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Impact of Melatonin and Thiourea as Foliar Application on Garlic Productivity and Storability Under Water Stress Conditions

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Abstract: Garlic (*Allium sativum* L.) is a vital crop with significant medicinal and culinary value, yet it is highly sensitive to water stress due to its shallow root system. This study was conducted during the 2022/2023 and 2023/2024 seasons at the El-Qanater El-Khiria Horticulture Research Station in Egypt to investigate the potential of foliar applications of melatonin (MT) and thiourea (TU) to mitigate the adverse effects of drought on garlic growth, yield, and storage ability. The experiment employed a split-plot design with three irrigation levels based on evapotranspiration (100%, 75% and 50% Etc) and three foliar treatments; melatonin (50 mg/l), thiourea (5 mM), and tap water as a control. Results indicated that water stress significantly reduced vegetative growth parameters, including plant length, leaves number, and bulb fresh weight, with the 50% ETc level yielding the lowest values. Conversely, the 100% ETc irrigation level (1468.36 m^3 water/fed. as average of the seasons) with melatonin (50 mg/l), followed by 100% Etc with thiourea (5 mM), gave the highest growth and yield characteristics as well as reduced weight loss percentage during storage period. Foliar application of melatonin and thiourea effectively counteracted drought-induced Impairment. Melatonin treatment significantly improved plant length, bulb diameter, and total chlorophyll content, likely due to its role as an antioxidant and regulator of plant growth. Thiourea also enhanced physiological resilience by increasing proline accumulation and maintaining higher photosynthetic rates. 75% ETc irrigation level (1180.06 m^3 water/fed. as average of the seasons) with melatonin (50 mg/l) increased water use efficiency. The highest proline levels were recorded under severe water stress (50% Etc at 891.46 m^3 water/fed. as average of the seasons) when combined with melatonin, indicating enhanced osmotic adjustment. Overall, the study demonstrates that foliar applications of melatonin or thiourea can serve as effective strategies to improve the drought tolerance and productivity of garlic crops in arid and semi-arid regions.

Key words: Garlic, ETc, Water Stress, Melatonin, Thiourea, Proline, Yield, Growth.

1. Introduction

Garlic (*Allium sativum* L.) Production has a long and varied history. It originated in Central Asia more than 5,000 years ago and was prized by ancient societies, including the Romans and Egyptians, for its culinary and medicinal qualities (**Pachore *et al.,* 2024**). Garlic is commonly known as a vital and extensively cultivated crop with significant agronomic, culinary, and medicinal value. Along with other well-known members of the Allium genus, such as onions, shallots, and leeks, this bulbous plant has a strong flavor. It is a member of the *Alliaceae* family and is distinguished by its underground bulb, which is consists of several cloves. Egypt ranked fourth after China, India, and Bangladesh in the world's garlic production (**FAO, 2024**). The harvested area of Egyptian garlic reached 22467 ha with a total production of 563,887 tons in 2024 (**MALR, 2025**). Garlic is a relatively shallow-rooted bulb crop that is particularly vulnerable to moisture stress during the early stages of bulb development. One of the most important inputs for garlic production is irrigation. The production is significantly impacted by the lack of irrigation during bulb growth, which typically occurs in the early summer. Water scarcity may worsen due to climate change predictions of rising temperatures and reduced falling precipitation (**Gupta *et al.,* 2020**).

Abiotic stressors like drought, which are more common in arid and semi-arid areas like Egypt, can directly reduce crop development by reducing cell elongation, cell turgor, or cell volume (**Banon *et al*., 2006 and Taha, *et al.,* 2019**). Abiotic stress like drought harms the growth and development of many species, which reduces their production (**Mirajkar *et al.,* 2019**). Drought stress has a significant effect on horticultural crops morphological, physiological, and biochemical processes. The most detrimental impacts that crop plants experience during drought stress are reduced root and shoot growth, compromised membrane integrity, unbalanced mineral accumulation, and damaged photosynthetic mechanism (**Tabassum, *et al.,* 2021**).

Melatonin, a derivative of tryptophan, is a significant indoleamine plant hormone that is frequently generated by several species (**Pang *et al*., 2020**). Numerous biological activities, such as germination, growth control, flowering, photosynthesis, senescence, postharvest quality, and abiotic stress tolerance, depend on Melatonin (**Arnao and Hernández-Ruiz, 2019**). It also has a crucial regulatory role in response to abiotic stresses like salt, drought, and extremes in ambient temperature (**Sezer *et al*., 2021**). Melatonin justifying effects may be attributed to many causes, including improvements in root morphology-related characteristics, growth parameters and antioxidant enzyme activity, improvement in photosynthetic capacity, and prevention of chlorophyll breakdown (**Altaf *et al*., 2020**). According to **Soriano *et al.* (2017)**, melatonin has auxin action as a growth regulator, controlling both root and shoot development, as well as functioning in plants as an antioxidant. Also, **Tan *et al*. (2007)** demonstrated that melatonin has increased agricultural output and drought tolerance.

Thiourea is a sulfhydryl molecule that has one SH group in addition to nitrogen in the form of NH, as an amino molecule similar to urea, it stimulates various plant physiological processes. Also, it mitigates drought effects in plants (**Nagar *et al.,* 2017**). Furthermore, it encourages the formation of cytokinin-dependent callus tissues. Additionally, it has been shown that thiourea improves carbon partitioning towards sinks and controls plant growth by sustaining a higher photosynthetic rate up to the reproductive stage and it is also a source of sulfur and nitrogen, which encourages the plant's vegetative growth (**Choudhary *et al.,* 2018**). Thiourea may have a positive impact on plant growth by increasing photosynthetic efficiency and playing a bioregulatory role in plants.

The current study was carried out to study the impact of foliar spray application of melatonin and thiourea on the growth and storage ability of garlic under water stress conditions.

2. Materials and Methods

2.1. Experimental site

During the two successive winter seasons of 2022/2023 and 2023/2024, a field experiment was conducted at the El-Qanater El-Khiria Horticulture Research Station (31°11' longitude, 30°28' latitude, and 14 m above mean sea level), Qalubia Governorate, Egypt. The soil samples were taken from the experimental site to identify the primary physical and chemical characteristics, as determined by **Page *et al.* (1982) and Ryan *et al*. (1996)** methods (Table 1).

Plant material: Sids-40 cultivar cloves were planted on the 22th of September in both seasons of 2022/2023 and 2023/2024. The metrological data for both seasons are shown in Table 2.

