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Enhancing onion growth and yield quality *via* soil amendments and foliar nutrition under deficit irrigation

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DEVELOPING a modern approach to sustain strategic crop productivity under conditions of water scarcity is a matter that occupies the thoughts of all researchers in the field of agricultural scientific research. So, a research trial was performed during the growing season of 2022/ 2023 for improving the onion growth performance and its quantitative and qualitative yield under deficit irrigation *via* some soil amendments and some beneficial element spraying. Three irrigation regimes [**I_1:** Four irrigations, **I_2:** Three irrigations and **I_3:** Two irrigations were evaluated as main plots. The soil amendments [**T_1:** Without soil amendments), **T_2:** Biochar, **T_3:** Zeolite, **T_4:** Compost (plant residues), at rate of 10 Mg ha^{-1} for each soil amendment] were evaluated as sub main plots. Also, the foliar application of nutrient elements [**F_1:** Without foliar application, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium, at rate of 10 mg L^{-1} for each element**)** was assessed as sub-main plots. Parameters expressing the growth performance (*e.g.,* foliage dry weight, chlorophyll, proline and catalase enzyme) at the period of 75 days from transplanting were determined. Also, traits expressing quantitative yield (*e.g.,* total and marketable bulb yield) and qualitative yield (*e.g.,* carbohydrate, protein, vitamin C, total dissolved solids and pyruvic acid) were estimated. The findings indicate that the traditional irrigation approach **(I_1)** caused the best performance in terms of both quantitative and qualitative yield. Following this, the water deficit treatments (**I_2** and **I_3**) resulted in lower performance, as the **I_3** treatment led to the lowest performance. When considering soil amendments, compost proved to be the most effective, followed by zeolite, then biochar, while, the control treatment (without soil amendments) was the least effective. Regarding the beneficial elements, the order of effectiveness from most to least was Se > Cu > B > F_1 (control). Generally, the most favorable outcomes were observed when combining compost (**T_4**) with selenium foliar application (**F_4**), within the framework of the traditional irrigation treatment (**I_1**). Notably, the growth performance, as well as the quantitative and qualitative yield, were better when employing the combined approach of compost **(T_4)** and selenium foliar application **(F_4)** under the water deficit treatment **(I_2)** compared to plants grown traditionally without any of the studied substances **(I_1 x T_1 x F_1).** In conclusion, this research underscores the potential of soil amendments, and nutrient application strategies to enhance onion growth and yield under water scarcity. By continuously refining these approaches and embracing a holistic perspective, the agricultural community can move closer to ensuring food security and sustainability in challenging environmental conditions.

Keywords: Biochar, zeolite, compost, boron, copper, selenium.

1. Introduction

Egypt has harnessed the potential of onions as both a strategic resource for export and a staple for local consumption. With their distinctive flavor and versatile culinary applications, onions play a vital role in shaping the country's agro-economic landscape **(Sidhu *et al.* 2019).** Beyond their culinary value, onions boast a remarkable nutritional profile, offering a spectrum of vitamins, minerals, and antioxidants that contribute to overall health and well-being **(Ekşi *et al.* 2020; Abd El-Nabi *et al.* 2021).** However, the prosperity of Egypt's onion

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production is not without challenges. Water scarcity looms as a critical factor affecting crop productivity and quality (**Elsherpiny and Helmy 2022).** Onions, known for their sensitivity to variations in irrigation water, are particularly susceptible to the harmful consequences of water deficit **(Amiri-Forotaghe *et al.* 2023).** Irrigation scheduling is an important factor that significantly influences onion growth, development, and yield **(Wakchaure *et al.* 2023).** Onion cultivation is sensitive to soil moisture deficit, which significantly affects its physiological processes (**El–Metwally *et al*. 2022**), such as diminished photosynthetic activity and altered nutrient uptake. The result is growth rate reduction and yield **(Almaroai and Eissa 2020; Ouda et al. 2020).** Recently, the challenge has been ensuring a stable onion production system in Egypt (**Elsherpiny, 2023**).

There is a necessity for innovative strategies that are used to mitigate the adverse effects of soil moisture deficit. The use of organic and mineral amendments like biochar, compost, and zeolite is considered an important strategy (**Elsherpiny 2023).** They save irrigation water because of their high water-holding capacity. Furthermore, they enhance soil to retain water and improve its structure, resulting in an optimal environment for root growth and development. The importance of organic and mineral amendments in saving irrigation water and increasing soil nutrients is indicated by many researchers **(Ghazi *et al.* 2023)**

Furthermore, many researchers confirmed the role of beneficial elements *e.g.,* selenium **(Sattar *et al.* 2019; Mahmoud *et al.* 2023; Elsherpiny and Kany 2023)**, copper **(Pérez-Labrada *et al.* 2019)** and boron **(Abdel-Motagally *et al.* 2018)** in adding another layer of complexity to the equation. These micronutrients are not only essential for optimal plant growth but also exhibit the potential to enhance plant tolerance to soil moisture deficit conditions. Selenium can help plants combat the oxidative stress associated with drought conditions. It may improve the overall resilience of plants to environmental stressors, including drought (**Elsherpiny and Kany 2023**). Copper has been found to help in the activation of stress-related enzymes and antioxidants, which can mitigate the damage caused by drought conditions **(Pérez-Labrada *et al.* 2019).** Boron plays a role in the regulation of stomatal function. Proper stomatal function is crucial for water-use efficiency in plants. Adequate boron levels can help plants optimize their water use and adapt to moisture-deficit conditions **(Abdel-Motagally *et al.* 2018).** By enhancing plant defense mechanisms and metabolic pathways, these elements contribute to improved stress tolerance, ultimately translating into enhanced crop performance under water-limited circumstances. In light of these considerations, the primary aim of this research is to explore and evaluate novel approaches that can mitigate the negative effects of water deficit on onion cultivation in Egypt. By investigating the effectiveness of various irrigation regimes, soil amendments, and beneficial element applications, this study seeks to uncover strategies that can enhance onion growth, quantitative and qualitative yield, and overall resilience under conditions of limited water availability. The findings of this research hold the promise of providing valuable insights and practical solutions to sustain and elevate Egypt's onion production, securing its pivotal role both locally and on the global agricultural stage.

2. Material and Methods

This investigation was conducted in the 2022/2023 cropping season to assess the response of onion plant, cultivated under soil moisture deficit conditions, to certain soil amendments and beneficial element spraying at the Farm of Agric. Fac., Mansoura Univ., Egypt, (31°03′00″N 31°22′9″E), El-Dakahlia Governorate, Egypt.

- Initial soil characteristics

Before initiating the experiment, a soil sample was collected from a depth of 0.0 to 25 cm. Soil physical and chemical analysis was done by standard methods outlined by **Dewis and Freitas (1970)**, and they are shown in Table 1.

- Studied substances

Biochar

Biochar production followed the methodology outlined by **Wang and Wang (2019).** Various organic materials, such as wood chips, agricultural waste, and other plant-based substances, were selected for the process. The chosen feedstock underwent chopping or shredding into smaller fragments to enhance surface area and ensure uniform charring. Subsequently, the prepared feedstock was confined within a container equipped with a lid. This enclosure restricted the oxygen supply, and the feedstock remained in this controlled environment for 30 minutes, subjected to temperatures ranging from 752 to 1292°F (400-700°C). The characteristics of the studied biochar are detailed in Table 2.

Zeolite

Natural zeolite used in the study was procured from the commercial market in Egypt. It is a naturally occurring sedimentary mineral with volcanic origins and constitutes a significant structural element in the formation of zeolite crystals. These crystals consist of crystalline tetrahedrons involving $[SiO_4]^{-4}$ and $[AlO_4]^{-5}$ units. The chemical composition of zeolite is listed in Table 2.

Compost

Compost preparation involved acquiring plant residues, specifically rice straw, along with the banana tree residues (peels, stems, leaves), The composting procedure was initiated half a year prior to conducting the field experiment at the designated research site, following the approach outlined by **Inckel *et al.* (2005).** The compost properties are presented in Table 2.

Boron (B), copper (Cu) and selenium (Se)

Boric acid as the B source, copper sulphate as the Cu source and sodium selenite as the Se source were used in this investigation. All sources were obtained from Sigma Company. The absorbed forms and concentrations of the studied elements in the higher plant tissue are shown in Table 3. Standard solutions were created individually for B, Cu, and Se, each with a specific concentration. This was accomplished by dissolving precise amounts of the respective salts in the selected solvent (water), separately. These standard solutions were then used to generate the specified concentrations needed for the research.

- Onion seedling

The onion cultivar ″Cv. Giza Red, 70 days old ″ was used in this investigation, as the thin, injured, injured and broken seedlings were excluded. The seedlings were obtained from private nurseries.

- Treatments and experimental design

The current research trial was executed under a split split-plot design with three replicates. Three irrigation water deficit treatments were evaluated as main plots as follows;

I_1: Five irrigation events (control treatment; full irrigation; 0% irrigation water deficit; 100% of Irrigation Requirements, IR), the same as the irrigation method used by farmers in the study area.

I_2: Three irrigation events (75% of IR; 25% irrigation water deficit).

I_3: Two irrigation events (50% of IR; 50% irrigation water deficit).

The soil amendments treatments were devoted in the sub-plots and took the following symbols;

T_1: Without soil amendments
T_2: Biochar, applied at a rate of 10 Mg ha^{-1}
T_3: Zeolite, applied at a rate of 10 Mg ha^{-1}
T_4: Compost, applied at a rate of 10 Mg ha^{-1}
Mg ″mega gram″=10^6 g (equivalent metric ton)

The foliar application treatments allocated in the sub-sub plots and took the following symbols;

F_1: Without exogenous application
F_2: Boron, at rate of 10 mg B L^{-1}
F_3: Copper, at rate of 10 mg Cu L^{-1}
F_4: Selenium, at rate of 10 mg Se L^{-1}

Fig 1 shows the flowchart of the experiment.

Table 1. Characteristics of the initial soil.

Clay, %	Sand, %	Silt, %	Texture class	N, mg kg^{-1}	P, mg kg^{-1}	K, mg kg^{-1}	O.M,%	EC, dS m^{-1} (1:2.5, soil extract)	pH (1:2.5, soil suspension)	Water holding capacity,%	CEC, cmolc kg^{-1}
49.3	20.0	30.7	Clayey	49.5	10.3	215.6	1.35	3.036	8.03	44	42.6
Particle size distribution (pipette method)			Using soil texture triangle	Kjeldahl method	Spectrophotometric method	Flame photometer	Walkly and Balck method	Using EC-meter	Using pH-meter	Mixing and burette	Using sodium acetate
Gee and Baudet (1986)				**Hesse, (1971)**			**Dewis and Freitas, (1970)**				**Black (1965)**

Table 2. Characteristics of the studied substances.

