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Investigating Zeolite's Role in Retaining Mineral Nitrogen Fertilizers and the Effects of Titanium and Selenium on Garlic plants under Water Deficit Conditions

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THIS STUDY explores how zeolite can aid in the retention of nitrogen and water and evaluates the effects of selenium and titanium on boosting plant tolerance and nitrogen fixation under drought stress. The aim is to reduce water and mineral nitrogen inputs while enhancing plant growth, resilience and yield. The experimental treatments involved garlic plants subjected to water deficit conditions (80% of irrigation requirements (IR) and 100% of IR (representing the control group) as the main factor. The sub-main factor included different ratios of the Nitrogen Recommended Dose (NRD) combined with a zeolite conditioner: 100% NRD as ammonium sulphate alone, 75% NRD as ammonium sulphate alone, 75% NRD as ammonium sulphate with 5.0 tons of zeolite ha^{-1} and 5.0 tons of zeolite ha^{-1} alone. The sub-sub-main factor involved spraying titanium (Ti) and selenium (Se) as beneficial elements and anti-stress agents, including control (without), titanium (5.0 mg L^{-1}) alone, selenium (5.0 mg L^{-1}) alone, and a combination of titanium (2.5 mg L^{-1}) and selenium (2.5 mg L^{-1}). Under the irrigation treatment of 80% IR, the combined treatment of 75% NRD with zeolite, Ti, and Se led to significant improvements in garlic growth, leaf chemical constituents, enzymatic antioxidants, and bulb yield compared to the treatment of 100% IR combined with 100% NRD. Overall, the results show that zeolite effectively retains nitrogen and water, improving soil fertility and reducing the need for excessive fertilizers. Selenium and titanium enhance plant resilience to drought, promote nitrogen fixation, and improve plant health. Integrating these elements into agricultural practices can mitigate drought stress and minimize environmental impact. Future research should assess the long-term effects across various crops and conditions to develop sustainable agricultural strategies.

Keywords: Nitrogen retention, Water retention, Drought stress, Nitrogen fixation, Sustainable.

1. Introduction

Water scarcity and environmental sustainability are pressing issues in agriculture, particularly in arid and semi-arid regions like Egypt (**Abd Ellah 2020; Ghazi *et al.* 2023)**. The challenge of water scarcity is compounded by the overuse of mineral nitrogen fertilizers, which are known to have detrimental effects on the environment and groundwater and pose risks to human and animal health. Addressing these challenges requires innovative solutions that enhance water and nutrient use efficiency while maintaining or improving crop yields **(ElGhamry *et al.* 2024a; Elsherpiny *et al.* 2024)**. Nitrogen is a crucial nutrient for crop systems, playing a significant role in yield performance and quality parameters **(Souri *et al.* 2019**). However, excessive use of nitrogen can pose serious health risks to plants, humans, and the environment. Over-application of nitrogen fertilizers can lead to nutrient runoff, causing water pollution and contributing to eutrophication in aquatic ecosystems **(Aghaye Noroozlo *et al.* 2019).** It can also result in soil degradation and the emission of greenhouse gases, which have negative impacts on climate change. Moreover, high levels of nitrogen in the food chain can affect human health, potentially leading to conditions such as methemoglobinemia or "blue baby syndrome" in infants. Therefore, it is essential to manage nitrogen application carefully to balance crop needs while minimizing environmental and health risks (**Huang *et al.* 2024)**.

Zeolite is a natural mineral with a porous structure, known for its exceptional capacity to retain water and nutrients. Its use in agriculture has shown promise in improving soil fertility and water retention, thereby reducing the need for frequent irrigation and excessive fertilizer application (**AbdEL-Azeiz *et al.* 2024; ElGhamry *et al.* 2024a)**. By holding

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mineral nitrogen in the soil, zeolite helps prevent nutrient leaching and enhances the availability of nitrogen to plants over time **(Elsherpiny *et al.* 2024)**. Titanium, though not traditionally considered an essential nutrient, has emerged as a beneficial element in plant nutrition. It plays a role in enhancing non-biological nitrogen fixation, potentially reducing the reliance on synthetic nitrogen fertilizers **(Elsherpiny and Faiyad 2023).** Additionally, titanium can improve plant resilience by promoting growth and development under various stress conditions (**ElGhamry *et al.* 2024b).** Selenium is another element with significant potential in agriculture, particularly in enhancing plant tolerance to drought stress **(Ahmed *et al.* 2023)**. It contributes to the plant's antioxidant defense system, helping to mitigate oxidative damage and support root growth. By bolstering the plant's ability to withstand adverse conditions, selenium can improve overall plant health and productivity (**ElGhamry *et al.* 2024b).**

Garlic (*Allium sativum)* holds substantial medical, nutritional, and economic importance in Egypt. It is renowned for its health benefits, including antimicrobial and antioxidant properties, and is a vital component of the Egyptian diet and agricultural economy. Enhancing garlic production through sustainable practices is crucial for meeting local and international demand while ensuring environmental protection **(Moustafa *et al.* 2024).** The aim of this research is to investigate the potential of zeolite, titanium, and selenium in improving garlic production under drought-stress conditions. The study focuses on reducing water and mineral nitrogen inputs while enhancing plant growth, resilience, and yield. By integrating these elements into garlic cultivation, the research seeks to develop strategies for sustainable agriculture that address water scarcity and environmental concerns.

2. Material and Methods

Experimental site and conditions

The experiment was conducted at the experimental farm of Mansoura University, Egypt during the 2021/2022 and 2022/2023 seasons. The region experiences a Mediterranean climate with hot, dry summers and mild, wet winters. Before planting, soil samples were collected and analyzed to determine baseline nutrient levels and physical properties (Table 1).

Experimental design and treatments

The experiment utilized a split-split-plot design with three replications (Fig1) to evaluate the effects of irrigation levels, nitrogen fertilization rates combined with zeolite, and foliar application of titanium and selenium on garlic plants.

Main plot factor: Irrigation Requirements (IR)

1. 100% of IR (full irrigation)
2. 80% of IR (reduced irrigation)

Sub-main plot factor: Nitrogen Recommended Dose (NRD) and zeolite application

1. 100% of NRD as ammonium sulphate alone
2. 75% of NRD as ammonium sulphate alone
3. 75% of NRD as ammonium sulfate + 5.0 tons/ha zeolite
4. 5.0 tons/ha zeolite alone

Sub-sub main plot factor: Foliar application of titanium (Ti) and selenium (Se)

1. Control (without Ti or Se)
2. Titanium (5 mg L^{-1}) alone
3. Selenium (5 mg L^{-1}) alone
4. Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1})

The characteristics of the studied materials are shown in Table 1.

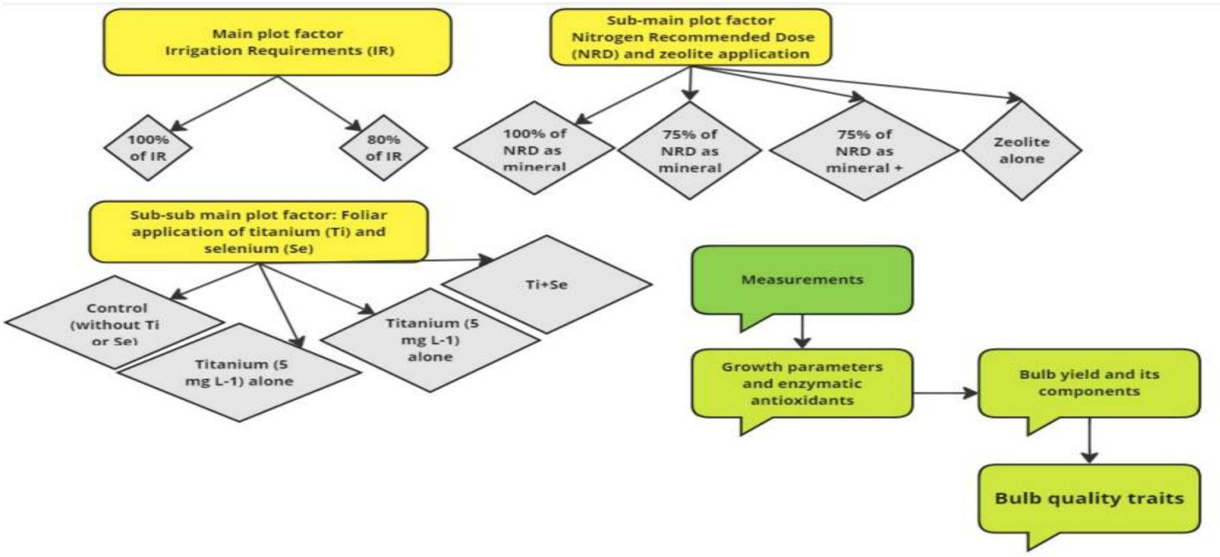

Fig. 1. The experimental flowchart.

