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Improving drought tolerance of *Leucophyllum frutescens* through the application of paclobutrazol and cycocel plant growth regulators

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Abstract: *Leucophyllum frutescens* is an evergreen shrub renowned for its drought tolerance. Paclobutrazol (PBZ) and cycocel (CCC) growth retardants were applied as foliar spray on *L. frutescens* plants cultivated in pots to assay the possibility of increasing these plants' tolerance to water stress while maintaining high quality. The experiment was accomplished under full sun in the open field of the Nursery of Ornamental Plants and Landscape Gardening Res. Dept., Hort. Res. Inst., ARC, Egypt during the 2022 and 2023 seasons. Different concentrations of PBZ at 50, 100 and 150 ppm and CCC at 1000, 2000 and 3000 ppm were combined with 100, 75 and 50% pot capacity (P.C.) irrigation water levels, and some morphological, chemical and tolerance indices were examined. The obtained results showed a great reduction in all studied parameters except for proline content due to reduced irrigation levels. All growth retardants applied increased the values over control except for plant height and fresh weight of 10 flowers. Regarding the interaction treatments, the highest concentration of PBZ (150 ppm) and CCC (3000) produced the highest values in most cases when combined with both 75 and 50% irrigation water levels. Such treatments increased the number of main and lateral branches/plant, fresh and dry weights of vegetative growth and roots and root length, while mediated values were obtained for chemical constituents. Water use efficiency, relative stress index and stress tolerance index are also, greatly enhanced by such treatments. Cycocel at 3000 ppm could be recommended to treat *Leucophyllum frutescens* plants cultivated in 30 cm pots and subjected to only 50% irrigation water level as this treatment demonstrated good performance with high stress tolerance index to drought.

1. Introduction

Leucophyllum frutescens (syn., *Leucophyllum texanum*) is native to Southwestern Texas and northeastern Mexico so it is known as Texas

Ranger or Texas-sage. It belongs to the family *Scrophulariaceae* and is considered the largest species in the genus *Leucophyllum*. The plant is an evergreen shrub with silver-grey foliage that reaches 2.0 meters in height and 2.5 meters in spread. The foliage is soft to the touch, and densely clustered along spreading branches. The leaves are small measuring 2.50 × 1.25 cm and broaden at the tip. The flowers are bell-shaped and range from white to pink to purple with up to 2.5 cm long. The plants bloom well in summer when the temperature and humidity are high. Texas Ranger is a popular choice for hedges, specimens, visual screening and wind control and could certainly be used as an accent plant (Mielke, 1993). *Leucophyllum frutescens* has recently been cultivated extensively in Egypt due to its reputation for drought and salinity tolerance, although more research is needed to substantiate this. Younis *et al.* (2017) found that, compared to other landscape plants, *L. frutescens* shows strong potential as it requires minimal water. In this context, Ashour and El-Attar (2017) concluded that *L. frutescens* can be irrigated with tap water every 10 days, and saline water at 2000 ppm can be used every 4 days without an obvious reduction in plant growth and quality.

Water insufficiency is a serious challenge affecting many countries worldwide. To address this issue the strategy of minimizing water use could be adopted, particularly in areas where it is not essential, such as the irrigation of green open spaces and landscape plants. Deister (2013) reported that, in Egypt, open and privately owned areas consume very high amounts of irrigation water (4.76-7.14 l/m²/day and 7.14 -11.9 l/m²/day, respectively) compared with other countries. To reduce the water consumption for open areas and landscape plants, selecting species with low water requirements or increasing the tolerance of the cultured species by different available means is required.

Research has demonstrated that plant growth regulators (PGRs), particularly growth-retarding types, can significantly improve drought tolerance in various plant species through multiple physiological mechanisms. These compounds help plants withstand water deficit conditions by: (1) strengthening antioxidant defenses against oxidative stress caused by drought (Abbasi *et al.*, 2015; Singh *et al*., 2016); (2) controlling stomatal function (Marshall *et al*., 1991; Dehghanzadeh and Adavi, 2023); (3) facilitating osmotic adjustment via accumulation of protective compounds like proline (Waqas *et al.,* 2017) and (4) improving water acquisition through enhanced root growth relative to shoot biomass (Fletcher *et al*., 2000).

Paclobutrazol (PBZ) inhibits gibberellin biosynthesis and subsequently limits stem elongation (Tesfahun, 2018). PBZ has been shown to help safeguard various crops against a range of environmental stresses, such as drought. Paclobutrazol (PBZ) has proven effective for drought mitigation in plants across multiple studies: *Robinia pseudoacacia* (Thakur *et al*., 2000); hybrid poplar and birch (ZhongZhu and XiangWei, 2006); *Lonicera implexa* (Navarro *et al.*, 2008); *Bougainvillea* spp. (Ting *et al*., 2014); *Odontonema strictum* (Rezazadeh *et al*., 2016); *Petunia* (Hatamifar and Samani, 2017); *Sequoia sempervirens* (Shu-ming *et al*., 2020); and *Salvia officinalis* (Maghsoudi *et al*., 2023).

Cycocel (CCC), a plant growth regulator valued for its low toxicity and broad crop effectiveness, can be absorbed by both roots and leaves. Cycocel is used to restrict plant growth while enhancing the harvest index through increased enzymatic activity, leaf thickness, pigment levels, and assimilation efficiency. Spraying cotton with 500 ppm of CCC resulted in higher chlorophyll and relative water content, along with improved nutrient uptake and a reduction in leaf size (Dhopte and Lall, 1987). Drought-protective effects of CCC have been documented in: sunflower (Kumari and Bharti, 1992); groundnut (Mathew and Pandey, 2006); barley (Sharif *et al*., 2007; Afkari and Ghaffari, 2018); Japanese mint (Mathur and Farooqi, 2009); olive (Memari *et al*., 2011; Akbari *et al*., 2015); safflower (Partovian *et al*., 2013); basil (Estakhroeih and Babaei, 2016); chickpea (Safari and Azadikhah, 2021); and wheat (Dehghanzadeh and Adavi, 2023).

This study hypothesized that foliar application of paclobutrazol (PBZ) and cycocel (CCC) at optimized concentrations would enhance water stress tolerance in potted *Leucophyllum frutescens*, while preserving morphological and physiological quality markers. This improvement is anticipated to be evident across varying irrigation regimes, with PBZ and CCC mitigating drought-induced damage through growth regulation and osmotic adjustment mechanisms.

2. Materials and Methods

The experiment was accomplished on *Leucophyllum frutescens* (Berland.) I.M. Johnst. shrubs in the open field under full sun at the Nursery of Ornamental Plants and Landscape Gardening Res. Dept., Hort. Res. Inst., ARC, Egypt, during the spring to autumn of 2022 and 2023 seasons to assay the possibility of increasing these plants' tolerance to water stress by applying foliar spraying with paclobutrazol (PBZ) and Cycocel (CCC) at different concentrations under different irrigation water levels.

Plant material

In the first week of March each season, well-developed healthy transplants of *L. frutescens* (30-35 cm height and 3 main branches) were acquired from a private nursery at Shibin El Qanater, Qalyubia governorate, Egypt. The transplants were planted in 30-diameter plastic pots (1 plant/pot) filled with 5.5 kg loamy soil. The analysis of the experiment's growing medium and meteorological parameters are shown in Tables 1 and 2. For complete establishment, the plants were left for about one month at the nursery to supply them with the original water amount and required maintenance.

