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Morpho-physiological traits, quality and productivity of garlic under drought stress of different growth stages

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DUE to the limited water supply and rising food demand, studying how applied irrigation rates affect crops at this critical time due to climate change is essential. Therefore, an experiment was carried out to examine the effect of different irrigation water rates, specifically 60, 80, 100, and 120 of the water requirements (WR), on the growth, bulb yield properties, and water status of garlic (*Allium sativum* L.) clone Sids-40. The data was recorded after 80 - 140 days from planting, where polynomial regression analysis was estimated between the growth stages and growth parameters. Similarly, 100% of the WR considerably increases plant height, leaf number, leaf fresh weight, and growth attributes like absolute growth rate, specific leaf area, leaf area index, chlorophyll a, b, and total carotenoids contents. While the irrigation at a rate of 60% WR led to an intrinsic rise in leaf water saturation deficit, proline content, and ascorbic acid content. Bulb parameters such as weight, diameter, and number of cloves per bulb, besides yield quantity with bulb grade one G1 (above 5.5 cm), pyruvic acid as pungency, and dry matter contents were determined to be at their highest values with irrigation at 100% of the WR. A 60% of the WR water shortage represented the high yield reduction with grade 4 (less than 3.5 cm). Pearson's correlation revealed positive relationships between bulb yield, characteristics, and growth attributes. Hence, garlic plants respond to irrigation at 100% of the WR by improving their morpho-physiological, productivity and bulb quality.

Keywords: Water stress; garlic yield and quality; water productivity and semiarid region.

1. Introduction

Climate change poses significant challenges to agricultural development, particularly in developing nations (Elsherpiny, 2023; Elbasiouny and Elbehiry, 2019; Dewedar et al., 2021). Understanding its projected impacts is crucial for future global food and water security (Abdelrahman et al., 2021), and improving irrigation management is essential for semi-arid regions (Ahmed et al., 2018; Mohamed et al., 2018). Agriculture requires careful water use to protect limited supplies, especially in inefficient irrigation practices (Aldambergenova et al., 2020). Irrigation management is beneficial, and estimating irrigation amounts is crucial for vegetable crop management (Yayeh et al., 2021).

The garlic plant (*Allium sativum* L.) is a member of the Alliaceae family. It is a perennial crop and the second-most significant bulb crop after onion (Elshaboury and Sakara, 2021; Wang et al., 2022). The economic yield is found in the underground, developed portion known as the bulb (Bai et al., 2023). Green tops and bulbs are a popular spice with a strong flavor (Verma et al., 2023), offering medical benefits like avoidance and treatment of diabetes, cancer, ulcers, rheumatism, worms, bacteria, and fungal infections (Çorbacı, 2022). Garlic needs sufficient moisture for proper establishment, growth, development, bulb production, and bulb quality (Moursy et al., 2019). The moisture content of the soil significantly influences garlic's growth, development, and yield. For optimum output, garlic must be regularly watered throughout its growth. Since garlic has a shallow root system, water is needed (Zhou et al., 2021). The bulbing stage is the most critical time to water, so smaller bulbs and quicker maturity will occur from insufficient irrigation. So, the soil's moisture content should be kept at its ideal level to promote continuous development and marketable production (Kendarini et al., 2022).

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The best production of this bulb crop depends on carefully controlled irrigation because the garlic crop is susceptible to water scarcity and shortage (Yayeh et al., 2021). Garlic cannot withstand both water stress and excess water since both can result in a 60% reduction in bulb yield (Meneguzzo et al., 2022). In addition, soil moisture should be maintained for continuous growth and marketable production (Shukla et al., 2018). Limited moisture availability during vegetative development results in stunted development, while an insufficient supply of water during the bulb formation stage may result in split or cracked bulbs and a lower yield (Sugianti et al., 2021). Water supply and management are the most significant factors in garlic productivity and quality (Goyal et al., 2022; Yoosefian et al., 2022). Water scarcity and drought stress significantly impact the morpho-physiological traits, quality, and productivity of garlic (Su et al., 2023). Therefore, the current study examined the effects of irrigation rates during the different growth stages on garlic plants' growth attributes, yield, quality, and water productivity.

2. Materials and methods

2.1. Experimental site

A field experiment relating to investigating the suitable scheduling irrigation for garlic growth and productivity was conducted at the farm of the Faculty of Agriculture, Al-Azhar University, El-Sadat city, Menoufia Governorate, Egypt, during the period from 20th September to 25th March in both 2021-2022 and 2022-2023 seasons. The site is placed at latitude 30.3878 and longitude 30.5352, and the weather data of the temperature, wind speed, relative humidity, average precipitation, and surface pressure are described in Table 1. The experimental soil was classed as loamy sand, and some physical and chemical analysis was done before the planting according to Page et al. (1982) and Klute (1986) are presented in Table 2.

2.2. Agricultural practices

One day prior to planting, the garlic bulb of the clone Sids-40 was divided into cloves and the largest and healthiest cloves were chosen and soaked in water overnight to speed up sprouting. On 20th September of both seasons, the same size and weight of cloves were sown individually at nearly 2-3 cm deep in the soil on both sides of the drip line with a spacing of 10 cm between plants in the plot area (10.5 m^2) which consisted of 3 rows (5 m length × 0.7 m width). All plants received the recommended N, P and K fertilizers. In addition, all other farming procedures were carried out as advised for the garlic growth according to the Egyptian Ministry of Agriculture and Land Reclamation followed during the two growing seasons of garlic.

2.3. Crop water requirements

Crop water requirements were determined with many steps. Crop evapotranspiration (ETc) was measured according to Doorenbos and Pruitt (1977) using the following equation and presented as (mm day^{-1}):

$$\text{ETc (mm day}^{-1}) = \text{ETo} \times \text{Kc}$$

Where the ETo represents the reference evapotranspiration (mm day^{-1}) and Kc represents the crop coefficient (dimensionless), was varies through plant garlic growth stages providing by Allen et al. (1998).

The reference evapotranspiration (ETo) was estimated according to Allen et al. (1998) using the Penman–Monteith equation:

$$ET_o\ (\text{mm day}^{-1}) = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

Where Δ is the slope vapor pressure curve (kPa °C^{-1}), Rn is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa °C^{-1}), T is the mean daily air temperature at 2 m height (°C), U2 is the wind speed at 200 cm height (m s^{-1}), es is the saturation vapor pressure (kPa), ea is the actual vapor pressure (kPa), and es-ea is the saturation vapor pressure deficit (kPa).

The reference evapotranspiration (ETo) and crop evapotranspiration (ETc) in all the applications throughout garlic growth was monthly during the experiment in the two growing seasons (Table 3). One of the four irrigation water rates described in Table 4 was calculated according to the equation published by Vermeiren and Jopling (1984) as follows:

$$\text{Crop water requirements (m}^3\ \text{ha}^{-1}) = \frac{\text{ETc} \times \text{A} \times \text{Ii}}{\text{Ea} \times (1\text{-LR})}$$

Where:

ETc: crop evapotranspiration (mm day^{-1}),

A: Cultivated areas (m^2),

Ii: irrigation interval (days) and

Ea: irrigation efficiency, Ea= 85%

LR: A value of 20% was used for leaching requirements stated by Khalil (1998). The rates mean that 100% of the WR application was considered a complete irrigation application (no stress), 120% of the WR application represented excessive water treatment, and 80% and 60% of the WR applications created stress treatments.

Table 1. Temperature (°C), wind speed (m s^{-1}), relative humidity (%), average precipitation (mm day^{-1}) and surface pressure (kPa) of experimental site during seasons 2021–22 and 2022–23.

Month	Temperature (°C)		Wind speed (m s^{-1})		Relative humidity (%)	Average precipitation (mm day^{-1})	Surface pressure (kPa)
	Max	Min	Max	Min			
2021–22							
Sep.	36.50	21.53	7.55	2.05	53.62	0.00	100.87
Oct.	32.24	18.47	6.33	2.12	56.91	0.06	101.23
Nov.	28.27	15.80	5.00	1.95	63.86	1.23	101.30
Dec.	19.89	10.05	5.90	2.25	69.21	0.72	101.45
Jan.	17.34	6.40	5.74	2.30	68.41	1.14	101.57
Feb.	19.79	7.29	5.75	2.27	67.33	0.32	101.52
Mar.	21.27	7.76	6.75	2.20	62.40	0.82	101.53
2022–23							
Sep.	37.31	21.80	7.07	2.13	52.07	0.01	100.80
Oct.	31.51	18.66	6.49	2.26	58.85	0.13	101.18
Nov.	26.24	14.29	5.14	1.65	60.28	0.08	101.32
Dec.	23.84	12.13	4.74	1.86	65.92	1.07	101.54
Jan.	21.29	9.26	5.08	2.18	69.26	0.91	101.53
Feb.	19.81	7.80	5.33	2.05	67.40	0.83	101.71
Mar.	25.96	11.42	6.57	2.07	55.93	0.37	101.06

Table 2. Some physical and chemical properties of soil at the experimental site before planting as an average of two growing seasons 2021– 22 and 2022–23.