Table 1. Properties of the initial soil and zeolite depending on the stander methods of Tandon, (2005) as well as the characteristics of the other studied substances.

Initial soil (Data is the combined data over both studied seasons)		**Zeolite** (from the Egyptian commercial market)	
Property	**Values**	**Property**	**Values**
pH	8.2	**EC, dSm^{-1}**	2.50
EC, dSm^{-1}	2.95	**CEC, cmol kg^{-1}**	160
Available N, mgKg^{-1}	33.3	**SiO_2,%**	64.75
Available P , mg kg^{-1}	8.26	**Al_2O_3**	12.50
Available K, mg kg^{-1}	211	**K_2O,%**	5.20
Organic matter,%	1.25	**Fe_2O_3,%**	6.0
Sand	20	**Na_2O,%**	1.5
Clay	49	**P_2O_5,%**	1.05
Silt	31	**CaO,%**	9.0
Textural	Clayey		

Ammonium sulphate characteristics

Chemical symbol	**Source**	**Physical properties**	**Chemical Properties**	**Role in Experiment**
$(NH_4)_2SO_4$	Egyptian commercial market	- White crystalline solid - Highly soluble in water	- Molecular Weight: 32.14 g/mol - Nitrogen content: 21% - Sulfur content: 24%	Used as a nitrogen source to evaluate its interaction with zeolite and its impact on garlic growth

Titanium dioxide characteristics

Chemical symbol	**Source**	**Physical properties**	**Chemical Properties**	**Role in Experiment**
TiO_2	Sigma-Aldrich	- White powder - Insoluble in water	- Molecular Weight: 79.87 g/mol	Used for non-biological nitrogen fixation and enhancing plant stress tolerance

Sodium selenite characteristics

Chemical symbol	**Source**	**Physical properties**	**Chemical Properties**	**Role in Experiment**
Na_2SeO_3	Sigma-Aldrich	- White crystalline powder - Soluble in water	- Molecular Weight: 172.94 g/mol	Used to increase drought stress tolerance and enhance root development

Plant material and cultivation

Garlic cloves were sourced from a local cultivar known for their adaptability and yield potential (C.V Balady). The cloves were planted manually at a spacing of 10 cm between plants and 25 cm between rows. Standard agronomic practices, including weed control and pest management, were followed throughout the growing season.

Zeolite was incorporated into the soil at a rate of 5.0 tons per hectare as per the designated treatments. Ammonium sulphate was applied at the recommended and reduced rates to align with the experimental design. The recommended dose is 1.9 tons of ammonium sulphate (21%N) per hectare according to the recommendations of MASR. Irrigation was supplied through a drip system. The amount of water applied was adjusted according to the 100% and 80% irrigation requirements, calculated based on evapotranspiration rates and crop water needs. Titanium and selenium solutions were prepared at the specified concentrations and applied as foliar sprays using a backpack sprayer. Applications were made at key growth stages: early vegetative growth, mid-season, and bulb formation.

Harvest and measurements

Harvesting was carried out 180 days after sowing. Data were collected on various parameters to assess the impact of treatments on garlic growth and yield. Measurements were recorded at two different stages, as detailed in Tables 2 and 3.

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using the appropriate statistical software **[CoStat, version 6.303 (1998-2004)].** Significant differences among treatment means were determined using the least significant difference (LSD) test at a 5% probability level using Duncan letters **(Gomez and Gomez, 1984).**

Table 2. Measurements at 100 days from sowing.

Parameters		Description	Method/Reference
Plant Height (cm)		The height of the plant measured from the base to the tip.	Direct measurement
No. of leaves plant^{-1}		Total number of leaves on each plant.	Direct count
Fresh weight, g plant^{-1}		Weight of the plant after harvesting, before drying.	Weighing scale
Dry weight, g plant^{-1}		Weight of the plant after drying in an oven at 70°C until constant weight.	Weighing scale
Leaves digestion		Using a mixture of $HClO_4$ + H_2SO_4	**Peterburgski (1968)**
Leaf chemical NPK (DW)	**N,%**	Percentage of nitrogen content in the leaves.	Micro-Kjeldahl **(Walinga *et al.* 2013)**
	P,%	Percentage of phosphorus content in the leaves.	Spectrophotometric**(Walinga *et al.* 2013)**
	K,%	Percentage of potassium content in the leaves.	Flame photometer**(Walinga *et al.* 2013)**
Chlorophyll, SPAD reading		Measured using a chlorophyll meter (SPAD-502).	SPAD-502 meter
Enzymatic antioxidants (FW)	**Peroxidase POD, unit mg^{-1} protein^{-1}**	Spectrophotometrically	**Elavarthi and Martin, (2010)**
	Catalase CAT, unit mg^{-1} protein^{-1}		
	Superoxide dismutase SOD, unit mg^{-1} protein^{-1}		

Table 3. Measurements at 180 days from sowing (yield and its components).

Parameters	Description	Method/Reference
Bulb yield and its components		
Average bulb weight (g)	Average weight of garlic bulbs.	Weighing scale
Bulb diameter (cm)	Diameter of each garlic bulb measured.	Caliper measurement
Neck diameter (cm)	Diameter of the garlic bulb neck.	Caliper measurement
Bulbing ratio (BR)	Ratio of the number of bulbs to the number of plants.	**Mann (1952)**
No. of cloves bulb^{-1}	Total number of cloves in each bulb.	Direct count
Bulb yield (ton ha^{-1})	Total yield of garlic bulbs per hectare.	Weighing scale
Marketable yield (ton ha^{-1})	Yield of garlic bulbs that meet market standards per hectare.	Weighing scale
Bulb quality traits		
Dry matter (DM, %)	Percentage of dry matter in garlic bulbs.	Using the oven **(AOAC 2000)**
Vitamin C (mg 100g^{-1})	Vitamin C content in garlic bulbs (Spectrophotometrically)	Using potassium permanganates **(AOAC 2000)**
Carbohydrates (%)	Percentage of carbohydrates in garlic bulbs.	Via Anthrone method **(AOAC 2000)**
Total dissolved solid TDS (%)	Percentage of total dissolved solids in garlic bulbs.	Using Hand refractometer **(AOAC 2000)**
Pungency (purvate content, µmol ml^{-1})	Content of pungency (pyruvate) in garlic bulbs.	**Anthon and Barrett (2003)**

3. Results

Growth criteria

Table 4 show the effect of the studied treatments on growth criteria, including plant height, No. of leaves, fresh and dry weights. The growth performance of garlic plants was significantly influenced by the different irrigation regimes, NRD rates combined with zeolite conditioner, and foliar application of titanium and selenium. The 100% IR treatment showed superior growth in both the 2021/2022 and 2022/2023 seasons, with increased plant height, number of leaves, fresh and dry weights compared to the 80% IR treatment. Specifically, plants under 100% IR achieved the maximum values of plant height (71.56 cm and 73.91 cm in the first and second seasons, respectively), compared to 69.01 cm and 71.28 cm under 80% IR. The combination of 75% NRD with 5.0 tons of zeolite resulted in the highest growth metrics, indicating the efficacy of zeolite in enhancing nutrient availability. This treatment recorded a plant height of 77.41 cm and 79.99 cm, and a fresh weight of 80.64 g and 84.62 g in the first and second seasons, respectively. In contrast, using 5.0 tons of zeolite alone resulted in the lowest growth performance. Additionally, the usage of 100 % of NRD as ammonium sulphate came in the second order, while the usage of 75% of NRD as ammonium sulphate alone came in the third order.