Soil addition substances			
Characteristics	**Values**		
	Biochar	**Zeolite**	**Compost**
EC, dSm^{-1}	4.85 (Extract 1:10)	2.870 (Extract 1:10)	3.54 (Extract 1:10)
pH	8.45	/	6.160
CEC, cmolc kg^{-1}	69.0	167	245.0
N,%	/	/	1.660
P,%	/	0.50	1.470
K,%	/	5.20	1.330
C,%	/	/	18.30
O,M,%	/	/	31.50
C/N ratio	/	/	11.02
SiO_2 %	/	72.00	/
Al_2O_3 %	/	11.90	/
Foliar application substances			
Characteristics	**Values**		
	Boric acid	**Copper sulphate**	**Sodium selenite**
Chemical Formula	H_3BO_3 (1٧%B)	$CuSO_4$ (25%Cu)	Na_2SeO_3 (45.56 %Se)
Solubility	- 2.52 g 100 mL^{-1} (0 °C) - 4.72 g 100 mL^{-1} (20 °C) - 5.7 g 100 mL^{-1} (25 °C) - 19.10 g 100 mL^{-1} (80 °C) - 27.53 g 100 mL^{-1} (100 °C)	- 316 g L^{-1} (0 °C) - 2033 g L^{-1} (100 °C)	- 85 g 100 mL^{-1} (20 °C)
Purity	99%	98%	99%
Density	1.435 g cm^{-3}	3.60 g cm^{-3}	3.1 g cm^{-3}
Appearance	White crystalline powder or solid	Blue crystalline solid	White crystalline powder or crystals
Melting Point	Approximately 170.9°C	110 °C	Approximately 710°C
Toxicity	Low to moderate toxicity	Toxic to aquatic life	Toxic, can be harmful if ingested or inhaled
Molecular Weight	Approximately 61.83 g mol^{-1}	159.61 g mol^{-1}	172.49 g mol^{-1}
pH Level	A dilute boric acid solution is slightly acidic, with a pH below 7. As the concentration increases, the pH can move closer to neutral (pH 7).	Acidic (approximately 4)	May slightly raise pH in aqueous solutions

/ :Not determined

Table 3. The absorbed forms and concentrations of B, Cu, and Se in the higher plant tissue.

Elements	**Form absorbed**	**Concentration range in dry higher plant tissue**
B	H_3BO_3	6-60, µg kg^{-1}
Cu	Cu^{+2}	5-20, µg kg^{-1}
Se	Selenite (SeO_4^{2-}) or selenite (SeO_3^{2-}) or in organic form as Se-amino acid, for example as Se-methionine (Se-met)	0.01o less than 1.0 µg g^{-1}

First replicate												
Soil addition treatments	**Irrigation treatments**											
	I_1				**I_2**				**I_3**			
	Foliar treatments											
T_1	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_2	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_3	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
Second replicate												
Soil addition treatments	**Irrigation treatments**											
	I_1				**I_2**				**I_3**			
	Foliar treatments											
T_1	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_2	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_3	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
Third replicate												
Soil addition treatments	**Irrigation treatments**											
	I_1				**I_2**				**I_3**			
	Foliar treatments											
T_1	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_2	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_3	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4
T_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4	F_1	F_2	F_3	F_4

Fig. 1. Flowchart of the experiment.

- Preparation of field and experimental layout

On the 14th of November 2022, following soil irrigation through a flood regime, seedlings were meticulously positioned, maintaining a 7.0 cm spacing between them, within double-row ridges spanning 60 cm in width. The onion plants were subjected to a total nitrogen dosage of 288 kg N ha^{-1}, applied in two equal doses. The initial dose was administered approximately one month after transplanting, with the subsequent dose applied after an additional month had elapsed. Before transplanting two weeks, calcium super-phosphate (15.5% P_2O_5) was added at a rate of 150 kg P_2O_5 ha^{-1}. Concurrently, the treatments of soil amendments were implemented. The foliar application of solutions containing boron (B), copper (Cu), and selenium (Se) was initiated alongside the first irrigation event, which took place 30 days after transplanting with a volume of 1000 L ha^{-1} for each studied solution, by hand sprayer. The irrigation process was executed using a flood regime, with the specified irrigation treatments as previously outlined. Adherence to the onion cultivation practices stipulated by the Ministry of Agriculture and Land Reclamation (MASR) was strictly observed. The harvesting was manually conducted after 155 days from transplanting.

- Measurements

a- At 70 days from transplanting

Five plants were chosen at the period of 70 days to determine the following traits;

- Foliage plant height (cm), fresh and dry weights (g $plant^{-1}$) were manually and visually measured.
- Chlorophyll [SPAD-502, Soil-Plant Analysis Development (SPAD) Section, Minolta Camera, Osaka, Japan] was measured as reported by **Castelli *et al.* (1996)**.
- Carotene (mg g^{-1}) in fresh leaves tissues under different treatments were measured using the spectrophotometric method as described by **Lichtenthaler and Wellburn (1983).**
- Dry weight of foliage samples were digested *via* mixed of $HClO_4$ + H_2SO_4 as described by **Peterburgski (1968)**.
- N, P and K (% DW) were determined using Micro-Kjeldahl, spectrophotometric and flame photometer methods, respectively as described by **Walinga *et al.* (2013)**.
- Proline (µmol g^{-1} FW) was estimated *via* colourimetric measurement according to **Ábrahám *et al.* (2010)**.
- Enzymatic antioxidants such as peroxidase (POD), catalase (CAT) and superoxide dismutase (SOD) (unit g^{-1} $protein^{-1}$) were spectrophotometry determined as described by **Alici and Arabaci (2016).**

b- At harvest stage (155 days from planting)

The following parameters were determined.

- Yield and its components like average bulb diameter (cm) and weight (g), nick diameter (cm), total bulb yield (Mg ha^{-1}) and marketable bulb yield (Mg ha^{-1}) were measured.
- Carbohydrates, protein, total dissolved solids percentage (TDS), fiber, total sugars, vitamin C (mg $100g^{-1}$) and dry matter D.M (%) were estimated according to **AOAC (2000),** while the anthocyanin pigment (mg $100g^{-1}$) was determined as described by **Schoefs (2004).** Pyruvic acid (µmol g^{-1}) was measured as described by **Anthon and Barrett (2003).**

c- Soil post-harvest analysis

Soil available nutrients such as nitrogen, phosphorus and potassium (mg kg^{-1}) as well as water holding capacity (%) and cation exchange capacity of soil (CEC, cmol kg^{-1}) were determined at harvest stage as formerly mentioned in initial soil sample.

- Statistical analysis

To facilitate the comparison of means across different treatments, Duncan's Multiple Range Test was employed by using the least significant difference. This analysis was conducted using the CoStat computer software package **(Version 6.303, CoHort, USA, 1998-2004),** following the methodology outlined by **Gomez and Gomez (1984).**

3. Results

1.1. Onion performance at 75 days from transplanting

The individual effects of different irrigation regimes (traditional and water deficit), soil amendments (biochar, zeolite, and compost), and beneficial elements (boron, copper, and selenium) are demonstrated in Tables 4 and 6 at a period of 75 days from transplanting during the onion growing season. Table 4 presents various parameters that reflect growth criteria such as plant height, fresh foliage and dry weights, as well as photosynthetic pigments (chlorophyll and carotene), and chemical constituents in foliage (nitrogen, phosphorus, and potassium). Concurrently, Table 6 outlines the impact of these factors on leaf antioxidant activity, including the non-enzymatic antioxidant expressed proline, as well as enzymatic antioxidants like peroxidase (POD), catalase (CAT), and superoxide dismutase (SOD), all evaluated at the same period (75 days from transplanting). Furthermore, Tables 5 and 7 provide insights into the interactions among the studied factors across all the previously mentioned traits.

- Growth criteria, photosynthetic pigment and leaves chemical constitutes

Table 4 indicates that the traditional irrigation approach (**I_1**) caused the best performance in terms of plant height, fresh foliage and dry weights, chlorophyll reading, carotene content and foliage NPK contents. Following this, the water deficit treatments (**I_2** and **I_3**) resulted in lower performance, as the **I_3** treatment led to the lowest performance. When considering soil amendments, compost proved to be the most effective, followed by zeolite, then biochar, while, the check treatment (without soil amendments) was the least effective. Regarding the beneficial elements, the order of effectiveness from most to least was Se > Cu > B > **F_1** (control).

Table 4. Individual effect of soil amendments and spraying beneficial element on growth performance of onion plant grown under various irrigation treatments (traditional and deficit treatments) at a period of 75 days from transplanting.

Treatments	Growth criteria (foliage)			Leaves photosynthetic pigment		Leaves chemical constitutes		
	Plant height	Fresh weight	Dry weight	Chlorophyll	Carotene	N	P	K
	(cm)	(g plant-1)		(SPAD reading)	(mg g-1)	(%)		
				Main factor : Irrigation treatments				
I1	76.80a	69.12a	8.31a	44.01a	0.505a	3.47a	0.329a	2.96a
I2	70.42b	65.98b	7.85b	43.03b	0.445b	3.16b	0.298b	2.74b
I3	63.62c	61.67c	7.11c	41.25c	0.380c	2.46c	0.238c	2.10c
LSD at 5%	**0.11**	**0.58**	**0.04**	**0.12**	**0.003**	**0.01**	**0.001**	**0.04**
				Sub main factor: Soil additions				
T1	65.66d	62.80d	7.33d	41.74d	0.392d	2.71d	0.258d	2.35d
T2	69.71c	65.44c	7.71c	42.65c	0.441c	3.00c	0.287c	2.58c
T3	72.09b	66.47b	7.88b	43.06b	0.460b	3.15b	0.298b	2.68b
T4	73.65a	67.64a	8.11a	43.61a	0.480a	3.26a	0.310a	2.78a
LSD at 5%	**0.67**	**0.78**	**0.07**	**0.22**	**0.003**	**0.03**	**0.002**	**0.04**
				Sub-sub main factor: Foliar applications				
F1	69.56c	65.11b	7.68c	42.59b	0.436d	2.98c	0.283d	2.56c
F2	70.10bc	65.49ab	7.73bc	42.71ab	0.442c	3.01bc	0.287c	2.59bc
F3	70.54ab	65.70ab	7.79ab	42.83ab	0.446b	3.05ab	0.290b	2.61b
F4	70.91a	66.04a	7.84a	42.94a	0.450a	3.08a	0.292a	2.64a
LSD at 5%	**0.79**	**0.67**	**0.08**	**0.24**	**0.002**	**0.04**	**0.002**	**0.03**

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

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

Concerning the interaction effect, Table 5 indicate that the most favorable outcomes in terms of the values of plant height, fresh foliage and dry weights, chlorophyll reading, carotene content and foliage NPK contents were observed when combining compost **(T_4)** with selenium foliar application **(F_4)**, within the framework of the traditional irrigation treatment **(I_1).** Notably, the performance was better when employing the combined approach of compost (T_4) and selenium foliar application **(F_4)** under the water deficit treatment **(I_2)** compared to plants grown traditionally without any of the studied substances **(I_1 x T_1 x F_1).**

Table 5. Interaction effect among soil amendments and beneficial element on growth performance of onion plant gown under various irrigation treatments (traditional and deficit treatments) at a period of 75 days from transplanting.

