |
| **$A_1$:** Without | | | 7.73a | 7.15a | 12.87a | 11.90a | 213.21a | 216.79a | 75.49a | 78.06a |
| **$A_2$:** Abscisic (5 mmol) | | | 7.66b | 7.09b | 12.73b | 11.74b | 210.47b | 214.04b | 74.44b | 76.99b |
| **$A_3$:** Abscisic (10 | | | 7.61b | 7.02c | 12.48c | 11.54c | 206.90c | 210.29c | 73.36c | 76.03c |
| **Interaction** | | | | | | | | | | |
| **$I_1$** | **$Z_1$** | **$A_1$** | 8.07 | 7.46 | 12.95 | 12.00 | 215.97 | 219.27 | 76.65 | 79.10 |
| | | **$A_2$** | 7.94 | 7.35 | 12.75 | 11.77 | 213.74 | 216.87 | 74.65 | 76.99 |
| | | **$A_3$** | 7.89 | 7.26 | 12.33 | 11.50 | 209.36 | 212.50 | 72.61 | 74.93 |
| | **$Z_2$** | **$A_1$** | 6.73 | 6.28 | 10.87 | 10.23 | 177.69 | 180.75 | 66.69 | 68.70 |
| | | **$A_2$** | 6.68 | 6.31 | 10.73 | 9.89 | 174.18 | 177.82 | 65.70 | 67.59 |
| | | **$A_3$** | 6.64 | 6.12 | 10.62 | 9.76 | 172.23 | 175.87 | 64.96 | 67.38 |
| | **$Z_3$** | **$A_1$** | 6.58 | 6.05 | 10.42 | 9.60 | 168.71 | 171.05 | 63.27 | 65.63 |
| | | **$A_2$** | 6.54 | 6.03 | 10.12 | 9.37 | 165.84 | 168.20 | 62.42 | 64.18 |
| | | **$A_3$** | 6.50 | 6.02 | 10.02 | 9.25 | 164.21 | 167.04 | 61.52 | 63.36 |
| **$I_2$** | **$Z_1$** | **$A_1$** | 8.25 | 7.62 | 13.44 | 12.41 | 228.63 | 231.41 | 78.08 | 80.35 |
| | | **$A_2$** | 8.19 | 7.55 | 13.39 | 12.35 | 222.99 | 226.53 | 77.24 | 80.01 |
| | | **$A_3$** | 8.13 | 7.52 | 13.15 | 12.11 | 220.79 | 224.14 | 77.09 | 79.76 |
| | **$Z_2$** | **$A_1$** | 7.09 | 6.53 | 11.93 | 10.99 | 203.42 | 206.63 | 72.54 | 74.76 |
| | | **$A_2$** | 7.03 | 6.46 | 11.89 | 10.96 | 198.76 | 201.37 | 70.98 | 73.77 |
| | | **$A_3$** | 6.97 | 6.42 | 11.70 | 10.87 | 192.98 | 196.00 | 70.85 | 73.55 |
| | **$Z_3$** | **$A_1$** | 6.91 | 6.41 | 11.52 | 10.67 | 188.83 | 191.91 | 70.34 | 72.87 |
| | | **$A_2$** | 6.84 | 6.33 | 11.52 | 10.60 | 186.65 | 189.12 | 68.39 | 70.73 |
| | | **$A_3$** | 6.79 | 6.25 | 11.06 | 10.23 | 182.80 | 185.75 | 67.37 | 70.01 |
| **$I_3$** | **$Z_1$** | **$A_1$** | 8.81 | 8.14 | 15.44 | 14.21 | 253.17 | 257.52 | 88.20 | 91.84 |
| | | **$A_2$** | 8.78 | 8.10 | 15.36 | 14.18 | 253.48 | 257.54 | 87.93 | 91.10 |
| | | **$A_3$** | 8.74 | 8.06 | 15.19 | 14.09 | 248.71 | 251.98 | 84.80 | 87.77 |
| | **$Z_2$** | **$A_1$** | 8.66 | 8.03 | 14.99 | 13.83 | 245.90 | 251.01 | 82.86 | 85.78 |
| | | **$A_2$** | 8.60 | 7.94 | 14.67 | 13.52 | 244.56 | 249.95 | 82.62 | 85.35 |
| | | **$A_3$** | 8.53 | 7.87 | 14.43 | 13.34 | 240.47 | 243.18 | 81.92 | 85.05 |
| | **$Z_3$** | **$A_1$** | 8.45 | 7.81 | 14.30 | 13.17 | 236.58 | 241.53 | 80.82 | 83.48 |
| | | **$A_2$** | 8.38 | 7.72 | 14.16 | 13.02 | 234.01 | 238.99 | 79.99 | 83.21 |
| | | **$A_3$** | 8.33 | 7.66 | 13.86 | 12.74 | 230.54 | 236.13 | 79.15 | 82.42 |
| **LSD at 5%** | | | **0.16** | **0.16** | **0.28** | **0.24** | **4.17** | **4.68** | **1.32** | **1.77** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

**Interaction Effects**

The interaction between irrigation, zeolite applications and ABA treatments produced significant variations in maize performance. For instance, the combination of high irrigation amount and maximum zeolite rates with high dose of ABA resulted in the highest yields and quality parameters, highlighting the synergistic effect of these treatments.