Foliar application of titanium and selenium, especially in combination, significantly enhanced the studied growth parameters. The treatment with combined titanium (2.5 mgL^{-1}) and selenium (2.5 mgL^{-1}) resulted in the highest values of plant height, number of leaves, fresh and dry weights, emphasizing the beneficial effects of these elements in stress mitigation. For instance, in the second season, the combined application resulted in a plant height of 73.35 cm and 8.67 leaves per plant. The treatment of selenium alone (5.0 mgL^{-1}) came in the second order followed by the treatment of titanium alone (5.0 mgL^{-1}). On the contrary, the corresponding plants grown without Ti and Se had the lowest values of plant height, No. of leaves, fresh and dry weights. Regarding the interaction effect, it can be noticed that, under the irrigation treatment of 80% IR, the combined treatment of 75% NRD with zeolite + Ti (2.5 mgL^{-1}) + Se (2.5 mgL^{-1}) led to significant improvements in garlic growth parameters compared to the treatment of 100% IR combined with 100% NRD.

Table 4. Effects of different irrigation regimes combined with various NRD rates, zeolite conditioner, and foliar application of titanium and selenium on the growth performance of garlic plants during the 2021/2022 and 2022/2023 seasons.

Treatments	Plant height, cm		No. of leaves plant^{-1}		Fresh weight, g plant^{-1}		Dry weight, g plant^{-1}	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Main factor (Irrigation Requirements IR)								
I_1	71.56a	73.91a	8.71a	9.04a	77.20a	81.03a	16.84a	17.39a
I_2	69.01b	71.28b	7.23b	7.35b	75.17b	78.99b	16.29b	16.84b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)								
N_1	70.56b	72.78b	8.42b	8.71b	76.77b	80.56b	16.64b	17.18b
N_2	68.46c	70.72c	7.63c	7.79c	75.37c	79.19c	16.34c	16.90c
N_3	77.41a	79.99a	10.75a	11.13a	80.64a	84.62a	17.77a	18.35a
N_4	64.72d	66.90d	5.08d	5.17d	71.96d	75.66d	15.51d	16.04d
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial element and anti-stress)								
F_1	69.58b	71.81b	7.63b	7.79b	75.56c	79.43c	16.40c	16.95c
F_2	69.95b	72.29b	7.83b	8.08b	76.06bc	79.89bc	16.49bc	17.03c
F_3	70.57a	72.92a	8.04ab	8.25ab	76.36ab	80.10ab	16.61b	17.17b
F_4	71.05a	73.35a	8.38a	8.67a	76.77a	80.60a	16.75a	17.31a
Interaction								
I_1 N_1 F_1	71.20	73.38	9.00	9.33	77.58	81.51	16.82	17.40
I_1 N_1 F_2	71.93	74.20	9.33	9.67	78.05	81.99	16.90	17.39
I_1 N_1 F_3	73.07	75.51	9.33	9.67	78.16	82.10	16.96	17.50
I_1 N_1 F_4	74.07	76.25	10.00	10.33	78.98	82.59	17.12	17.69
I_1 N_2 F_1	69.23	71.36	8.33	8.33	75.97	79.86	16.43	16.96
I_1 N_2 F_2	69.27	71.59	8.33	8.67	76.75	80.77	16.59	17.09
I_1 N_2 F_3	70.00	72.06	8.67	9.00	76.71	80.28	16.59	17.18
I_1 N_2 F_4	70.23	72.55	8.67	9.33	77.44	81.52	16.70	17.31
I_1 N_3 F_1	77.73	80.43	11.00	11.33	80.86	85.16	17.78	18.35
I_1 N_3 F_2	78.53	81.34	11.00	11.67	81.16	85.15	17.92	18.49
I_1 N_3 F_3	78.73	81.37	11.33	11.67	81.71	85.33	18.37	19.01
I_1 N_3 F_4	79.00	81.44	11.33	11.67	81.89	86.12	18.53	19.10
I_1 N_4 F_1	64.63	66.85	5.33	5.67	72.01	75.60	15.49	16.06
I_1 N_4 F_2	64.90	66.89	5.67	6.00	72.41	75.74	15.61	16.15
I_1 N_4 F_3	66.03	68.49	6.00	6.00	72.41	75.81	15.73	16.22
I_1 N_4 F_4	66.47	68.80	6.00	6.33	73.07	76.86	15.88	16.42
I_2 N_1 F_1	68.13	70.16	7.00	7.33	74.88	78.76	16.30	16.82
I_2 N_1 F_2	68.43	70.64	7.33	7.67	75.19	78.92	16.31	16.83
I_2 N_1 F_3	68.67	70.96	7.33	7.67	75.38	79.02	16.34	16.90
I_2 N_1 F_4	68.97	71.10	8.00	8.00	75.90	79.59	16.34	16.92
I_2 N_2 F_1	66.73	68.94	6.33	6.33	73.18	76.83	15.99	16.48
I_2 N_2 F_2	67.23	69.69	6.67	6.33	73.86	77.79	16.06	16.66
I_2 N_2 F_3	67.40	69.52	7.00	7.00	74.48	78.14	16.14	16.66
I_2 N_2 F_4	67.60	70.03	7.00	7.33	74.57	78.30	16.24	16.84
I_2 N_3 F_1	75.27	77.77	10.00	10.33	78.92	82.71	17.17	17.74
I_2 N_3 F_2	75.60	78.11	10.33	10.67	79.65	83.59	17.24	17.79
I_2 N_3 F_3	76.83	79.37	10.33	10.67	80.44	84.53	17.44	18.03
I_2 N_3 F_4	77.57	80.09	10.67	11.00	80.52	84.35	17.69	18.26
I_2 N_4 F_1	63.73	65.61	4.00	3.67	71.06	75.00	15.26	15.75
I_2 N_4 F_2	63.70	65.88	4.00	4.00	71.40	75.18	15.31	15.84
I_2 N_4 F_3	63.83	66.08	4.33	4.33	71.58	75.59	15.34	15.89
I_2 N_4 F_4	64.47	66.56	5.33	5.33	71.77	75.51	15.47	15.97
LSD at 5%	**1.44**	**1.49**	**1.38**	**1.51**	**1.60**	**1.49**	**0.35**	**0.33**

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

Where, I_1:100% of IR, **I_2:** 80% of IR, **N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone**, F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1}).

Leaves chemical constituents

Table 5 illustrates the effects of different irrigation regimes combined with various NRD rates, zeolite conditioner, and foliar application of titanium and selenium on the leaves chemical constituents of garlic plants as well as chlorophyll content during the 2021/2022 and 2022/2023 seasons. The data of this Table show that the full irrigation regime (100% IR) resulted in significantly higher nitrogen, phosphorus and potassium content in the leaves compared to 80% IR in both seasons, indicating that adequate water availability enhances NPK uptake. Chlorophyll content was significantly higher in 100% IR during the second season, emphasizing the role of water in photosynthetic efficiency and chlorophyll biosynthesis. The combination of 75% NRD with 5.0 tons of zeolite recorded the highest values of nitrogen content, significantly surpassing all other treatments, including 100% NRD alone. This suggests that zeolite significantly enhances nitrogen retention and availability. Additionally, the 75% NRD combined with zeolite significantly increased phosphorus and potassium contents, suggesting that zeolite improves phosphorus and potassium availability or retention in the soil. The combination of 75% NRD with zeolite led to the highest chlorophyll content, suggesting improved nutrient efficiency and photosynthetic capacity.