Particle size distribution:				Texture class
Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	
7.08	78.88	4.42	9.62	Loamy sand
Field capacity (%)	Permanent wilting point (%)	Available water (%)	Bulk density (Mg m^{-3})	Total porosity (%)
12.97	5.40	7.57	1.70	35.85
pH (1:2.5 Soil water suspension)	EC_e (Soil paste extract, dS m^{-1})	Organic carbon (g kg^{-1})	Organic matter (g kg^{-1})	$CaCO_3$ content (g kg^{-1})
8.49	0.68	2.69	4.63	44.37

Soluble cations (mmolc L^{-1}):			
Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
1.65	1.78	2.98	0.43
Soluble anions (mmolc L^{-1}):			
CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}
0.00	1.86	4.27	0.71

Table 3. Aggregate monthly amounts of reference evapotranspiration (ETo) and garlic crop evapotranspiration (ETc) for both growing seasons 2021–22 and 2022–23.

Months	2021–22		2022–23	
	ETo (mm)	ETc (mm)	ETo (mm)	ETc (mm)
Sep. (10 days)	46.45	23.77	43.35	22.18
Oct. (31 days)	115.78	68.92	119.21	70.96
Nov. (30 days)	75.45	59.36	74.98	58.98
Dec. (31 days)	69.97	67.71	64.14	62.07
Jan. (31 days)	65.71	65.71	65.48	65.48
Feb. (28 days)	80.34	73.36	73.24	66.87
Mar. (10 days)	36.99	28.14	33.32	25.34
Total	490.70	386.96	473.70	371.88

Table 4. Description of treatments in the experiment with different irrigation rates as water requirements in (m^3 ha^{-1}) during 2021–22 and 2022–23 seasons.

Treatments	Irrigation rates (m^3 ha^{-1})		
	Treatments	2021–22	2022–23
WR 1	Irrigation at 60 % of the water requirements	3414.44	3281.29
WR 2	Irrigation at 80 % of the water requirements	4552.59	4375.06
WR 3	Irrigation at 100 % of the water requirements	5690.74	5468.82
WR 4	Irrigation at 120 % of the water requirements	6828.88	6562.59

Irrigation was carried out using a drip irrigation system. Water irrigation was applied by drip line of 16 mm diameter with 0.3 m emitter spacing and 4 L h^{-1} flow rate at 1.5 bar working pressure. The line of 16 mm was placed on the surface of the ridge between two rows of plants. From planting until 30 days, garlic plants were initially irrigated with 100% of the WR application to ensure good emergence and growth for all treatments, and then the irrigation treatments were started. To prevent overlap, a row was left between each irrigation treatment.

2.4. Plant growth determination

Measurements of garlic plant morphological and chemical characteristics were initiated at 80 days from planting and continued up to 140 days at 20-day intervals of 80, 100, 120, and 140 days. Five samples were randomly chosen from the inner rows of replications to determine plant physical characteristics. For example, plant height was measured from bulb base to top leaf blade, number of leaves per plant was counted, and leaf fresh weight (g) was determined by balance. Specific leaf area (SLA) (cm^2 g^{-1}), which represents the leaf area per unit of leaf dry weight, was measured simultaneously on the same leaves. To do this, leaf area was measured before oven drying by using an equation:

$$\text{Leaf area } (cm^2) = W \times L \times a$$

Where W (cm) = Maximum leaf width, L (cm) = Leaf length, a correction factor for garlic (0.72), and SLA was calculated according to the formula:

$$\text{Specific leaf area } (cm^2\ g^{-1}) = LA/LDW$$

Which published by Patane et al. (2022) where LA is leaf area (cm^2) and LDW is leaf dry weight (g) and may be used as a measure of leaf thickness (the lower of the SLA, mean the greater the leaf thickness), leaf area index = leaf area (cm^2) / land area per plant (cm^2) according to Moravčević et al. (2011), and the absolute growth rate (AGR) calculates for two growth variables using the formula from Mishu et al. (2013).

$$\text{Absolute growth rate (mg plant day}^{-1}) = \frac{W2\text{-}W1}{T1\text{-}T2}$$

Dry matter (mg) at times T1 and T2 is referred to as W1, W2, respectively. In the case of producing dry matter per plant, it was stated in mg plant dry matter day^{-1}.

In addition to the leaf chemical contents namely the contents of leaf pigment as chlorophyll a, and b, and total carotenoids (mg g^{-1} FW) in the leaf of garlic plants were measured on each sampling date by using spectrophotometry to monitor the colour development (6800 UV/Vis Spectrophotometer, Jenway, Bibby Scientific Ltd., Staffordshire, UK) according to the procedure outlined by Lichtenther (1987). Water saturation deficit (%) was determined according to Catasky (1963). The colorimetric method at wavelengths of 520 nm was used to determine proline content (µg g^{-1} FW) according to Bates et al. (1973).

2.5. Bulb yield

Before 15 days from the harvest date, the irrigation treatments were stopped. Garlic plants were harvested after 186 from the planting. Before cutting off dried leaves and roots, plants were given time to cure, followed by the measured data. Five bulbs randomly were selected and taken from each treatment to record the average bulb weight by balance (g), average bulb diameter using a vernier caliper (cm) and number of cloves per bulb was counted. The total yield (ton ha^{-1}) was determined by weighing all of the harvested garlic bulbs from each plot. Also, bulbs were graded by sorting them into first grade (G1: above 5.5 cm), second grade (G2: between 4.5 and 5.5 cm), third grade (G3: between 3.5 and 4.4 cm), and fourth grade (G4: less than 3.5 cm) according to Abou El-Khair (2004). Yield reduction percentage was calculated according to Rosielle and Hamblin (1981) as follows the equation:

$$\text{Yield reduction rate } (\%) = \frac{YNS\text{-}YS}{YNS} \times 100$$

Where the YNS and YS, are the average yields of a given treatment assessed under normal, excessive and drought stress circumstances, respectively.

2.6. Water productivity (WP)

WP values for cured garlic bulb yield (kg m^{-3}) were calculated according to (Zhang, 2003) as follows:

$$WP = \frac{\text{Garlic yield (kg ha}^{-1})}{\text{Applied irrigation water (m}^3\text{ha}^{-1})}$$

2.7. Analysis of bulb chemical contents

pyruvic acid determination was done according to Anthon and Barrett (2003), where the pyruvic acid concentration (µM g^{-1} FW) as indicator for pungency was measured by Spectrophotometer using 2,4-dinitrophenylhydrazine (2,4-DNPH) at 515 nm. The garlic bulb tissue was crushed, left at ambient temperature for 30 minutes, and then filtered through a paper filter. One ml of 2,4 DNPH solution was blended with a 25 µL aliquot of garlic juice, then placed into a water bath which kept at 37°C for 10 minutes. Then The samples taken out of the water bath and 1 mL of 1.5 M NaOH was added.

The dry matter content was determined in percentage after the bulb was dried in a 70°C oven until a consistent weight was attained.

Total soluble solids (TSS) as percentage were determined in the will-mixed juice of five cloves using a digital refractometer (38-B1, Bellingham Stanley, UK) according to A.O.A.C. (1980).

Ascorbic acid was determined on the same harvest day to avoid the lack of any ascorbic acid from 5g cloves were peeled and crushed well in a mortar with10 ml of 4% oxalic acid (w/v). The admixture was filtered amid a muslin cloth and the volume was made up to 25 mL with oxalic acid 4 %. 5 mL of the admixture sample was titrated against the dye solution to become pale pink colour. The titration with 2, 6-dichlorophenol indophenol (DCPIP) titration method described by Casanas et al. (2002).

2.8. Statistical analysis

The data were subjected to statistical analysis by using CoStat version 6.4 software (CoHort Software, Monterey, CA, USA) to conduct the variance method. The least significant difference (LSD) between means within factors was determined using Duncan's multiple range tests at 5%, according to Snedecor and Cochran (1980). The Pearson test was used to calculate correlations by using OriginPro 2023 software.

3. Results

3.1. Growth parameters

The data in Table 5 displays the variations in garlic plant morphology caused by irrigation using different watering rates during plant growth and development. With the increasing application of irrigation water up to 100% of the WR during the examined ages from 80 up to 140 days from planting, the results showed that plant height, number of leaves, and leaf fresh weight obtained a significant increment, after which their significant decreases were correlated with the irrigation amount at 120% of WR. However, insignificant decreases happened in the first season for plant height for watering at 80 and 100% of the WR and the number of leaves through the examined ages. At the same time, the changes that occurred in these parameters exhibited a sharp increase till 120 days of growth stages. Then, a slow increase was followed up to 140 days. Polynomial regression analysis was estimated between the growth stages and growth parameters under the tested treatments of irrigation water rates Fig. (1). The significant relations were observed with regression (R2) equal 0.9988 and 0.9875 for plant height, (R2) equal 0.9494 and 0.9413 for number of leaves and (R2) equal 0.994 and 0.9914 for leaf fresh weight, in both seasons, respectively.

These findings conclude that 100% of the WR treatment can result in considerable increases in plant height, number of leaves, and leaf fresh weight, but contrarily, in 80%, 60%, and 120% of the WR treatments through garlic growth.