Experimental layout

A factorial experiment with two factors in a randomized complete block design (RCBD) as reported by Gomez and Gomez (1984) was utilized to lay out this pot experiment. Three irrigation levels at 100, 75 and 50% of pot capacity were represented as factor A, while factor B included seven foliar spray treatments, three concentrations of paclobutrazol (PBZ: 50, 100, and 150 ppm), three concentrations of cycocel (CCC: 1000, 2000, and 3000 ppm), and an untreated control (0 ppm PBZ or CCC). Consequently, the present experiment contained 21 treatments (3 irrigation levels × 7 foliar spraying with growth retardants), each treatment was replicated three times, and each replicate contained 5 pots.

Irrigation water treatments

Different water irrigation levels were applied one month after transplantation (on the first week of April each season) as a percentage (100, 75, 50%) of pot capacity (the equivalent of field capacity for soils in pots). The weighing method described by Brown

Table 1 - Physical and chemical analyses of the used soil

Soil type	Particle size distribution (%)			S.P. (%)	E.C. (dS/m)	pH	Cations (meq/l)				Anions (meq/l)		
	Sand	Silt	Clay				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	HCO_3	Cl^{-}	SO_4^{--}
Loamy	48.0	35.5	16.5	44.0	1.36	8.28	3.5	2.5	6.63	0.65	0.5	7.5	5.28

S.P. = Saturation percentage; E.C. = Electrical conductivity.

Table 2 - Some meteorological parameters at Giza governorate during the experiment period of 2022 and 2023 seasons

Months	2022						2023					
	Temperature (°C)			R.H. (%)	W.S. (m/s)	Precip. (mm/d)	Temperature (°C)			R.H. (%)	W.S. (m/s)	Precip. (mm/d)
	Avg.	Max.	Min.				Avg.	Max.	Min.			
March	13.39	28.98	2.40	59.98	3.02	1.30	17.46	32.65	6.97	54.11	2.67	0.19
April	21.82	40.00	8.51	44.97	3.20	0.00	21.03	36.58	8.64	45.51	2.88	0.10
May	25.06	41.25	11.75	39.75	3.37	0.00	25.08	38.39	11.69	42.51	3.43	0.03
June	29.24	44.30	17.36	42.11	3.24	0.00	29.30	42.56	18.42	39.58	3.50	0.04
July	29.91	40.61	19.26	42.45	3.02	0.06	31.52	43.89	20.49	40.54	3.23	0.00
August	30.32	41.90	21.25	46.09	3.06	0.06	30.86	43.53	20.66	44.56	3.21	0.00
Septemb	28.43	39.48	18.87	49.15	3.12	0.13	29.62	43.48	19.82	45.29	2.87	0.00
October	23.80	39.56	15.76	57.68	2.72	0.18	25.10	35.81	17.19	58.10	2.59	1.71

RH= Relative humidity at 2 meters; WS= Wind speed at 2 meters; Precip.: Precipitation.
Power Data Access Viewer Program of NASA was utilized to collect daily data, and then the data were averaged monthly to fit the experiment period (https://power.larc.nasa.gov).

(2002) was adopted to determine water pot capacity. The plants were irrigated three times a week. The amount of water applied/pot/irrigation and the total water applied/pot/season (6 months/season) is shown in Table 3.

Table 3 - Amount of water applied for each pot (l/pot)

Irrigation level (% of pot capacity)	For each irrigation (l/pot)	Total water applied each season (l/pot)
100%	0.820	59.040
75%	0.615	44.280
50%	0.410	29.520

Foliar spraying with growth retardants

Both paclobutrazol (PBZ) and cycocel (CCC) were dissolved in distilled water to present solutions with the applied concentrations (50, 100 and 150 ppm for PBZ and 1000, 2000 and 3000 ppm for CCC). In this study, plants that did not receive foliar spray application of growth retardants served as the control treatment. Plants received six foliar applications of PBZ or CCC (at specified concentrations) at monthly intervals, with each treatment applied to runoff (defined as the first appearance of solution droplets from leaf margins, indicating full surface coverage and absorption saturation). The first application was done in the first week of April each season. Paclobutrazol ($C_{15}H_{20}ClN_3O$, MW: 293.80) and cycocel (chlormequat chloride; $C_5H_{13}Cl_2N$, MW: 158.10) were obtained from a local company in Egypt.

Data recorded

At the beginning of October each season the following data and measurements were done:

Vegetative growth and flowers. Plant height (cm), number of main branches/plant (emerged on main stems), number of lateral branches/plant (emerged on main branches), vegetative growth fresh and dry weights (g) and fresh weight of 10 flowers (g).

Root system parameters. At the end of this study, plants were extracted by tilting the pots and tapping the bases until the root balls released. Roots were cleaned through sequential shaking, low-pressure washing, and soft brushing to remove all soil while preserving root architecture. The following parameters were recorded on the clean extracted roots: root system length (cm) and fresh and dry weights of the root system (g).

Chemical composition analysis. Chlorophylls a+b (mg/g f.w.) and carotenoids (mg/g f.w.) in fresh leaves according to Wellburn and Lichtenthaler (1984), total carbohydrates (%) in dry leaves according to Herbert *et al.* (1971), proline (mg/g d.w.) in dry leaves according to Bates *et al.* (1973). These determinations were done in the second season only.

Water use efficiency and stress indices. Water use efficiency (WUE) g/l according to Karkanis *et al.* (2011), relative stress index (RSI) according to Fischer and Wood (1979), and Stress tolerance index (STI) according to Fernandez (1993). The following equations were adopted based on the aerial parts dry mass of plants subjected to different treatments:

$$\text{WUE (g/l)} = D/A.$$
$$\text{RSI} = (Dp/Ds)/(Xs/Xp)$$
$$\text{STI} = (Dp \times Ds)/Xp^2$$

Where D: dry mass of aerial parts (g) whether under normal or water stress conditions, A: amount of water applied per pot (l) during the experiment, Dp: dry mass of aerial parts of plants of each treatment under normal water conditions, Ds: dry mass of aerial parts of plants of each treatment under water stress conditions, Xp: mean dry mass of aerial parts for all plants under normal conditions and Xs: mean dry mass of aerial parts for all plants under stress conditions.

Statistical analysis

MSTAT Computer Program (MSTAT, 1989) was used to statistically analyze the obtained data by applying an ANOVA test for the two-factor experiment in RCBD (Gomez and Gomez, 1984). The means were compared using Duncan's Multiple Range Test as described by (Duncan, 1955).