Titanium and selenium treatments, especially when combined, improved nitrogen content over the control, with the highest increase seen in the combined treatment of titanium and selenium, indicating a synergistic effect. The combined treatment of titanium and selenium showed the greatest increase in phosphorus content, indicating enhanced phosphorus metabolism or uptake. In addition, the combined titanium and selenium treatment significantly increased potassium content compared to other treatments, reflecting enhanced nutrient assimilation or stress mitigation.

Although individual treatments of titanium and selenium showed improvements, their combination resulted in the highest chlorophyll content, indicating a combined beneficial effect on chlorophyll synthesis or protection.

The interaction of 100% IR, 75% NRD with zeolite, and the combined foliar application of titanium and selenium produced the highest values for all measured parameters. This suggests that adequate irrigation, optimized nitrogen dose with zeolite, and foliar supplementation work synergistically to enhance nutrient status and chlorophyll content in garlic leaves. on the other hand, under the irrigation treatment of 80% IR, the combined treatment of 75% NRD with zeolite + Ti (2.5 mgL^{-1}) + Se (2.5 mgL^{-1}) led to significant improvements in N, P, K and chlorophyll contents in leaves compared to the treatment of 100% IR combined with 100% NRD.

Enzymatic antioxidants

Regarding the enzymatic antioxidants in garlic leaves under different irrigation regimes, nitrogen rates, zeolite conditioner, and foliar applications of titanium and selenium, Table 6 shows that. The data show that irrigation significantly impacts the enzymatic antioxidant activities in garlic plants. In both the 2021/2022 and 2022/2023 seasons, peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD) activities were higher under the 100% irrigation requirement (IR) treatment compared to the 80% IR. This indicates that optimal irrigation enhances the enzymatic activities, which are crucial for the plant's oxidative stress response. The higher enzyme activities under adequate irrigation suggest improved plant metabolism and stress tolerance, highlighting the importance of sufficient water supply in maintaining the balance of oxidative stress in plants.

Regarding nitrogen application and the use of zeolite, the combination of 75% of the nitrogen recommended dose (NRD) with 5.0 tons of zeolite resulted in the highest activities for all three enzymes: POD, CAT, and SOD. This suggests that the addition of zeolite may enhance the stress tolerance of garlic plants by boosting enzymatic activity. The zeolite likely aids in the retention and efficient utilization of nutrients, leading to enhanced plant health and stress resistance. In contrast, treatments with only zeolite resulted in the lowest enzymatic activity, indicating that the combination of nitrogen with zeolite is crucial for achieving the optimal stress response.

Foliar applications of titanium and selenium, both alone and in combination, had a notable impact on the enzymatic activities in garlic leaves. The combined application of titanium (2.5 mgL^{-1}) and selenium (2.5 mgL^{-1}) led to the highest increase in POD, CAT, and SOD activities across both seasons. This suggests a synergistic effect that enhances the plant's antioxidant defense mechanisms, offering increased protection against oxidative stress. The results indicate that foliar applications of these elements can be an effective strategy to improve the plant's resilience under stress conditions by enhancing its antioxidant capacity.

In terms of interaction effects, the combination of 100% IR with 75% NRD and zeolite consistently resulted in the highest enzymatic activities across all measured parameters. This demonstrates a synergistic effect, indicating that adequate irrigation and nutrient management with zeolite significantly enhance the plant's oxidative stress response. Furthermore, when combined with the foliar application of titanium and selenium, this treatment combination provided optimal conditions for boosting antioxidant enzyme activities, ultimately improving the plant's stress tolerance and overall health. This comprehensive approach of integrating irrigation, nutrient management, and foliar treatments offers a promising strategy for enhancing plant resilience in challenging environmental conditions.

Table 5. Effects of different irrigation regimes combined with various NRD rates, zeolite conditioner, and foliar application of titanium and selenium on the leaves chemical constituents of garlic plants as well as chlorophyll content during the 2021/2022 and 2022/2023 seasons.

Treatments			N, %		P, %		K, %		Chlorophyll, SPAD	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor (Irrigation Requirements IR)										
I_1			3.22a	3.30a	0.307a	0.320a	2.57a	2.66a	40.64a	41.28a
I_2			3.04b	3.10b	0.290b	0.301b	2.41b	2.49b	40.09a	40.82b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)										
N_1			3.19b	3.26b	0.305b	0.317b	2.60b	2.68b	40.62b	41.25b
N_2			3.06c	3.13c	0.293c	0.305c	2.48c	2.56c	40.18c	40.89b
N_3			3.52a	3.61a	0.334a	0.348a	2.79a	2.88a	41.44a	42.20a
N_4			2.74d	2.80d	0.261d	0.272d	2.11d	2.18d	39.22d	39.86c
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial element and anti-stress)										
F_1			3.07d	3.15d	0.293d	0.305d	2.45d	2.53d	40.21a	40.92a
F_2			3.11c	3.18c	0.297c	0.309c	2.48c	2.57c	40.32a	41.01a
F_3			3.15b	3.22b	0.300b	0.313b	2.51b	2.59b	40.42a	41.12a
F_4			3.18a	3.25a	0.303a	0.315a	2.53a	2.62a	40.51a	41.16a
Interaction										
I_1	**N_1**	**F_1**	3.24	3.31	0.310	0.322	2.68	2.77	40.79	41.43
		F_2	3.29	3.36	0.314	0.328	2.68	2.76	41.00	41.66
		F_3	3.29	3.37	0.318	0.331	2.69	2.78	41.02	41.57
		F_4	3.37	3.44	0.322	0.335	2.71	2.80	41.09	41.80
	N_2	**F_1**	3.17	3.25	0.299	0.311	2.59	2.67	40.33	41.19
		F_2	3.18	3.24	0.304	0.316	2.62	2.70	40.45	41.26
		F_3	3.21	3.30	0.307	0.319	2.62	2.71	40.53	41.09
		F_4	3.22	3.30	0.308	0.321	2.65	2.75	40.65	41.27
	N_3	**F_1**	3.55	3.65	0.335	0.348	2.79	2.89	41.48	42.13
		F_2	3.57	3.65	0.338	0.352	2.82	2.91	41.61	42.11
		F_3	3.59	3.67	0.341	0.356	2.83	2.93	41.68	42.35
		F_4	3.61	3.70	0.342	0.358	2.85	2.94	41.76	42.39
	N_4	**F_1**	2.77	2.84	0.262	0.273	2.09	2.17	39.30	39.92
		F_2	2.80	2.86	0.265	0.276	2.11	2.18	39.39	39.91
		F_3	2.83	2.89	0.274	0.287	2.20	2.27	39.51	40.13
		F_4	2.88	2.94	0.275	0.287	2.22	2.30	39.61	40.24
I_2	**N_1**	**F_1**	3.03	3.09	0.290	0.302	2.42	2.50	40.17	40.73
		F_2	3.06	3.12	0.292	0.303	2.50	2.58	40.25	40.86
		F_3	3.14	3.18	0.295	0.306	2.53	2.62	40.27	40.92
		F_4	3.15	3.19	0.299	0.311	2.56	2.65	40.35	41.05
	N_2	**F_1**	2.90	2.97	0.277	0.288	2.27	2.34	39.80	40.38
		F_2	2.92	2.98	0.281	0.292	2.34	2.43	39.78	40.62
		F_3	2.96	3.03	0.284	0.296	2.36	2.44	39.92	40.81
		F_4	2.96	3.02	0.288	0.300	2.39	2.48	40.01	40.51
	N_3	**F_1**	3.38	3.45	0.324	0.337	2.72	2.81	41.13	41.97
		F_2	3.45	3.53	0.327	0.339	2.75	2.84	41.21	42.05
		F_3	3.47	3.57	0.332	0.345	2.76	2.85	41.26	42.25
		F_4	3.54	3.63	0.335	0.348	2.79	2.88	41.42	42.37
	N_4	**F_1**	2.56	2.63	0.250	0.260	2.02	2.08	38.72	39.57
		F_2	2.63	2.69	0.253	0.263	2.06	2.13	38.91	39.62
		F_3	2.73	2.79	0.253	0.263	2.06	2.13	39.15	39.83
		F_4	2.73	2.80	0.255	0.265	2.08	2.15	39.15	39.65
LSD at 5%			**0.07**	**0.06**	**0.006**	**0.005**	**0.04**	**0.04**	**0.83**	**0.79**

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

Where, I_1:100% of IR, **I_2:** 80% of IR, **N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone**, F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1}).