Treatments			Growth criteria (foliage)			Leaves photosynthetic pigment		Leaves chemical constitutes		
			Plant height	Fresh weight	Dry weight	Chlorophyll	Carotene	N	P	K
			(cm)	(g plant^{-1})		(SPAD reading)	(mg g^{-1})		(%)	
I_1	T_1	F_1	68.53	63.98	7.57	42.39	0.412	2.94	0.281	2.59
		F_2	68.60	64.18	7.61	42.45	0.417	2.96	0.284	2.62
		F_3	68.93	64.20	7.67	42.55	0.422	3.01	0.285	2.65
		F_4	69.30	64.72	7.74	42.71	0.424	3.03	0.287	2.68
	T_2	F_1	74.73	68.74	8.20	43.78	0.498	3.44	0.326	2.92
		F_2	75.87	69.22	8.24	43.84	0.508	3.43	0.330	2.95
		F_3	77.03	69.29	8.27	44.01	0.514	3.53	0.334	2.96
		F_4	78.33	69.98	8.34	43.95	0.521	3.54	0.336	2.98
	T_3	F_1	78.60	69.91	8.36	44.08	0.528	3.62	0.340	3.04
		F_2	79.93	70.52	8.42	44.33	0.531	3.63	0.344	3.06
		F_3	80.53	71.16	8.50	44.44	0.538	3.70	0.347	3.10
		F_4	80.80	71.46	8.62	44.66	0.543	3.70	0.348	3.11
	T_4	F_1	81.43	71.64	8.66	44.87	0.550	3.73	0.351	3.13
		F_2	81.90	71.93	8.75	45.19	0.553	3.75	0.354	3.14
		F_3	81.97	72.27	8.96	45.36	0.561	3.77	0.356	3.17
		F_4	82.23	72.66	9.03	45.58	0.568	3.79	0.360	3.19
I_2	T_1	F_1	66.27	63.24	7.47	42.20	0.403	2.86	0.262	2.45
		F_2	67.07	63.45	7.48	42.23	0.407	2.86	0.265	2.47
		F_3	67.23	63.68	7.54	42.28	0.408	2.90	0.272	2.50
		F_4	67.43	63.79	7.55	42.26	0.408	2.93	0.275	2.63
	T_2	F_1	70.00	64.80	7.80	42.83	0.430	3.05	0.291	2.70
		F_2	70.07	65.42	7.83	42.91	0.435	3.09	0.295	2.74
		F_3	70.17	66.04	7.88	43.01	0.436	3.10	0.299	2.73
		F_4	70.73	66.11	7.92	43.08	0.442	3.16	0.301	2.77
	T_3	F_1	71.07	66.33	7.94	43.18	0.448	3.20	0.303	2.80
		F_2	71.33	66.73	7.95	43.18	0.453	3.28	0.306	2.80
		F_3	71.70	66.75	7.97	43.29	0.459	3.29	0.310	2.81
		F_4	71.93	67.29	7.97	43.47	0.465	3.32	0.310	2.83
	T_4	F_1	71.90	67.42	8.01	43.48	0.472	3.32	0.315	2.85
		F_2	72.77	67.97	8.09	43.67	0.481	3.36	0.318	2.88
		F_3	73.10	67.99	8.09	43.66	0.487	3.37	0.319	2.89
		F_4	73.90	68.63	8.14	43.78	0.493	3.39	0.322	2.92
I_3	T_1	F_1	60.53	59.88	6.76	40.18	0.341	2.20	0.215	1.85
		F_2	60.83	60.69	6.83	40.34	0.350	2.24	0.218	1.88
		F_3	61.57	60.81	6.87	40.52	0.355	2.28	0.221	1.90
		F_4	61.63	60.97	6.94	40.75	0.362	2.31	0.226	1.95
	T_2	F_1	61.97	61.23	6.97	40.97	0.366	2.36	0.229	1.99
		F_2	62.30	61.39	6.99	41.02	0.379	2.40	0.232	2.03
		F_3	62.57	61.49	7.05	41.16	0.382	2.43	0.236	2.07
		F_4	62.73	61.56	7.07	41.26	0.382	2.47	0.238	2.11
	T_3	F_1	63.73	61.58	7.09	41.35	0.387	2.50	0.238	2.15
		F_2	64.60	61.63	7.19	41.44	0.388	2.52	0.241	2.16
		F_3	65.23	61.94	7.20	41.65	0.392	2.55	0.242	2.18
		F_4	65.60	62.33	7.32	41.63	0.393	2.56	0.245	2.19
	T_4	F_1	65.93	62.60	7.31	41.77	0.397	2.58	0.251	2.21
		F_2	65.97	62.80	7.33	41.86	0.398	2.62	0.254	2.30
		F_3	66.47	62.82	7.43	41.98	0.402	2.68	0.259	2.32
		F_4	66.23	62.99	7.45	42.10	0.402	2.75	0.262	2.37
LSD at 5%			**2.75**	**2.33**	**0.27**	**0.84**	**0.009**	**0.13**	**0.006**	**0.12**

Means are statistically different at a 0.05 level

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium

- Proline and enzymatic antioxidants

Tables 6 and 7 indicate the influences of the studied factors (either solely or in combination) on the plant's self-production of antioxidants *i.e.*, proline, POD, CAT and SOD. It's important to note that the trends of these antioxidants differed from those observed in the growth performance parameters. For instance, within the irrigation treatments, the $\mathbf{I_3}$ treatment exhibited the highest values. Similarly, the $\mathbf{T_1}$ treatment (control) among soil amendments and the $\mathbf{F_1}$ treatment (control) among foliar treatments resulted in the highest levels of proline, POD, CAT, and SOD. This implies that the combined treatment of $\mathbf{I_3 \times T_1 \times F_1}$ yielded the most significant production of all studied antioxidants **(**Table 7**).**

In contrast, plants irrigated traditionally ($\mathbf{I_1}$) or cultivated in soil treated with compost ($\mathbf{T_4}$) displayed the lowest levels of proline, POD, CAT, and SOD. Similarly, plants subjected to foliar application of selenium exhibited the lowest values. In general, the combined treatment of $\mathbf{I_1 \times T_4 \times F_4}$ resulted in the lowest antioxidant production **(**Table 7**)**. Regarding irrigation treatments, the order of antioxidant production from highest to lowest was $\mathbf{I_3 > I_2 > I_1}$. In terms of soil amendments treatments, the sequence was $\mathbf{T_1}$ (control) > $\mathbf{T_2 > T_3 > T_4}$. Concerning foliar treatments, the sequence was $\mathbf{F_1}$ (control) > $\mathbf{F_2 > F_3 > F_4}$ **(**Table 6**).**

Overall, it's apparent that the application of soil amendments (biochar, zeolite, and compost) and the application of beneficial elements (boron, copper, and selenium) contributed to a reduction in the need for the synthesis of proline, POD, CAT, and SOD by the plants especially under water deficit treatments ($\mathbf{I_2}$ and $\mathbf{I_3}$). This suggests that these treatments helped enhance the plant's natural antioxidant mechanisms.

Table 6. Individual effect of soil amendments and spraying beneficial element on leaves content of onion plant grown under various irrigation treatments (traditional and deficit treatments) from proline and enzymatic antioxidants at a period of 75 days from transplanting.

Treatments	Proline, μmol g^{-1} F.W	Enzymatic antioxidants		
		POD	CAT	SOD
		(Unit min^{-1} g^{-1} protein)		
Main factor : Irrigation treatments				
I_1	7.57c	44.27c	147.05c	112.53c
I_2	8.79b	50.98b	162.52b	119.34b
I_3	10.20a	62.81a	190.44a	133.05a
LSD at 5%	**0.08**	**0.05**	**0.17**	**2.22**
Sub main factor: Soil additions				
T_1	9.36a	55.46a	175.52a	125.31a
T_2	9.03b	53.61b	168.90b	122.83b
T_3	8.67c	51.80c	163.66c	120.31c
T_4	8.35d	49.87d	158.60d	118.10d
LSD at 5%	**0.06**	**0.10**	**0.27**	**0.70**
Sub-sub main factor: Foliar applications				
F_1	8.98a	53.32a	168.79a	122.50a
F_2	8.89b	52.99b	167.13b	121.87b
F_3	8.80c	52.38c	166.15c	121.44b
F_4	8.74d	52.05d	164.60d	120.75c
LSD at 5%	**0.05**	**0.10**	**0.34**	**0.48**

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

$\mathbf{I_1}$**:** Four irrigations (100% of Irrigation Requirements IR), $\mathbf{I_2}$**:** Three irrigations (75% of IR), $\mathbf{I_3}$**:** Two irrigations (50 % of IR), $\mathbf{T_1}$**:** Control (without soil amendments), $\mathbf{T_2}$**:** Biochar (plant residues), $\mathbf{T_3}$**:** Zeolite, $\mathbf{T_4}$**:** Compost (plant residues), $\mathbf{F_1}$**:** Control, $\mathbf{F_2}$**:** Boron, $\mathbf{F_3}$**:** Copper, $\mathbf{F_4}$**:** Selenium

Table 7. Interaction effect among soil amendments and beneficial element on leaves content of onion plant grown under various irrigation treatments (traditional and deficit treatments) from proline and enzymatic antioxidants at a period of 75 days from transplanting.