Table (1). The physical and chemical properties of the experimental soil

Characters		2022/2023	2023/2024
Physical properties	**Coarse sand (%)**	1.25	1.35
	Fine sand (%)	33.8	33.2
	Silt (%)	33.2	32.8
	Clay (%)	31.75	32.65
	Textural class	**Clay loam**	
Chemical properties			
pH, in soil suspension (1:2.5)		7.85	7.92
OM (%)		2.15	2.08
EC_e (dS m^{-1}), in saturated soil paste extract		0.48	0.52
Soluble cations (meq L^{-1})	**Ca^{2+}**	3.12	3.05
	Mg^{2+}	2.58	2.62
	Na^{+}	4.05	3.95
	K^{+}	0.43	0.46
Soluble anions (meq L^{-1})	**HCO_3^-**	3.72	3.55
	Cl^-	3.75	3.82
	SO_4^{2-}	2.70	2.74
Macro-elements (ppm)	**N**	43.50	40.20
	P	11.80	9.5
	K	188.5	192.20

Table (2). Metrological data in 2022/2023 and 2023/2024 seasons obtained from the Central Laboratory for Agricultural Climate

	2022/2023							2023/2024						
	T.max	**T.min.**	**W.S**	**R.H.**	**S.S**	**S.R**	**R.F**	**T.max**	**T.min.**	**W.S**	**R.H.**	**S.S**	**S.R**	**R.F**
Sept.	36.5	21.26	3.1	49.1	10.9	557	3.9	24.3	11.1	2.6	59.8	5.9	392	14.9
Oct.	31.5	17.7	3.0	54.7	9.3	437	1.3	32.0	19.4	2.6	58.1	8.6	416	53.0
Nov.	27.5	14.9	2.3	62.6	8.0	335	20.1	26.7	14.9	2.4	65.1	7.8	330	5.3
Dec.	19.5	9.0	2.6	68.3	6.1	261	30.3	22.5	11.5	2.4	71.7	6.5	270	26.0
Jan.	16.8	5.4	2.5	67.1	6.7	289	33.2	20.4	8.3	2.2	59.2	6.7	289	4.4
Feb.	19.5	6.6	2.5	66.6	7.7	370	10.6	21.3	8.2	2.4	61.3	7.3	359	7.6
Mar.	25.7	10.8	2.7	54.1	9.2	480	5.9	25.6	10.3	2.5	51.6	9.1	476	3.0

where: T.max., T.min.= maximum and minimum temperatures °C; **W.S** = wind speed (m/ sec); **R.H**.= relative humidity (%); **S.S**= actual sun shine (hour); **S.R**= solar radiation cal/cm^2/ day). **RF**= rainfall (mm/month)

2.2. Experimental design and tested treatment

The field experiment was conducted using a split-plot design in a randomized complete block design with three replications. This experiment included 9 treatments (3 irrigation water amounts and 3 foliar application) Three levels of water applied at different rates of evapotranspiration (100, 75 and 50% Etc which equal 1468.36, 1180.06 and 891.46 m^3 water/fed., respectively as average of the two seasons) in the main plots, and three foliar spray applications of melatonin (MT) at 50 mg/l, thiourea at 5mM and tap water as a control in the sub-plots. Foliar application was started at 60 days after planting three times every 15 days. Melatonin ($C_{13}H_{16}N_2O_2$) and thiourea (CH_4N_2S) of El Gomhouria Company for Trading Medicines, Chemicals and Medical Appliances were used. The Irrigation treatments were applied at 40 days after planting (from 1st November to 5th March). A drip irrigation system was used, with a 30 cm spacing between drippers. The experimental plot area was $10.5m^2$ consisting of 3 ridges 5 m in length and 0.70m in width. Cloves of garlic Sids-40 cultivar were planted 10 cm apart on both sides of the ridges. One row was left unplanted between plots to prevent overlying filtration. The agricultural practices were applied as recommended by the Egyptian Ministry of Agriculture and Land Reclamation.

Three amounts of applied irrigation water based on the Penman-Monteith equation were tested in this experiment. The irrigation treatments were as follows:

1- Irrigation with an amount of water equals 100 % of potential evapotranspiration (ETcrop).

2- Irrigation with an amount of water equals 75 % of potential evapotranspiration (ETcrop).

3- Irrigation with an amount of water equals 50 % of potential evapotranspiration (ETcrop).

2.3. Crop-soil-water relations

Calculation of crop coefficient and evapotranspiration

Reference evapotranspiration (ETo)

Reference evapotranspiration (ETo) was calculated using the meteorological data using formulae as cited by (WATER software) **Doorenbos and Pruitt (1977) and Allen *et al.*, (1998)**. It was applied by using the WATER model. The equation adapted the radiation formula of **Makkink (1957)** to predict potential evapotranspiration as follows:

ETp: bw Rs/L- 0.3

Where: **ETp**: Daily potential evapotranspiration (mm/day).
b: Adjustment factor based on wind and mean relative humidity.
w: Weighting factor based on temperature and elevation above sea level
Rs: Daily total incoming solar radiation for the period of consideration (cal/cm2/day).
L: Latent heat of vaporization of water (cal/ cm^2/ day)
Factors (**b**) and (**w**) could be obtained from the tables cited by **Doorenbos and Pruitt 1977.**

Crop evapotranspiration (ETc)

The ETc values were calculated according to the following equation given by **FAO (1977):ETc = ETo × Kc**

Where:
ETc: crop evapotranspiration (mm day^{-1})
ETo: reference crop evapotranspiration (mm day^{-1})
Kc: crop coefficient.

Amount of applied irrigation water (AIW)

The amounts of applied irrigation water were calculated according to the equation given by **Vermeiren and Jopling (1984)** as

$$\mathbf{AIW} = \frac{\mathbf{ETc} \times \mathbf{I}}{\mathbf{E}\boldsymbol{a}\,(\mathbf{1} - \boldsymbol{LR})}$$

Where:
AIW: depth of applied irrigation water (mm)
Etc: crop evapotranspiration (mm day^{-1}).
I: irrigation interval (days)
Ea: irrigation application efficiency for the drip irrigation system (≈ 100% at the site location).

LR: leaching requirements: the extra amount of applied water needed for salt leaching, calculated according to **FAO (1985)** as follows:

$$\mathbf{LR} = \frac{\mathbf{ECiw}}{\mathbf{EC}e}$$

Where:
ECiw: salinity of irrigation water (dS m^{-1}) and **ECe**: average soil salinity tolerated by the crop as measured by soil saturated extract (dS m^{-1}). Under the current experimental conditions, no additional water was added for leaching to avoid any effect on stress treatments.