3.2. Absolute growth rate, specific leaf area and leaf area index

The information in Table 6 demonstrates the impact of various irrigation water rates on the absolute growth rate (AGR), specific leaf area (SLA), and leaf area index (LAI) during the studied ages. The table reflects that these characteristics significantly increased after irrigation at 100% of the WR, with ages progressing up to 140 days. Then, a significant decrease occurred in the last irrigated water rate at 120% of the WR, except that resulted between the irrigation rates at 100 and 120% of the WR in the character of specific leaf areas where the difference did not attain a significant level during the growth ages. The mean values of AGR and LAI increased slowly at the growth stages of 80 and 100 days, and then there was a sharp increase at the growth stages of 120 and 140. These patterns differed in SLA at 120 and 140 days in the 60 and 80% of the WR, where a slight decrease happened. Polynomial regression analysis in Fig. 2 showed that the relations were $R^2 = 0.9752$ and $R^2 = 0.9308$ for AGR, $R^2 = 0.9473$ and $R^2 = 0.4409$ for SLA, and $R^2 = 0.9637$ and $R^2 = 0.9412$ for LAI, in both seasons, respectively.

Hence, 100% of the WR treatments recorded the highest results, which were considerably different from those of 80%, 60%, and 120% of the WR treatments, and these were obviously in the examined growth stages.

Table 5. Effects of irrigation rates and different growth stages on the plant height, number of leaves per plant, and leaf fresh weight of garlic plants growing seasons in 2021–22 and 2022–23.

Irrigation rates	2021–22				2022–23			
	Growth stages (day)							
	80	100	120	140	80	100	120	140
	Plant height (cm)							
WR 1	44.04b	51.17b	58.07c	61.83c	45.33b	56.00b	58.32c	64.33c
WR 2	48.67a	58.17a	62.33b	66.10b	49.31a	58.05b	62.37b	67.67b
WR 3	50.10a	59.50a	67.17a	69.67a	50.43a	60.67a	67.00a	73.31a
WR 4	45.67b	52.50b	61.50b	65.14b	46.09b	56.00b	60bc	66.00bc
	Leaves number per plant							
WR 1	7.00b	6.67b	12.33b	14.66b	6.67c	7.33c	12.67c	14.33c
WR 2	7.67ab	9.67a	14.00ab	17.00a	8.33a	9.34ab	14.33b	16.66b
WR 3	8.36a	10.14a	15.66a	17.67a	8.66a	10.00a	15.67a	17.33a
WR 4	7.33b	7.67b	13.67b	16.33ab	7.33b	8.67b	13.67b	15.67b
	Leaf fresh weight (g)							
WR 1	1.39c	1.69b	2.17c	1.85b	1.35c	1.79b	2.51b	2.29b
WR 2	1.83b	2.88a	2.53b	2.05b	1.96b	2.94a	2.71b	2.41b
WR 3	2.09a	3.05a	2.99a	2.567a	2.15a	2.92a	3.13a	2.68a
WR 4	1.56c	1.73b	2.47b	1.95b	1.32c	1.97b	2.69b	2.369b

WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively.

Table 6. Effects of irrigation rates and different growth stages on the absolute growth rate, specific leaf area and leaf area index of garlic plants growing seasons in 2021–22 and 2022–23.

Irrigation rates	2021–22				2022–23			
	Growth stages (day)							
	80	100	120	140	80	100	120	140
	Absolute growth rate (mg day^{-1})							
WR 1	87.17c	91.60d	133.88d	170.13d	95.24c	116.72d	122.73d	153.73c
WR 2	114.91b	176.58c	201.44c	222.69c	116.03b	170.45c	161.07c	265.78b
WR 3	151.20a	274.04a	296.39a	365.19a	138.67a	254.67a	278.93a	362.54a
WR 4	130.52b	246.16b	248.31b	289.47b	118.94b	226.42b	241.54b	334.17a
	Specific leaf area (cm^2 g^{-1})							
WR 1	142.17b	150.59a	148.39b	140.75c	144.60b	130.72a	137.09b	130.31b
WR 2	142.99b	154.54a	151.41ab	148.36c	144.38b	130.90a	172.69a	137.72b
WR 3	155.12a	156.13a	157.77ab	169.82b	165.87a	138.47a	161.80a	184.11a
WR 4	148.66ab	158.98a	167.22a	182.92a	151.48ab	140.67a	177.59a	190.98a
	leaf area index							
WR 1	0.745c	0.969c	1.659d	2.015d	0.621c	0.729d	1.588c	1.765d
WR 2	0.814bc	0.982c	2.076c	2.363c	0.717c	1.014c	2.323b	2.363c
WR 3	1.221a	1.522a	3.108a	3.937a	1.242a	1.537a	3.179a	4.184a
WR 4	0.985b	1.355b	2.467b	3.379b	1.046b	1.276b	2.507b	3.223b

WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively.

3.3. Chlorophyll a, b, and total carotenoids

Figs. 3 and 4 illustrate the effect of irrigation water rates on the changes in the pigment content of the developing garlic leaf. The data show that when irrigation rates reached up to 100% of the WR, chlorophyll a, b, and total carotenoids considerably increased, followed by a reduction in the irrigation rate of 120% of the WR during the developmental stages from 80 to 140 days. However, the differences did not clear for chlorophyll a in the second season and total carotenoids contents in both seasons between the irrigation rates at 100 and 120% of the WR for 120 days, as well as 60, 80 and 100% of the WR for chlorophyll b content during 140 days in the second season, and between 100% and 120% of the WR in chlorophyll b for 80 days. Also, the figures show a continuous gradual increase in these contents with age progress until 120 days and then turned to be moderately up to 140 days. Hence, the mean values during two seasons of 100% of the WR were 0.564, 0.684, 0.673 and 0.649 (mg g^{-1} FW) for chlorophyll a, 0.2357, 0.2732, 0.2748, 0.2748 and 0.2228 (mg g^{-1} FW) for chlorophyll b and 0.0895, 0.1509, 0.1403 and 0.1322 (mg g^{-1} FW) for total carotenoids at 80, 100, 120, and 140 days, respectively. Also, Fig. 4 showed that the continuous gradual increase in these contents with growth stage progressed until 120 days and then turned to a reduction up to 140 days with polynomial regression R^2 = 0.9989 and R^2 =0.9672 for Chl a, R^2 = 0.9892 and R^2 = 0.9139 for Chl b and R^2 = 0.9281and R^2 = 0.8713 for carotenoids, in both seasons, respectively.

3.4. Water saturation deficit and proline content

The differences in water saturation deficit and proline contents because of irrigation water rates at 140 days are shown in Fig. 5. The findings demonstrated that there was an intrinsic rise in leaf water saturation deficit and proline contents as irrigation rate was lowered, despite the non-significant variations between the rates at 100 and 120% of the WR for proline content in the first season only. Therefore, the most significant values of water saturation deficit and proline contents were obtained from 60% of the WR with a mean of 26.19 (%) and 40.8 (µg g^{-1}), respectively.

3.5. Bulb parameters

The results in Fig. 6 describe the behaviour of bulb parameters due to irrigation water rates after harvesting at 180 days. The figures reflect that there are significant increases in the parameters of bulbs as bulb weight, diameter, and number of cloves per bulb by the increase in irrigation water rates up to 100% of the WR, despite the difference between rates 80 and 100% of the WR did not achieve the significance level for bulb diameter in second season, after which there were un-significant decreases by using the rate of 120% of the WR. Hence, only the highest parameters of bulb were recorded at the rate 100% of the WR with mean values 31.89 (g), 4.78 (cm), and 18.56 (cloves $bulb^{-1}$) for bulb weight, bulb diameter, and number of cloves per bulb, respectively.

3.6. Total yield and yield grades

Regarding the effect of applied water irrigation rates on garlic bulb yield in Fig. 7, the findings showed that irrigation treatment at 100% of the WR had a significant impact on the yield of garlic with a value of around 30.794 (ton ha^{-1}) compared to 60, 80, and 120% of the WR with mean 18.508, 28.113 and 28.343 (ton ha^{-1}), respectively.

The grades of garlic bulbs varied depending on the treatments of irrigation rates Fig. 7. The highest significant values in grade bulb G1 (above 5.5 cm) were recorded for irrigation at 100% of the WR with a mean of 2.539 (ton ha^{-1}). In contrast, the lowest significant values resulted from irrigation at 60% of the WR with a mean of zero (ton ha^{-1}). The grade bulb G2 (4.5 -5.5 cm) produced the highest significant values in the rate at 100% of the WR with mean 19.449 (ton ha^{-1}) and the meanwhile one recorded for treatment at 60% of the WR with mean 6.639 (ton ha^{-1}) Grade 3 (3.5 - 4.4 cm) in treatment at 80% of the WR recorded the highest values with mean 12.125 (ton ha^{-1}), while the minimum one obtained from 100% and 120% of the WR with mean 8.192, 8.334 (ton ha^{-1}), respectively. Grade 4 (less than 3.5 cm) at 60% of the WR recorded the highest values with a mean of 1.561 (ton ha^{-1}), while the lowest one was exerted from 120% of WR with a mean of 0.378 (ton ha^{-1}).

3.7. Pyruvic acid content and bulb dry matter

The alteration in bulb pyruvic acid content as affected by irrigation water rates discussed in Fig. 8. The increase in pyruvic acid content was increased significantly with the increment of the irrigation from 60% to100% of the WR, followed by an insignificant reduction observed at 120% of the WR. Hence, the highest content was produced at 100% with an average value of 55.84 (µM g^{-1} FW), while the lowest one was exerted at 60% of the WR with an average of 42.4 (µM g^{-1} FW). The behaviour of pyruvic acid was like bulb dry matter content. The result in Fig. 8 showed that the accumulation of bulb dry matter was increased significantly with exposure to the irrigation rate at 100% of the WR. Then, a reduction was recorded at 120% of the WR. Thus, the highest significant value with a mean of 33.62% was exerted from 100% of the WR, while the lowest value with a mean of 31.07% resulted from 60% of the WR.