**Table 5. Impact of different irrigation regimes, varying zeolite rates and foliar application of abscisic acid at different concentrations on yield and its component of maize during the 2023 and 2024 seasons.**

| Treatments | | | Weight of cob, g | | Cob length, cm | | No. seeds cob$^{-1}$ | | Weight of 100 grain, g | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor: Irrigation treatments** | | | | | | | | | | |
| **$I_1$** (5500 $m^3$ $ha^{-1}$) | | | 289.48a | 293.09a | 25.16a | 25.46a | 378.70a | 383.07 | 43.08a | 43.23a |
| **$I_2$** (4400 $m^3$ $ha^{-1}$) | | | 278.69b | 282.32b | 22.99b | 23.32b | 351.22b | 356.52 | 41.28b | 41.47b |
| **$I_3$** (3300 $m^3$ $ha^{-1}$) | | | 221.85c | 224.22c | 16.69c | 17.00c | 286.89c | 291.89 | 37.46c | 18.52c |
| **Sub main factor: Soil addition treatments** | | | | | | | | | | |
| **$Z_1$:** Without | | | 254.32c | 257.57c | 19.21c | 19.51c | 312.15c | 317.00c | 38.78c | 32.71c |
| **$Z_2$:**Zeolite (5 ton $ha^{-1}$) | | | 264.33b | 267.73b | 22.14b | 22.43b | 344.56b | 349.04b | 41.06b | 33.93b |
| **$Z_3$:** Zeolite (10 ton $ha^{-}$ | | | 271.37a | 274.33a | 23.50a | 23.85a | 360.11a | 365.44a | 41.98a | 36.58a |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | | | |
| **$A_1$:** Without | | | 261.65b | 265.03b | 21.21c | 21.48c | 332.56c | 337.33c | 40.23b | 33.22c |
| **$A_2$:** Abscisic (5 mmol) | | | 263.07b | 266.09b | 21.62b | 21.98b | 339.74b | 344.63b | 40.52b | 34.83b |
| **$A_3$:** Abscisic (10 | | | 265.30a | 268.51a | 22.01a | 22.32a | 344.52a | 349.52a | 41.06a | 35.18a |
| **Interaction** | | | | | | | | | | |
| **$I_1$** | **$Z_1$** | **$A_1$** | 273.69 | 276.62 | 21.33 | 21.58 | 332.67 | 338.00 | 40.24 | 40.29 |
| | | **$A_2$** | 276.33 | 279.44 | 22.26 | 22.58 | 345.67 | 349.00 | 40.60 | 40.73 |
| | | **$A_3$** | 276.68 | 280.82 | 22.49 | 22.70 | 349.67 | 352.33 | 41.27 | 41.44 |
| | **$Z_2$** | **$A_1$** | 289.66 | 293.58 | 25.97 | 26.26 | 385.67 | 389.67 | 43.52 | 43.71 |
| | | **$A_2$** | 289.41 | 293.11 | 26.40 | 26.74 | 388.67 | 392.33 | 43.63 | 43.86 |
| | | **$A_3$** | 296.82 | 300.43 | 26.74 | 26.98 | 395.33 | 399.67 | 44.17 | 44.36 |
| | **$Z_3$** | **$A_1$** | 300.23 | 304.38 | 26.70 | 27.06 | 399.33 | 403.67 | 44.25 | 44.37 |
| | | **$A_2$** | 300.72 | 304.18 | 26.71 | 27.06 | 403.67 | 408.67 | 44.79 | 44.97 |
| | | **$A_3$** | 301.78 | 305.23 | 27.88 | 28.20 | 407.67 | 414.33 | 45.20 | 45.36 |
| **$I_2$** | **$Z_1$** | **$A_1$** | 270.53 | 274.95 | 19.77 | 20.09 | 308.67 | 314.67 | 38.89 | 39.04 |
| | | **$A_2$** | 271.73 | 274.28 | 20.20 | 20.60 | 319.67 | 325.00 | 39.22 | 39.42 |
| | | **$A_3$** | 272.20 | 275.20 | 20.80 | 21.17 | 325.67 | 331.00 | 39.89 | 40.08 |
| | **$Z_2$** | **$A_1$** | 278.22 | 282.77 | 23.52 | 23.78 | 352.33 | 357.00 | 41.27 | 41.40 |
| | | **$A_2$** | 278.48 | 282.48 | 23.60 | 23.93 | 358.67 | 365.67 | 41.88 | 42.06 |
| | | **$A_3$** | 280.32 | 284.06 | 23.72 | 24.01 | 362.00 | 366.67 | 42.23 | 42.36 |
| | **$Z_3$** | **$A_1$** | 282.56 | 286.02 | 24.66 | 24.93 | 368.67 | 373.67 | 42.26 | 42.50 |
| | | **$A_2$** | 285.03 | 288.15 | 25.15 | 25.53 | 379.67 | 384.33 | 42.57 | 42.83 |
| | | **$A_3$** | 289.13 | 292.99 | 25.50 | 25.82 | 385.67 | 390.67 | 43.30 | 43.50 |
| **$I_3$** | **$Z_1$** | **$A_1$** | 213.59 | 216.00 | 15.20 | 15.43 | 272.33 | 276.67 | 36.04 | 36.32 |
| | | **$A_2$** | 216.89 | 220.25 | 15.39 | 15.61 | 276.67 | 281.33 | 36.21 | 36.52 |
| | | **$A_3$** | 217.22 | 220.56 | 15.45 | 15.83 | 278.33 | 285.00 | 36.63 | 15.41 |
| | **$Z_2$** | **$A_1$** | 220.59 | 223.20 | 15.84 | 15.85 | 281.67 | 285.67 | 37.37 | 15.61 |
| | | **$A_2$** | 222.58 | 225.07 | 16.46 | 16.93 | 286.00 | 290.67 | 37.42 | 15.92 |
| | | **$A_3$** | 222.91 | 224.90 | 17.00 | 17.39 | 290.67 | 294.00 | 38.01 | 16.06 |
| | **$Z_3$** | **$A_1$** | 225.79 | 227.79 | 17.90 | 18.36 | 291.67 | 297.00 | 38.27 | 10.20 |
| | | **$A_2$** | 226.46 | 227.83 | 18.42 | 18.86 | 299.00 | 304.67 | 38.31 | 10.28 |
| | | **$A_3$** | 230.63 | 232.41 | 18.54 | 18.79 | 305.67 | 312.00 | 38.88 | 10.37 |
| **LSD at 5%** | | | **6.00** | **5.64** | **0.47** | **0.50** | **6.42** | **6.70** | **0.86** | **0.79** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