Table 6. Effects of different irrigation regimes combined with various NRD rates, zeolite conditioner, and foliar application of titanium and selenium on the enzymatic antioxidants in leaves of garlic plants during the 2021/2022 and 2022/2023 seasons.

Treatments			POD, Unit min^{-1} g^{-1} protein		CAT, Unit min^{-1} g^{-1} protein		SOD, Unit min^{-1} g^{-1} protein	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor (Irrigation Requirements IR)								
I_1			53.62a	54.44a	154.80a	158.40a	114.35a	116.11a
I_2			49.66b	50.53b	148.61b	151.81b	111.67b	113.62b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)								
N_1			52.35b	53.17b	152.46b	155.40b	112.86b	114.59b
N_2			49.68c	50.51c	148.23c	151.63c	110.98c	112.82c
N_3			60.41a	61.48a	165.98a	169.99a	120.31a	122.49a
N_4			44.12d	44.79d	140.15d	143.39d	107.90d	109.56d
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial element and anti-stress)								
F_1			50.58d	51.44d	150.11b	153.75b	112.27c	114.14c
F_2			51.38c	52.24c	151.14b	154.26b	112.66bc	114.58bc
F_3			51.90b	52.73b	152.41a	155.88a	113.26ab	115.12ab
F_4			52.70a	53.54a	153.16a	156.52a	113.86a	115.61a
Interaction								
I_1	**N_1**	**F_1**	53.39	54.30	154.58	158.25	113.63	115.40
		F_2	54.85	55.73	155.48	158.71	114.30	116.09
		F_3	55.75	56.62	157.55	161.26	115.18	116.93
		F_4	56.85	57.74	158.05	161.15	116.21	118.23
	N_2	**F_1**	51.53	52.57	151.56	155.22	112.50	114.61
		F_2	52.09	53.17	151.99	155.08	112.50	114.90
		F_3	52.41	53.04	152.80	157.04	112.66	114.24
		F_4	53.17	53.99	153.50	157.53	113.33	114.80
	N_3	**F_1**	61.13	62.05	167.89	172.59	119.73	121.64
		F_2	61.82	62.61	168.53	172.23	120.52	121.96
		F_3	61.93	62.80	168.88	172.59	122.39	124.16
		F_4	62.17	63.16	170.05	174.12	123.46	125.33
	N_4	**F_1**	43.99	44.61	140.40	143.82	107.83	109.36
		F_2	45.29	45.85	141.69	144.68	108.30	109.72
		F_3	45.36	45.99	141.80	144.95	108.48	110.03
		F_4	46.16	46.88	141.98	145.12	108.59	110.31
I_2	**N_1**	**F_1**	48.21	48.89	146.16	149.11	110.22	111.61
		F_2	48.77	49.59	147.78	150.71	110.71	112.61
		F_3	49.59	50.27	149.96	151.86	110.97	112.63
		F_4	51.38	52.22	150.13	152.11	111.68	113.22
	N_2	**F_1**	46.24	46.93	142.64	145.90	108.74	110.32
		F_2	46.87	47.74	143.71	146.26	108.75	110.90
		F_3	47.10	48.04	143.90	147.43	109.39	111.49
		F_4	48.02	48.62	145.72	148.59	109.95	111.33
	N_3	**F_1**	57.79	58.88	159.90	163.46	118.34	120.76
		F_2	58.62	59.78	161.59	164.91	118.79	121.21
		F_3	59.61	60.94	164.99	169.68	119.42	122.16
		F_4	60.24	61.65	165.98	170.34	119.80	122.66
	N_4	**F_1**	42.40	43.31	137.78	141.63	107.18	109.43
		F_2	42.70	43.43	138.32	141.50	107.42	109.25
		F_3	43.46	44.19	139.36	142.23	107.55	109.33
		F_4	43.58	44.05	139.89	143.20	107.83	109.00
LSD at 5%			**1.03**	**0.94**	**3.02**	**3.17**	**2.13**	**2.35**

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

Where, I_1:100% of IR, **I_2:** 80% of IR**,** **N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone**,** **F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1}).

Bulb yield and quality parameters

Table 7 illustrates the impact of irrigation regimes, nitrogen recommended doses (NRD), zeolite conditioner, and foliar applications of titanium and selenium on garlic bulb yield and its components [Average bulb weight, bulb diameter, neck diameter, bulbing ratio, No. of cloves, bulb yield and ton marketable yield (Fig 2)] during the 2021/2022 and 2022/2023 seasons. Garlic plants grown under 100% of the irrigation requirements (IR) had higher average bulb weight, bulb diameter, neck diameter, bulbing ratio, No. of cloves, bulb yield and ton marketable yield compared to those receiving 80% of IR. This trend suggests that full irrigation is critical for optimizing bulb development and overall yield. The data indicate a significant statistical difference between the two irrigation regimes, reinforcing the importance of adequate water supply in garlic cultivation. The application of 75% of NRD combined with 5.0 tons of zeolite ha^{-1} significantly improved bulb yield and components, surpassing the effects of using 100 and 75% NRD alone or 5.0 tons of zeolite without NRD. This finding underscores the synergistic effect of zeolite in enhancing nitrogen utilization and potentially improving nutrient availability. The lowest yields were observed with the zeolite alone treatment, highlighting the critical role of nitrogen in garlic growth. The application of titanium (2.5 mgL^{-1}) combined with selenium (2.5 mgL^{-1}) resulted in the highest values of Average bulb weight, bulb diameter, neck diameter, bulbing ratio, No. of cloves, bulb yield and ton marketable yield across both seasons. The treatment of selenium alone (5.0 mgL^{-1}) came in the second order followed by the treatment of titanium alone (5.0 mgL^{-1}). On the contrary, the corresponding plants grown without Ti and Se had the lowest values of bulb yield and components. This suggests that the combined application of these elements may offer a complementary effect in improving garlic growth and resilience, likely due to their roles in stress mitigation and enhancement of nutrient uptake.

Table 8 examines the quality traits of garlic cloves, including dry matter percentage, vitamin C, carbohydrate, total dissolved solids and pungency influenced by the same set of treatments. Garlic plants receiving 100% of IR exhibited higher quality traits compared to those under 80% of IR. This indicates that full irrigation not only supports better bulb development but also enhances the nutritional quality of the cloves, which may be attributed to improved overall plant health and productivity. The combination of 75% NRD with 5.0 tons of zeolite consistently resulted in the highest values for dry matter percentage, vitamin C content, carbohydrate content, total dissolved solids and pungency. This suggests that the zeolite treatment, in conjunction with a reduced NRD, can still optimize garlic quality traits, potentially due to improved nutrient retention and release. In contrast, the sole application of zeolite resulted in lower quality metrics, emphasizing the importance of adequate nitrogen supply. The combined application of titanium and selenium showed the most significant improvements in garlic clove quality traits, including higher dry matter percentage, vitamin C, carbohydrate, total dissolved solids and pungency. This reinforces the notion that these elements, especially in combination, can enhance the nutritional profile of garlic, likely through their beneficial effects on plant stress responses and nutrient utilization. Overall, these Tables (7 and 8) demonstrate that both irrigation and nutrient management strategies, including the use of zeolite and foliar applications of beneficial elements, significantly impact not only the yield but also the quality of garlic. The interactions between these factors highlight the complex nature of garlic cultivation and the potential for optimizing both yield and quality through tailored agronomic practices.

Table 7. Effects of different irrigation regimes combined with various NRD rates, zeolite conditioner, and foliar application of titanium and selenium on the yield of garlic and its components during the 2021/2022 and 2022/2023 seasons.