Treatments			Proline, µmol g^{-1} F.W	Enzymatic antioxidants POD	CAT	SOD
				(Unit min^{-1} g^{-1} protein)		
I_1	T_1	F_1	7.98	45.98	152.72	114.70
		F_2	7.87	45.70	151.82	114.25
		F_3	7.74	45.24	151.26	114.21
		F_4	7.67	45.15	149.40	113.41
	T_2	F_1	7.64	44.30	149.15	112.83
		F_2	7.65	44.08	148.17	112.79
		F_3	7.64	44.01	147.35	112.77
		F_4	7.61	43.97	147.25	112.58
	T_3	F_1	7.58	43.87	147.03	112.35
		F_2	7.56	43.84	145.92	111.91
		F_3	7.55	43.76	145.26	111.92
		F_4	7.53	43.76	144.70	111.75
	T_4	F_1	7.40	43.81	143.62	111.46
		F_2	7.31	43.65	143.13	111.39
		F_3	7.25	43.65	143.06	111.12
		F_4	7.16	43.53	142.98	111.04
I_2	T_1	F_1	9.48	55.46	174.41	124.32
		F_2	9.45	55.26	172.25	124.17
		F_3	9.41	54.37	171.58	123.90
		F_4	9.23	54.08	167.84	123.22
	T_2	F_1	9.15	53.56	166.00	122.78
		F_2	9.13	53.37	163.93	120.64
		F_3	9.08	51.46	163.67	119.73
		F_4	8.94	50.65	161.47	118.44
	T_3	F_1	8.81	50.02	160.66	117.92
		F_2	8.60	49.88	159.45	117.56
		F_3	8.33	48.90	158.48	116.89
		F_4	8.28	48.64	157.96	116.83
	T_4	F_1	8.24	48.03	157.48	116.67
		F_2	8.21	47.89	156.00	115.94
		F_3	8.18	47.13	155.53	115.36
		F_4	8.08	47.02	153.56	114.99
I_3	T_1	F_1	11.10	66.50	205.75	138.49
		F_2	10.93	66.13	205.13	137.99
		F_3	10.80	65.90	203.27	137.79
		F_4	10.72	65.76	200.73	137.27
	T_2	F_1	10.58	64.90	198.63	136.28
		F_2	10.39	64.54	196.23	135.62
		F_3	10.26	64.30	193.71	135.26
		F_4	10.24	64.18	191.21	134.22
	T_3	F_1	10.13	63.48	189.01	133.28
		F_2	10.00	62.55	187.04	132.07
		F_3	9.87	61.97	185.25	131.19
		F_4	9.85	60.89	183.14	130.05
	T_4	F_1	9.75	59.94	181.04	128.91
		F_2	9.52	59.00	176.48	128.07
		F_3	9.53	57.88	175.39	127.11
		F_4	9.52	56.97	174.97	125.17
LSD at 5%			**0.19**	**0.31**	**1.17**	**1.67**

Means within a row are statistically different at a 0.05 level

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

- Quantitative and qualitative yield

The utilization of diverse soil amendments (biochar, zeolite, and compost) alongside beneficial elements (boron, copper, and selenium), whether administered alone or in combination, exerted significant influence on multiple aspects concerning the quantitative and qualitative yield of onion plants which subjected to varying irrigation regimes (**I_1:** Four irrigations, **I_2:**

Three irrigations, **I_3:** Two irrigations). These effects on average bulb weight, bulb diameter, neck diameter, total bulb yield and marketable bulb yield are presented in Tables 8 and 9, detailing both individual contributions and interactions among factors. Additionally, certain quality attributes, such as carbohydrates, protein, total dissolved solids (TDS), fiber, total sugar, anthocyanin pigment, vitamin C (VC), dry matter (DM) and pyruvic acid (**Tables 10** and **11** for individual and interactions effects, respectively), were also assessed during the harvest stage. Also, Figs from 2 to 4 show the individual effect of the studied treatments on total and marketable bulb yield.

The traditional irrigation approach **(I_1)** caused the maximum values of quantitative and qualitative parameters followed by the water deficit treatments (**I_2** and **I_3,** respectively). The outcomes reveal that among the soil amendments, the most effective in achieving the maximum values was the compost treatment (**T_4**), followed closely by the zeolite treatment (**T_3**) and then biochar treatment (**T_2**), all of which surpassed the control group (**T_1**)**.** In terms of foliar spraying treatments, the selenium treatment **(F_4)** showed the most favorable results, ranking first for all the mentioned quantitative and qualitative yield characteristics. While the copper came in the second order and boron came the third order. On the other hand, the check treatment (**T_1**) realized the lowest values. Regarding the interaction effect, Table 9 and 11 demonstrate that the highest values of average bulb weight, bulb diameter, neck diameter, total bulb yield, marketable bulb yield carbohydrates, protein, total dissolved solids (TDS), fiber, total sugar, anthocyanin pigment, vitamin C (VC), dry matter (DM) and pyruvic acid were observed when combining compost **(T_4)** with selenium foliar application **(F_4),** within the framework of the traditional irrigation treatment **(I_1).** Notably, the values of all aforementioned traits were more when employing the combined approach of compost (**T_4**) and selenium foliar application **(F_4)** under the water deficit treatment **(I_2)** compared to those of the plants grown traditionally without any of the studied substances **(I_1 x T_1 x F_1)**.

Table 8. Individual effect of soil amendments and spraying beneficial element on yield and its components of onion plant grown under various irrigation treatments (traditional and deficit treatments) at harvest stage.

Treatments	**Average bulb weight**	**Bulb diameter**	**Neck diameter**	**Total bulb yield**	**Marketable bulb yield**
	(g)	**(cm)**		**(Mg ha^{-1})**	
Main factor : Irrigation treatments					
I_1	111.75a	7.11a	2.22a	42.55a	40.91a
I_2	102.86b	6.34b	1.52b	39.17b	37.76b
I_3	85.26c	4.41c	0.75c	32.47c	30.70c
LSD at 5%	**0.72**	**0.03**	**0.04**	**0.27**	**0.27**
Sub main factor: Soil additions					
T_1	91.81d	5.09d	0.94d	34.96d	33.41d
T_2	99.56c	5.90c	1.43c	37.91c	36.20c
T_3	102.63b	6.24b	1.66b	39.08b	37.41b
T_4	105.80a	6.58a	1.96a	40.29a	38.81a
LSD at 5%	**0.64**	**0.07**	**0.04**	**0.24**	**0.23**
Sub-sub main factor: Foliar applications					
F_1	98.66d	5.81d	1.40d	37.57d	35.99c
F_2	99.46c	5.92c	1.48c	37.88c	36.33b
F_3	100.36b	6.00b	1.54b	38.22b	36.65a
F_4	101.33a	6.08a	1.58a	38.59a	36.86a
LSD at 5%	**0.61**	**0.60**	**0.04**	**0.23**	**0.22**

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

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

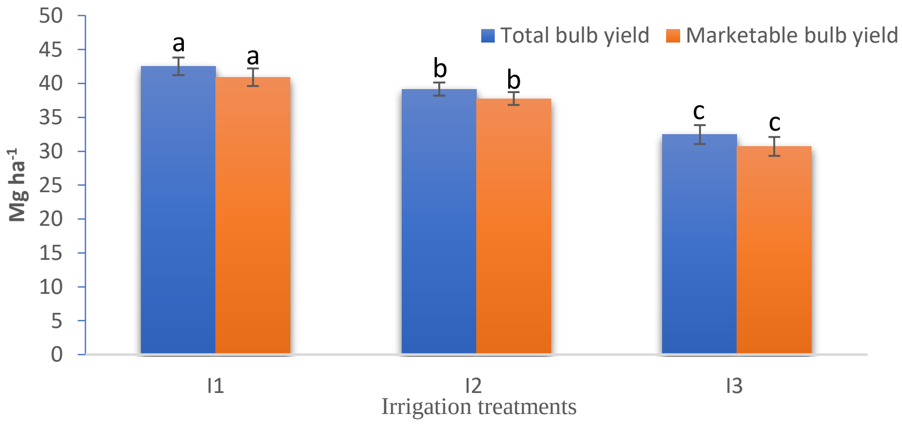

Fig. 2. Individual effect of irrigation treatments on total and marketable bulb yield.
I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR).

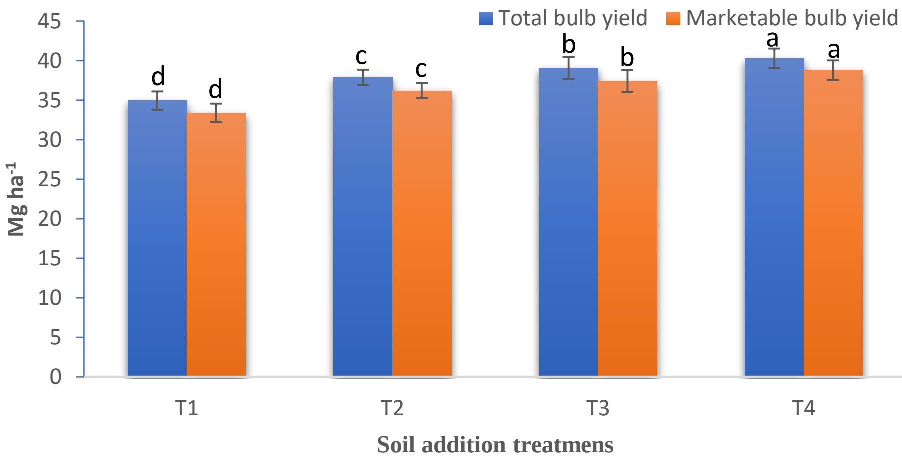

Fig. 3. Individual effect of soil amendments on total and marketable bulb yield.
T_1: Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues).