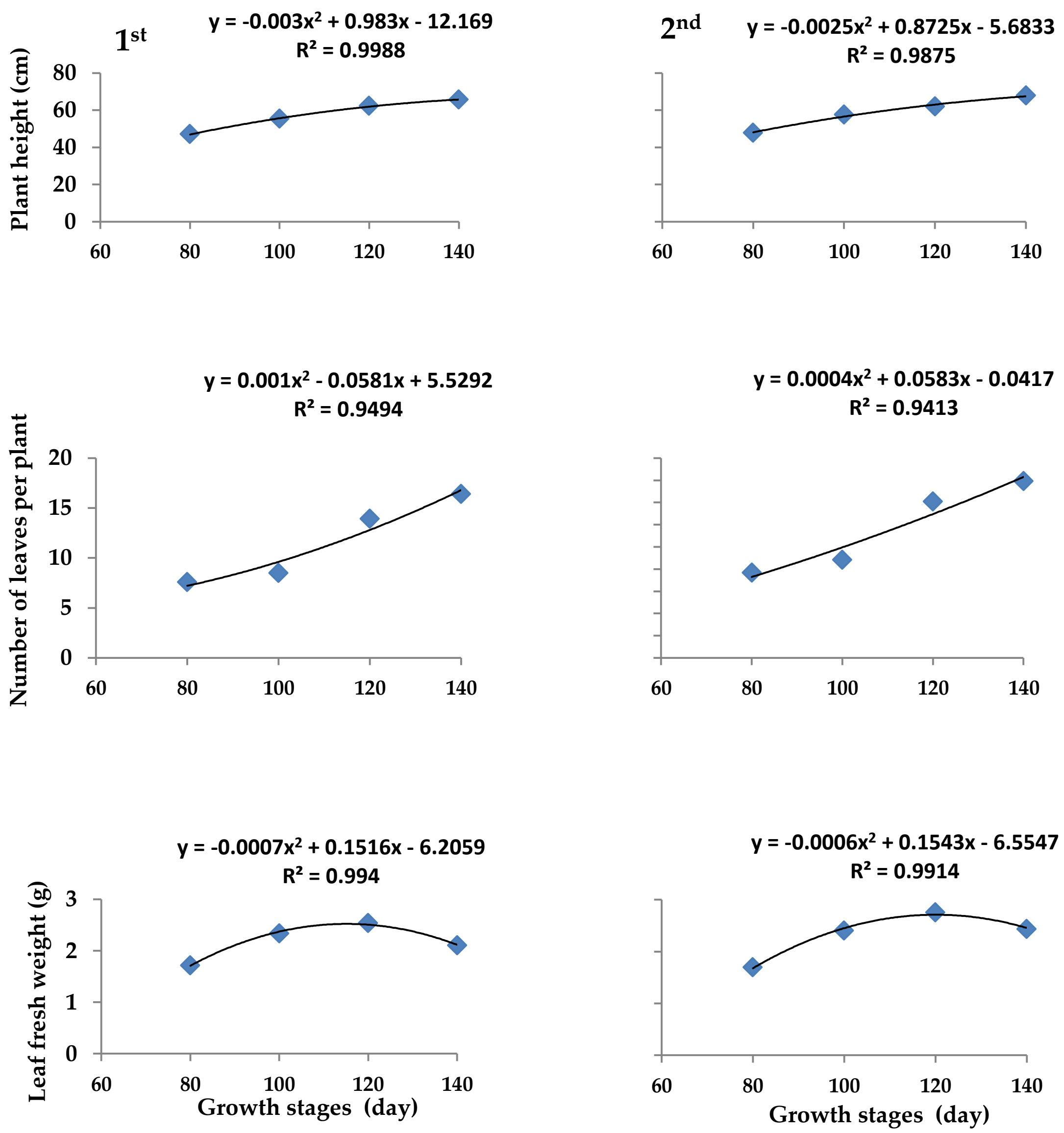

Fig. 1. The polynomial regression analysis for plant height, number of leaves and leaf fresh weight at different growth stages of garlic growing seasons in 2021–22 and 2022–23.

3.8. Total soluble solids and ascorbic acid

The effect of the different irrigation water rates on total soluble solids (TSS) and ascorbic acid contents in the bulb are presented in Fig. 9. The figures indicated that these contents increased continuously with exposure to water stress, especially at 60% of the WR. However, the difference between the two-irrigation series did not attain the significance level for TSS content in both seasons. At 120% of the WR, the values for ascorbic acid contents in the bulb were significantly reduced.

3.9. Yield reduction rate and water productivity

According to the data in Fig. 10, 60% of the WR recorded a high yield reduction of garlic bulbs with values of 42.64 and 37.12%, as well as in the 80% and 120% of the WR treatments, yield reduction was 8.64, 8.76%, and 8.95 and 6.95% as compared with the full irrigation at 100% of the WR in both seasons, respectively.

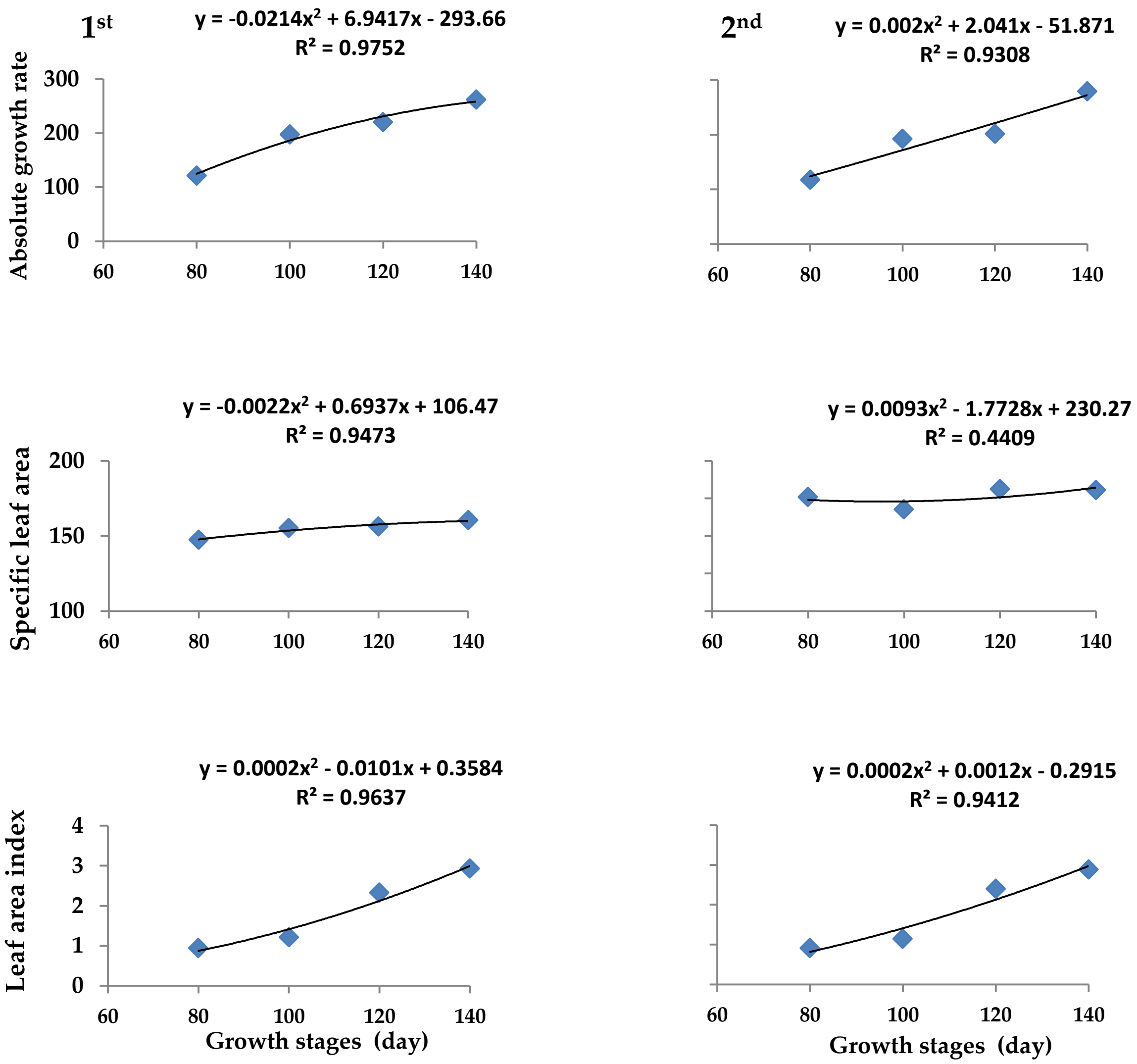

Fig. 2. The polynomial regression analysis for the absolute growth rate (AGR), specific leaf area (SLA) and leaf area index (LAI) at different growth stages of garlic growing seasons in 2021–22 and 2022–23.