**Cont. Table 5.**

| Treatments | | | Grain yield, Mg ha$^{-1}$ | | Biological yield, Mg ha$^{-1}$ | | Harvest index, % | |
|---|---|---|---|---|---|---|---|---|
| | | | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season | 1$^{st}$ season | 2$^{nd}$ season |
| **Main factor : Irrigation treatments** | | | | | | | | |
| **I $_1$** (5500 m$^3$ ha$^{-1}$) | | | 8.99a | 9.16a | 17.50a | 17.84a | 51.25a | 51.26a |
| **I $_2$** (4400 m$^3$ ha$^{-1}$) | | | 8.26b | 8.43b | 16.69b | 17.04b | 49.45b | 49.43b |
| **I $_3$** (3300 m$^3$ ha$^{-1}$) | | | 6.13c | 6.25c | 14.40c | 14.70c | 42.43c | 42.44c |
| **Sub main factor: Soil addition treatments** | | | | | | | | |
| **Z$_1$:** Without | | | 6.93c | 7.07c | 15.39c | 15.71c | 44.74c | 44.70c |
| **Z$_2$:**Zeolite (5 ton ha$^{-1}$) | | | 7.94b | 8.10b | 16.27b | 16.58b | 48.47b | 48.49b |
| **Z$_3$:** Zeolite (10 ton ha$^{-1}$) | | | 8.50a | 8.68a | 16.94a | 17.30a | 49.93a | 49.93a |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | |
| **A$_1$:** Without | | | 7.61c | 7.76c | 16.02c | 16.33c | 47.09b | 47.14b |
| **A$_2$:** Abscisic (5 mmol) | | | 7.79b | 7.95b | 16.15b | 16.49b | 47.86a | 47.83a |
| **A$_3$:** Abscisic (10 mmol) | | | 7.98a | 8.14a | 16.43a | 16.77a | 48.18a | 48.15a |
| **Interaction** | | | | | | | | |
| **I $_1$** | **Z$_1$** | **A$_1$** | 7.81 | 7.97 | 16.38 | 16.66 | 47.68 | 47.87 |
| | | **A$_2$** | 7.85 | 7.97 | 16.40 | 16.74 | 47.84 | 47.64 |
| | | **A$_3$** | 8.15 | 8.31 | 16.54 | 16.90 | 49.31 | 49.18 |
| | **Z$_2$** | **A$_1$** | 9.22 | 9.42 | 17.54 | 17.81 | 52.59 | 52.88 |
| | | **A$_2$** | 9.26 | 9.42 | 17.55 | 17.92 | 52.77 | 52.59 |
| | | **A$_3$** | 9.49 | 9.66 | 17.91 | 18.29 | 52.97 | 52.81 |
| | **Z$_3$** | **A$_1$** | 9.57 | 9.78 | 18.01 | 18.37 | 53.13 | 53.28 |
| | | **A$_2$** | 9.62 | 9.81 | 18.33 | 18.67 | 52.49 | 52.57 |
| | | **A$_3$** | 9.91 | 10.09 | 18.88 | 19.22 | 52.49 | 52.50 |
| **I $_2$** | **Z$_1$** | **A$_1$** | 7.32 | 7.46 | 15.61 | 15.93 | 46.93 | 46.85 |
| | | **A$_2$** | 7.55 | 7.70 | 16.01 | 16.39 | 47.19 | 47.00 |
| | | **A$_3$** | 7.66 | 7.84 | 16.09 | 16.45 | 47.62 | 47.67 |
| | **Z$_2$** | **A$_1$** | 8.16 | 8.34 | 16.68 | 17.04 | 48.90 | 48.95 |
| | | **A$_2$** | 8.32 | 8.49 | 16.73 | 17.03 | 49.76 | 49.89 |
| | | **A$_3$** | 8.49 | 8.64 | 17.05 | 17.34 | 49.82 | 49.87 |
| | **Z$_3$** | **A$_1$** | 8.67 | 8.82 | 17.29 | 17.69 | 50.17 | 49.86 |
| | | **A$_2$** | 8.99 | 9.21 | 17.33 | 17.71 | 51.87 | 52.04 |
| | | **A$_3$** | 9.20 | 9.39 | 17.45 | 17.81 | 52.76 | 52.73 |
| **I $_3$** | **Z$_1$** | **A$_1$** | 5.29 | 5.40 | 13.73 | 13.98 | 38.52 | 38.65 |
| | | **A$_2$** | 5.34 | 5.44 | 13.82 | 14.12 | 38.60 | 38.55 |
| | | **A$_3$** | 5.42 | 5.53 | 13.93 | 14.21 | 38.92 | 38.91 |
| | **Z$_2$** | **A$_1$** | 5.91 | 6.02 | 14.00 | 14.24 | 42.19 | 42.30 |
| | | **A$_2$** | 6.30 | 6.41 | 14.16 | 14.43 | 44.46 | 44.43 |
| | | **A$_3$** | 6.34 | 6.46 | 14.83 | 15.12 | 42.76 | 42.70 |
| | **Z$_3$** | **A$_1$** | 6.52 | 6.65 | 14.91 | 15.26 | 43.74 | 43.60 |
| | | **A$_2$** | 6.89 | 7.05 | 15.05 | 15.39 | 45.77 | 45.80 |
| | | **A$_3$** | 7.14 | 7.30 | 15.21 | 15.54 | 46.93 | 47.01 |
| **LSD at 5%** | | | **0.17** | **0.18** | **0.36** | **0.38** | **1.60** | **1.68** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