Table (3). Doorenbos-Pruitt formulae in 2022/2023 and 2023/2024 seasons

Season / Month	Kc	Evapotranspiration Eto			
		2022/2023		**2023/2024**	
		mm/day	**mm/month**	**mm/day**	**mm/month**
September	0.30	5.8	46.4	3.23	25.84
October	0.45	4.18	129.6	3.94	122.1
November	0.60	2.86	85.8	2.77	83.1
December	0.75	1.84	57.0	2.04	63.2
January	1.0	1.9	58.9	2.1	65.1
February	0.90	2.71	75.9	2.74	76.7
March	0.75	4.14	20.7	4.07	20.35
Seasonal (mm)			474.3		456.39

Applied irrigation water

Table (4). Monthly and seasonal applied irrigation water to garlic by three amounts of irrigation water in 2022/2023and 2023/2024 growing seasons

Season	**2022/2023**					
Month	**100% ETc**		**75% ETc**		**50% ETc**	
	m^3/ day/fed.	**m^3/ month/fed.**	**m^3/ day/fed.**	**m^3/ month/fed.**	**m^3/ day/fed.**	**m^3/ month/fed.**
September (100 %ETc)	8.12	64.96	8.12	64.96	8.12	64.96
October (100 %ETc)	8.78	272.1	8.78	272.1	8.78	272.1
November	8.01	240.2	6.01	180.2	4.0	120.1
December	6.44	199.6	4.83	149.7	3.2	99.8
January	8.87	266.0	6.65	199.5	4.4	133.0
February	11.38	352.8	8.54	264.6	5.7	176.4
March	14.49	72.45	10.87	54.35	7.2	36
Seasonal (m^3/fed.)		**1468.11**		**1185.41**		**902.36**
2023/2024						
September (100 %ETc)	4.52	36.16	4.52	36.16	4.52	36.16
October (100 %ETc)	8.27	256.5	8.27	256.5	8.27	256.5
November	7.76	232.7	5.82	174.5	3.9	116.3
December	7.14	221.3	5.36	166.0	3.6	110.7
January	9.80	294.0	7.35	220.5	4.9	147.0
February	11.51	356.7	8.63	267.6	5.8	178.4
March	14.25	71.25	10.69	53.45	7.1	35.5
Seasonal (m^3/fed.)		**1468.61**		**1174.71**		**880.56**

2.4. Recorded data

Vegetative growth characteristics

Physical characteristics

From each experimental replicate three random plants were selected at 150 days after planting (DAP) to determine plant length (cm), number of leaves per plant, neck and bulb diameter (cm) and fresh weight of leaves and bulb (g.) was measured.

Chemical characteristics

The leaves and bulb dry matter% (dry matter was measured by drying leaves or bulb tell constant weight at 65 °C in an electric oven). The third and fourth leaves of each plant sample were gathered to measure photosynthetic pigments; 0.5 g of leaves fresh weight (FW) were placed in centrifuge tubes containing 30 mL (V) of 80% acetone and left in the dark for 24 hours. Samples were measured using a UV-1200 spectrophotometer at 663, 646, and 470 nm (**Arnon, 1949**). Chlorophyll a and b concentrations, total chlorophyll, and carotenoids were computed according to the following equations (**Wellburn, 1994**):

Chlorophyll a (mg/g.) $= \frac{(12.72 \text{ X } A663 - 2.69 \text{ X } A645)\ V}{1000\ FW}$

Chlorophyll b (mg/g.) $= \frac{(22.88 \text{ X } A645 - 4.67 \text{ X } A663)\ V}{1000\ FW}$

Total Chlorophyll (mg/g.) =Chl a + Chl b

Carotenoids(mg/g.) $= \frac{(1000 \text{ X } A470 - 3.27 \text{ X Chlorophyll a} - 104 \text{ X Chlorophyll b})\ V}{229 \text{ X } 1000\ FW}$

Free proline was measured in leaf tissue (µmole/g) using the **Bates *et al.,* (1973)** ninhydrin technique. After mixing 0.5 g of fresh leaf material with 5 ml of distilled water, the mixture was heated for 30 minutes in a water bath. Following centrifugation, samples were filtered through paper, and 2 ml of freshly made ninhydrin reagent (0.5 g ninhydrin in 50 ml of 60% acetic acid) was combined with 1 ml of the supernatant. The samples were incubated in a boiling water bath for one hour before the color reaction appeared. Following toluene extraction, the samples were measured spectrophotometrically, and proline content was estimated by using a standard curve that had already been created.

Yield components

The harvesting was carried out after 180 days from planting in both seasons; the yield of three intermediate rows from each replicate were weighed for total yield (ton/fed) determination. From these three rows ten plants were selected randomly for measurement of the following data:

Bulb fresh weight, number of cloves per bulb, average cloves weight, neck diameter, and Bulb diameter.

Water use efficiency (WUE): was calculated from the following equation:

WUE $= \frac{\text{Yield (kg)}}{\text{Total Applied Water } (m^3)}$.

Bulb dry matter

Bulb dry matter%was measured by drying the bulb to a constant weight at 65°C in an electric oven.

Pungency determination

Pungency was measured as pyruvic acid content using the colorimetric method as described by **Schwimmer and Weston (1961).** The pungency was assessed by the sodium pyruvate standard curve. The results were reported asµmol of pyruvic acid per ml of garlic juice. µmol/ml.

Total Carbohydrates

Total carbohydrate (%) was determined colorimetrically in fresh bulbs, as described by the method of **Michel *et al.* (1956).**

Storage

After the curing process, five-kilogram samples were randomly selected from each treatment and kept at room temperature. After four, and seven months of storage, the bulb weight loss percentage was calculated, using the subsequent equation according to **Wills *et al.* (1982)** as follows:

$$\text{Weight loss \%} = \frac{\text{Initial garlic lobes weight} - \text{final garlic lobes weight}}{\text{Initial garlic lobes weight}} \times 100$$

Statistical analysis

A split-plot design with three replicates was employed. The analysis of variance method was applied to the collected data from both seasons, and the means of the treatments were compared using the least significant difference (L.S.D.) at the 0.05 probability level. According to **Snedecor and Cochran (1991).**

3. Results and Discussion

The highest significant values of plant length, number of leaves per plant and neck diameter resulted from irrigation with the level of 100% evapotranspiration (ETc), whereas the level of 50%ETc recorded the lowest significant values on the same characteristics at 150 days after planting in both seasons (Table 5).

The foliar application with melatonin resulted in the highest significant plant length. The highest values of the number of leaves per plant and neck diameter were obtained from the foliar application of melatonin or thiourea. On the other side, the foliar application with melatonin obtained the highest neck diameter in the first season, while the highest significant values of neck diameter were recorded with the application of melatonin or thiourea in the second season, as illustrated in Table 5.