3. Results

Vegetative growth and flower parameters:

Different irrigation water levels showed a significant influence (Tables 4 and 5). Reducing water levels gradually caused a reduction in all studied vegetative growth and flowers. The lowest values were obtained by the lowest irrigation water level for plant height (86.00 and 77.05 cm), number of main branches/plant (12.86 and 15.62), number of lateral

Table 4 - Effect of water irrigation levels and two plant growth retardants on plant height (cm), number of main branches/plant and number of lateral branches/plant of Leucophyllum frutescens during two seasons of 2022 and 2023

Treatments	Plant height (cm)		Number of main branches/plant		Number of lateral branches/plant	
	1st season	2nd season	1st season	2nd season	1st season	2nd season
Water irrigation levels						
100% P.C.	117.30 a	114.60 a	16.00 a	19.24 a	47.90 a	52.90 a
75% P.C.	100.30 b	90.50 b	14.33 b	17.00 b	41.29 b	45.81 b
50% P.C.	86.00 c	77.05 c	12.86 c	15.62 c	33.05 c	37.48 c
Growth retardants						
Control	115.90 a	110.30 a	6.78 f	8.67 f	19.67 f	20.89 e
PBZ 50 ppm	117.80 a	100.70 b	10.33 e	13.22 e	30.33 d	31.78 d
PBZ 100 ppm	102.30 c	94.33 c	15.44 c	16.67 c	45.67 c	52.44 c
PBZ 150 ppm	94.44 d	91.89 d	19.67 a	23.22 a	54.33 b	61.33 b
CCC 1000 ppm	108.40 b	90.00 e	12.33 d	14.67 d	26.67 e	31.56 d
CCC 2000 ppm	88.22 e	86.78 f	16.78 b	20.78 b	47.11 c	51.22 c
CCC 3000 ppm	81.33 f	84.33 g	19.44 a	23.78 a	61.44 a	68.56 a

P.C. = Pot capacity.
Means within a season followed by the same letter are not significantly different ($p>0.05$) according to Duncan (1955).

Table 5 - Effect of water irrigation levels and two plant growth retardants on vegetative growth fresh weight (g), vegetative growth dry weight (g) and fresh weight of 10 flowers (g) of *Leucophyllum frutescens* during two seasons of 2022 and 2023

Treatments	Vegetative growth fresh weight		Vegetative growth dry weight (g)		Fresh weight of 10 flowers (g)	
	1st season	2nd season	1st season	2nd season	1st season	2nd season
Water irrigation levels						
100% P.C.	194.10 a	206.10 a	50.83 a	58.36 a	1.36 a	1.51 a
75% P.C.	159.70 b	172.80 b	42.64 b	47.08 b	1.24 b	1.35 b
50% P.C.	131.50 c	139.20 c	32.09 c	35.83 c	1.08 c	1.19 c
Growth retardants						
Control	99.98 e	109.20 f	24.78 f	27.04 g	1.08 d	1.22 d
PBZ 50 ppm	125.40 d	138.00 e	33.19 d	38.54 e	1.09 d	1.23 d
PBZ 100 ppm	166.40 c	179.50 d	44.02 c	51.66 d	1.22 c	1.31 c
PBZ 150 ppm	204.10 ab	213.70 b	50.28 b	58.11 b	1.30 b	1.42 ab
CCC 1000 ppm	127.40 d	138.60 e	29.97 e	34.35 f	1.28 b	1.37 bc
CCC 2000 ppm	199.80 b	208.80 c	49.83 b	55.58 c	1.28 b	1.40 b
CCC 3000 ppm	209.40 a	221.20 a	60.93 a	64.33 a	1.35 a	1.48 a

P.C. = Pot capacity.
Means within a season followed by the same letter are not significantly different ($p>0.05$) according to Duncan (1955).

branches/plant (33.05 and 37.48), vegetative growth fresh weight (131.50 and 139.20 g), vegetative growth dry weight (32.09 and 35.83 g) and fresh weight of 10 flowers (1.08 and 1.19 g) in both seasons, respectively.

Foliar spraying with paclobutrazol and cycocel at various concentrations generally reduced plant height, except for paclobutrazol at 50 ppm, which unexpectedly insignificantly increased plant height in the first season (117.80 cm) compared to the control untreated plants (115.90 cm). Notably, cycocel at 3000 ppm resulted in the lowest plant height values for both seasons, measuring 83.33 and 84.33 cm, respectively. Regarding other vegetative growth characteristics, cycocel at 3000 ppm, followed by paclobutrazol at 150 ppm, resulted in the highest values. However, an exception occurred with paclobutrazol at 150 ppm, which produced the highest number of main branches per plant (19.67) in the first season only, surpassing cycocel at 3000 ppm (19.44 main branches/plant). The highest values obtained by foliar spraying with cycocel at 3000 ppm were 23.78 for number of main branches/plant (in the second season only), then 61.44 and 68.56 for number of lateral branches/plant, 209.40 and 221.20 g for vegetative growth fresh weight, 60.93 and 64.33 g for vegetative growth dry weight and 1.35 and 1.48 g for fresh weight of 10 flowers in both seasons, respectively (Tables 4 and 5).

Regarding the interaction between irrigation water levels and plant growth retardants, there was a great influence on vegetative growth and flowering traits (Tables 6 and 7). The different treatments greatly influenced plant height. The tallest plants were obtained either by the control (without foliar spraying with growth retardants) or with paclobutrazol at 50 ppm, when both of them were combined with the 100% irrigation water level. In the first season, these two combined treatments resulted in plant heights of 140.30 and 136.70 cm, respectively, while in the second season, the heights were 150.30 and 127.80 cm, respectively. The shortest plants were obtained by cycocel at 2000 ppm (71.00 and 71.50 cm in both seasons, respectively) and cycocel at 3000 ppm (72.00 and 96.17 cm in both seasons, respectively) when combined with the lowest water level (50%). Despite plant height, cycocel at 3000 ppm resulted in the highest values on the other characteristics when combined with the irrigation water level of 100%

Table 6 - Effect of interaction between water irrigation levels and two plant growth retardants on plant height (cm), number of main branches/plant and number of lateral branches/plant of *Leucophyllum frutescens* during two seasons of 2022 and 2023

Growth retardants	Water irrigation levels					
	100% P.C.	75% P.C.	50% P.C.	100% P.C.	75% P.C.	50% P.C.
	1st season			2nd season		
Plant height (cm)						
Control	140.30 a	115.70 cd	91.63 hi	150.30 a	98.17 f	82.33 kl
PBZ 50 ppm	136.70 a	114.00 cd	102.70 f	127.80 b	93.67 g	80.67 lm
PBZ 100 ppm	117.70 bc	100.30 fg	89.00 h-j	110.50 c	92.00 gh	80.50 lm
PBZ 150 ppm	110.00 de	93.00 hi	80.33 k	106.00 d	90.50 hi	79.17 m
CCC 1000 ppm	123.00 b	107.00 ef	95.33 gh	105.00 d	89.00 ij	76.00 n
CCC 2000 ppm	105.30 ef	88.33 ij	71.00 l	102.20 e	86.67 j	71.50 o
CCC 3000 ppm	88.00 ij	84.00 jk	72.00 l	100.30 ef	83.50 k	69.17 o
Number of main branches/plant						
Control	7.67 k	6.67 k	6.00 k	9.33 j	9.00 jk	7.67 k
PBZ 50 ppm	14.00 gh	9.67 j	7.33 k	16.00 gh	12.33 i	11.33 i
PBZ 100 ppm	17.67 de	15.33 fg	13.33 h	20.67 ef	14.67 h	14.67 h
PBZ 150 ppm	20.33 a	19.67 a-c	19.00 a-d	24.33 ab	23.33 b-d	22.00 de
CCC 1000 ppm	13.67 gh	12.33 hi	11.00 ij	16.67 g	16.00 gh	11.33 i
CCC 2000 ppm	18.33 b-e	16.67 ef	15.33 fg	22.67 cd	20.00 f	19.67 f
CCC 3000 ppm	20.33 a	20.00 ab	18.00 c-e	25.00 a	23.67 a-c	22.67 cd
Number of lateral branches/plant						
Control	29.33 kl	18.00 o	11.67 p	27.33 hi	23.00 i	12.33 j
PBZ 50 ppm	39.00 hi	33.00 jk	19.00 no	40.33 fg	33.67 gh	21.33 i
PBZ 100 ppm	57.00 cd	45.33 g	34.67 ij	64.33 bc	50.00 d	43.00 ef
PBZ 150 ppm	62.33 ab	58.00 b-d	42.67 gh	69.67 b	64.67 bc	49.67 de
CCC 1000 ppm	29.67 j-l	27.00 lm	23.33 mn	34.67 g	33.67 gh	26.33 i
CCC 2000 ppm	50.67 ef	46.00 fg	44.67 g	53.33 d	52.67 d	47.67 de
CCC 3000 ppm	67.33 a	61.67 bc	55.33 de	80.67 a	63.00 bc	62.00 c