As shown in Fig. 10, the water productivity (WP) values for the cured garlic bulb yield (kg m^{-3}) are influenced by the total amount of water used for each treatment. The mean irrigation water productivity varied between the studied treatments generally. WP values were raised as applied irrigation water rates decreased in both seasons. Hence, the applied irrigation water rates at 80% and 60% of the WR led to higher average WP values, ranging from 6.20 to 6.39 (kg m^{-3}) and 5.19 to 5.87 (kg m^{-3}), respectively, in both seasons.

In Fig. 11, Pearson's correlation examination revealed substantial associations (positive or negative) between the average different garlic characteristics in both seasons under the irrigation water rates. Red circles denote a positive correlation, while blue circles indicate a negative correlation among the measured characteristics. The relation between AGR and number of leaves, bulb fresh weight, diameter, cloves number, and pyruvic acid content were positively correlated ($P < 0.05$ and 0.01). However, a negative correlation ($P <$ 0.05 and 0.01) between AGR and TSS ascorbic acid was observed. An appositive correlation (($P < 0.05$) was seen between the cloves number and the number of leaves, AGR, and bulb fresh weight. Moreover, $P < 0.01$ was noted for bulb diameter, pyruvic acid, and bulb dry matter. Also, the positive correlation between bulb yield and the most examined traits was obtained in this figure.

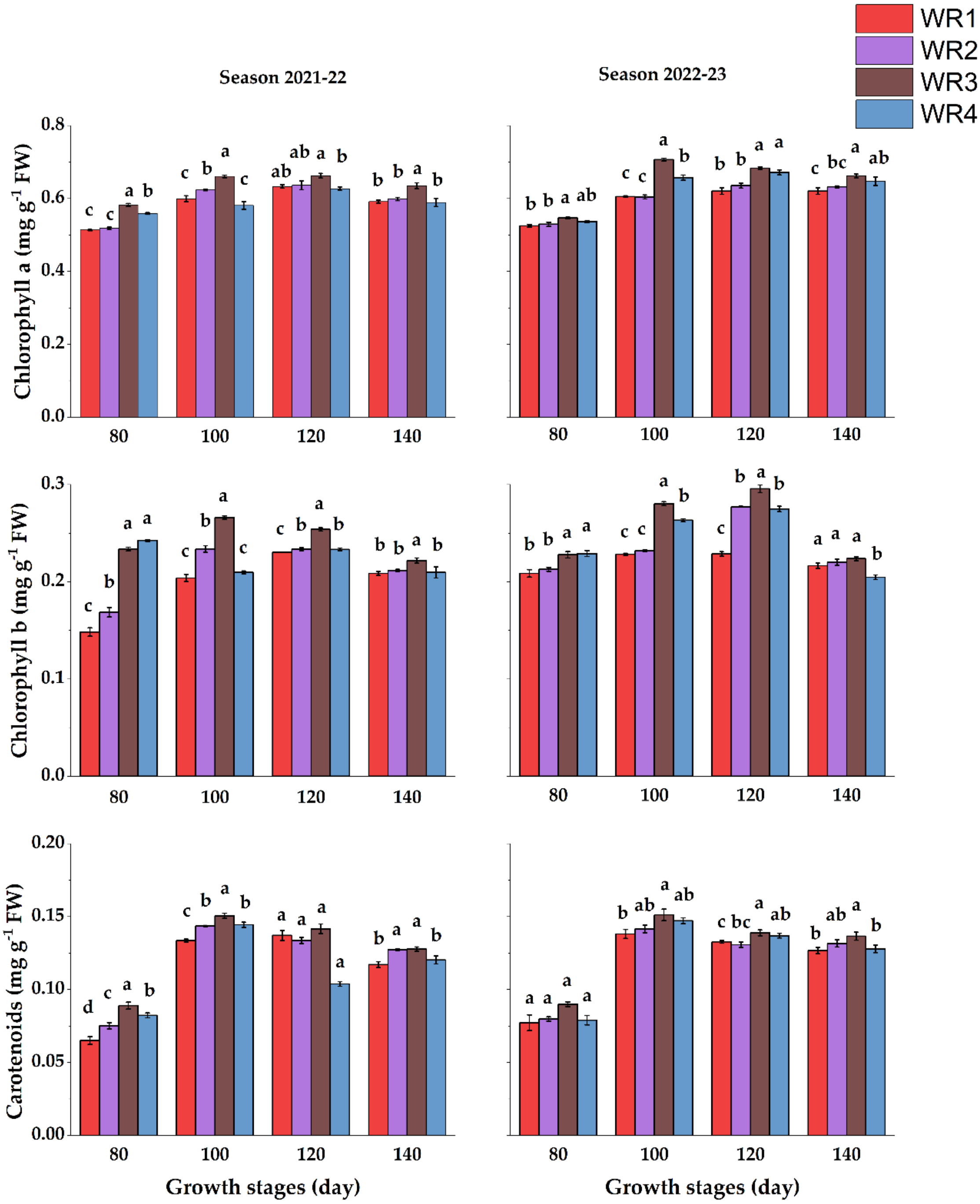

Fig. 3. Effects of irrigation rates and different growth stages on chlorophyll a, b, and carotenoids of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively. Data are mean value ± SE. Bars with same letters are not significant at $p < 0.05$ level.

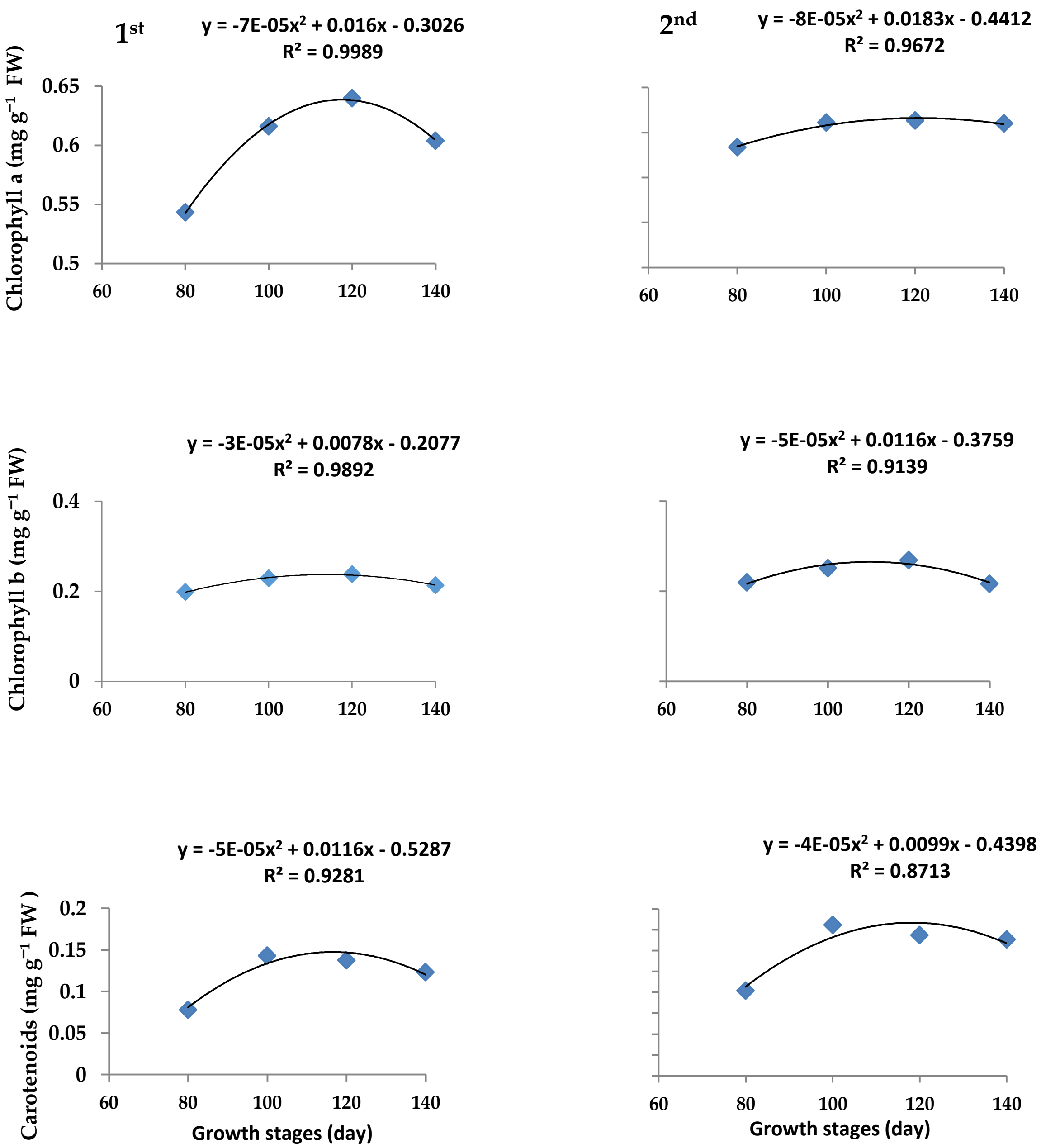

Fig. 4. The polynomial regression analysis for leaf contents of the chlorophyll a, b, and carotenoids at different growth stages of garlic growing seasons in 2021–22 and 2022–23.