Table (5). Impact of different irrigation levels and foliar spray with melatonin and thiourea on plant length, number of leaves/plant and neck diameter of garlic plant at 150 days after planting in two seasons of 2022/2023 and 2023/2024

Irrigation levels	Treatments	Plant length (cm)		Number of leaves /plant		Neck diameter (cm)	
		2022	2023	2022	2023	2022	2023
100 % ETc		87.11	86.56	10.33	10.22	1.81	1.91
75 % ETc		68.00	64.22	8.00	7.89	1.19	1.41
50 % ETc		55.33	52.78	6.67	6.11	0.89	1.04
L.S.D. at 5%		**2.86**	**4.67**	**0.436**	**0.398**	**0.22**	**0.315**
	Melatonin	76.11	73.22	8.67	8.44	1.59	1.62
	Thiourea	70.78	68.22	8.33	8.00	1.26	1.52
	Control	63.56	62.11	8.00	7.78	1.03	1.22
L.S.D. at 5%		**3.97**	**3.28**	**0.541**	**0.541**	**0.188**	**0.231**
100 % ETc	**Melatonin**	98.67	94.67	11.33	11.00	2.23	2.10
	Thiourea	85.00	85.00	10.33	10.33	1.83	1.87
	Control	77.67	80.00	9.33	9.33	1.33	1.77
75% ETc	**Melatonin**	70.67	66..00	8.00	7.67	1.40	1.53
	Thiourea	70.67	68.00	8.00	7.67	1.10	1.60
	Control	62.67	58.67	8.00	8.33	1.07	1.10
50% ETc	**Melatonin**	59.00	59.00	6.67	6.67	1.13	1.23
	Thiourea	56.67	51.67	6.67	6.00	0.83	1.00
	Control	50.33	47.67	6.67	5.67	0.70	0.80
L.S.D. at 5%		**6.87**	**5.69**	**0.938**	**0.938**	**0.326**	**0.40**

Data in Table 5 showed the interaction between different water irrigation levels and the foliar application of melatonin or thiourea. The highest significant plant length was recorded at irrigation level of 100%ETc with melatonin foliar application in both seasons. Additionally, the highest number of leaves per plant was obtained with the irrigation level of 100%ETc sprayed with melatonin in the first season. In the second season, the highest values were recorded at the same water level (100%ETc) and with foliar application of melatonin or thiourea. The highest neck diameter was obtained with the irrigation level of 100%ETc sprayed with melatonin in the first season, while in the second season, the same irrigation level of 100%ETc sprayed with melatonin, thiourea, or control gave the highest neck diameter.

Data in Table 6 showed that the irrigation with an irrigation level of 100%ETc gave the highest significant bulb diameter, leaves and bulb fresh weight in both seasons.

Table (6). Impact of different irrigation levels and foliar spray with melatonin and thiourea on bulb diameter, leaves fresh weight (g.) and bulb fresh weight (g.) of garlic plant at 150 days after planting in two seasons of 2022/2023 and 2023/2024

Irrigation levels	Treatments	Bulb diameter (cm)		Leaves fresh weight (g.)		Bulb fresh weight (g.)	
		2022	2023	2022	2023	2022	2023
100 % ETc		5.10	5.14	100.54	98.09	62.89	59.56
75 % ETc		3.84	4.12	35.02	32.93	30.33	28.44
50 % ETc		2.88	3.33	21.23	19.35	18.44	18.89
L.S.D. at 0.05%		**0.63**	**0.23**	**11.63**	**10.09**	**4.18**	**2.48**
	Melatonin	4.27	4.58	65.77	63.56	46.00	44.56
	Thiourea	4.04	4.19	53.33	50.90	34.67	34.44
	Control	3.51	3.83	37.70	35.61	31.00	27.89
L.S.D. at 0.05%		**0.44**	**0.29**	**11.28**	**10.96**	**4.83**	**3.27**
100 % ETc	Melatonin	5.53	5.60	133.65	131.16	80.33	78.33
	Thiourea	5.50	5.13	100.30	97.39	57.67	58.00
	Control	4.27	4.70	67.68	65.73	50.67	42.33
75% ETc	**Melatonin**	4.20	4.37	39.23	36.74	35.33	33.67
	Thiourea	3.80	4.23	36.18	33.81	29.00	27.00
	Control	3.53	3.77	29.66	26.33	26.67	24.67
50% ETc	**Melatonin**	3.07	3.77	24.44	22.77	22.33	21.6
	Thiourea	2.83	3.20	23.51	21.49	17.33	18.33
	Control	2.73	3.03	15.75	13.78	15.67	16.67
L.S.D. at 0.05%		**0.76**	**0.50**	**19.55**	**18.98**	**8.36**	**5.67**

The foliar application with melatonin or thiourea recorded the highest significant values of bulb diameter in the first season only, while in the second season melatonin only recorded the highest values. Also, the foliar application with melatonin gave the highest significant values of leaves and bulb fresh weight in both seasons. (Table 6).

The interaction between the irrigation level of 100%ETc and the foliar application with melatonin or thiourea resulted in the largest significant bulb diameter in both studied seasons (Table 6). The heaviest significant leaves and bulb fresh weight were obtained with the irrigation level of 100%ETc and foliar application with melatonin in both seasons.

Different morphological characteristics presented in Tables (5&6) were affected by the water levels 100% of ETc produced the tallest plants (87.1- 86.6 cm, in both seasons respectively), the largest number of leaves (10.3-10.2 per plant, in both seasons respectively) and bulb diameter (5.1-5.1 cm, in both seasons respectively). 100% of ETc enhanced vegetative growth characteristics while 50% of ETc yielded the lowest values of all morphological characteristics. In this respect, **Moustafa *et al*. (2024)** indicated that the decline in the number of leaves is connected to the reduction in the leaf turgor potential. Better moisture availability throughout the garlic growth period could be the cause of this beneficial effect of irrigation treatment at 100% of ETc. Water is necessary for nutrient uptake and transport as well as photosynthesis, which promotes growth and has an effect on bulb yield and its parts, by enhancing cell division and expansion are the primary drivers of leaf growth **(Embiale *et al.,* 2016).** Since cellular expansion is regulated by the turgor pressure plants with less water availability have poorer growth characteristics (**Taiz and Zeiger, 2009 and Moustafa *et al*., 2024).**

Melatonin spraying maximized plant length, number of leaves per plant, bulb diameter, leaves and bulb fresh weight. Similar results for leaves and neck diameter were obtained by thiourea. Thiourea is an osmoprotectant and antioxidant, reducing oxidative stress and enhancing plant metabolism under various environmental conditions **(Hanci and Bingol, 2020).** Also, **Arnao and Hernández-Ruiz (2019)** reported that melatonin is "plant master regulator," it is an important regulator of several plant hormone components, including plant growth and yield. From the other perspective, **Arnao and Hernández-Ruiz (2021)** noted that melatonin is a specific antioxidant and a plant master regulator that protects against oxidative stress and regulates various plant responses to environmental stress, particularly water stress. Melatonin treatment increased plant growth and biomass by increasing chlorophyll concentrations, which play a principal role in the photosynthesis process (**Khan *et al.,* 2024**).