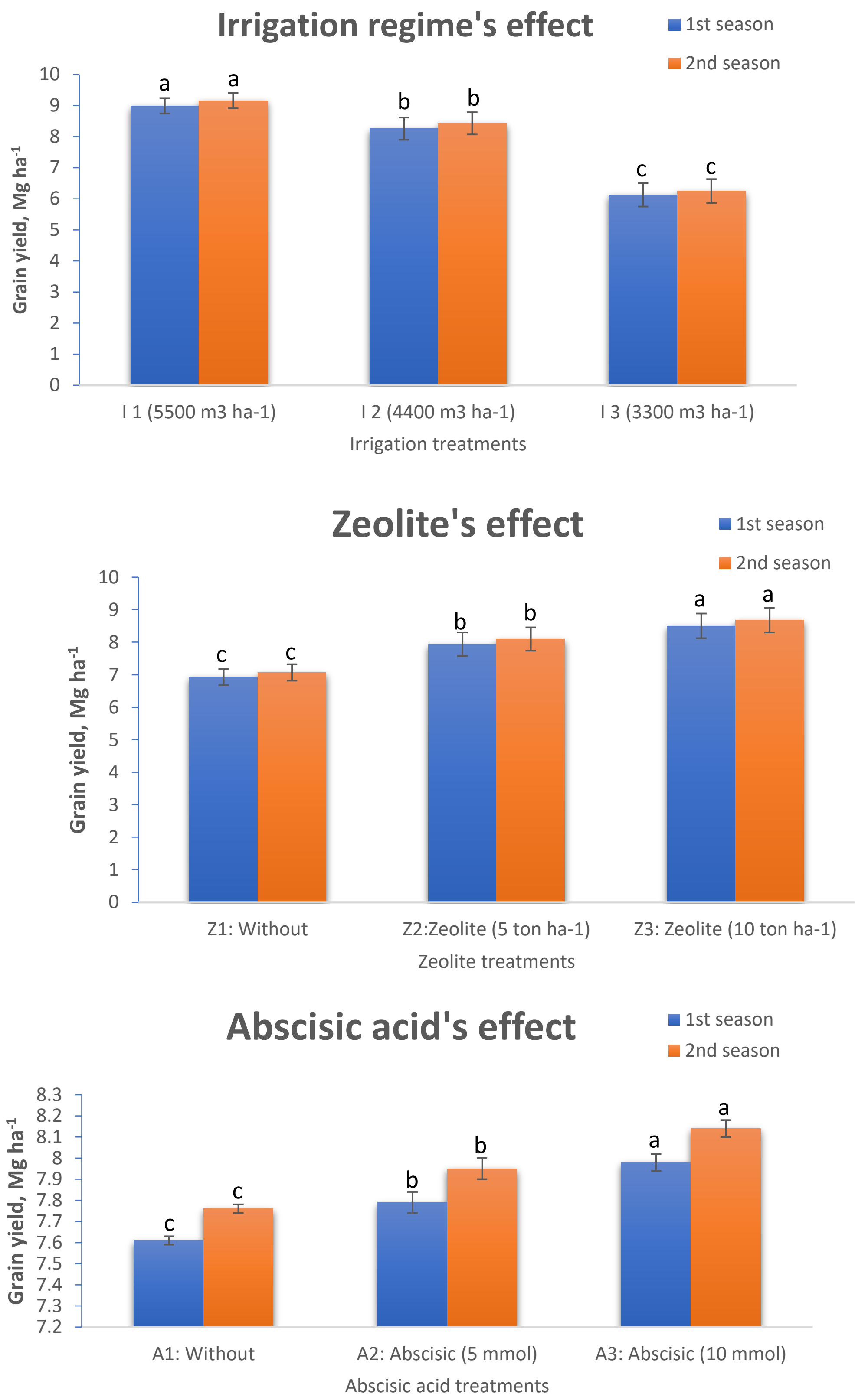


**Fig. 2. Impact of different irrigation regimes, varying zeolite rates and foliar application of abscisic acid at various concentrations on grain yield of maize during the 2023 and 2024 seasons as individual effects for each factor.**

**Table 6. Impact of different irrigation regimes, varying zeolite rates and foliar application of abscisic acid at different concentrations on seed quality of maize during the 2023 and 2024 seasons.**

| Treatments | | | Carbohydrates, % | | Protein, % | | Oil, % | | Anthocyanin, mg100g$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor : Irrigation treatments** | | | | | | | | | | |
| **I$_1$** (5500 m$^3$ ha$^{-1}$) | | | 72.75a | 74.47a | 14.69a | 15.14a | 6.42a | 6.53a | 29.69a | 30.16a |
| **I$_2$** (4400 m$^3$ ha$^{-1}$) | | | 70.73b | 72.06b | 13.79b | 14.24b | 5.61b | 5.71b | 28.42b | 28.86b |
| **I$_3$** (3300 m$^3$ ha$^{-1}$) | | | 66.35c | 67.94c | 11.61c | 11.97c | 3.85c | 3.92c | 25.42c | 25.91c |
| **Sub main factor: Soil addition treatments** | | | | | | | | | | |
| **Z$_1$:** Without | | | 67.91c | 69.42c | 12.48c | 12.88c | 4.48c | 4.56c | 26.48c | 26.92c |
| **Z$_2$:**Zeolite (5 ton ha$^{-1}$) | | | 70.21b | 71.75b | 13.53b | 13.97b | 5.46b | 5.55b | 28.13b | 28.58b |
| **Z$_3$:** Zeolite (10 ton ha$^{-1}$) | | | 71.72a | 73.29a | 14.09a | 14.52a | 5.93a | 6.06a | 28.94a | 29.43a |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | | | |
| **A$_1$:** Without | | | 69.57b | 71.05b | 13.16c | 13.58c | 5.13c | 5.23c | 27.55c | 28.00c |
| **A$_2$:** Abscisic (5 mmol) | | | 69.79b | 71.38b | 13.35b | 13.79b | 5.28b | 5.39b | 27.85b | 28.31b |
| **A$_3$:** Abscisic (10 mmol) | | | 70.47a | 72.04a | 13.58a | 14.00a | 5.45a | 5.55a | 28.14a | 28.61a |
| **Interaction** | | | | | | | | | | |
| **I$_1$** | **Z$_1$** | **A$_1$** | 69.63 | 71.30 | 13.28 | 13.69 | 5.06 | 5.14 | 27.67 | 28.12 |
| | | **A$_2$** | 70.03 | 71.37 | 13.55 | 13.95 | 5.28 | 5.38 | 27.87 | 28.33 |
| | | **A$_3$** | 70.26 | 72.20 | 13.61 | 14.01 | 5.45 | 5.54 | 28.13 | 28.65 |
| | **Z$_2$** | **A$_1$** | 73.37 | 75.21 | 14.89 | 15.35 | 6.58 | 6.68 | 29.92 | 30.55 |