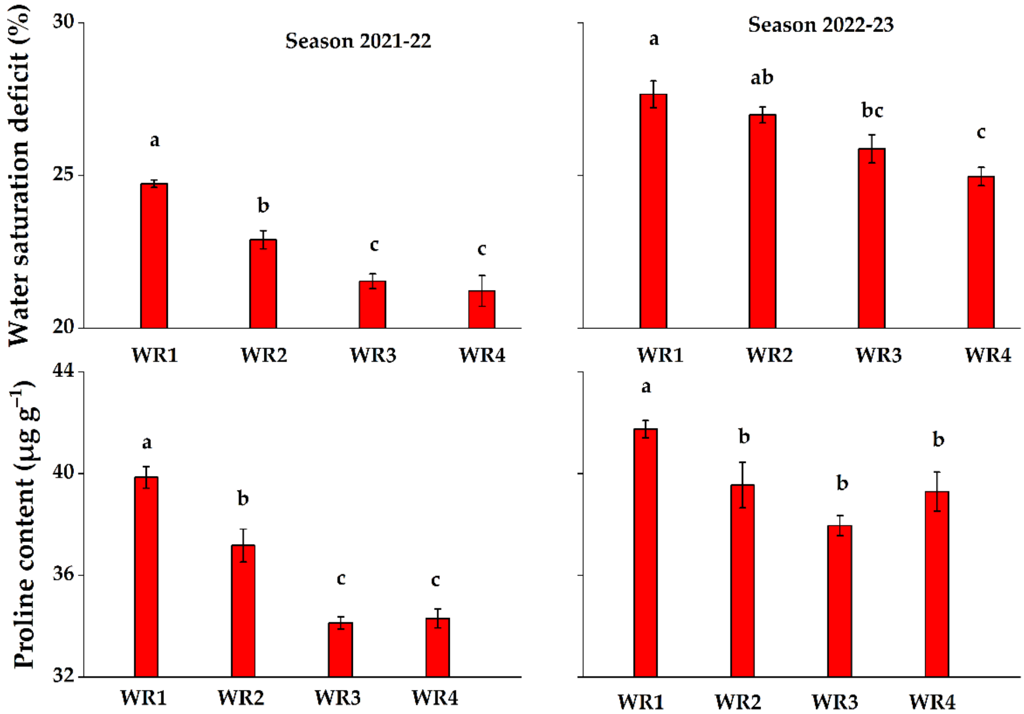

Fig. 5. Effect of irrigation rates on the water saturation deficit and proline content of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively. Data are mean value ± SE. Bars with same letters are not significant at *p* < 0.05 level.

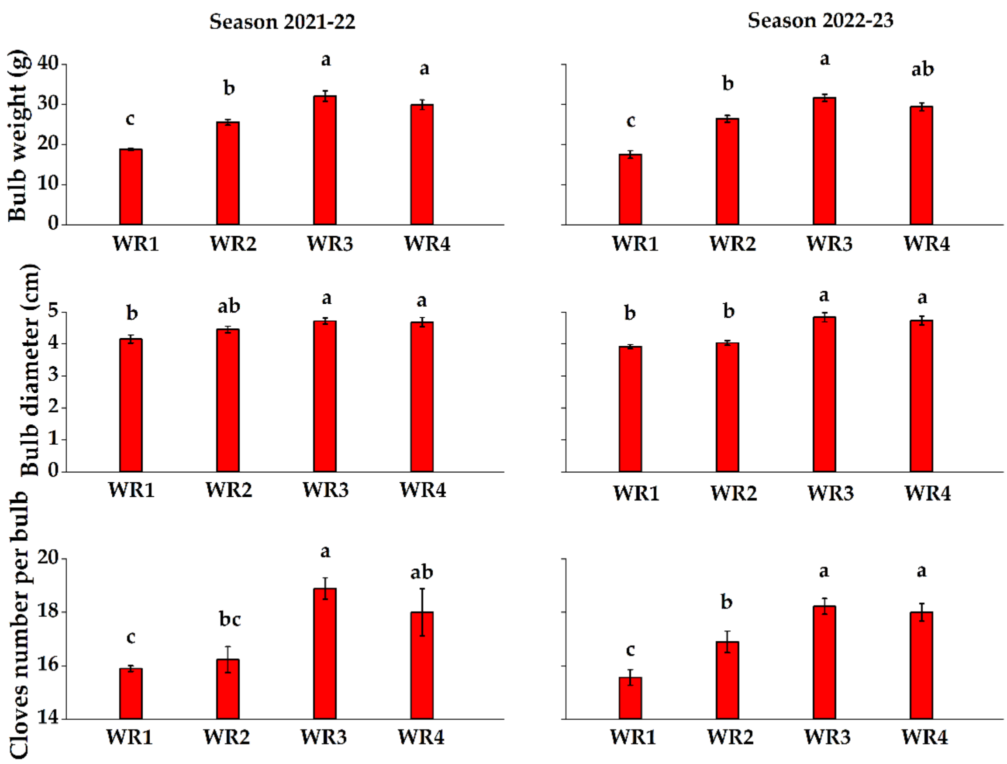

Fig. 6. Effect of irrigation rates on the bulb weight, bulb diameter, and cloves number per bulb of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively. Data are mean value ± SE. Bars with same letters are not significant at *p* < 0.05 level.

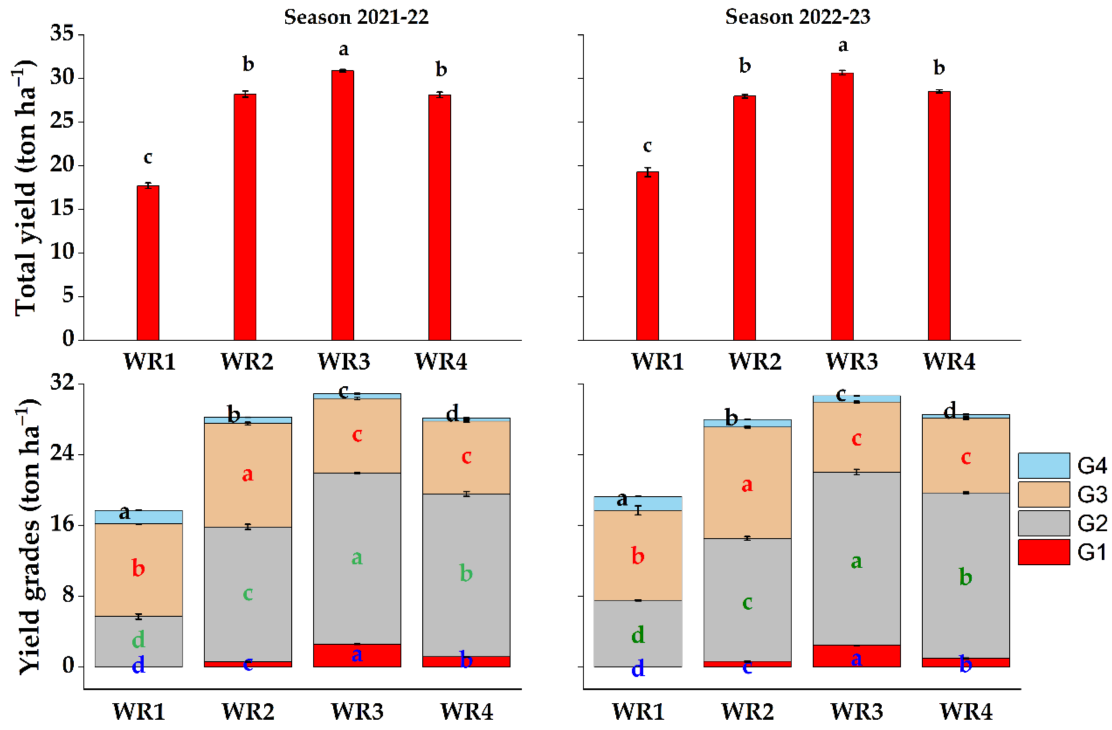

Fig. 7. Effect of irrigation rates on the total yield and yield grades of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively; G1, G2, G3 and G4: First, second, third, and fourth of yield grades, respectively. Data are mean value ± SE. Bars with same letters are not significant at *p* < 0.05 level.