The data presented in Table 6 show that the heaviest leaves dry matter and bulb diameter were recorded with a water level of 100%ETc in both seasons. These results were in harmony with those obtained by **Moustafa *et al*. (2024).** Also, the rise in bulb dry matter with 100% of ETc is related to improved absorption of nutrients, which increased plant height and leaves number, which in turn increased photosynthate accumulation **(Ghule *et al.,* 2013)**. Furthermore, the highest significant content of proline was obtained at 50% of ETc level in both seasons. Leaf proline concentration increased as a result of prolonged exposure to soil water deficit, up to 150 days after planting. The increased production of proline in plant cells enhances the defenses against oxidative damage caused by water stress **(Patane *et al.,* 2022).** In response to drought, proline, an osmolyte that shields cell tissues from oxidative damage, accumulates in leaves or rises in concentration **(Moustafa *et al.,* 2024).**

The foliar spray application with melatonin or thiourea recorded the highest significant leaves dry matter in both seasons under this study. The heaviest bulb dry matter was obtained with the melatonin treatment in both seasons. Moreover, the spray with melatonin recorded the highest content of proline in the first season, while in the second one, the highest content was recorded with the foliar application of thiourea, followed by melatonin (Table 7). Through the direct scavenging of Reactive Oxygen Species (ROS), Reactive Nitrogen Species (RNS) and the indirect recovery of leaf ultrastructure, enhancement of the photosynthetic system, stimulation of plant growth regulators, and activation of antioxidant activities in plants, melatonin played a significant role in reducing both biotic and abiotic stress **(Biswajit, 2019)**. Furthermore, **Jafari and Shahsavar (2021)** stated that melatonin maintained the stability of the plant membrane by encouraging the production of solutes like proline, which aids in osmotic adjustment. Also, **Luo, *et al.* (2023)** stated that melatonin foliar application increased proline levels in drought-stressed plants, which raised water intake, strengthened photosynthetic systems, and ultimately enhanced growth characteristics in drought-stressed plants. Also, thiourea stimulates a variety of plant physiological processes; improved the generation and activity of proline, antioxidants, and osmolytes under both normal and drought stress, restoring wheat growth and yield properties **(Ishfaq *et al*., 2024).** Many physiological processes in plants are known to be stimulated by thiourea. Furthermore, thiourea has been demonstrated to increase yield by improving carbon partitioning towards the sink and to regulate plant growth by maintaining a higher photosynthetic rate until the reproductive stage **(Verma *et al*., 2017).** Applications of thiourea restored plant growth and yield characteristics by increasing the production and activity of proline, antioxidants, and osmolytes under drought stress **(Ishfaq *et al*., 2024).**

The interaction between the irrigation level of 100% or 50% ETc and melatonin or thiourea, as well as the water level of 75% ETc and thiourea, produced the highest leaves dry matter in the first season, while in the second season using water level of 100% ET and sprayed with melatonin or tape water (control) recorded the highest leaves dry matter (Table 7). The highest bulb dry matter was obtained with a water level of 100%ETc sprayed with melatonin or thiourea, and the water level of 75% ETc sprayed with melatonin in the first season, whereas in the second season, the highest bulb dry matter was recorded with the water levels of 100% or 75% ETc sprayed with melatonin. Otherwise, the highest proline content was stated with the water level of 50%ETc sprayed with melatonin.

Table (7). Impact of different irrigation levels and foliar spray with melatonin and thiourea on leaves dry weight, bulb dry matter and proline content of garlic plant at 150 days after planting in two seasons of 2022/2023 and 2023/2024

Irrigation levels	treatments	Leaves dry matter%		Bulb dry matter %		Proline (µ mole/g)	
		2022	2023	2022	2023	2022	2023
100 % ETc		24.98	25.85	25.13	25.59	38.44	39.44
75 % ETc		22.12	22.13	23.60	24.10	42.44	43.78
50 % ETc		21.76	21.53	20.58	21.42	49.89	50.11
L.S.D. at 5%		**1.7**	**2.23**	**0.904**	**0.904**	**0.398**	**1.07**
	Melatonin	23.93	23.90	24.35	25.35	46.11	45.00
	Thiourea	24.03	23.43	22.85	23.31	43.44	45.33
	Control	20.90	22.19	22.11	22.44	41.22	43.00
L.S.D. at 5%		**2.03**	**1.21**	**0.545**	**0.545**	**0.484**	**0.839**
100 % ETc	**Melatonin**	26.17	26.63	25.96	26.96	36.00	36.67
	Thiourea	25.70	25.69	25.23	24.59	39.33	40.67
	Control	33.08	25.24	24.19	25.23	40.00	41.00
75% ETc	**Melatonin**	21.82	21.86	25.18	26.18	46.00	45.33
	Thiourea	23.20	22.56	21.79	24.29	40.67	44.00
	Control	21.35	21.97	21.82	21.82	40.67	42.00
50% ETc	**Melatonin**	23.81	23.20	21.92	22.92	56.33	53.00
	Thiourea	23.20	22.04	20.57	21.07	50.33	51.33
	Control	18.27	19.36	19.26	20.26	43.00	46.00
L.S.D. at 5%		**3.52**	**2.10**	**0.944**	**0.940**	**0.839**	**1.453**

Results illustrated that chlorophyll a and total chlorophyll content recorded the highest values with a water level of 75 % ETc in both seasons (Table 8). Whereas the highest values of chlorophyll b content were obtained with the water levels of 100% or 75% ETc in both seasons. Also, the highest carotenoid content was shown with the water level of 100% ETc in both studied seasons. The pigments content with the high rate of irrigation water (100% of ETc) through the critical growth period up to 140 days after planting is necessary for photosynthesis, which is important to growth and productivity **(Ghodke *et al*., 2018).** The reduction of chlorophyll content in stressed plants is a clear indicator of oxidative stress, which affects the chlorophyll synthesis (**Romdhane *et al*., 2020)**.