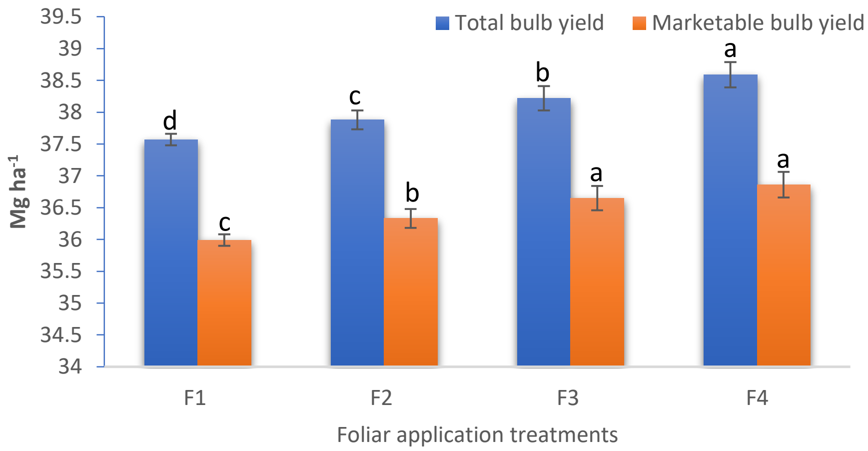

Fig. 4. Individual effect of spraying the beneficial elements on total and marketable bulb yield.
F_1: Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

Table 9. Interaction effect among soil amendments and beneficial element on yield and its components of onion plant grown under various irrigation treatments (traditional and deficit treatments) at harvest stage.

Treatments			Average bulb yield (g)	Bulb diameter (cm)	Neck diameter (cm)	Total bulb yield (Mg ha^{-1})	Marketable bulb yield (Mg ha^{-1})
I$_1$	T$_1$	F$_1$	96.86	5.90	1.21	36.88	35.90
		F$_2$	98.49	5.96	1.31	37.50	36.15
		F$_3$	99.41	5.98	1.33	37.86	36.44
		F$_4$	100.74	6.13	1.33	38.36	36.81
	T$_2$	F$_1$	111.15	7.13	2.10	42.33	40.66
		F$_2$	112.19	7.20	2.14	42.72	41.08
		F$_3$	112.64	7.21	2.16	42.89	41.33
		F$_4$	113.52	7.21	2.25	43.23	41.70
	T$_3$	F$_1$	114.44	7.33	2.31	43.58	41.97
		F$_2$	115.93	7.38	2.44	44.15	42.26
		F$_3$	116.59	7.47	2.50	44.40	42.65
		F$_4$	118.28	7.52	2.55	45.04	42.88
	T$_4$	F$_1$	118.29	7.63	2.75	45.04	43.19
		F$_2$	118.56	7.73	2.87	45.15	43.58
		F$_3$	120.16	7.94	3.11	45.76	43.82
		F$_4$	120.70	8.05	3.19	45.96	44.16
I$_2$	T$_1$	F$_1$	92.28	5.32	0.99	35.14	34.76
		F$_2$	92.32	5.57	1.02	35.16	35.04
		F$_3$	94.84	5.64	1.10	36.11	35.36
		F$_4$	96.34	5.78	1.13	36.69	35.60
	T$_2$	F$_1$	100.97	6.17	1.37	38.45	37.06
		F$_2$	101.56	6.22	1.45	38.68	37.35
		F$_3$	102.70	6.37	1.46	39.11	37.66
		F$_4$	103.83	6.40	1.52	39.54	37.93
	T$_3$	F$_1$	104.64	6.49	1.54	39.85	38.20
		F$_2$	106.29	6.69	1.63	40.48	38.58
		F$_3$	106.85	6.71	1.72	40.69	38.91
		F$_4$	106.88	6.71	1.78	40.70	38.11
	T$_4$	F$_1$	108.02	6.79	1.82	41.13	39.45
		F$_2$	108.75	6.79	1.93	41.41	39.78
		F$_3$	108.76	6.81	1.94	41.41	40.07
		F$_4$	110.67	6.91	1.99	42.14	40.32
I$_3$	T$_1$	F$_1$	81.57	3.35	0.39	31.06	28.28
		F$_2$	82.49	3.66	0.41	31.41	28.56
		F$_3$	83.05	3.87	0.55	31.62	28.86
		F$_4$	83.34	3.97	0.56	31.74	29.16
	T$_2$	F$_1$	83.66	4.16	0.61	31.86	29.43
		F$_2$	84.09	4.17	0.66	32.02	29.82
		F$_3$	84.07	4.18	0.68	32.02	30.02
		F$_4$	84.38	4.33	0.78	32.13	30.31
	T$_3$	F$_1$	84.51	4.51	0.82	32.18	30.74
		F$_2$	84.74	4.60	0.88	32.27	31.12
		F$_3$	85.45	4.71	0.88	32.54	31.52
		F$_4$	87.02	4.76	0.90	33.14	31.91
	T$_4$	F$_1$	87.55	4.91	0.92	33.34	32.22
		F$_2$	88.14	5.04	0.99	33.56	32.58
		F$_3$	89.82	5.13	0.99	34.20	33.12
		F$_4$	90.24	5.26	0.99	34.36	33.47
LSD at 5%			**2.13**	**0.21**	**0.14**	**0.81**	**0.77**

Means within a row are statistically different at a 0.05 level

I$_1$: Four irrigations (100% of Irrigation Requirements IR), **I$_2$:** Three irrigations (75% of IR), **I$_3$:** Two irrigations (50 % of IR), **T$_1$:** Control (without soil amendments), **T$_2$:** Biochar (plant residues), **T$_3$:** Zeolite, **T$_4$:** Compost (plant residues), **F$_1$:** Control, **F$_2$:** Boron, **F$_3$:** Copper, **F$_4$:** Selenium.

Table 10. Individual effect of soil amendments and spraying beneficial element on bulb quality of onion plant grown under various irrigation treatments (traditional and deficit treatments) at harvest stage.

Treatments	Carbohy-drates	Protein	TDS	Fiber	T. Sugar	Anthocya-nin	V. C	DM	Pyruvic
	(%)					(mg 100g^{-1})		(%)	(πmol.
Main factor : Irrigation treatments									
I_1	18.41a	8.73a	12.14a	3.91a	7.77a	28.90a	13.13a	12.47a	7.06a
I_2	17.55b	8.16b	11.33b	3.33b	7.02b	27.91b	12.45b	11.46b	6.22b
I_3	15.32c	7.31c	9.64c	2.41c	5.53c	25.76c	10.04c	9.43c	4.41c
LSD at 5%	**0.06**	**0.03**	**0.09**	**0.03**	**0.13**	**0.02**	**0.45**	**0.08**	**0.02**
Sub main factor: Soil additions									
T_1	16.08d	7.58d	10.21d	2.71d	5.92d	26.54d	10.91c	10.10d	4.87d
T_2	17.06c	8.04c	10.95c	3.18c	6.72c	27.39c	11.59b	11.02c	5.91c
T_3	17.41b	8.22b	11.32b	3.38b	7.08b	27.80b	12.31a	11.51b	6.27b
T_4	17.83a	8.41a	11.68a	3.59a	7.37a	28.36a	12.70a	11.85a	6.54a
LSD at 5%	**0.10**	**0.09**	**0.07**	**0.04**	**0.03**	**0.05**	**0.42**	**0.07**	**0.04**
Sub-sub main factor: Foliar applications									
F_1	16.94c	7.99c	10.91d	3.14d	6.66d	27.37d	11.51b	10.96d	5.76d
F_2	17.05b	8.05bc	10.99c	3.19c	6.72c	27.45c	11.88ab	11.06c	5.84c
F_3	17.12b	8.09ab	11.07b	3.24b	6.83b	27.58b	12.02a	11.18b	5.94b
F_4	17.27a	8.13a	11.17a	3.30a	6.88a	27.69a	12.09a	11.29a	6.03a
LSD at 5%	**0.10**	**0.08**	**0.07**	**0.04**	**0.03**	**0.05**	**0.39**	**0.07**	**0.07**

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

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

- Soil post-harvest analyses

Table 12 shows the effects of different irrigation regimes (traditional and water deficit), soil amendments (biochar, zeolite, and compost), and beneficial elements (boron, copper, and selenium) on the soil's nutrient availability (N, P, and K), water holding cabacity (WHC) and cation exchange capacity (CEC) following the onion harvest as average values. The same Table shows that the irrigation treatments did not have any clear effect on the studied soil properties as well as the foliar applications. While the treatments of soil amendments clearly affected those properties. Generally, the obtained data indicate that the levels of available N, P, K, water-holding capacity (WHC), and cation exchange capacity (CEC) exceeded those of the original soil (pre-sowing). Additionally, Table 12 illustrates that the incorporation of plant compost into the soil resulted in the highest values for all the aforementioned soil attributes, except WHC, followed by zeolite and then biochar, with the control group's corresponding soil exhibiting the lowest values. Regarding the WHC, the highest values were achieved due to biochar followed by zeolite then compost and lately group control.

In essence, the data underscore the significant role played by all the investigated soil amendments in improving the chemical characteristics of the soil, with compost exhibiting the highest efficacy.

Table 11. Interaction effect among soil amendments and beneficial element on bulb quality of onion plant grown under various irrigation treatments (traditional and deficit treatments) at harvest stage.