Treatments			Average bulb weight, g		Bulb diameter, cm		Neck diameter, cm		Bulbing ratio	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor (Irrigation Requirements IR)										
I1			44.82a	45.39a	3.81a	3.87a	1.05a	1.06a	0.273a	0.272a
I2			42.29b	43.04b	3.54b	3.60b	0.90b	0.92b	0.253b	0.253b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)										
N1			44.98b	45.53b	3.80b	3.86b	1.00b	1.02b	0.262b	0.261b
N2			42.85c	43.53c	3.61c	3.67c	0.92c	0.94c	0.255c	0.255c
N3			48.48a	49.34a	4.18a	4.25a	1.24a	1.26a	0.396a	0.296a
N4			37.90d	38.47d	3.10d	3.15d	0.74d	0.75d	0.237d	0.238d
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial element and anti-stress)										
F1			43.02c	43.67c	3.59d	3.64d	0.95d	0.96d	0.261c	0.260c
F2			43.24c	43.83c	3.65c	3.71c	0.97c	0.98c	0.263b	0.263b
F3			43.77b	44.47b	3.70b	3.76b	0.98b	1.00b	0.263b	0.263b
F4			44.17a	44.89a	3.76a	3.82a	1.01a	1.02a	0.264a	0.265a
Interaction										
I1	**N1**	**F1**	46.21	46.69	3.84	3.90	1.09	1.11	0.280	0.280
		F2	46.40	47.15	3.96	4.02	1.11	1.13	0.280	0.280
		F3	46.50	46.91	4.01	4.06	1.13	1.15	0.280	0.280
		F4	46.98	47.44	4.01	4.08	1.13	1.15	0.280	0.280
	N2	**F1**	44.21	44.79	3.73	3.79	0.96	0.97	0.260	0.253
		F2	44.62	45.06	3.77	3.85	1.02	1.03	0.270	0.270
		F3	45.18	45.64	3.78	3.82	1.02	1.04	0.270	0.270
		F4	45.49	46.12	3.79	3.84	1.05	1.06	0.280	0.280
	N3	**F1**	48.74	49.28	4.18	4.23	1.25	1.27	0.300	0.300
		F2	49.02	49.73	4.24	4.30	1.28	1.30	0.300	0.300
		F3	49.29	50.26	4.29	4.34	1.32	1.34	0.310	0.310
		F4	49.81	50.67	4.42	4.49	1.34	1.36	0.300	0.300
	N4	**F1**	38.02	38.48	3.14	3.17	0.76	0.77	0.240	0.240
		F2	38.37	38.88	3.21	3.25	0.77	0.78	0.240	0.240
		F3	39.05	39.60	3.31	3.36	0.77	0.78	0.230	0.230
		F4	39.20	39.62	3.32	3.37	0.80	0.81	0.240	0.240
I2	**N1**	**F1**	42.88	43.41	3.56	3.60	0.86	0.87	0.240	0.240
		F2	43.27	43.80	3.61	3.67	0.88	0.89	0.240	0.240
		F3	43.73	44.31	3.72	3.78	0.91	0.92	0.243	0.240
		F4	43.86	44.54	3.73	3.78	0.93	0.95	0.250	0.250
	N2	**F1**	40.10	41.10	3.41	3.45	0.81	0.83	0.240	0.240
		F2	40.13	40.22	3.43	3.50	0.83	0.84	0.240	0.240
		F3	41.16	42.34	3.45	3.52	0.83	0.85	0.240	0.240
		F4	41.92	42.93	3.54	3.58	0.86	0.88	0.240	0.250
	N3	**F1**	47.23	48.41	4.01	4.08	1.15	1.18	0.290	0.290
		F2	47.27	48.36	4.06	4.15	1.17	1.20	0.290	0.290
		F3	48.13	48.76	4.11	4.19	1.20	1.22	0.290	0.290
		F4	48.35	49.23	4.16	4.25	1.22	1.24	0.290	0.290
	N4	**F1**	36.75	37.19	2.85	2.91	0.69	0.70	0.240	0.240
		F2	36.87	37.47	2.92	2.97	0.70	0.71	0.240	0.240
		F3	37.12	37.94	2.96	3.01	0.70	0.71	0.240	0.240
		F4	37.79	38.59	3.09	3.13	0.72	0.73	0.230	0.230
LSD at 5%			**0.90**	**0.87**	**0.07**	**0.07**	**0.02**	**0.02**	**0.002**	***NS**

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

Where, I_1:100% of IR, **I_2:** 80% of IR, **N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone, **F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1}).

***NS=no significant.**

Cont. Table 7

Treatments			No. of cloves bulb^{-1}		Bulb yield, ton ha^{-1}		Marketable yield, ton ha^{-1}	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor (Irrigation Requirements IR)								
I_1			26.65a	26.25a	15.56a	15.89a	14.18a	14.48a
I_2			24.17b	24.02b	14.65b	14.99b	13.21b	13.52b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)								
N_1			26.92b	26.63b	15.61b	15.91b	14.07b	14.35b
N_2			25.00c	25.21c	14.82c	15.13c	13.44c	13.76c
N_3			30.13a	29.21a	16.85a	17.27a	15.42a	15.78a
N_4			19.58d	19.50d	13.16d	13.45d	11.84d	12.10d
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial elements and anti-stress)								
F_1			24.63b	24.25b	14.89c	15.22c	13.48d	13.76d
F_2			25.42a	25.04ab	15.07b	15.40b	13.62c	13.93c
F_3			25.63a	25.46a	15.14b	15.45b	13.74b	14.06b
F_4			25.96a	25.79a	15.33a	15.69a	13.92a	14.23a
Interaction								
I_1	N_1	F_1	27.67	27.00	15.94	16.26	14.60	14.85
		F_2	28.00	27.33	16.20	16.52	14.70	15.00
		F_3	28.33	27.67	16.28	16.54	14.79	15.09
		F_4	28.67	28.00	16.28	16.62	14.95	15.26
	N_2	F_1	26.33	26.33	15.35	15.67	14.01	14.31
		F_2	27.00	26.00	15.48	15.80	14.12	14.44
		F_3	27.33	26.33	15.61	15.96	14.22	14.62
		F_4	27.33	26.67	15.81	16.19	14.48	14.75
	N_3	F_1	30.33	29.33	16.91	17.35	15.40	15.74
		F_2	31.00	29.67	17.09	17.41	15.56	15.89
		F_3	30.33	29.67	17.14	17.50	15.76	16.15
		F_4	30.67	30.33	17.28	17.66	15.89	16.21
	N_4	F_1	20.33	19.33	13.24	13.55	11.90	12.16
		F_2	20.67	21.00	13.32	13.60	12.01	12.26
		F_3	21.00	22.33	13.42	13.71	12.14	12.38
		F_4	21.33	23.00	13.67	13.95	12.29	12.51
I_2	N_1	F_1	25.00	25.33	14.69	14.99	13.03	13.30
		F_2	25.67	25.67	15.02	15.31	13.25	13.54
		F_3	26.00	26.00	15.14	15.46	13.38	13.58
		F_4	26.00	26.00	15.31	15.63	13.88	14.18
	N_2	F_1	22.00	23.33	13.74	13.96	12.45	12.72
		F_2	22.67	24.00	14.03	14.34	12.61	12.88
		F_3	23.00	24.33	14.06	14.34	12.75	13.08
		F_4	24.33	24.67	14.44	14.76	12.86	13.27
	N_3	F_1	29.33	28.00	16.44	16.88	15.03	15.35
		F_2	29.67	28.67	16.54	17.04	15.18	15.64
		F_3	29.67	29.00	16.55	16.91	15.23	15.57
		F_4	30.00	29.00	16.87	17.38	15.27	15.67
	N_4	F_1	16.00	15.33	12.84	13.12	11.41	11.66
		F_2	18.67	18.00	12.85	13.19	11.53	11.82
		F_3	19.33	18.33	12.90	13.17	11.67	12.02
		F_4	19.33	18.67	13.00	13.34	11.76	12.01
LSD at 5%			**1.78**	**2.27**	**0.32**	**0.26**	**0.29**	**0.27**

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

Where, I_1: 100% of IR**, I_2:** 80% of IR**, N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone**, F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1}).