P.C. = Pot capacity.
Within each season, values sharing the same letter across water levels and growth retardant treatments indicate no significant difference

Table 7 - Effect of interaction between water irrigation levels and two plant growth retardants on vegetative growth fresh weight (g), vegetative growth dry weight (g) and fresh weight of 10 flowers (g) of *Leucophyllum frutescens* during two seasons of 2022 and 2023

Growth retardants	Water irrigation levels					
	100% P.C.	75% P.C.	50% P.C.	100% P.C.	75% P.C.	50% P.C.
	1st season			2nd season		
Vegetative growth fresh weight (g)						
Control	134.40 g	100.90 h	64.70 j	141.60 h	112.20 i	73.72 k
PBZ 50 ppm	165.50 f	130.70 g	80.14 i	180.40 f	139.40 h	94.35 j
PBZ 100 ppm	196.00 cd	172.20 f	131.20 g	221.20 cd	174.80 f	142.70 h
PBZ 150 ppm	234.60 b	205.60 c	172.10 f	250.30 b	228.40 c	162.50 g
CCC 1000 ppm	128.30 g	127.20 g	126.70 g	141.00 h	137.40 h	137.30 h
CCC 2000 ppm	241.70 b	187.80 de	169.90 f	242.70 b	202.00 e	181.90 f
CCC 3000 ppm	258.50 a	193.90 cd	175.80 ef	265.80 a	215.60 d	182.30 f
Vegetative growth dry weight (g)						
Control	32.10 i	22.63 lm	19.62 m	34.21 ij	24.36 l	22.54 l
PBZ 50 ppm	50.73 ef	29.95 ij	18.90 m	58.40 d	32.68 ij	24.55 kl
PBZ 100 ppm	52.53 d-f	48.37 f	31.15 ij	66.15 bc	53.11 ef	35.74 i
PBZ 150 ppm	57.62 c	56.00 cd	37.22 h	68.35 b	64.89 bc	41.08 h
CCC 1000 ppm	37.90 h	27.07 jk	24.94 kl	43.39 h	31.63 j	28.03 k
CCC 2000 ppm	55.05 c-e	51.97 d-f	42.48 g	62.78 c	56.63 de	47.32 g
CCC 3000 ppm	69.90 a	62.53 b	50.35 f	75.24 a	66.22 bc	51.52 f
Fresh weight of 10 flowers (g)						
Control	1.28 e-g	1.07 l	0.89 m	1.48 bc	1.18 ij	0.99 k
PBZ 50 ppm	1.25 f-h	1.10 kl	0.93 m	1.39 c-f	1.23 g-i	1.07 jk
PBZ 100 ppm	1.33 de	1.21 g-i	1.13 j-l	1.41 b-e	1.32 d-h	1.21 hi
PBZ 150 ppm	1.36 b-d	1.34 c-e	1.19 h-j	1.53 ab	1.43 b-e	1.30 e-i
CCC 1000 ppm	1.39 b-d	1.25 f-h	1.19 h-j	1.52 bc	1.35 d-g	1.25 g-i
CCC 2000 ppm	1.42 b	1.32 d-f	1.08 kl	1.54 ab	1.44 b-d	1.22 g-i
CCC 3000 ppm	1.50 a	1.41 bc	1.15 i-k	1.66 a	1.52 b	1.27 f-i

P.C. = Pot capacity.
Within each season, values sharing the same letter across water levels and growth retardant treatments indicate no significant difference ($p>0.05$) according to Duncan's multiple range test (Duncan, 1955).

P.C., this was followed significantly or insignificantly with other treatments e.g. cycocel at 3000 ppm + 75% water level, paclobutrazol at 150 ppm + 100% water level and paclobutrazol at 150 ppm + 75% water level. In this regard, cycocel at 3000 ppm + 75% water level resulted in intermediate values 20.00 and 23.67 for number of main branches/plant, 61.67 and 63.00 for number of lateral branches/ plant, 193.90 and 215.60 g for vegetative growth fresh weight, 62.53 and 66.22 g for vegetative growth dry weight and 1.41 and 1.52 g for fresh weight of 10 flowers in both seasons, respectively. The lowest values (except for plant height) were obtained by the lowest irrigation water level (50%) when the plants were deprived of growth retardants or sprayed with paclobutrazol at 50 ppm.

Although plants treated with the highest concentrations of PBZ (150 ppm) and CCC (3000 ppm) under the lowest irrigation level (50%) did not achieve the highest values for vegetative growth and flower parameters, these values were still relatively high compared to plants exposed to the three irrigation levels without foliar application of PBZ and CCC, except for plant height and the fresh weight of 10 flowers.

Root system parameters

Table 8 showed that both irrigation levels at 100 and 75% resulted in the longest roots without significant differences between them (48.88 and 55.79 cm for 100% and 47.74 and 55.91 cm for 75%, in both seasons, respectively). the highest water level (100%) produced the highest fresh weight of root system (47.40 and 54.83 g) and dry weight of root

Table 8 - Effect of water irrigation levels and two plant growth retardants on root system length (cm), root system fresh weight (g) and root system dry weight (g) of *Leucophyllum frutescens* during two seasons of 2022 and 2023

Treatments	Root system length (cm)		Root system fresh weight (g)		Root system dry weight (g)	
	1st season	2nd season	1st season	2nd season	1st season	2nd season
Water irrigation levels						
100% P.C.	48.88 a	55.79 a	47.40 a	54.83 a	16.30 a	17.77 a
75% P.C.	47.74 a	55.91 a	42.58 b	47.56 b	14.74 b	16.01 b
50% P.C.	43.49 b	49.18 b	36.85 c	43.13 c	12.02 c	13.45 c
Growth retardants						
Control	33.71 e	42.40 d	23.70 f	29.77 f	7.92 f	10.06 d
PBZ 50 ppm	39.69 d	44.57 d	30.68 e	36.00 e	9.28 e	10.13 d
PBZ 100 ppm	46.21 c	53.02 c	38.93 d	45.43 c	13.00 c	13.98 c
PBZ 150 ppm	53.97 b	60.00 b	55.21 b	59.08 b	18.17 b	19.59 b
CCC 1000 ppm	38.99 d	43.32 d	32.19 e	38.73 d	10.88 d	12.47 c
CCC 2000 ppm	51.61 b	58.19 b	52.77 c	57.56 b	17.73 b	19.44 b
CCC 3000 ppm	62.74 a	73.89 a	62.47 a	72.98 a	23.52 a	24.55 a

P.C. = Pot capacity.
Means within a season followed by the same letter are not significantly different (p>0.05) according to Duncan (1955).

system (16.30 and 17.77 g) in both seasons, respectively. the lowest irrigation water level (50%) the lowest values were recorded.