| | | **A$_2$** | 73.60 | 75.49 | 14.99 | 15.41 | 6.70 | 6.83 | 30.23 | 30.62 |
| | | **A$_3$** | 73.81 | 75.38 | 15.05 | 15.62 | 7.03 | 7.16 | 30.54 | 30.94 |
| | **Z$_3$** | **A$_1$** | 74.17 | 75.79 | 15.12 | 15.64 | 7.18 | 7.32 | 30.70 | 31.19 |
| | | **A$_2$** | 74.34 | 76.14 | 15.74 | 16.20 | 7.18 | 7.32 | 30.91 | 31.34 |
| | | **A$_3$** | 75.56 | 77.34 | 16.01 | 16.43 | 7.29 | 7.41 | 31.25 | 31.65 |
| **I$_2$** | **Z$_1$** | **A$_1$** | 68.68 | 70.13 | 12.54 | 12.94 | 4.50 | 4.58 | 26.89 | 27.35 |
| | | **A$_2$** | 68.99 | 70.43 | 12.71 | 13.15 | 4.69 | 4.77 | 27.17 | 27.52 |
| | | **A$_3$** | 69.60 | 71.07 | 13.09 | 13.55 | 4.86 | 4.95 | 27.44 | 27.79 |
| | **Z$_2$** | **A$_1$** | 70.79 | 72.12 | 13.80 | 14.18 | 5.60 | 5.70 | 28.43 | 28.84 |
| | | **A$_2$** | 70.75 | 72.24 | 13.80 | 14.32 | 5.77 | 5.85 | 28.67 | 29.14 |
| | | **A$_3$** | 70.86 | 71.86 | 14.36 | 14.93 | 5.99 | 6.06 | 28.95 | 29.37 |
| | **Z$_3$** | **A$_1$** | 72.07 | 72.87 | 14.43 | 14.93 | 6.10 | 6.24 | 29.11 | 29.58 |
| | | **A$_2$** | 72.13 | 73.84 | 14.53 | 14.99 | 6.44 | 6.62 | 29.44 | 29.88 |
| | | **A$_3$** | 72.68 | 73.99 | 14.82 | 15.18 | 6.49 | 6.65 | 29.73 | 30.22 |
| **I$_3$** | **Z$_1$** | **A$_1$** | 64.26 | 65.70 | 11.00 | 11.37 | 3.42 | 3.51 | 23.91 | 24.22 |
| | | **A$_2$** | 64.41 | 65.77 | 11.19 | 11.62 | 3.46 | 3.54 | 24.52 | 25.03 |
| | | **A$_3$** | 65.33 | 66.84 | 11.31 | 11.62 | 3.58 | 3.67 | 24.69 | 25.24 |
| | **Z$_2$** | **A$_1$** | 65.54 | 66.83 | 11.48 | 11.83 | 3.70 | 3.77 | 25.10 | 25.39 |
| | | **A$_2$** | 65.68 | 67.53 | 11.63 | 11.96 | 3.84 | 3.90 | 25.43 | 25.92 |
| | | **A$_3$** | 67.45 | 69.14 | 11.75 | 12.11 | 3.90 | 3.97 | 25.86 | 26.40 |
| | **Z$_3$** | **A$_1$** | 67.67 | 69.47 | 11.90 | 12.25 | 4.06 | 4.13 | 26.20 | 26.78 |
| | | **A$_2$** | 68.19 | 69.64 | 12.04 | 12.48 | 4.20 | 4.28 | 26.41 | 27.02 |
| | | **A$_3$** | 68.63 | 70.52 | 12.19 | 12.54 | 4.46 | 4.54 | 26.70 | 27.22 |
| **LSD at 5%** | | | **1.48** | **1.36** | **0.31** | **0.63** | **0.12** | **0.13** | **0.59** | **0.59** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