Treatments			Carbohy-drates	Protein	TDS	Fiber	T. Sugar	Anthocya-nin	V. C	DM	Pyruvic acid
			(%)					(mg 100g^{-1})		(%)	(πmol.g^{-1})
I_1	T_1	F_1	16.97	7.89	10.84	3.07	6.32	27.38	11.87	10.97	5.57
		F_2	17.12	7.95	10.99	3.11	6.37	27.38	12.05	10.98	5.59
		F_3	17.14	7.99	11.01	3.15	6.46	27.45	12.13	11.04	5.80
		F_4	17.25	8.01	11.06	3.17	6.51	27.59	12.24	11.25	5.88
	T_2	F_1	18.35	8.69	12.06	3.83	7.83	28.81	9.88	12.37	7.15
		F_2	18.41	8.74	12.13	3.90	7.85	28.88	13.25	12.42	7.16
		F_3	18.54	8.80	12.22	3.95	7.94	29.09	13.35	12.59	7.35
		F_4	18.64	8.84	12.31	4.05	8.08	29.09	13.45	12.72	7.36
	T_3	F_1	18.65	8.89	12.40	4.04	8.14	29.20	13.66	12.80	7.49
		F_2	18.73	8.95	12.47	4.15	8.18	29.34	13.67	12.92	7.54
		F_3	18.71	9.00	12.55	4.17	8.24	29.39	13.88	12.97	7.58
		F_4	18.88	9.09	12.66	4.30	8.25	29.51	13.89	13.16	7.58
	T_4	F_1	18.95	9.11	12.72	4.30	8.39	29.66	14.08	13.18	7.64
		F_2	19.20	9.17	12.83	4.33	8.47	29.71	14.16	13.26	7.66
		F_3	19.39	9.20	12.90	4.44	8.59	29.91	14.28	13.33	7.70
		F_4	19.63	9.33	13.04	4.57	8.65	29.99	14.28	13.53	7.84
I_2	T_1	F_1	16.43	7.61	10.60	2.80	6.09	26.97	11.37	10.54	5.08
		F_2	16.60	7.70	10.64	2.88	6.16	27.03	11.53	10.73	5.21
		F_3	16.73	7.72	10.73	2.93	6.19	27.22	11.65	10.78	5.22
		F_4	16.84	7.73	10.80	3.01	6.25	27.27	11.72	10.81	5.36
	T_2	F_1	17.34	8.04	11.16	3.22	6.56	27.65	12.41	11.27	5.97
		F_2	17.50	8.12	11.23	3.25	6.61	27.68	12.40	11.30	6.15
		F_3	17.52	8.16	11.30	3.30	7.06	27.85	12.49	11.46	6.19
		F_4	17.73	8.17	11.39	3.36	7.11	27.97	12.62	11.49	6.32
	T_3	F_1	17.77	8.26	11.40	3.39	7.28	28.02	12.64	11.52	6.40
		F_2	17.74	8.29	11.56	3.40	7.42	28.07	12.69	11.68	6.49
		F_3	17.88	8.29	11.55	3.49	7.47	28.26	12.85	11.73	6.62
		F_4	17.98	8.37	11.71	3.51	7.51	28.29	12.85	11.90	6.68
	T_4	F_1	18.07	8.41	11.72	3.62	7.58	28.44	12.86	11.93	6.81
		F_2	18.15	8.49	11.74	3.62	7.63	28.50	13.01	11.95	6.92
		F_3	18.24	8.55	11.89	3.71	7.72	28.64	13.06	12.15	6.98
		F_4	18.28	8.58	11.89	3.79	7.74	28.66	13.11	12.16	7.05
I_3	T_1	F_1	14.34	7.01	8.86	2.02	5.10	24.92	8.86	8.34	3.49
		F_2	14.39	7.09	8.91	2.09	5.16	24.98	8.97	8.44	3.58
		F_3	14.48	7.13	8.99	2.12	5.21	25.09	9.14	8.62	3.72
		F_4	14.67	7.16	9.09	2.18	5.27	25.18	9.35	8.73	3.93
	T_2	F_1	14.84	7.19	9.23	2.24	5.32	25.30	9.55	8.91	4.07
		F_2	15.11	7.20	9.37	2.31	5.37	25.41	9.72	9.07	4.25
		F_3	15.31	7.24	9.46	2.36	5.43	25.45	9.91	9.24	4.41
		F_4	15.47	7.27	9.52	2.44	5.50	25.54	10.04	9.44	4.53
	T_3	F_1	15.58	7.30	9.68	2.51	5.54	25.65	10.20	9.68	4.60
		F_2	15.63	7.34	9.71	2.52	5.57	25.76	10.34	9.85	4.65
		F_3	15.70	7.38	9.93	2.54	5.65	25.97	10.49	9.92	4.71
		F_4	15.67	7.45	10.17	2.54	5.69	26.17	10.53	9.96	4.85
	T_4	F_1	15.95	7.45	10.25	2.60	5.82	26.46	10.69	10.06	4.87
		F_2	15.99	7.50	10.34	2.70	5.87	26.66	10.76	10.06	4.93
		F_3	15.85	7.55	10.37	2.71	5.95	26.70	11.02	10.29	5.01
		F_4	16.21	7.61	10.41	2.73	6.03	26.97	11.04	10.32	5.03
LSD at 5%			**0.36**	**0.28**	**0.23**	**0.13**	**0.12**	**0.18**	**1.35**	**0.23**	**0.21**

Means within a row are statistically different at a 0.05 level

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

Table 12. Effect of soil amendments and spraying beneficial element on the soil nutrient availability, water-holding capacity (WHC) and CEC following onion plant (as means).

Treatments			Available-N	Available-P	Available-K	WHC	CEC
			(mg kg^{-1})			(%)	(cmol kg^{-1})
I_1	T_1	F_1	50.5	10.51	225.1	44.1	42.9
		F_2	50.3	10.42	224.3	44.2	42.7
		F_3	50.1	10.64	222.5	44.1	42.6
		F_4	50.1	10.43	223.4	44.2	42.8
	T_2	F_1	51.4	10.91	229.3	46.3	43.6
		F_2	51.4	11.12	228.1	46.1	43.6
		F_3	51.1	10.93	227.2	46.1	43.4
		F_4	51.0	11.10	227.1	46.2	43.6
	T_3	F_1	52.2	11.20	231.2	45.9	45.7
		F_2	52.4	11.33	229.1	45.9	45.6
		F_3	51.9	11.31	229.2	45.8	45.8
		F_4	51.9	11.21	229.9	45.9	45.3
	T_4	F_1	53.9	11.52	235.5	44.3	45.2
		F_2	53.2	11.60	234.9	45.2	47.5
		F_3	53.2	11.31	232.6	45.3	47.5
		F_4	53.2	11.52	232.3	45.3	47.6
I_2	T_1	F_1	50.6	10.66	228.1	44.2	47.3
		F_2	50.5	10.56	227.1	44.2	42.5
		F_3	50.2	10.75	225.1	44.3	42.5
		F_4	50.1	10.50	226.3	44.2	42.7
	T_2	F_1	51.5	11.06	232.2	46.2	42.4
		F_2	51.4	11.26	231.1	46.5	43.3
		F_3	51.0	11.06	230.2	46.3	43.8
		F_4	51.2	11.26	230.1	46.5	43.7
	T_3	F_1	52.3	11.37	234.2	45.5	43.4
		F_2	52.2	11.47	232.2	45.6	45.6
		F_3	52.0	11.45	232.2	45.7	45.7
		F_4	51.9	11.37	232.4	45.2	45.9
	T_4	F_1	53.6	11.67	238.3	44.4	45.6
		F_2	53.3	11.73	237.3	45.3	45.9
		F_3	53.0	11.44	235.3	45.3	47.4
		F_4	53.1	11.70	235.2	45.1	47.9
I_3	T_1	F_1	51.23	10.70	228.6	44.3	42.4
		F_2	51.15	10.70	227.7	44.2	42.4
		F_3	50.05	10.88	225.6	44.1	42.3
		F_4	50.85	10.70	226.8	44.4	42.7
	T_2	F_1	52.17	11.20	232.7	46.3	43.2
		F_2	52.17	11.40	231.8	46.2	43.5
		F_3	51.87	11.19	230.8	46.3	43.3
		F_4	51.76	11.40	230.7	46.5	43.2
	T_3	F_1	53.19	11.50	234.7	45.1	45.4
		F_2	52.98	11.60	232.6	45.6	45.6
		F_3	52.88	11.65	232.7	45.4	45.4
		F_4	52.67	11.51	232.5	45.1	45.6
	T_4	F_1	54.71	11.81	238.4	44.2	45.9
		F_2	53.99	11.91	237.9	45.1	47.9
		F_3	53.89	11.60	235.3	45.1	47.8
		F_4	53.89	11.81	235.8	45.2	47.3

I_1: Four irrigations (100% of Irrigation Requirements IR), **I_2:** Three irrigations (75% of IR), **I_3:** Two irrigations (50 % of IR), **T_1:** Control (without soil amendments), **T_2:** Biochar (plant residues), **T_3:** Zeolite, **T_4:** Compost (plant residues), **F_1:** Control, **F_2:** Boron, **F_3:** Copper, **F_4:** Selenium.

4. Discussion

The observed results can be explained by considering the physiological and biochemical responses of onion plants to different irrigation regimes, soil amendments, and beneficial elements. A scientific explanation will be provided for each aspect as follows:

- Growth criteria, photosynthetic pigment and leaves chemical constitutes

Plant height, fresh foliage, and dry weights: Adequate water availability is crucial for plant growth. The traditional irrigation approach (**I_1**) provided the optimal water supply, leading to the best performance in terms of plant height, fresh foliage, and dry weights. Water shortage in the water deficit treatments (**I_2** and **I_3**) would have induced physiological stress, resulting in reduced cell expansion and overall plant growth **(Parkash**

and Singh (2020). The gradual decrease in performance from $\mathbf{I_1}$ to $\mathbf{I_3}$ indicates a dose-dependent response to water availability. Chlorophyll is essential for photosynthesis, and carotenes contribute to photosynthetic pigment content **(Stirbet *et al*. 2020**). Insufficient water supply can lead to decreased chlorophyll synthesis and degradation, as well as reduced carotene accumulation. This can result in lower chlorophyll readings and carotene content in water deficit treatments ($\mathbf{I_2}$ and $\mathbf{I_3}$) compared to the traditional irrigation ($\mathbf{I_1}$). Nitrogen, phosphorus, and potassium are key macronutrients required for onion plant growth and development. Water scarcity can negatively impact these nutrient elements' uptake due to reduced root activity **(Moustafa-Farag *et al.* 2020).** The higher NPK contents in traditional irrigation **($\mathbf{I_1}$)** suggest that plants had better access to these essential nutrients, resulting in improved overall growth and development. The compost used is rich in organic matter and nutrients (Table 2), enhancing soil structure and nutrient availability and this positively reflected on the growth traits and photosynthetic pigments as well as leaves chemical constituents of onion plants (**Elsherpiny *et al.* 2023).** All of these positives made it come in the first order. Zeolite, which came in the second order, could improve water retention and nutrient exchange capacity, while biochar, which came in the third order, contributes to soil water-holding capacity and nutrient retention **(Ghazi *et al.* 2023)**. These amendments positively affect soil properties, promoting better root development, nutrient uptake, and water availability, leading to improved plant growth. The order of effectiveness (compost > zeolite > biochar) likely reflects their varying impacts on soil's physical and chemical properties.

The studied elements are essential for various biochemical processes, including antioxidant defense and enzyme activation. Selenium was superior due to its role in water deficit stress tolerance and antioxidant mechanisms **(Rady *et al.* 2020**). Copper came in the second order due to it is important for enzyme functions, including those involved in photosynthesis and stress response **(Pérez-Labrada *et al.* 2019).** Boron came in the third order due to it is involved in cell wall structure and membrane integrity **(Abdel-Motagally *et al.* 2018)**. The order of effectiveness (Se > Cu > B) suggests that selenium has a more significant positive impact on stress tolerance and overall biochemical processes compared to copper and boron. The control treatment ($\mathbf{F_1}$) lacking these beneficial elements might exhibit suboptimal stress responses and reduced enzymatic activities. When compost **($\mathbf{T_4}$)** and selenium **($\mathbf{F_4}$)** are combined within the traditional irrigation treatment **($\mathbf{I_1}$),** the observed favorable outcomes in terms of plant height, fresh foliage, dry weights, chlorophyll reading, carotene content, and foliage NPK contents suggest that the combined effect of these two factors enhances various aspects of plant growth and physiology. Interestingly, under water deficit conditions **($\mathbf{I_2}$),** the combined application of compost **($\mathbf{T_4}$)** and selenium **($\mathbf{F_4}$)** resulted in better performance compared to plants grown traditionally without any additives **($\mathbf{I_1}$ x $\mathbf{T_1}$ x $\mathbf{F_1}$).** This finding highlights the potential synergy between compost and selenium in improving plant responses to water scarcity.