As shown in Table 8, cycocel at 3000 ppm followed significantly by paclobutrazol at 150 ppm produced the highest values in terms of root system characteristics (62.74 and 73.89 cm for root system length, 62.47 and 72.98 g for fresh weight of root system and 23.52 and 24.55 g for dry weight of root system, in the first and second seasons, respectively). Control plants (deprived of plant growth retardants) recorded the lowest values for all studied root system characteristics.

Data presented in Table 9 cleared that there were no significant differences between foliar spraying with cycocel at 3000 ppm when combined with the highest irrigation water level (100%) and the medium one (75%) in case of root length (63.53 and 62.70 cm in the first season and 74.23 and 74.17 cm in the second one for these two treatments, respectively), fresh weight of root system (65.95 and 62.69 g in the first season for these two treatments, respectively) and dry weight of root system (24.08 and 23.81 g in the first season, 25.69 and 25.62 g in the second season for these two treatments, respectively), while a significant difference was observed between these two combined treatments in the second season only in the case of fresh weight of root system (76.30 and 71.90 g, for cycocel at 3000 ppm + 100% water level and cycocel at 3000 ppm + 75% water level, respectively). Although plants treated with the highest concentrations of PBZ (150 ppm) and CCC (3000 ppm) under the lowest irrigation level (50%) did not achieve the highest values for root system parameters, these values were still relatively high compared to plants exposed to the three irrigation levels without foliar application of PBZ and CCC.

Chemical composition analysis

The highest level of irrigation water (100%) as shown in Table 10 resulted in the highest values in case of chlorophylls a+b (1.88 mg/g f.w.), carotenoids (0.51 mg/g f.w.) and total carbohydrates (27.14%) and the lowest value of proline (0.97 mg/g d.w.). The highest proline content was obtained by water irrigation level of 50% (1.70 mg/g d.w.).

The two growth retardants also had a significant, though varying, impact on the biochemical variable evaluated in this study (Table 10). Cycocel at 3000 ppm seems to be more effective than other treatments on chlorophylls a+b, total carbohydrates and proline as produced the highest values (1.98 mg/g f.w., 26.75% and 1.62 mg/g d.w., respectively). The same treatment recorded the lowest carotenoids content (0.41 mg/g f.w.). Control plants deprived of spraying with growth retardants produced the highest value for carotenoids and the lowest values in terms of chlorophylls a+b (1.38 mg/g f.w.), total carbohydrates (21.30%) and proline (1.08 mg/g d.w.).

Regarding the combined treatment effects on chlorophyll (a + b) content, the highest concentration (2.18 mg/g fresh weight) was

Table 9 - Effect of interaction between water irrigation levels and two plant growth retardants on root system length (cm), root system fresh weight (g) and root system dry weight (g) of *Leucophyllum frutescens* during two seasons of 2022 and 2023

Growth retardants	Water irrigation levels					
	100% P.C.	75% P.C.	50% P.C.	100% P.C.	75% P.C.	50% P.C.
	1st season			2nd season		
Root system length (cm)						
Control	38.63 h-j	35.43 j	27.07 k	44.50 ij	42.13 i-k	40.57 j-l
PBZ 50 ppm	42.67 gh	41.90 g-i	34.50 j	49.97 fg	45.33 hi	38.40 kl
PBZ 100 ppm	47.63 d-f	47.00 ef	44.00 fg	53.17 ef	55.00 e	50.90 fg
PBZ 150 ppm	55.97 b	56.03 b	49.90 c-e	59.27 cd	65.20 b	55.53 de
CCC 1000 ppm	41.93 g-i	37.93 ij	37.10 j	48.80 gh	44.37 ij	36.80 l
CCC 2000 ppm	51.80 b-d	53.17 bc	49.87 c-e	60.57 c	65.20 b	48.80 gh
CCC 3000 ppm	63.53 a	62.70 a	62.00 a	74.23 a	74.17 a	73.27 a
Root system fresh weight (g)						
Control	27.17 j	26.11 j	17.82 k	33.35 hi	33.23 hi	22.73 j
PBZ 50 ppm	39.21 gh	26.71 j	26.11 j	43.72 f	33.23 hi	31.04 i
PBZ 100 ppm	43.55 f	41.73 fg	31.51 i	52.07 e	43.85 f	40.37 fg
PBZ 150 ppm	63.80 a	56.27 cd	45.55 f	69.30 b	56.93 d	51.00 e
CCC 1000 ppm	36.60 h	31.81 i	28.15 ij	43.83 f	36.58 gh	35.77 h
CCC 2000 ppm	55.53 cd	52.70 de	50.07 e	65.23 c	57.17 d	50.28 e
CCC 3000 ppm	65.95 a	62.69 ab	58.77 bc	76.30 a	71.90 b	70.73 b
Root system dry weight (g)						
Control	9.04 jk	8.09 kl	6.62 l	11.58 g-i	9.56 h-j	9.05 ij
PBZ 50 ppm	13.33 gh	8.04 kl	6.45 l	14.05 fg	8.42 j	7.91 j
PBZ 100 ppm	15.68 f	15.17 fg	8.16 kl	17.16 de	16.39 ef	8.39 j
PBZ 150 ppm	20.63 bc	19.11 cd	14.75 fg	22.09 b	20.23 bc	16.44 ef
CCC 1000 ppm	12.40 hi	10.88 ij	9.35 jk	13.48 g	12.25 gh	11.66 g-i
CCC 2000 ppm	18.93 cd	18.11 de	16.15 ef	20.35 bc	19.63 b-d	18.34 c-e
CCC 3000 ppm	24.08 a	23.81 a	22.67 ab	25.69 a	25.62 a	22.35 b

P.C. = Pot capacity.
Within each season, values sharing the same letter across water levels and growth retardant treatments indicate no significant difference (p>0.05) according to Duncan's multiple range test (Duncan, 1955).