**Cont. Table 6**

| Treatments | | | N, % | | P, % | | K, % | |
|---|---|---|---|---|---|---|---|---|
| | | | 1st season | 2nd season | 1st season | 2nd season | 1st season | 2nd season |
| **Main factor : Irrigation treatments** | | | | | | | | |
| **I 1** (5500 $m^3$ $ha^{-1}$) | | | 2.56a | 2.63a | 0.314a | 0.323a | 2.03a | 2.06a |
| **I 2** (4400 $m^3$ $ha^{-1}$) | | | 2.40b | 2.48b | 0.296b | 0.307b | 1.90b | 1.94b |
| **I 3** (3300 $m^3$ $ha^{-1}$) | | | 2.02c | 2.08c | 0.253c | 0.262c | 1.63c | 1.66c |
| **Sub main factor: Soil addition treatments** | | | | | | | | |
| **$Z_1$:** Without | | | 2.17c | 2.24c | 0.267c | 0.276c | 1.72c | 1.76c |
| **$Z_2$:**Zeolite (5 ton $ha^{-1}$) | | | 2.35b | 2.43b | 0.292b | 0.302b | 1.88b | 1.92b |
| **$Z_3$:** Zeolite (10 ton $ha^{-1}$) | | | 2.45a | 2.52a | 0.304a | 0.315a | 1.95a | 1.99a |
| **Sub-sub main factor: Abscisic acid treatments** | | | | | | | | |
| **$A_1$:** Without | | | 2.29c | 2.36c | 0.284c | 0.294c | 1.83b | 1.86b |
| **$A_2$:** Abscisic (5 mmol) | | | 2.32b | 2.40b | 0.287b | 0.297b | 1.85ab | 1.89ab |
| **$A_3$:** Abscisic (10 mmol) | | | 2.36a | 2.43a | 0.292a | 0.302a | 1.87a | 1.91a |
| **Interaction** | | | | | | | | |
| **I 1** | **$Z_1$** | **$A_1$** | 2.31 | 2.38 | 0.283 | 0.291 | 1.83 | 1.86 |
| | | **$A_2$** | 2.36 | 2.43 | 0.285 | 0.294 | 1.86 | 1.90 |
| | | **$A_3$** | 2.37 | 2.44 | 0.287 | 0.295 | 1.88 | 1.92 |
| | **$Z_2$** | **$A_1$** | 2.59 | 2.67 | 0.317 | 0.329 | 2.06 | 2.10 |
| | | **$A_2$** | 2.61 | 2.68 | 0.323 | 0.334 | 2.09 | 2.13 |
| | | **$A_3$** | 2.62 | 2.72 | 0.327 | 0.336 | 2.10 | 2.14 |
| | **$Z_3$** | **$A_1$** | 2.63 | 2.72 | 0.330 | 0.339 | 2.13 | 2.17 |
| | | **$A_2$** | 2.74 | 2.82 | 0.333 | 0.343 | 2.14 | 2.18 |
| | | **$A_3$** | 2.78 | 2.86 | 0.339 | 0.351 | 2.16 | 2.20 |
| **I 2** | **$Z_1$** | **$A_1$** | 2.18 | 2.25 | 0.274 | 0.283 | 1.75 | 1.79 |
| | | **$A_2$** | 2.21 | 2.29 | 0.275 | 0.283 | 1.79 | 1.83 |
| | | **$A_3$** | 2.28 | 2.36 | 0.280 | 0.291 | 1.80 | 1.84 |
| | **$Z_2$** | **$A_1$** | 2.40 | 2.47 | 0.296 | 0.308 | 1.91 | 1.95 |
| | | **$A_2$** | 2.40 | 2.49 | 0.299 | 0.310 | 1.93 | 1.97 |
| | | **$A_3$** | 2.50 | 2.60 | 0.306 | 0.316 | 1.95 | 1.98 |
| | **$Z_3$** | **$A_1$** | 2.51 | 2.60 | 0.310 | 0.322 | 1.97 | 2.02 |
| | | **$A_2$** | 2.53 | 2.61 | 0.312 | 0.324 | 1.99 | 2.03 |
| | | **$A_3$** | 2.58 | 2.64 | 0.316 | 0.327 | 2.03 | 2.07 |
| **I 3** | **$Z_1$** | **$A_1$** | 1.91 | 1.98 | 0.235 | 0.243 | 1.50 | 1.53 |
| | | **$A_2$** | 1.95 | 2.02 | 0.239 | 0.247 | 1.53 | 1.56 |
| | | **$A_3$** | 1.97 | 2.02 | 0.249 | 0.258 | 1.59 | 1.62 |
| | **$Z_2$** | **$A_1$** | 2.00 | 2.06 | 0.251 | 0.260 | 1.61 | 1.64 |
| | | **$A_2$** | 2.02 | 2.08 | 0.252 | 0.260 | 1.63 | 1.66 |
| | | **$A_3$** | 2.04 | 2.11 | 0.255 | 0.265 | 1.65 | 1.68 |
| | **$Z_3$** | **$A_1$** | 2.07 | 2.13 | 0.263 | 0.271 | 1.69 | 1.73 |
| | | **$A_2$** | 2.09 | 2.17 | 0.267 | 0.277 | 1.71 | 1.75 |
| | | **$A_3$** | 2.12 | 2.18 | 0.270 | 0.281 | 1.73 | 1.77 |
| **LSD at 5%** | | | **0.05** | **0.11** | **0.004** | **0.004** | **0.08** | **0.09** |