Table (8). Impact of different irrigation levels and foliar spray with melatonin and thiourea on chlorophyll a, chlorophyll b, total chlorophyll and carotenoid content of garlic plant at 150 days after planting in two seasons of 2022/2023 and 2023/2024

Irrigation levels	Treatments	Chlorophyll a (mg/g) f.w		Chlorophyll b (mg/g) f.w		Total Chlorophyll (mg/g) f.w		Carotenoids (mg/g) f.w	
		2022	2023	2022	2023	2022	2023	2022	2023
100 % ETc		0.580	0.594	0.198	0.204	0.778	0.798	0.916	0.921
75 % ETc		0.648	0.647	0.198	0.202	0.846	0.849	0.754	0.746
50 % ETc		0.495	0.488	0.181	0.180	0.676	0.668	0.506	0.522
L.S.D. at 5%		**0.022**	**0.013**	**0.012**	**0.017**	**0.027**	**0.026**	**0.028**	**0.012**
	Melatonin	0.643	0.636	0.211	0.210	0.854	0.845	0.999	1.011
	Thiourea	0.659	0.662	0.222	0.224	0.881	0.886	0.959	0.961
	Control	0.421	0.432	0.144	0.152	0.564	0.584	0.217	0.218
L.S.D. at 5%		**0.018**	**0.014**	**0.010**	**0.016**	**0.021**	**0.022**	**0.024**	**0.016**
100 % ETc	Melatonin	0.621	0.620	0.214	0.217	0.835	0.837	1.240	1.244
	Thiourea	0.663	0.676	0.244	0.253	0.907	0.929	1.220	1.231
	Control	0.457	0.486	0.137	0.143	0.593	0.629	0.287	0.290
75% ETc	Melatonin	0.780	0.756	0.228	0.225	1.008	0.981	0.995	0.988
	Thiourea	0.759	0.768	0.228	0.226	0.986	0.994	0.992	0.987
	Control	0.404	0.416	0.139	0.156	0.542	0.572	0.273	0.264
50% ETc	Melatonin	0.527	0.531	0.193	0.187	0.720	0.717	0.762	0.800
	Thiourea	0.555	0.540	0.196	0.195	0.751	0.735	0.665	0.665
	Control	0.402	0.394	0.156	0.158	0.558	0.552	0.091	0.100
L.S.D. at 5%		**0.031**	**0.023**	**0.012**	**0.028**	**0.037**	**0.038**	**0.041**	**0.013**

In general, water stress reduced chlorophyll (e.g., total Chl down to 0.55 mg/g) and carotenoids. Moderate stress 75% of ETc paradoxically maximized some pigments, suggesting adaptive hormesis. At an irrigation level of 100% of ET, the highest total chlorophyll content was recorded compared with other irrigation rates; it had the least effect on the light-receptor complexes on the thylakoid membrane, as demonstrated by enhanced photosynthesis (**Chaudhry *et al*., 2020**). On the other hand, oxidative stress is linked to reduced chlorophyll production, typically evidenced by a reduction in chlorophyll content in 50% of ETc-stressed plants (**Romdhane *et al.,* 2020**). Similarly, the negative consequences of water stress caused a decrease in carotenoid contents as reported by **Chaudhry *et al.* (2020).**

In Table 8 the highest values of chlorophyll a in the first season and chlorophyll b in the second season were recorded with the treatments of melatonin or thiourea, whereas the highest values of chlorophyll a and chlorophyll b in the second and first seasons were recorded with the thiourea treatments. The total chlorophyll content obtained with the thiourea content in both seasons. while the highest carotenoid content was recorded as a result of melatonin foliar application. The higher chlorophyll content indicates that melatonin enhances the plant photosystem **(Liang *et al.,* 2019).** Also, **Farag *et al.* (2020)** reported that melatonin application to plants increases cytokinin levels and a few associated signaling pathways, thereby improving photosynthetic efficiency and drought-induced tolerance. Furthermore, **Wang *et al*. (2013)** reported that melatonin increases the effectiveness of the photosystem and reduces the inhibition of photosynthesis caused by drought stress. It also enables the leaves to maintain a higher capacity for stomatal conductance and CO_2 assimilation. Thiourea is a sulphydryl chemical and an amino compound like urea stimulate many physiological processes in plants, as a nitrogenous compound can play vital to plants since it is a crucial part of chlorophyll **(Choudhary *et al*., 2018).** Otherwise, Thiourea is crucial to plant physiology since it is a sulphydryl chemical and, to some extent, an amino compound like urea. Many physiological processes in plants are known to be stimulated by thiourea. Nitrogen is vital to plants since it is a crucial part of chlorophyll **(Choudhary *et al.,* 2018).** The detrimental impacts of drought stress were considerably reduced by foliar spray of thiourea, which enhanced plant phenology, photosynthetic pigments, and yield characteristics. **Ishfaq *et al.* (2024).** In another study, **Ahmad *et al.* (2024)** reported that thiourea is one of the vital nutrients and plant growth regulators that help lessen the detrimental impacts of abiotic stress by reestablishing photosynthetic processes, particularly in adverse circumstances.

The irrigation level of 75% ETc sprayed with melatonin or thiourea gave the highest values of chlorophyll a and total chlorophyll in both seasons. Otherwise, the highest significant content of chlorophyll b was obtained with the water level of 100%ETc treated with thiourea in the first season, but in the second season, the highest values were obtained with a water level of 100%ETc treated with thiourea or a water level of 75% ETc treated with melatonin or thiourea (Table 8). The highest values of carotenoids were recorded with a water level of 100%ETc sprayed with melatonin or thiourea in the first season, while in the second season, the water level of 100% ETc treated with melatonin recorded the highest carotenoid value.

The data presented in Table 9 showed that a water level of 100%ETc gave the highest significant values of total yield, bulb weight and bulb diameter in both studied seasons. These enhancements in bulb characteristics with the high level of water 100%ETc may be due to the significant role of water in nutrient uptake and cell division, which led to bulb growth and development **(Ahmed and Kasem 2019).** Also, **Moustafa *et al.* (2024)** stated that the increase in total yield reflected the effect of water on promoting vegetative growth and bulb development. However, the high percentage of garlic bulb yield drop has been linked to stress at 50% ETc. In the same respect, different irrigation rates result in different soil water absorption and evapotranspiration **(Lipiec *et al.,* 2013).**

Table (9). Impact of different irrigation levels and foliar spray with melatonin and thiourea on total yield, bulb weight and bulb diameter of garlic plant at the harvest time in two seasons of 2022/2023 and 2023/2024