Table 10 - Effect of water irrigation levels and two plant growth retardants on chemical composition analysis of *Leucophyllum frutescens* during the second season 2023

Treatments	Chlorophylls a+b (mg/g f.w.)	Carotenoids (mg/g f.w.)	Total carbohydrates (%)	Proline (mg/g d.w.)
Water irrigation levels				
100% P.C.	1.88 a	0.51 a	27.14 a	0.97 c
75% P.C.	1.74 b	0.39 c	23.82 b	1.24 b
50% P.C.	1.52 c	0.49 b	19.15 c	1.70 a
Growth retardants				
Control	1.38 g	0.51 a	21.30 e	1.08 g
PBZ 50 ppm	1.58 f	0.49 b	22.00 d	1.13 f
PBZ 100 ppm	1.68 e	0.49 b	22.82 c	1.26 d
PBZ 150 ppm	1.80 c	0.46 c	24.21 b	1.39 c
CCC 1000 ppm	1.73 d	0.45 c	22.58 cd	1.24 e
CCC 2000 ppm	1.85 b	0.44 d	23.92 b	1.42 b
CCC 3000 ppm	1.98 a	0.41 e	26.75 a	1.62 a

P.C. = Pot capacity.
Means followed by the same letter are not significantly different (p>0.05) according to Duncan (1955).

observed under the 3000 ppm cycocel treatment with 100% irrigation. This was followed by the 2000 ppm cycocel + 100% water level treatment (2.02 mg/g fresh weight). Total chlorophyll concentrations were relatively lower with both paclobutrazol at 150 ppm + water level at 100% and cycocel at 3000 ppm + water level at 75%, without significant differences between them. These four treatments also yielded the highest total carbohydrate contents: cycocel at 3000 ppm + 100% water level (31.74%), cycocel at 2000 ppm + 100% water level (27.42%), paclobutrazol at 150 ppm + 100% water level (28.14%), and cycocel 3000 ppm + 75% water level (26.37%). The highest carotenoid concentration (0.58 mg/g f.w.) was observed in control plants at 50% irrigation, with progressively lower values under paclobutrazol treatments at 100 ppm (0.57 mg/g f.w.) and 150 ppm (0.56 mg/g f.w.) combined with full irrigation (100% water level).

Data presented in Table 11 demonstrated that proline was enhanced by cycocel at 3000 ppm when combined with the lowest water level (50%) as the highest value was recorded (2.01 mg/g d.w.). The lowest chlorophylls a+b (1.23 mg/g f.w.), carotenoids (0.32 mg/g f.w.), total carbohydrates (17.21%) and proline (0.82) were obtained by control + 50% water level, cycocel at 3000 ppm + 75% water level, paclobutrazol at 50 ppm + 50% water level and control + 100% water level, respectively.

Table 11 - Effect of interaction between water irrigation levels and two plant growth retardants on some chemical constituents of *Leucophyllum frutescens* during the second season of 2023

Growth retardants	Water irrigation levels		
	100% P.C.	75% P.C.	50% P.C.
Chlorophylls a+b (mg/g			
Control	1.57 jk	1.33 m	1.23 n
PBZ 50 ppm	1.71 hi	1.66 i	1.38 m
PBZ 100 ppm	1.79 ef	1.73 gh	1.53 kl
PBZ 150 ppm	1.97 bc	1.85 d	1.59 j
CCC 1000 ppm	1.94 c	1.78 efg	1.48 l
CCC 2000 ppm	2.02 b	1.83 de	1.69 hi
CCC 3000 ppm	2.18 a	1.99 bc	1.77 fg
Carotenoids (mg/g			
Control	0.43 f	0.53 b	0.58 a
PBZ 50 ppm	0.51 cd	0.42 f	0.53 b
PBZ 100 ppm	0.57 a	0.39 g	0.50 d
PBZ 150 ppm	0.56 a	0.35 h	0.46 e
CCC 1000 ppm	0.46 e	0.38 g	0.51 cd
CCC 2000 ppm	0.50 d	0.36 h	0.46 e
CCC 3000 ppm	0.52 bc	0.32 i	0.38 g
Total carbohydrates			
Control	23.70 f	22.13 h	18.06 kl
PBZ 50 ppm	25.61 e	23.17 f-h	17.21 l
PBZ 100 ppm	27.11 b-d	23.20 fg	18.15 kl
PBZ 150 ppm	28.14 b	25.40 e	19.10 jk
CCC 1000 ppm	26.25 de	22.29 gh	19.21 ij
CCC 2000 ppm	27.42 bc	24.16 f	20.18 i
CCC 3000 ppm	31.74 a	26.37 c-e	22.13 h
Proline (mg/g d.w.)			
Control	0.82 q	1.08 m	1.33 g
PBZ 50 ppm	0.84 p	1.14 jk	1.40 f
PBZ 100 ppm	0.90 o	1.15 j	1.73 d
PBZ 150 ppm	0.96 n	1.31 h	1.91 b
CCC 1000 ppm	0.89 o	1.10 l	1.73 d
CCC 2000 ppm	1.13 k	1.32 gh	1.80 c
CCC 3000 ppm	1.29 i	1.56 e	2.01 a

P.C. = Pot capacity.
Values sharing the same letter across water levels and growth retardant treatments indicate no significant difference (p>0.05) according to Duncan's multiple range test (Duncan, 1955).

WUE and stress indices

Although the lowest water level (50%) produced the lowest dry mass, as shown in figure 1 and Table 12 this was accompanied by the highest water use efficiency (WUE) obtained (1.09 and 1.21 g/l for both seasons, respectively). On the other hand, cycocel at 3000 ppm enhanced WUE in both seasons as the highest values (1.43 and 1.51 g/l, respectively) were obtained. In the case of the combined treatments, the superiority was observed by cycocel at 3000 ppm + 50% irrigation water level (1.71 and 1.75 g/l in both seasons, respectively), this was followed significantly by cycocel at 2000 ppm + 50% water level (1.44 and 1.60 g/l) then cycocel at 3000 ppm + 75% water level (1.41 and 1.50 g/l) in both seasons respectively.

Water stress caused by reducing irrigation water levels was measured by the relative stress index (RSI) and presented in figure 2. At 150 ppm, paclobutrazol reduced water stress effects most effectively under 75% irrigation, showing the lowest RSI values (1.23 and 1.31 in both seasons, respectively), meaning that these plants treated with this treatment experienced minimal water stress and are in good condition. This was followed by paclobutrazol at 100 ppm, cycocel at 2000 ppm and 3000 ppm resulting in low RSI values and mitigated water stress at 75% level compared with 50% level. It is worth mentioning that the highest water stress experienced by plants was observed with the application of PBZ at 50 ppm

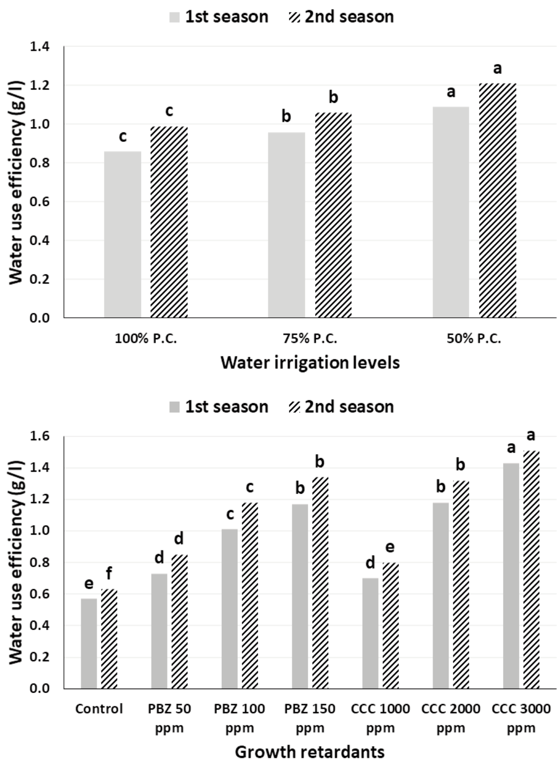

Fig. 1 - Effect of water irrigation levels and two plant growth retardants on water use efficiency (g/l) of *Leucophyllum frutescens* during two seasons of 2022 and 2023. Means within a season followed by the same letter are not significantly different (p > 0.05) according to Duncan (1955).

under an irrigation level of 50%, as the highest RSI levels were recorded (4.24 and 3.87 in both seasons, respectively).