**Means within a row followed by a different letter (s) are statistically different at a 0.05 level**

## Discussion

### Growth criteria and leaves chemical constituents

The results confirm that the higher irrigation regime ($I_1$: 5500 $m^3$ $ha^{-1}$) led to the best growth indicators in maize. This can be attributed to sufficient water availability, which plays a crucial role in supporting key physiological processes such as photosynthesis and nutrient transport within the plant, promoting optimal growth. In contrast, the lower irrigation regime ($I_3$: 3300 $m^3$ $ha^{-1}$) resulted in poor performance due to water stress, which limits the plant's ability to absorb the necessary water and nutrients, thus negatively impacting biomass and overall productivity (**Elsherpiny, 2023; Mostafa *et al.* 2024).** Generally, water deficit stress significantly affected maize growth performance. When maize plants were subjected to water shortage, their physiological processes, such as photosynthesis and nutrient uptake, are disrupted, leading to reduced growth rates and smaller leaf areas **(El-Bauome *et al.* 2022; Doklega *et al.* 2024)**. The data show that applying zeolite at 10 tons $ha^{-1}$ ($Z_3$) significantly enhanced growth performance. This improvement is likely due to zeolite's ability to retain water and nutrients in the soil, providing a steady supply to plants even under stressful conditions. Zeolite acts as a soil amendment, increasing the availability of essential nutrients such as nitrogen, phosphorus, and potassium (NPK), which boosts nutrient uptake and stimulates growth. Additionally, it improved chlorophyll content, enhancing photosynthetic efficiency and supporting carbohydrate production, which is vital for plant growth (**Elawady *et al.* 2024; Abd El-Azeiz *et al.* 2024).** The foliar application of abscisic acid (ABA) at a concentration of 10 mmol ($A_3$) resulted in the highest growth parameters. This effect is likely due to ABA's role in regulating stress responses, particularly under water deficit conditions. ABA helps maintain stomatal closure, reducing water loss through transpiration and enhancing water-use efficiency. This, in turn, supports better growth under limited water conditions, leading to increased fresh and dry weights. Moreover, ABA improved chlorophyll content, which supports enhanced photosynthesis, and increased NPK concentrations in maize leaves, indicating its role in improving nutrient absorption **(Ali *et al.* 2020; Muhammad-Aslam *et al.* 2022; Gao *et al*. 2024).** The combination of zeolite and abscisic acid (ABA) under a moderate water deficit condition ($I_2$: 4400 $m^3$ $ha^{-1}$) demonstrated a clear synergistic effect on maize growth and nutrient uptake. This treatment ($Z_3$: 10 tons $ha^{-1}$ + A3: 10 mmol) outperformed the traditional irrigation regime ($I_1$: 5500 $m^3$ $ha^{-1}$) without the combined application of zeolite and ABA. The enhanced performance can be attributed to the complementary functions of zeolite and ABA. Zeolite improves soil moisture retention and nutrient availability, while ABA helps the plant manage water stress by reducing transpiration and improving water-use efficiency. Together, these treatments optimize growth and nutrient absorption, even under suboptimal irrigation conditions, highlighting the potential of this combination to mitigate the negative impacts of water stress. This synergistic effect shows that the integrated application of soil amendments and plant growth regulators can significantly enhance plant resilience and productivity under water-limited conditions. The obtained results are in harmony with those of **Elawady *et al.* (2024); Gao *et al*. (2024).**