Irrigation levels	Treatments	Total yield ton/fed.		Bulb weight (g)		Bulb diameter (cm)	
		2022	2023	2022	2023	2022	2023
100 % ETc		8.13	7.66	82.06	78.28	5.33	5.33
75 % ETc		6.19	6.03	51.62	51.13	4.59	4.50
50 % ETc		3.87	3.42	31.58	31.84	3.60	3.53
L.S.D. at 5%		**0.468**	**0.694**	**0.939**	**1.095**	**0.31**	**0.36**
	Melatonin	6.78	6.19	60.16	57.32	4.87	4.79
	Thiourea	6.05	5.76	57.08	56.62	4.56	4.44
	Control	5.36	5.17	48.36	47.31	4.10	4.13
L.S.D. at 5%		**0.486**	**0.352**	**0.371**	**0.683**	**0.22**	**0.17**
100%ETc	Melatonin	8.14	7.43	86.37	80.73	5.60	5.97
	Thiourea	8.19	7.84	83.57	78.97	5.53	5.30
	Control	8.05	7.68	76.23	75.13	4.87	4.73
75% ETc	Melatonin	7.17	6.93	55.07	55.27	5.00	4.70
	Thiourea	6.34	6.27	56.23	57.83	4.57	4.47
	Control	5.06	4.89	43.90	40.30	4.20	4.33
50% ETc	Melatonin	5.04	4.16	39.03	35.97	4.00	3.70
	Thiourea	3.62	3.17	30.77	33.07	3.57	3.57
	Control	2.96	2.93	24.93	26.50	3.23	3.33
L.S.D. at 5%		**0.841**	**0.610**	**0.643**	**1.830**	**0.379**	**0.297**

In the same table, the highest significant level of total yield, bulb weight and bulb diameter were obtained with foliar application of melatonin at both seasons. In this respect, many studies have shown that melatonin has the capacity to regulate growth, delay senescence, and enhance plant resistance to abiotic stress by modifying physiological processes and strengthening antioxidant defense systems, both of which boost bulb quality and yield **(EL-Bauome *et al.,* 2024 andMansour *et al.,* 2024).**

The interaction between the water level of 100%ETc and all the sprayed treatments (melatonin, thiourea and tap water) recorded the heaviest total yield in both seasons (Table 9). Data also showed that the highest significant bulb weight was obtained with the interaction between a water level of 100%ETc and melatonin in both seasons. Regarding the highest bulb diameter recorded with a water level of 100%ETc sprayed with melatonin or thiourea in the first season, while in the second season, the highest values were recorded with the water level of 100%ETc sprayed with melatonin. Under drought stress treatment (50% ETc) melatonin and thiourea foliar application enhanced mitigation of drought as reflected in total yield, bulb weight and bulb diameter in both seasons.

The results in Table 10 illustrated that the water levels of 100% and 75% ETc gave the highest significant cloves number per bulb in the first season. The heaviest average clove weight was obtained with the water level 100%ETc at both seasons. Also, the highest WUE was recorded with the water level of 100%ETc in the first season, but in the second season, the highest values were obtained with the water levels of 100% and 75% ETc.

Table (10). Impact of different irrigation levels and foliar spray with melatonin and thiourea on cloves number per bulb, average cloves weight and WUE of garlic plant at the harvest time in two seasons of 2022/2023 and 2023/2024

Irrigation levels	Treatments	Cloves number/bulb		Average cloves weight (g)		WUE	
		2022	2023	2022	2023	2022	2023
100 % ETc		14.69	15.14	5.61	5.18	3.04	2.67
75 % ET		14.52	15.11	3.59	3.45	2.83	2.57
50 % ET		12.26	14.85	2.58	2.14	2.21	1.83
L.S.D. at 5%		**0.552**	**N.S**	**0.267**	**0.144**	**0.20**	**0.282**
	Melatonin	14.63	16.74	4.08	3.45	3.06	2.59
	Thiourea	14.33	15.44	3.88	3.69	2.67	2.37
	Control	12.51	12.92	3.82	3.64	2.33	2.11
L.S.D. at 5%		**0.647**	**0.459**	**0.19**	**0.121**	**0.24**	**0.148**
100 % ETc	**Melatonin**	15.00	15.77	5.77	5.12	3.04	2.60
	Thiourea	15.44	15.88	5.48	4.97	3.06	2.73
	Control	13.64	13.77	5.59	5.46	3.01	2.68
75% ETc	**Melatonin**	16.22	19.33	3.40	2.86	3.28	2.96
	Thiourea	15.89	14.33	3.52	4.04	2.90	2.68
	Control	11.44	11.66	3.85	3.46	2.31	2.09
50% ETc	**Melatonin**	12.66	15.11	3.09	2.38	2.87	2.22
	Thiourea	11.66	16.11	2.64	2.05	2.06	1.70
	Control	12.44	13.33	2.01	1.99	1.69	1.57
L.S.D. at 5%		**1.121**	**3.272**	**0.330**	**0.210**	**0.42**	**0.26**

Melatonin or thiourea treatments recorded the highest significant cloves number per bulb in the first season, whereas in the second season, melatonin only gave the highest value. The highest average clove weight was obtained with the melatonin in the first season, while in the second season, the highest values were obtained by thiourea or foliar spray with water. According to **Balai *et al.* (2017) and**

Choudhary *et al.* (2018), foliar application of thiourea increased the activity of carboxylating enzymes, photosynthetic rates, translocation and accumulation of metabolites in the sink, and ultimately increased garlic yield and its quality. The highest WUE was observed in melatonin treatment in both seasons (Table 10). Application of melatonin improved the stomatal and trichome characteristics, thereby resulting in increased WUE through partial stomatal closure, which is essential for improving crop productivity **(Armero *et al.,* 2018).** The result coincides with the findings of **Mumithrakamatchi *et al*. (2024).**

The highest significant cloves number per bulb obtained by the interaction between water level 100%of ETc with thiourea or 75% of ETc with the foliar spray of melatonin or thiourea in the first season, while in the second season the interaction between the water level 75% of ETc and melatonin. Table 10 data showed that the highest significant average clove weight was obtained with the irrigation level 100% of ETc with all the foliar application treatments (melatonin, thiourea or tap water as control) in the first season, whereas the highest values were obtained with the water level 100% of ETc sprayed with tap water (control). The highest significant value of WUE were recorded with the water level 100% of ETc sprayed with melatonin, thiourea or tape water also, with the water level 75% of ETc sprayed with melatonin or thiourea and with the water level 50% of ETc sprayed with melatonin though the first season while in the second season the highest WUE recorded with the water level 100% of ETc sprayed with thiourea or control and also the water level 75% of ETc sprayed with melatonin.