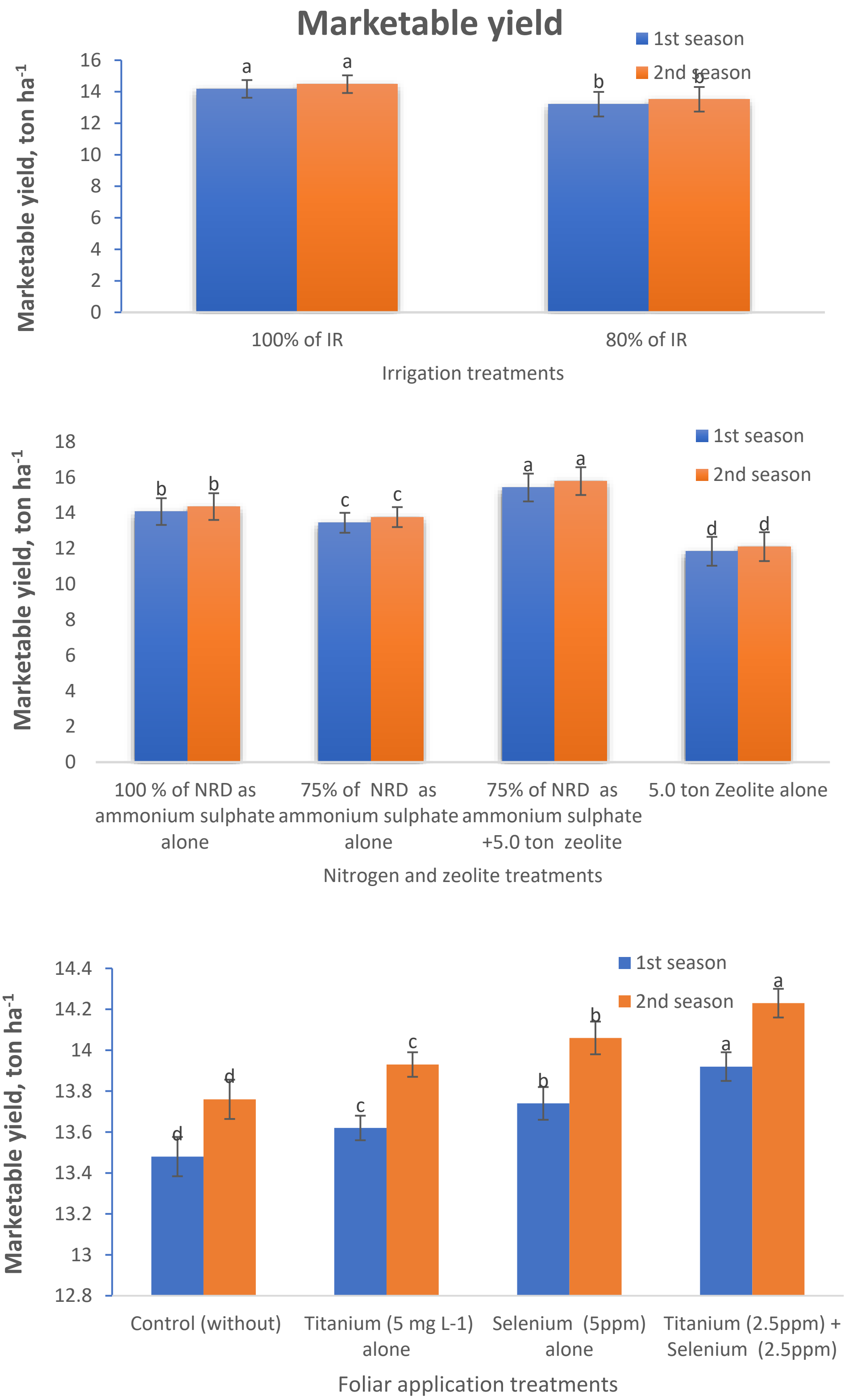

Fig. 2. Effect of the studied treatments on marketable bulb yield during both studied seasons.

Table 8. Effects of different irrigation regimes combined with various NRD rates, zeolite conditioner, and foliar application of titanium and selenium on the cloves /bulb quality traits of garlic during the 2021/2022 and 2022/2023 seasons.

Treatments			Dry matter, %		Vitamin C, mg 100g^{-1}		Carbohydrates, %	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor (Irrigation Requirements IR)								
I1			24.06a	24.55a	15.41a	15.91a	25.31a	25.69a
I2			22.90b	23.44b	14.71b	15.20b	24.08b	24.50b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)								
N1			23.82b	24.33b	15.38b	15.88b	25.11b	25.54b
N2			23.09c	23.62c	15.02c	15.51c	24.41c	24.80c
N3			25.89a	26.47a	16.38a	16.91a	26.78a	27.24a
N4			21.12d	21.57d	13.47d	13.92d	22.47d	22.80d
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial elements and anti-stress)								
F1			23.18c	23.68d	14.87d	15.35d	24.42d	24.83d
F2			23.43b	23.90c	15.00c	15.49c	24.61c	25.00c
F3			23.55b	24.11b	15.12b	15.62b	24.75b	25.15b
F4			23.76a	24.30a	15.24a	15.76a	24.99a	25.41a
Interaction								
I1	**N1**	**F1**	24.33	24.81	15.61	16.13	25.70	26.09
		F2	24.32	24.86	15.68	16.12	25.84	26.26
		F3	24.76	25.26	15.70	16.21	26.00	26.47
		F4	24.82	25.44	15.87	16.40	26.20	26.77
	N2	**F1**	23.45	23.90	15.25	15.68	24.88	25.22
		F2	23.79	24.27	15.41	15.91	25.06	25.41
		F3	23.86	24.37	15.42	15.96	25.27	25.64
		F4	23.91	24.45	15.43	15.99	25.68	26.01
	N3	**F1**	25.92	26.42	16.40	16.96	26.81	27.23
		F2	26.32	26.84	16.65	17.17	26.95	27.38
		F3	26.38	26.88	16.69	17.23	27.14	27.52
		F4	26.50	27.06	16.89	17.42	27.21	27.53
	N4	**F1**	21.46	21.90	13.66	14.15	22.67	22.96
		F2	21.57	21.95	13.83	14.32	22.94	23.33
		F3	21.62	22.07	13.99	14.42	23.18	23.50
		F4	21.98	22.31	14.07	14.54	23.38	23.75
I2	**N1**	**F1**	22.90	23.35	14.89	15.38	23.95	24.31
		F2	23.00	23.45	14.98	15.44	24.28	24.67
		F3	23.04	23.58	15.12	15.64	24.28	24.62
		F4	23.36	23.93	15.18	15.71	24.62	25.11
	N2	**F1**	22.08	22.74	14.48	14.90	23.46	23.95
		F2	22.46	22.93	14.55	15.08	23.50	23.78
		F3	22.54	23.20	14.71	15.15	23.51	23.98
		F4	22.63	23.07	14.89	15.43	23.92	24.40
	N3	**F1**	25.17	25.81	15.87	16.41	26.25	26.83
		F2	25.40	25.90	16.02	16.52	26.58	27.22
		F3	25.62	26.24	16.15	16.67	26.62	27.15
		F4	25.84	26.63	16.37	16.91	26.65	27.09
	N4	**F1**	20.14	20.53	12.83	13.22	21.62	22.00
		F2	20.54	21.03	12.92	13.36	21.72	21.98
		F3	20.60	21.25	13.21	13.66	22.02	22.30
		F4	21.06	21.48	13.25	13.66	22.26	22.59
LSD at 5%			**0.41**	**0.47**	**0.29**	**0.28**	**0.40**	**0.40**

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

Where, I_1: 100% of IR, **I_2:** 80% of IR, **N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone, **F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1}).