**Oxidative activity**

The antioxidant activity in maize leaves, as indicated by proline, malondialdehyde (MDA), catalase (CAT), and peroxidase (POX) levels, is influenced by several scientific factors. Firstly, under adequate irrigation ($I_1$: 5500 $m^3$ $ha^{-1}$), lower levels of proline and MDA suggest minimal oxidative stress, as sufficient water availability prevents lipid peroxidation and maintains cellular integrity. In contrast, restricted irrigation ($I_3$: 3300 $m^3$ $ha^{-1}$) leads to elevated MDA levels, reflecting increased oxidative damage due to water deficiency (**Elsherpiny, 2023; Mostafa *et al.* 2024).** The application of zeolite plays a critical role in improving soil conditions, enhancing moisture retention, and facilitating nutrient availability. This reduction in oxidative stress is evidenced by decreased proline and MDA levels when higher rates of zeolite ($Z_2$ and $Z_3$) are utilized (**Elawady *et al.* 2024; Abd El-Azeiz *et al.* 2024).** Moreover, foliar application of abscisic acid (ABA) further mitigates oxidative stress by promoting stomatal closure and reducing transpiration, thus conserving water. ABA also enhances the expression of antioxidant genes, leading to lower CAT and POX levels, indicative of a robust defense mechanism against oxidative damage **(Ali *et al.* 2020; Muhammad-Aslam *et al.* 2022; Gao *et al*. 2024).** The combined effects of these treatments suggest a synergistic enhancement of the antioxidant profile in maize, particularly under stress conditions, by reducing oxidative stress markers and improving plant resilience.

**Yield and quality parameters**

Higher irrigation levels ensure adequate water supply, enhancing nutrient uptake and promoting metabolic activities essential for plant growth. This leads to increased cob weight, length, and overall yield (**Elsherpiny, 2023; Mostafa *et al.* 2024).** Zeolite improves soil structure, increases moisture retention, and enhances nutrient availability. This allows for better root development and nutrient absorption, resulting in higher yield and quality metrics(**Elawady *et al.* 2024; Abd El-Azeiz *et al.* 2024).** ABA plays a critical role in plant stress response, particularly under water deficit conditions. It helps regulate stomatal closure, reducing water loss while improving stress tolerance, which contributes to better growth and yield. ABA may have promoted the closure of stomata, reducing transpiration and water loss. This helps maintain internal water balance and prevent dehydration during periods of limited water availability. ABA may have regulated the expression of drought-responsive genes, facilitating the production of protective proteins and metabolites that enhance stress tolerance.as ABA acts as a signaling molecule that triggers physiological responses in plants, coordinating various mechanisms to cope with water scarcity, such as the synthesis of osmoprotectants and antioxidants. By modulating metabolic pathways and promoting physiological adaptations, ABA helps improve overall plant resilience to drought, leading to better growth, yield, and quality under adverse conditions **(Ali *et al.* 2020; Muhammad-Aslam *et al.* 2022; Gao *et al*. 2024).**

## 4. Conclusion

Finally, the obtained results confirm that the application of zeolite and ABA under water-deficit conditions ($I_2$ and $I_3$) markedly improved maize growth and yield. Based on these results, it can be concluded that the application of zeolite and abscisic acid (ABA) under water deficit conditions significantly improves maize growth performance, yield, and quality parameters. Zeolite's capacity to retain moisture and nutrients enhances the plant's resilience to drought, while ABA effectively mitigates stress responses, leading to better growth and productivity. It is recommended that farmers incorporate zeolite into their soil management practices and utilize foliar applications of ABA to optimize crop performance during water scarcity. Future studies should explore the synergistic effects of these treatments across various crops to promote agricultural sustainability in arid regions.

**Conflicts of interest**

The authors have declared that no competing interests exist.

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