The interaction between compost and selenium suggests that compost-enhanced soil properties, such as increased nutrient availability and water-holding capacity, combined with the stress-tolerance and antioxidant properties of selenium, contribute to improved plant growth, photosynthetic efficiency, and nutrient uptake. This combined approach likely supports the plant's ability to cope with water deficit stress and maintain its physiological functions.

- Proline and enzymatic antioxidants

The variations in antioxidant levels compared to growth performance parameters highlight the complex interactions between plant responses to stress, nutrient availability, and physiological processes.

The highest levels of self-produced antioxidants (proline, POD, CAT, and SOD) were observed in the $\mathbf{I_3}$ treatment, which received the lowest amount of irrigation water (50% of IR). This is indicative of a stress response mechanism where plants under water deficit conditions often increase antioxidant production to counteract the adverse effects of stressors like dehydration and oxidative damage. The sequence of antioxidant production from highest to lowest was $\mathbf{I_3 > I_2 > I_1}$**.** This sequence reflects the escalating response of onion plants to increasing water deficit, suggesting that more severe water scarcity triggers a stronger antioxidant defense response. The control treatment **($\mathbf{T_1}$)** resulted in the highest levels of antioxidants among the soil amendments. This might be due to a lack of external factors that could potentially mitigate the need for increased antioxidant production. Soil amendments like biochar, zeolite, and compost likely create conditions that support better nutrient and water availability, leading to reduced stress and subsequently lower levels of self-produced antioxidants. The sequence of antioxidant production from highest to lowest was $\mathbf{T_1 > T_2 > T_3 > T_4}$. This sequence suggests that the application of soil amendments (especially T4, compost) assists in alleviating stress and, as a result, lowers the need for self-produced antioxidants. Similar to the control treatment in soil amendments, the $\mathbf{F_1}$ treatment exhibited the highest antioxidant levels among the foliar treatments. This indicates that the absence of beneficial elements might lead to a lack of support for plant defense mechanisms, resulting in increased self-production of antioxidants. The sequence of antioxidant production from highest to lowest was $\mathbf{F_1 > F_2 > F_3 > F_4}$. This order suggests that the application of beneficial elements like selenium, copper, and boron can contribute to enhancing the plant's antioxidant defense systems, reducing the reliance on self-produced antioxidants. The combined treatment **of** $\mathbf{I_3 \times T_1 \times F_1}$ resulted in the highest production of antioxidants. This suggests that under severe water deficit conditions, the absence of external support (no soil amendments, no beneficial elements) leads to a strong antioxidant defense response. Conversely, the combined treatment of $\mathbf{I_1 \times T_4 \times F_4}$ displayed the lowest antioxidant production. This combination involves traditional irrigation **($\mathbf{I_1}$),** which provides ample water, compost **($\mathbf{T_4}$)** which supports soil health, and selenium **($\mathbf{F_4}$)** which enhances stress tolerance. The low antioxidant production here suggests that these treatments effectively reduce the need for self-produced antioxidants.

In summary, the observed trends indicate that the application of soil amendments and beneficial elements can contribute to the enhancement of the plant's natural antioxidant defense mechanisms. This helps the plants better cope with water deficit conditions by reducing the need for excessive self-produced antioxidants, ultimately improving their overall stress tolerance and physiological resilience. These findings underscore the potential of integrated strategies to mitigate the negative effects of environmental stressors on crop plants.

- Quantitative and qualitative yield

Data highlights the intricate interactions between different treatments, irrigation regimes, and their combined effects on onion plant yield and quality attributes. The traditional irrigation approach ($\mathbf{I_1}$) resulted in the highest quantitative and qualitative yield parameters, indicating the importance of adequate water supply for achieving optimal crop performance. The water deficit treatments ($\mathbf{I_2}$ and $\mathbf{I_3}$) led to lower values in comparison to I1, highlighting the adverse impact of reduced water availability on onion yield and quality. Among the soil amendments, compost **($\mathbf{T_4}$)** exhibited the most significant positive influence on both quantitative and qualitative parameters. This suggests that compost contributes to improved soil fertility, water retention, and overall plant health, resulting in higher yields and better quality attributes. Zeolite **($\mathbf{T_3}$)** and biochar **($\mathbf{T_2}$)** also showed positive effects on yield and quality attributes, demonstrating their potential to enhance soil properties and support plant growth compared to the control treatment ($\mathbf{T_1}$). Selenium ($\mathbf{F_4}$) stood out as the most effective foliar treatment, leading to the highest values for all yield and quality characteristics. The order of effectiveness among the beneficial elements suggests that selenium plays a critical role in enhancing crop yield and quality attributes. Copper and boron ($\mathbf{F_2}$ and $\mathbf{F_3}$) also contributed positively to yield and quality attributes, underlining the importance of these micronutrients in promoting plant growth and development. The combination of compost ($\mathbf{T_4}$) with selenium foliar application ($\mathbf{F_4}$) under the traditional irrigation treatment ($\mathbf{I_1}$) resulted in the highest values for various yield and quality traits. This indicates a synergistic effect where both treatments enhance each other's positive impacts, leading to superior crop outcomes. Notably, even under water deficit treatment ($\mathbf{I_2}$), the combined approach of compost ($\mathbf{T_4}$) and selenium foliar application (F4) yielded higher values compared to traditional irrigation without any treatments **($\mathbf{I_1}$ x $\mathbf{T_1}$ x $\mathbf{F_1}$).** This suggests that these combined strategies can mitigate the negative effects of water scarcity on yield and quality. The findings underline the significance of incorporating diverse approaches to enhance crop productivity and quality under varying conditions. The interaction effects highlight the potential for tailored combinations of soil amendments and beneficial elements to achieve optimal results, especially in challenging environments.

- Soil post-harvest analyses

Compost, zeolite, and biochar are three soil amendments that play distinct yet complementary roles in enhancing soil properties. Each of these amendments brings unique benefits to the soil, contributing to improved nutrient availability, water retention, and overall soil health. Their functions of them in enhancing soil properties were as follows:

Compost: When added to the soil, compost acts as a valuable source of organic matter. This organic matter improves soil structure, aggregation, and porosity, creating a more favorable environment for root growth and microbial activity. The presence of organic matter in compost increases the soil's water-holding capacity. It helps the soil retain moisture, reducing water stress on plants during dry periods **(Singh *et al.* 2020).**

Zeolite: When added to soil, zeolites increase water-holding capacity, reducing water runoff and enhancing plant access to moisture. Also, Zeolites have a high cation exchange capacity (CEC), which allows them to hold onto and exchange nutrients with plant roots. This contributes to improved nutrient retention in the root zone and more efficient nutrient uptake by onion plants **(Ghazi *et al.* 2023)**.

Biochar: It is rich in carbon and resistant to decomposition, making it an effective means of carbon sequestration in the soil. Similar to compost and zeolite, biochar can enhance water retention in the soil due to its porous structure. This helps mitigate drought stress and improves onion plant resilience to water scarcity **(Mosa *et al.*, 2020).**

Data indicates that the irrigation treatments and foliar applications had limited direct effects on the studied soil properties. This suggests that the changes in irrigation frequency and foliar applications might not have immediate, significant impacts on soil nutrient availability or physical characteristics. It's important to note that the lack of clear effects might stem from the relatively short-term nature of the experiment or the specific conditions of the study. The treatments involving soil amendments clearly impacted soil properties. This highlights the ability of soil amendments to influence the soil's chemical and physical characteristics over the course of the onion growth cycle. The data show that incorporating biochar, zeolite, and especially compost led to improvements in available nitrogen (N), phosphorus (P), potassium (K), water holding capacity (WHC) and cation exchange capacity (CEC) compared to the original soil properties (pre-sowing). Among the soil amendments, compost (plant compost) exhibited the highest efficacy in improving the most of the studied soil attributes. This suggests that the addition of organic matter through compost contributes significantly to nutrient availability and soil structure improvement. The variations in soil Water Holding Capacity (WHC) values observed among biochar, zeolite, compost, and the control group stem from the distinct attributes inherent to each amendment. The porous structure of biochar, the water adsorption capabilities of zeolite, and the organic matter enrichment of compost synergistically amplify their aptitude for retaining water when juxtaposed with the control group. Notably, zeolite and biochar exhibit particularly favorable impacts on soil water dynamics. Biochar augments water-holding proficiency and nutrient preservation, while zeolite is likely to bolster water retention and foster nutrient exchange capacity. These reasons make the biochar come in the first order in terms of its ability in raising the values of soil WHC followed by zeolite then compost. The improvements in soil nutrient availability, water-holding capacity, and cation exchange capacity have positive implications for crop growth and health. Enhanced nutrient availability can support better plant nutrition, while improved soil structure (higher water-holding capacity and CEC) promotes root development and nutrient uptake efficiency. It's important to consider that the effects of soil amendments might continue to develop and strengthen over the long term, contributing to sustained improvements in soil health and crop productivity. The findings suggest that adopting these soil amendments can be beneficial for improving soil conditions and potentially reducing the need for synthetic fertilizers in the long run.

In summary, this study underscores the substantial role of soil amendments, particularly compost, in enhancing soil chemical and physical attributes. While the effects of irrigation regimes and foliar applications on soil properties might not be immediate, the incorporation of organic matter and other amendments can lead to lasting improvements in soil health and nutrient availability.