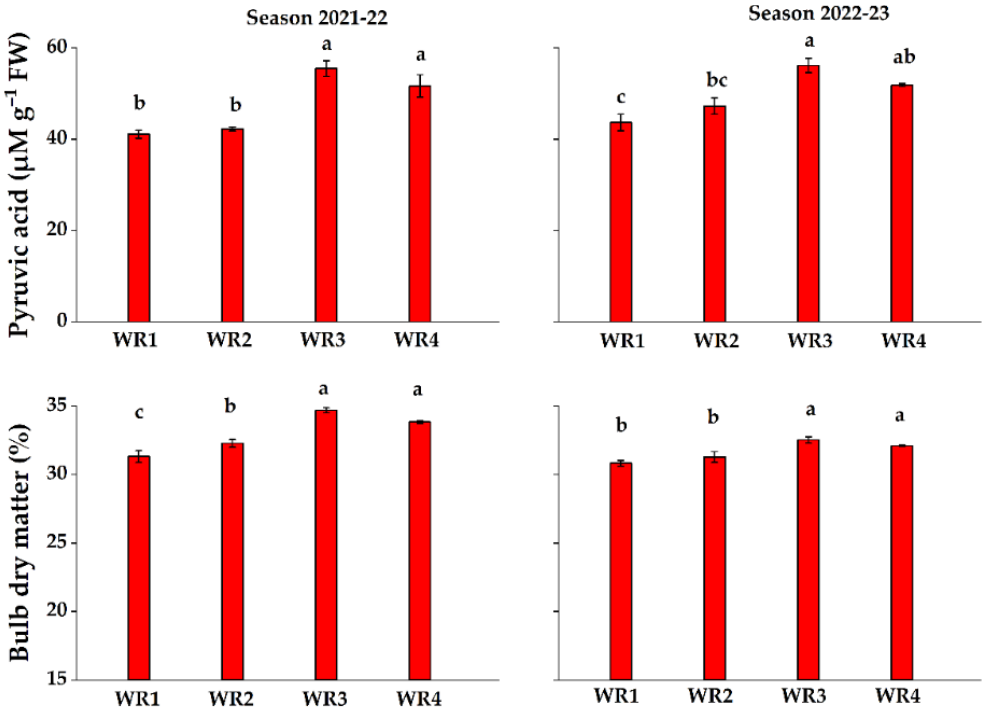

Fig. 8. Effect of irrigation rates on the pyruvic acid and bulb dry matter of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively. Data are mean value ± SE. Bars with same letters are not significant at *p* < 0.05 level.

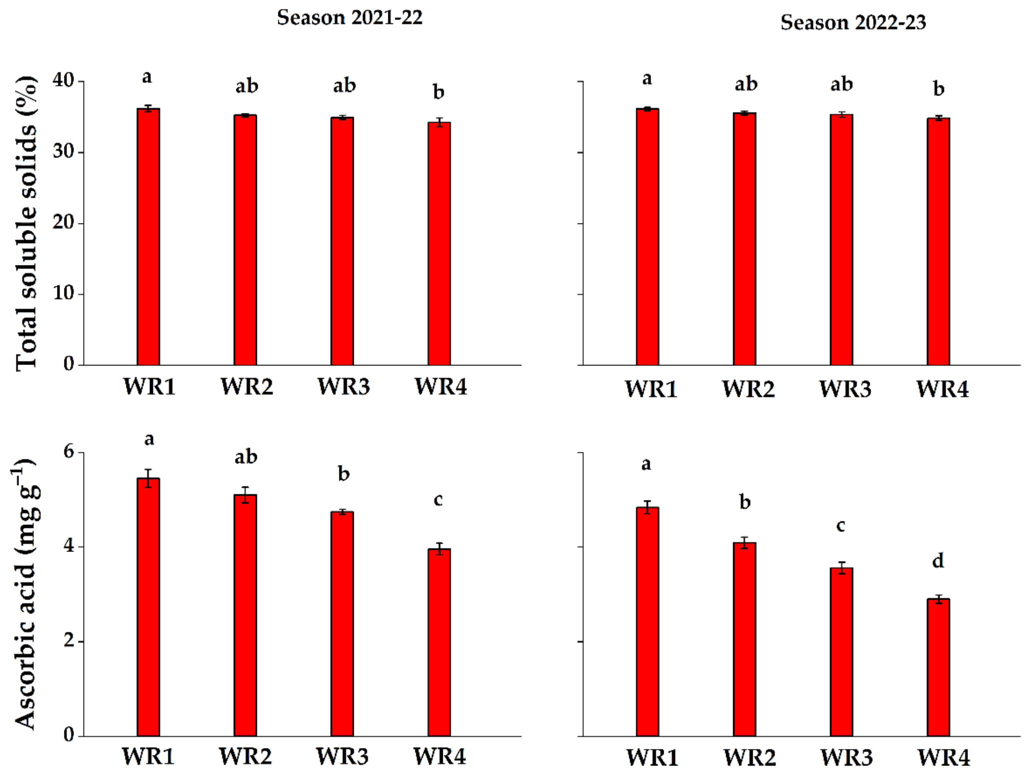

Fig. 9. Effect of irrigation rates on the total soluble solids and ascorbic acid of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively. Data are mean value ± SE. Bars with same letters are not significant at *p* < 0.05 level.

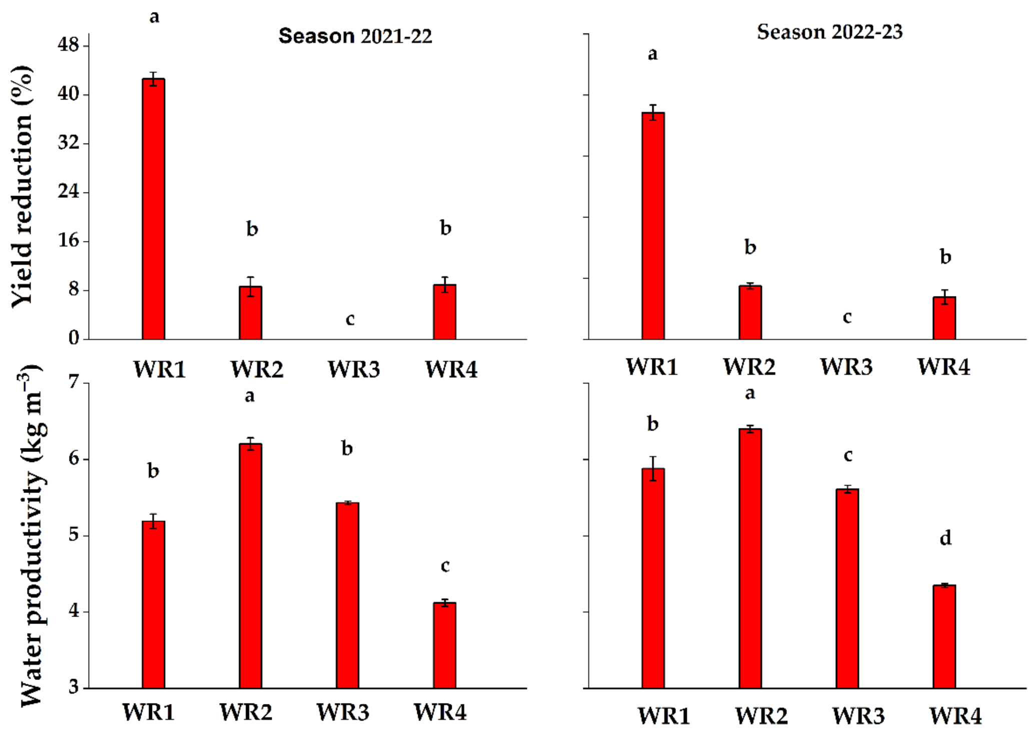

Fig. 10. Effect of irrigation rates on the yield reduction and water productivity of garlic growing seasons in 2021–22 and 2022–23. WR 1, WR 2, WR 3 and WR 4: Irrigation at 60%, 80%, 100% (control) and 120% of the water requirements (WR), respectively. Data are mean value ± SE. Bars with same letters are not significant at *p* < 0.05 level.

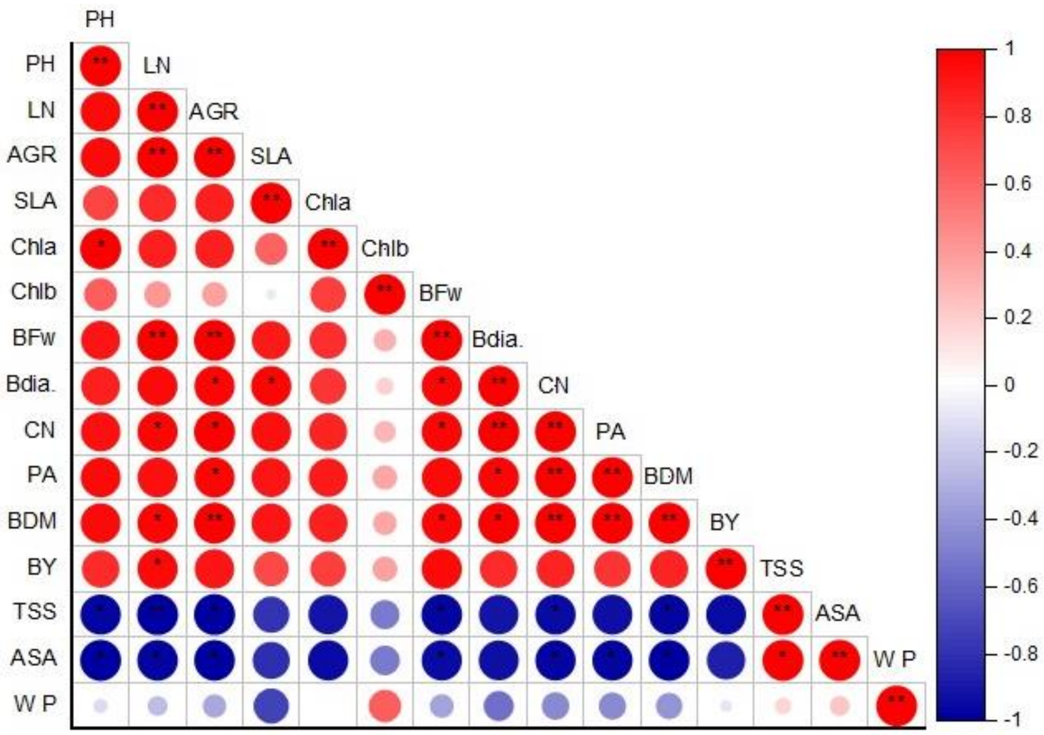

Fig. 11. Pearson's analysis of correlations between the most important parameters of garlic. plant height (PH), number of leaves (LN), absolute growth rate (AGR), specific leaf area (SLA), chlorophyll a (Chla), b (Chlb), bulb fresh weight (BFw), bulb diameter (Bdia.), number of cloves (CN), pyruvic acid (PA), bulb dry matter (BDM), bulb yield (BY), Total soluble solids (TSS), ascorbic acid (ASA) and water productivity (WP).