The data presented in Table 11 showed that the highest bulb dry matter, pungency, and total carbohydrates were recorded with a water level of 100% of ETc in both seasons. Irrigation rate at 100% of ETc improved nutrient availability absorption, which increased plant height and leaf number, thereby increasing photosynthate production and subsequent accumulation, increasing bulb dry matter content **(Ghule *et al*., 2013) and (Moustafa *et al*., 2024).**

Table (11). Impact of different irrigation levels and foliar spray with melatonin and thiourea on bulb dry weight, pungency and total carbohydrates of garlic plant at the harvest time in two seasons of 2022/2023 and 2023/2024

Irrigation levels	treatments	Bulb dry matter (%)		Pungency (µmol/ml)		Total carbohydrates (%)	
		2022	2023	2022	2023	2022	2023
100 % ETc		31.50	31.39	38.34	37.18	26.57	27.81
75 % ETc		29.50	28.82	37.05	36.10	25.64	26.24
50 % ETc		26.19	26.56	35.98	35.62	23.94	25.02
L.S.D. at 5%		**1.56**	**1.11**	**0.794**	**0.37**	**0.71**	**1.22**
	Melatonin	30.39	29.65	37.47	36.62	27.00	27.34
	Thiourea	29.15	28.99	37.20	36.24	25.21	26.19
	Control	28.12	28.13	36.70	36.05	23.93	25.53
L.S.D. at 5%		**0.87**	**0.53**	**0.61**	**0.49**	**0.911**	**0.53**
100% ETc	**Melatonin**	33.15	32.91	36.63	37.58	27.43	27.91
	Thiourea	31.71	30.65	35.33	37.01	26.61	28.23
	Control	30.14	30.61	35.98	36.98	25.67	27.29
75% ETc	**Melatonin**	29.47	28.58	36.96	37.33	27.29	28.59
	Thiourea	29.69	29.91	38.97	34.91	25.17	25.53
	Control	29.33	27.97	39.09	36.06	24.35	24.59
50% ETc	**Melatonin**	27.64	27.46	36.49	34.95	26.29	25.53
	Thiourea	26.06	26.41	38.11	36.78	23.75	24.82
	Control	24.9	25.81	36.54	35.13	21.78	24.70
L.S.D. at 5%		**1.5**	**0.92**	**1.06**	**0.848**	**1.58**	**0.91**

The pungency content increases when the alliinase enzyme interacts with precursors collectively known as Allyl cysteine sulfoxide, which is expressed as pyruvic acid **(Magray, 2015)**. Higher moisture levels in the root zone improved nutrient solubility in the soil, leading to greater mineral uptake by the plants, which caused a favorable effect on the pyruvic acid content of bulbs **(Silabut *et al*., 2014).** Furthermore, the increase in carbohydrate content in the bulb is a good indicator of a high rate of photosynthesis, a plentiful supply of carbohydrates available for growth and an excess of dry matter accumulation, which reflects the best yield quantity and quality **(Mustafa *et al*., 2017).**

The foliar application with melatonin recorded the highest significant bulb dry matter, pungency and total carbohydrates in both studied seasons, without significant differences between melatonin and thiourea in pungency content in both seasons (Table 11). Similarly, **Jafari and Shahsavar (2021)** stated that the foliar application of melatonin promotes the synthesis of appropriate soluble carbohydrates, and preserves the stability of the plant membrane.

Regarding the interaction between irrigation levels and foliar spray with melatonin, thiourea or tap water. Data in Table 11 showed that the water level100% of ETc, sprayed with melatonin or thiourea, recorded the highest bulb dry matter in the first season only, while in the second season, the water level 100% of ETc, sprayed with melatonin, recorded the highest values. The highest concentration of pungency was obtained with 75% ETc treated with thiourea or tap water and with50% of ETc treated with thiourea in the first season, whereas the highest values of pungency were found with a water level 100% of ETc with melatonin or thiourea or tap water (control) and 75% of ETc sprayed with melatonin in the second season. The highest content of carbohydrates was stated with 100% of ETc treated with melatonin or thiourea, 75% and 50% of ETc treated with melatonin in the first season, while in the second season the highest significant values of carbohydrates were recorded with 100% treated with melatonin, thiourea or tap water (control) and 75% of ETc sprayed with melatonin.

An inverse relationship between the water level percent of ETc and the weight loss under storage conditions after four and seven months (Table 12). The lowest weight loss was recorded at a water level of 100%ETc in both seasons. Stress increased post-harvest weight loss (up to 34% after 7 months at 50% ETc).

Table (12). Impact of different irrigation levels and foliar spray with melatonin and thiourea on the weight loss percentage after four and seven months of storage in two seasons of 2022/2023 and 2023/2024

Irrigation levels	treatments	Weight loss % after four months of storage		Weight loss % after seven months of storage	
		2022	2023	2022	2023
100% ETc		17.18	19.46	26.69	28.71
75% ETc		20.69	22.09	28.91	31.88
50 % ETc		22.00	23.97	30.01	32.72
L.S.D. at 5%		**0.464**	**0.876**	**0.530**	**0.777**
	Melatonin	18.38	21.18	27.67	29.47
	Thiourea	20.42	21.94	28.46	31.05
	Control	21.06	22.43	29.48	32. 78
L.S.D. at 5%		**0.622**	**0.511**	**0.399**	**0.538**
100% ETc	**Melatonin**	15.57	18.82	24.59	26.96
	Thiourea	17.26	20.30	27.60	28.76
	Control	18.72	19.25	27.88	30.41
75% ETc	**Melatonin**	19.05	22.33	28.61	30.90
	Thiourea	20.99	21.24	28.89	30.96
	Control	22.02	22.70	29.22	33.76
50% ETc	**Melatonin**	20.52	22.38	29.80	30.56
	Thiourea	23.04	24.19	28.89	33.44
	Control	22.43	25.34	**31.35**	**34.16**
L.S.D. at 5%		**1.08**	**0.885**	**0.690**	**0.931**

Melatonin caused the lowest weight loss after four and seven months under storage conditions in both seasons of the study (Table 12). Melatonin functions as a potent post-harvest therapy to extend the shelf life and storage capacity by preventing weight loss and decay, it maintains quality and is frequently useful **(Kakaei *et al.,* 2024).**

The interaction between different irrigation levels and the foliar application illustrated that after four months of storage, 100% of ETc treated with melatonin recorded the lowest weight loss in the first season while in the second one the lowest values were obtained with 100% of ETc sprayed with melatonin and control (Table 12). Otherwise, the lowest significant weight loss in the seven months of the store was recorded with 100% of ETc sprayed with melatonin, which minimized the weight loss to 15-25%. This ties to higher dry matter and carbohydrates, reducing respiration and shrinkage after seven months of storage.

4. Conclusion

The results of this study proved that irrigation at 100% of evapotranspiration (ET) which equal 1468.36 m^3 water/ fed., as average of the two seasons with melatonin (50 mg/l), followed by 100% Etc with thiourea (5 mM), resulted in optimal plant growth and yield characteristics. Irrigation at 50% ET which equals 891.46 m^3 water/ fed, as average of the two seasons with melatonin (50 mg/l), caused a significant rise in leaf proline concentration, indicating a defensive response to oxidative damage. 75% ETc irrigation level (1180.06 m^3 water/fed. as average of the seasons) with melatonin (50 mg/l) increased water use efficiency. Both melatonin and thiourea improve plant resilience and antioxidant capacity, presenting effective strategies for sustaining garlic productivity in arid and semi-arid regions with water scarcity.

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