Cont. Table 8

Treatments			Total dissolved solids, %		Pungency, purvate content πmol.ml^{-1}	
			1st season	2nd season	1st season	2nd season
Main factor (Irrigation Requirements IR)						
I_1			26.55a	26.96a	11.72a	11.96a
I_2			25.48b	25.93b	10.79b	11.05b
Sub main factor (Nitrogen Recommended Dose NRD as combined with zeolite conditioner)						
N_1			26.38b	26.85b	11.73b	11.99b
N_2			25.71c	26.17c	11.14c	11.39c
N_3			28.19a	28.63a	12.97a	13.27a
N_4			23.78d	24.13d	9.17d	9.37d
Sub-sub main factor (spraying titanium Ti and selenium Se as beneficial elements and anti-stress)						
F_1			25.70d	26.12c	11.02d	11.26d
F_2			25.92c	26.36b	11.18c	11.40c
F_3			26.14b	26.57a	11.36b	11.62b
F_4			26.31a	26.73a	11.46a	11.72a
Interaction						
I_1	N_1	F_1	26.90	27.45	12.15	12.42
		F_2	26.96	27.52	12.18	12.43
		F_3	26.98	27.36	12.51	12.76
		F_4	27.35	27.76	12.51	12.83
	N_2	F_1	26.18	26.56	11.58	11.80
		F_2	26.25	26.56	11.77	11.99
		F_3	26.58	26.98	11.91	12.16
		F_4	26.59	26.99	11.98	12.27
	N_3	F_1	28.34	28.71	13.01	13.27
		F_2	28.55	28.91	13.00	13.27
		F_3	28.68	29.05	13.10	13.37
		F_4	28.86	29.38	13.34	13.61
	N_4	F_1	23.84	24.18	9.10	9.27
		F_2	23.97	24.37	9.52	9.69
		F_3	24.35	24.73	9.85	10.05
		F_4	24.45	24.83	10.01	10.16
I_2	N_1	F_1	25.42	25.81	10.89	11.10
		F_2	25.65	26.16	11.01	11.24
		F_3	25.84	26.41	11.24	11.49
		F_4	25.98	26.30	11.36	11.64
	N_2	F_1	24.73	25.23	10.14	10.45
		F_2	24.82	25.34	10.47	10.66
		F_3	25.22	25.81	10.51	10.83
		F_4	25.28	25.89	10.74	10.94
	N_3	F_1	27.34	27.91	12.74	13.05
		F_2	27.75	28.23	12.82	13.09
		F_3	27.88	28.35	12.88	13.20
		F_4	28.15	28.48	12.89	13.29
	N_4	F_1	22.85	23.13	8.55	8.72
		F_2	23.42	23.77	8.64	8.86
		F_3	23.59	23.86	8.86	9.13
		F_4	23.81	24.17	8.86	9.04
LSD at 5%			**0.41**	**0.50**	**0.22**	**0.19**

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

Where, I_1:100% of IR**, I_2:** 80% of IR**, N_1:** 100 % of NRD as ammonium sulphate alone, **N_2:** 75% of NRD as ammonium sulphate alone, **N_3:** 75% of NRD as ammonium sulphate +5.0 ton, **N_4:** 5.0 ton Zeolite alone, **F_1:** Control (without), **F_2:** Titanium (5 mg L^{-1}) alone, **F_3:** Selenium (5 mg L^{-1}) alone**, F_4:** Titanium (2.5 mg L^{-1}) + Selenium (2.5 mg L^{-1})

4. Discussion

Garlic is highly dependent on adequate water and soil conditions for optimal growth and productivity. Water is essential for maintaining turgor pressure, nutrient uptake, and metabolic processes within the plant **(Taha *et al.* 2019).** Insufficient irrigation water can lead to reduced growth rates, diminished bulb size, and decreased overall yield. Soil conditions, including texture, structure, and fertility, also significantly influence garlic growth. Poor soil management and water shortages can impair root development, limiting the plant's ability to access essential nutrients and leading to suboptimal growth. Water scarcity adversely affects garlic plants by inducing stress conditions that hinder their physiological and biochemical processes **(Sun *et al.* 2020).** Under limited water availability, garlic plants may exhibit reduced cell expansion, lower photosynthetic rates, and impaired nutrient absorption. The production of stress-related islets, such as antioxidants, increases as a defense mechanism to counteract oxidative damage caused by drought conditions. The plant's ability to produce and utilize these antioxidants is crucial for maintaining cellular integrity and ensuring survival under water deficit conditions **(Wu *et al.* 2022).**

Zeolite, a natural mineral with high cation-exchange capacity, plays a significant role in retaining both water and nitrogen in the soil. Its porous structure allows for the adsorption of water molecules, which enhances soil moisture availability and reduces the frequency of irrigation. Additionally, zeolite can retain nitrogen in the soil, reducing the leaching losses of this essential nutrient and improving its availability to plants (**AbdEL-Azeiz *et al.* 2024**). This results in better growth and productivity of garlic plants while simultaneously reducing the amount of nitrogen fertilizers required. The incorporation of zeolite into the soil may have improved various growth characteristics of garlic, such as bulb size, weight, and yield. By stabilizing moisture levels and optimizing nitrogen availability, zeolite enhances the plant's ability to grow and produce higher-quality bulbs. The reduced need for frequent fertilization also lowers input costs and minimizes environmental impacts associated with excessive fertilizer use. These results are in harmony with those of **ElGhamry *et al.* (2024a)** and **Elsherpiny *et al.* 2024)**.

Titanium (Ti) has been shown to play a role in abiotic nitrogen fixation, a process that can contribute to nitrogen nutrition in plants. Titanium enhances the activity of nitrogen-fixing enzymes and improves the efficiency of nitrogen assimilation. This is particularly beneficial under conditions of nitrogen deficiency or limited fertilizer application. By facilitating nitrogen uptake and utilization, titanium contributes to improved plant growth and yield **(Elsherpiny and Faiyad 2023; ElGhamry *et al.* 2024b)**. Selenium (Se) is a vital micronutrient with well-documented antioxidant properties. It helps mitigate oxidative stress caused by environmental stressors, such as water deficit, by enhancing the activity of antioxidant enzymes like glutathione peroxidase. This defensive role of selenium helps protect garlic plants from cellular damage, improves stress tolerance, and supports overall plant health and productivity **(Ahmed *et al.* 2023; ElGhamry *et al.* 2024b).**

The combined application of titanium, selenium, and zeolite offers a synergistic effect that enhances water and nitrogen use efficiency. Titanium and selenium work together to improve the plant's stress resilience and antioxidant defense systems, while zeolite optimizes water and nitrogen retention in the soil. This integrated approach results in better growth, higher yield, and reduced fertilizer and water requirements. The synergistic interaction of these treatments provides a comprehensive strategy for improving garlic production under water deficit conditions, promoting sustainable agricultural practices.

5. Conclusion

The study demonstrated that incorporating zeolite, titanium, and selenium into garlic cultivation under water deficit conditions significantly enhances plant growth and productivity. Zeolite's ability to retain both water and nitrogen reduces the frequency of irrigation and minimizes the need for excessive nitrogen fertilizers, leading to improved plant health and yield. Titanium contributes to better nitrogen utilization and abiotic nitrogen fixation, while selenium's antioxidant properties mitigate oxidative stress and support plant resilience. The synergistic effects of these treatments offer a comprehensive approach to managing water scarcity and optimizing nutrient use, resulting in higher quality and quantity of garlic bulbs. Overall, these findings highlight the potential of integrating zeolite, titanium, and selenium into garlic cultivation practices to address the challenges posed by water and nutrient limitations.

Future research should focus on exploring the long-term effects and sustainability of using zeolite, titanium, and selenium in garlic cultivation. Studies could investigate the optimal application rates and combinations of these treatments for various soil types and environmental conditions. Additionally, examining the impacts on garlic quality attributes, such as flavor and shelf life, would provide a more comprehensive understanding of the benefits. Research into the economic feasibility and practical implementation of these practices in different agricultural settings will be crucial for their adoption.

Conflicts of interest

The authors have declared that no competing interests exist.

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