4. Discussion

The different morphological characteristics were observed after irrigation four rates of the water requirements (WR), and the behaviour of characteristics varies among the developmental stages of garlic plants. Morphological traits are responsible for continuous and adaptive growth under irrigation rates monitored after 80 days from planting to 140 days. Our findings lead to the conclusion that at a rate of 100% WR can result in considerable increases in the values of plant height, number of leaves and leaf fresh weight, and growth attributes such as AGR, SLA, and LAI during the examined ages, but contrarily in the 80%, 60% and 120% of the WR treatments. These results might be attributed to the effectiveness of the irrigation rate at 100% of the WR in promoting the vegetative development of garlic plants. This beneficial effect of irrigation treatment at 100% of the WR may be due to better aeration in the root zone and moisture availability throughout the entire period of garlic growth, and it is well known that water is essential for nutrient uptake and transport as well as photosynthesis, which favours growth and had an impact on bulb yield and its constituent parts. Additionally, the leading causes of leaf growth are cell division and expansion, and the turgor pressure of the cells controls the cellular expansion, so it can only take place when there is an adequate supply of water, which explains why plants with lower water availability have lower growth attributes (Taiz and Zeiger, 2009). On the other hand, as a first reaction to a water shortage, a plant's active cells grow more slowly, reducing the number of leaves and their growth. The decline in leaves number and leaf area is connected to the reduction in the leaf turgor potential (Embiale et al., 2016). Here, it is worth mentioning that AGR indicates the rate of growth variable increase based on dry matter accumulation per plant at a time (Ghule et al., 2013). Therefore, AGR grew considerably from 120 to 140 days, especially at the irrigation rate of 100% of the WR. This might be because the garlic bulb started to fill up and perform as a sink at 120 days. It was clear that the maximum number of photosynthetic substrates was transferred from the leaves to the bulb. The environmental conditions were also favourable at this growth stage to improve photosynthetic efficiency and encourage the transfer of photosynthetic substrates from leaves to bulbs, as shown in bulb characteristics and yield (Abou El-Magd et al., 2013). SLA, which represents the leaves' thickness, SLA was lower in irrigation water rates at 60 and 80% of the WR than 100% and 120% of the WR, indicating a tendency for leaf blades to thicken under a soil water shortage. This result may be viewed as an adaptation process operating under reduced soil water content, resulting in decreased leaf expansion and maintenance of leaf dry matter (Torrecillas et al., 1995).

The presented study reported that monitoring green garlic leaves through the chlorophyll a, b, and total carotenoids is the physiological strategy for determining how well they can withstand irrigation conditions. Hence, the information show that when irrigation rates reached 100% of the WR, chlorophyll a, b, and total carotenoids considerably increased, followed by a reduction in the irrigation rate of 120% of the WR during the developmental stages from 80 to 140 days. Garlic's chlorophyll content in leaf tissue shows that it retains its stay-green characteristics at a rate of 100% WR during the growth up to 140 days, which is a necessary condition for photosynthesis and assimilate generation is associated with crop growth and productivity (Ghodke et al., 2018). The treatment irrigation at 100% of the WR had a higher total chlorophyll content during the examined ages, which was attributed to the minimum impact on the light-harvesting complexes on the thylakoid membrane, as seen by improved photosynthesis as compared to other irrigation rates (Chaudhry et al., 2020). However, the reduction of chlorophyll in stressed plants is the overall indication of oxidative stress, which is linked to a reduction in chlorophyll synthesis (Romdhane et al., 2020). Also, the detrimental effects of water stress with decreased carotenoids contents result in photoinhibition (Chaudhry et al., 2020).

Proline is an osmolyte that builds up in leaves or increases with the concentration in response to abiotic stress conditions, such as drought, which protects cell tissues from oxidative damage. In this investigation, the total proline content was kept high under water stress at 60% of the WR and low under irrigation at 100%, followed by 120% of the WR. The increase in leaf proline concentration could be an adaptation mechanism resulting from protracted exposure to soil water deficiency up to 140 days from planting. These findings demonstrate an osmotic plant adjustment because of the low soil water content (Patane et al., 2022). This showed that higher proline production in plant cells improves the plant defence mechanism to prevent oxidative damage sparked by water stress. They studied maize grown under well-watered or drought circumstances (Desoky et al., 2021). The current study revealed that water supply levels significantly impacted the yield attributes. Therefore, the figures reflect that there are significant increases in bulb yield as bulb weight, diameter, and number of cloves per bulb by the increase in irrigation water rates up to 100% of the WR, despite the difference between 80% and 100% of the WR did not achieve the significance level for bulb weight and diameter, after which there were significant decreases by using the rate of 120% of the WR. The enhancement of plant water intake at moderate water levels without being subject to water stress is the factor that has led to the increase in bulb characteristics. In addition, these results may be due to the significance of water in the process of cell division, and the creation of protein could explain the positive impact of an adequate amount of water, which improves the intake of nutrients to meet the needs of bulb growth and development (Ahmed and Kasem, 2019). Also, the effect of water on raising yield (ton ha^{-1}) as affected by 100% of the WR may reflect the influence of water on promoting vegetative development and bulb parameters, as previously described in Fig. 4. Hence, the significant improvement in growth characteristics may be the cause of the yield's improved performance as affected by 100% followed by 80% of the WR treatment. Barakat et al. (2020) reported similar results for bulb yield parameters. On the other side, bulb features have been associated with a decline in response to stress at 60% of the WR with the high percentage of yield reduction of garlic bulbs, and this may be due to the variation in soil water absorption and evapotranspiration among irrigation rates, (Pelter et al., 2004; Lipiec et al., 2013). Also, our findings found that the quality of the bulb as the grades of garlic bulbs varied depending on the treatments of irrigation rates, and this is because these treatments included sufficient soil moisture for different bulb grade production (Patel and Rajput, 2013).

Regarding pyruvic acid content, the 100% and 80% of the WR had the most significant pyruvic acid content values. Pyruvic acid content can be used to predict this pungency of garlic when the enzyme allianase interacts with the precursors commonly referred to as S-allyl cysteine sulfoxide (Magray, 2015). Numerous factors, such as Sulphur-based fertilization, cultivar genotypes, dry matter, abiotic stress environments, and storage, impact the bulb's pungency (Chope et al., 2007). This may explain the beneficial effect of appropriate irrigation rates on the pyruvic acid content of bulbs because of higher moisture levels in the root zone may have enhanced the solubility of nutrients in the soil, which may have led to higher mineral uptake by the plants (Silabut et al., 2014). The current study found that drought stress at 60% of the WR caused the garlic's quality attribute pyruvic acid to decrease.

The rise in bulb dry matter content because of exposing the irrigation rate at 100% of the WR may be attributable to improved nutrient availability absorption, which led to an increase in plant height and leaf number, which in turn led to an increase in photosynthate production and subsequent accumulation in the plant (Ghule et al., 2013).

Total soluble solids (TSS) have been suggested to be a helpful predictor of garlic flavor. In the current study, the figures indicated that these contents increased continuously with exposure to water stress, especially the rate at 60% of the WR. However, the difference resulted in 60, 80, and 100% of the WR not attaining the significance level for TSS content. Thus, up to a certain point, water stress may help garlic crops by increasing their TSS levels, improving their quality. However, the diluting effect may cause the decreasing content with increased irrigation water level at 120% of the WR. Ascorbic acid followed a similar pattern to that found in bulb TSS content. The ascorbic acid content increased continuously with exposure to water stress, especially at 60% of the WR. Ascorbic acid contents have been shown to decrease (Subramanian et al., 2006) or increase (Metwaly et al., 2020) with varying irrigation levels. However, it was found in this study that conditions of water deficiency were associated with higher ascorbic acid content.

Regarding the water relationship, the mean irrigation water productivity generally varied between the studied treatments. WP values rose as applied irrigation water rates decreased in both seasons. The findings were by those of Shdeed (2001), who showed that water productivity will likely become more crucial as access to water becomes scarcer. The Pearson correlation revealed positive relationships between bulb yield, characteristics, and growth attributes.

Conclusions

The previous results suggest that garlic plants respond to irrigation at a rate of 100% WR by improving the morphological, chemical, and productivity properties and bulb quality. Therefore, the study found that irrigation at 100% of the WR significantly increases plant height, leaf number, fresh weight, and growth attributes like AGR, SLA, LAI, chlorophyll a, b, and total carotenoids contents. However, irrigation at 60% of the WR led to an intrinsic rise in leaf water saturation deficit, proline content, bulb TSS, and ascorbic acid contents. Also, the Pearson correlation showed positive relationships between bulb yield, characteristics, and growth attributes.

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