Under moderate and low irrigation water levels, the stress tolerance index was calculated to determine how far the applied plant growth retardants can enhance the plants under these stress conditions (Fig. 2). Cycocel at 3000 ppm significantly enhanced water stress tolerance, particularly under 75% and 50% irrigation levels. This treatment yielded the highest values in both seasons, as recorded 1.70 and 1.36 (season 1) and 1.47 and 1.14 (season 2),

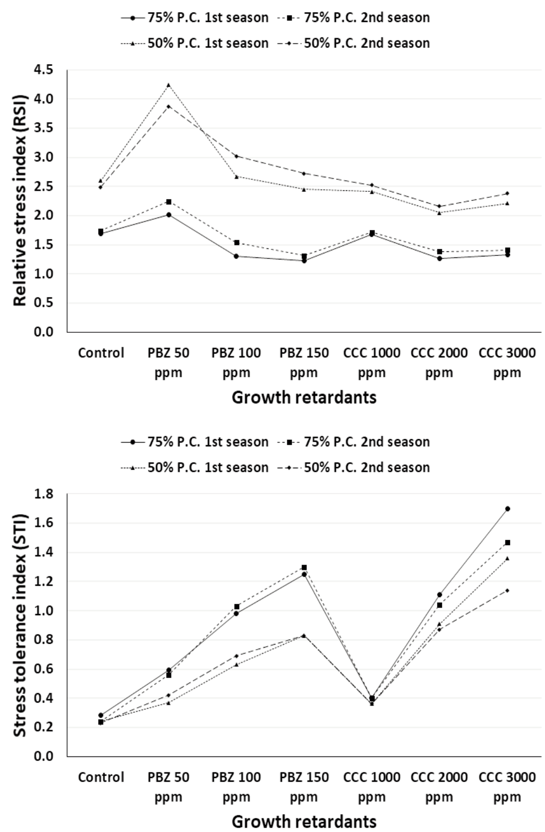

Fig. 2 - Effect of water irrigation levels and two plant growth retardants on relative stress index (RSI) and stress tolerance index (STI) of *Leucophyllum frutescens* during two seasons of 2022 and 2023.

Table 12 - Effect of interaction between water irrigation levels and two plant growth retardants on water use efficiency (g/l) of *Leucophyllum frutescens* during two seasons of 2022 and 2023

Growth retardant	Water irrigation levels					
	100% P.C.	75% P.C.	50% P.C.	100% P.C.	75% P.C.	50% P.C.
	1st season			2nd season		
Control	0.54 jk	0.51 k	0.66 i	0.58 m	0.55 m	0.76 kl
PBZ 50 ppm	0.86 h	0.68 i	0.64 i	0.99 ij	0.74 l	0.83 k
PBZ 100 ppm	0.89 gh	1.09 de	1.06 ef	1.12 gh	1.20 e-g	1.21 ef
PBZ 150 ppm	0.98 fg	1.26 c	1.26 c	1.16 fg	1.47 cd	1.39 d
CCC 1000 ppm	0.64 i	0.61 ij	0.85 h	0.74 l	0.71 l	0.95 j
CCC 2000 ppm	0.93 gh	1.18 cd	1.44 b	1.06 hi	1.28 e	1.60 b
CCC 3000 ppm	1.18 cd	1.41 b	1.71 a	1.27 e	1.50 c	1.75 a

P.C. = Pot capacity.
Within each season, values sharing the same letter across water levels and growth retardant treatments indicate no significant difference (p>0.05) according to Duncan's multiple range test (Duncan, 1955).

respectively. However, paclobutrazol at 150 ppm enhanced the tolerance to water stress at 75% level (1.25 and 1.30, in the first and second seasons, respectively).

4. Discussion and Conclusions

The findings of the present study revealed a marked reduction in all assessed parameters at 50% irrigation level, except proline content and water use efficiency (WUE), both of which increased under severe water deficit. Application of paclobutrazol (PBZ) and cycocel (CCC) significantly enhanced drought tolerance in *Leucophyllum frutescens* under these conditions, with the highest concentrations of each compound producing the most pronounced effects. Although both growth regulators led to a significant reduction in plant height, this effect was accompanied by notable increases in the number of branches and the fresh and dry biomass of shoots and roots, suggesting an overall improvement in plant vigor. Furthermore, CCC demonstrated greater efficacy than PBZ in enhancing growth-related parameters, indicating its superior potential for mitigating the adverse effects of severe water limitation.

Regarding the effect of irrigation levels, the results obtained were consistent with similar trials i.e. Ashour and El-Attar (2017) who reported that water deficiency induced by prolonged irrigation intervals reduced survival percentage, plant height, number of branches/plant, root length, and fresh and dry weights of vegetative growth and roots of *Leucophyllum frutescens*. Multiple studies demonstrate consistent physiological responses to water deficit across diverse plant species. Research by Noor El-Deen (2020) on *Duranta erecta* L. 'Golden Edge', Noor El-Deen *et al*. (2018) on *Zinnia elegans*, and Khalil *et al*. (2012) on *Jatropha curcas* L. revealed a common pattern where reduced irrigation significantly decreased most growth parameters (plant height, biomass), while simultaneously increasing proline accumulation - a key osmoprotectant. Similar findings were reported by Amin (2013) in *Pinus radiate* and *Robinia pseudoacacia* transplants, where extended irrigation intervals reduced shoot and root biomass.

Closing stomata, inefficient carbon fixation process, photosynthesis rate reduction and decreasing formation and expansion of leaf tissues are the main disorders of water deficit (Pallardy, 2008). On the other hand, Dhopte and Ramteke (2017) divided the effects of drought into physiological (desiccation of protoplasm which causes inhibition of cell division, elongation and differentiation as well as reduction of water absorption and dehydration, stopping stem and leaf elongation) and biochemical (proteolysis and protein synthesis retardation, nucleic acid synthesis failure, effect on enzyme synthesis, cytokinin levels are low, toxic products accumulation like ammonia-a main cause of drought injury, starch synthesis inhibition and ABA level in roots are increased) effects. Under drought conditions, the excessive production of reactive oxygen species (ROS) and the generation of radical-scavenging compounds like ascorbate and glutathione further intensify the negative effects (Deotale, 2017). ROS-generated compounds cause oxidative damage to plant cells by restraining membrane attributes (Singh *et al.*, 2016).

In this study, WUE was calculated as the ratio of aerial biomass (shoot dry weight) to total water applied during the experimental period under each level of water. The values obtained showed that WUE in drought-stressed plants (50%), relative to 100% PC-grown plants, was improved. This result suggests that the reduction in biomass (due to water deficit) was proportionally smaller than the 50% reduction in water application, so the value was high in this case.