5. Conclusion

This research offers valuable insights into sustainable approaches for enhancing onion growth and yield. Through meticulous examination of irrigation strategies, soil amendments, and foliar nutrient applications, this study has illuminated key factors influencing crop performance. The traditional irrigation approach (**I_1**) demonstrated its superiority, yielding optimal results in both quantitative and qualitative onion yield. This reaffirms the significance of adequate water supply in promoting crop success. However, in scenarios of reduced water availability (**I_2** and **I_3**), a combination of strategic soil amendments and targeted nutrient applications showcased their potential to mitigate the negative effects of water deficit. Compost emerged as a standout soil amendment, followed by zeolite and biochar, emphasizing their positive influence on onion growth under various irrigation conditions. The effectiveness hierarchy of beneficial elements –

selenium (Se), copper (Cu), boron (B), and control – underscores the role of micro-nutrient supplementation in enhancing yield. The combined application of compost (**T_4**) and selenium foliar spraying (**F_4**) emerged as an especially promising strategy. Its success in improving growth, quantitative, and qualitative yield, particularly under water deficit conditions (**I_2**), highlights the potential of synergy between organic amendments and targeted nutrient delivery.

Based on the findings, the following recommendations are suggested:

1. Farmers are recommended to use compost and selenium together, as this combined application can provide a multifaceted approach to improve water-use efficiency, stress tolerance, and nutrient acquisition in crop plants.
2. Further research into refining the application rates and combinations of soil amendments can offer insight into achieving even more robust crop performance.
3. In-depth studies could delve into the intricate interplay of beneficial elements and their synergistic effects. Experimentation with various nutrient combinations and concentrations may uncover novel ways to enhance growth and yield under various conditions.
4. Identifying and cultivating onion varieties with increased tolerance to water scarcity could provide an additional tool for sustainable onion production under challenging conditions.
5. Exploring holistic approaches that combine irrigation management, soil amendments, and nutrient applications could yield comprehensive solutions for addressing water scarcity challenges. Such integrated strategies could provide greater resilience against environmental stressors.
6. Dissemination of the study's findings to farmers can equip them with the knowledge to make informed decisions regarding irrigation practices, soil amendments, and nutrient applications, enhancing overall crop productivity and sustainability.

Finally, this research underscores the potential of soil amendments and nutrient application strategies to bolster onion growth and yield under water scarcity. By continuously refining these approaches and embracing a holistic perspective, the agricultural community can move closer to ensuring food security and sustainability in challenging environmental conditions.

Conflicts of interest

Authors have declared that no competing interests exist.

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6. References

Abd El-Nabi, A., Doklega, S., & Imryed, Y. F. E. (2021). Irrigation with magnetically treated water, foliar application of ascorbic acid and cobalt for improving onion growth, yield and quality. Journal of Plant Production, 12(12), 1329-1334.

Abdel-Motagally, F. M. F., & El-Zohri, M. (2018). Improvement of wheat yield grown under drought stress by boron foliar application at different growth stages. Journal of the Saudi Society of Agricultural Sciences, 17(2), 178-185.

Ábrahám, E., Hourton-Cabassa, C., Erdei, L., & Szabados, L. (2010). Methods for determination of proline in plants. In Plant Stress Tolerance (pp. 317-331). Humana Press.

Alici, E. H and Arabaci, G. (2016). Determination of SOD, POD, PPO and CAT enzyme activities in *Rumex obtusifolius* L. Annual Research & Review in Biology, 1-7.

Almaroai, Y. A., & Eissa, M. A. (2020). Role of marine algae extracts in water stress resistance of onion under semiarid conditions. Journal of Soil Science and Plant Nutrition, 20, 1092-1101.

Amiri-Forotaghe, Z., Souri, M. K., Ghanbari Jahromi, M., & Mohammadi Torkashvand, A. (2022). Influence of humic acid application on onion growth characteristics under water deficit conditions. Journal of Plant Nutrition, 45(7), 1030-1040.

Anthon, A & Barrett, D (2003). Modified method for the determination of pyruvic acid with di-nitrophenyl hydrazine in the assessment of onion pungency. J Sci. Food Agric., 83:1210-1213.

AOAC, (2000).˝ Official Methods of Analysis˵. 18th Ed. Association of Official Analytical Chemists, Inc., Gaithersburg, MD, Method 04.

Black C.A. (1965). "Method of Soil Analysis, Part 2, Chemical and Microbiological Properties, American Society of Agronomy", Inc, Publisher, Madison, Wisconsin USA.

Castelli, F., Contillo, R., & Miceli, F. (1996). Non-destructive Determination of Leaf Chlorophyll Content in Four Crop Species 1. Journal of Agronomy and Crop Science, 177(4): 275-283.

CoStat, Version 6.303, Copyright (1998-2004), CoHort Software, Monterey, CA, USA.

Dewis, J., & Freitas, F. (1970). Physical and chemical methods of soil and water analysis. FAO soils Bulletin, (10).

Ekşi, G., Özkan, A. M. G., & Koyuncu, M. (2020). Garlic and onions: An eastern tale. Journal of Ethnopharmacology, 253, 112675.

El–Metwally, I., Geries, L., & Saudy, H. (2022). Interactive effect of soil mulching and irrigation regime on yield, irrigation water use efficiency and weeds of trickle–irrigated onion. Archives of Agronomy and Soil Science, 68(8), 1103-1116.

Elsherpiny, M. A. (2023). Role of compost, biochar and sugar alcohols in raising the maize tolerance to water deficit conditions. Egyptian Journal of Soil Science, 63(1), 67-81.

Elsherpiny, M. A., & Helmy, A. (2022). Response of maize plant grown under water deficit stress to compost and melatonin under terraces and alternate furrow irrigation techniques. Egyptian Journal of Soil Science, 62(4), 383-394.

Elsherpiny, M. A., & Kany,M.A (2023). Maximizing faba bean tolerance to soil salinity stress using gypsum, compost and selenium. Egyptian Journal of Soil Science, 63(2), 243-253.

Elsherpiny, M. A., Baddour, A., & Kany, M. (2023). Effect of organic and bio fertilization and magnesium foliar application on soybean production. Egyptian Journal of Soil Science, 63(1), 127-141.

Gee, G.W. and J.W. Bauder. (1986). Particle-size Analysis. p 383-411 In A. Klute (ed.) Methods of Soil Analysis Part 1. Soil Science Society of America Book Series 5, Madison, Wisconsin, USA.

Ghazi, D., Hafez, S., & Elsherpiny, M. A. (2023). Rice cultivation adaption to water resources shortage in Egypt. Egyptian Journal of Soil Science, 63(1), 113-126.

Gomez, K. A., & Gomez, A. A. (1984). "Statistical procedures for agricultural research". John Wiley and Sons, Inc., New York.pp:680.

Hesse, P. R. (1971). ″A textbook of soil chemical analysis″. Joon Murry (Publishers) Ltd, 50, Albemarle Street, London.

Inckel, M., de Smet, P., Tersmette, T., & Veldkamp, T. (2005). The preparation and use of compost (Vol. 27). Wageningen, The Netherlands: Agromisa.

Lichtenthaler, H. K., & Wellburn, A. R. (1983). Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents.

Mahmoud, S., Shedeed, S., El-Ramady, H., Abdalla, Z. F., El-Bassiony, A. E. M., & El-Sawy, S. (2023). Biological Nano-selenium for eggplant biofortification under soil nutrient deficiency. Egyptian Journal of Soil Science, 63(2): 151-162.

Mosa, A., El-Ghamry, A., & Tolba, M. (2020). Biochar-supported natural zeolite composite for recovery and reuse of aqueous phosphate and humate: Batch sorption-desorption and bioassay investigations. Environmental Technology & Innovation,(19): 100807.

Moustafa-Farag, M., Mahmoud, A., Arnao, M. B., Sheteiwy, M. S., Dafea, M., Soltan, M., ... & Ai, S. (2020). Melatonin-induced water stress tolerance in plants: Recent advances. *Antioxidants*, *9*(9), 809.

Ouda, S., Zohry, A. E. H., & Noreldin, T. (2020). Deficit irrigation: A remedy for water scarcity. Springer Nature.

Parkash, V., & Singh, S. (2020). A review on potential plant-based water stress indicators for vegetable crops. Sustainability, 12(10), 3945.

Pérez-Labrada, F., López-Vargas, E. R., Ortega-Ortiz, H., Cadenas-Pliego, G., Benavides-Mendoza, A., & Juárez-Maldonado, A. (2019). Responses of tomato plants under saline stress to foliar application of copper nanoparticles. Plants, 8(6), 151.

Peterburgski, A. V. (1968). "Hand Book of Agronomic Chemistry". Kolas Publishing House Moscow, (in Russian).

Rady, M. M., Belal, H. E., Gadallah, F. M., & Semida, W. M. (2020). Selenium application in two methods promotes drought tolerance in Solanum lycopersicum plant by inducing the antioxidant defense system. Scientia Horticulturae, 266, 109290.

Sattar, A., Cheema, M. A., Sher, A., Ijaz, M., Ul-Allah, S., Nawaz, A., ... & Ali, Q. (2019). Physiological and biochemical attributes of bread wheat (*Triticum aestivum* L.) seedlings are influenced by foliar application of silicon and selenium under water deficit. Acta Physiologiae Plantarum, 41, 1-11.

Schoefs, B. (2004). Determination of pigments in vegetables. Journal of chromatography A, 1054(1-2): 217-226.

Sidhu, J. S., Ali, M., Al-Rashdan, A., & Ahmed, N. (2019). Onion (*Allium cepa* L.) is potentially a good source of important antioxidants. Journal of food science and technology, 56, 1811-1819.

Singh, T. B., Ali, A., Prasad, M., Yadav, A., Shrivastav, P., Goyal, D., & Dantu, P. K. (2020). Role of organic fertilizers in improving soil fertility. Contaminants in agriculture: sources, impacts and management, 61-77.

Stirbet, A., Lazár, D., Guo, Y., & Govindjee, G. (2020). Photosynthesis: basics, history and modelling. Annals of Botany, 126(4), 511-537.

Tandon, H. L. S. (2005). Methods of analysis of soils, plants, waters, fertilizers & organic manures. Fertilizer Development and Consultation Organization.

Wakchaure, G. C., Khapte, P. S., Kumar, S., Kumar, P. S., Sabatino, L., & Kumar, P. (2023). Exogenous growth regulators and water stress enhance long-term storage quality characteristics of onion. Agronomy, 13(2), 297.

Walinga, I., Van Der Lee, J. J., Houba, V. J., Van Vark, W., & Novozamsky, I. (2013). Plant analysis manual. Springer Science & Business Media.

Wang, Z., Hassan, M. U., Nadeem, F., Wu, L., Zhang, F., & Li, X. (2020). Magnesium fertilization improves crop yield in most production systems: A meta-analysis. Frontiers in plant science, 10, 1727.