Our study demonstrated that the highest concentrations of both PBZ and CCC significantly improved drought tolerance in *Leucophyllum frutescens* under severe water deficit (50% irrigation level). Regarding PBZ, our results agreed with Thakur *et al.* (2000) on *Robinia pseudoacacia* seedlings, who found that paclobutrazol improved water relations, enhanced drought tolerance, and increased proline and soluble sugar contents. Also, this fits ZhongZhu and XiangWei (2006) on two-year-old seedlings of *Populus alba × Populus berolinensis*, *Ulmus pumila* and *Betula platyphylla*, who reported an increase of water use efficiency. In the same line Navarro *et al.* (2008) on *Lonicera implexa* seedlings, found that PBZ was significant for leaf water potential and leaf osmotic potential, and demonstrated that PBZ attenuates the effects of deficit irrigation. Hatamifar and Samani (2017) found that application of paclobutrazol on *Petunia × grandiflora* 'Bravo Blue' increased the number of flowers, aerial parts dry weight and number of lateral branches, and decreased the plant height, root dry weight and amount of carotenoids. The above-mentioned findings were confirmed in *Bougainvillea spp.* (Ting *et al*., 2014), later observed in *Odontonema strictum* (Rezazadeh *et al*., 2016), *Sequoia sempervirens* (Shuming *et al*., 2020), and most recently in *Salvia officinalis* (Maghsoudi *et al*., 2023).

The principal role of paclobutrazol (PBZ), as a triazole compound, is the reduction in plant height by inhibiting gibberellin biosynthesis by blocking the oxidative steps from ent-kaurene to ent-kaurenoic acid, a key step in the gibberellin production pathway (Rademacher, 1997). This leads to decreased levels of active gibberellins and subsequently limits stem elongation (Tesfahun, 2018). This could explain our results, which showed a reduction in the height of plants treated with PBZ.

Our study showed that application of paclobutrazol (PBZ) and cycocel (CCC) significantly reduced plant height by inhibiting gibberellin biosynthesis; they concurrently increased the number of branches and enhanced fresh and dry biomass of leaves and shoots. These results were in agreement with Youssef and Abd El-Aal (2013), who showed that PBZ at 50 ppm or CCC at 1000 ppm increased the number of branches/plant as well as leaves and roots fresh and dry weights of *Tabernaemontana coronaria* compared to control untreated plants.

These enhancements in branching and biomass likely result from hormonal modulation: PBZ suppresses gibberellin synthesis and shifts the isoprenoid pathway toward elevated cytokinin levels and abscisic acid accumulation, thereby reducing stem elongation while promoting lateral and root growth. CCC similarly inhibits gibberellin action, diminishes apical dominance, and encourages lateral bud outgrowth, collectively leading to increased branching and biomass (Rademacher, 2000).

On the other hand, Singh *et al.* (2016) enumerated the positive role of PBZ-treated plants grown under drought conditions. These plants possess a superior defense mechanism against free radicals, allowing them to neutralize harmful oxygen species. PBZ treatment enhances stress resistance by boosting the activity of certain antioxidant enzymes. It also protects plants from oxidative damage by either increasing antioxidant levels or reducing the activity of oxidative enzymes. Furthermore, PBZ treatment stimulates the production of abscisic acid and phytol, hormones that promote plant growth and health. Fletcher *et al*. (2000) added that PBZ induces a large elastic module in the cell walls of treated plants, which in turn maintains turgor and thus increases the plant tolerance to drought stress.

The elevated proline levels likely result from biosynthesis enzymes ornithine aminotransferase (OAT) and pyrroline-5-carboxylate reductase (P5CR) combined with suppressed activity of proline oxidase, the key catabolic enzyme (Debnath, 2008). Paclobutrazol seems to increase proline content by increasing the enzyme activity of OAT, which is involved in the biosynthesis of proline via ornithine (precursors for L-proline biosynthesis) pathway (Zhang *et al.*, 2024).

PBZ blocks the oxidation of ent-kaurene to ent-kaurenoic acid by inhibiting cytochrome P450-dependent oxygenases. This inhibition reduces gibberellin (GA) production, causing precursors in the terpenoid pathway to accumulate. These accumulated precursors, such as farnesyl diphosphate (FPP) and geranylgeranyl diphosphate (GGPP), are redirected toward ABA biosynthesis, leading to higher ABA levels. PBZ also inhibits the activity of ABA 8’-hydroxylase, an enzyme responsible for ABA degradation, further increasing ABA concentrations in plant tissues (Soumya *et al*., 2017).

PBZ can also control stomata movements under drought stress. Jack pine seedlings treated with paclobutrazol before a drought showed improved drought tolerance. This was evident in their quicker closure of leaf stomata to conserve water, better water content within the plant, and higher survival rates compared to untreated seedlings (Marshall *et al*., 1991). Additionally, MingEr and SanYu (1999) reported the role of paclobutrazol treatment in decreasing the leaf transpiration rate of *Satsuma mandarin*, and prorogue its reduction during drought stress. Abbasi *et al.* (2015) showed that paclobutrazol minimizes the negative effects of drought stress with evidence of enhancing chlorophyll content and antioxidant enzymes such as alternative oxidase (APX), catalase (CAT) and glutathione peroxidase (GPX) that reduces hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) content.

As an anti-gibberellin agent, cycocel inhibits the conversion of geranyl geranyl pyrophosphate (GGPP) into ent-kaurene by blocking ent-kaurene synthetases in the mevalonic acid pathway. This results in lower gibberellin levels, ultimately decreasing plant height (Rademacher, 1997).

Applying cycocel (CCC) in plants enhances root growth, water potential, and stomatal resistance in leaves, ultimately improving water-use efficiency by stimulating root activity and reducing transpiration (Deotale, 2017). CCC is considered highly effective in mitigating the negative impacts of various abiotic and biotic stresses on crops. CCC plays a key role in the signal transduction pathways of plants under environmental challenges, including drought stress. Khondoker *et al.* (2019) reported the positive role of CCC on the growth and flowering of tuberose subjected to drought stress. In this regard, exogenous application of CCC is believed to influence nutrient uptake and transport, regulate stomatal function, and enhance growth, photosynthesis, chlorophyll synthesis, and transpiration processes (Dehghanzadeh and Adavi, 2023). The interoperation of the positive role of PBZ under drought stress could be applied in the case of cycocel, particularly further enhancing the activities of the key antioxidant enzymes and accumulation of osmolytes, and decreasing the levels of H_2O_2 (as harmful ROS compounds) and malondialdehyde in drought-stressed plants (Dehghanzadeh and Adavi, 2023). As mentioned in the case of the effect of PBZ on ABA synthesis, the accumulated precursors induced by the CCC block of gibberellin synthesis are redirected toward ABA biosynthesis, leading to higher ABA levels.

It is noteworthy that, based on the obtained results, CCC generally exhibited greater effectiveness than PBZ. This may be attributed to differences in absorption pathways: paclobutrazol is usually applied either as a foliar spray or through soil drenching, and when applied to foliage, its uptake through mature leaves is relatively limited, with absorption likely occurring via the stem or from droplets reaching the soil. In contrast, cycocel is readily absorbed by both leaves and roots (Barrett and Bartuska, 1988; Rademacher, 2000; Maghsoudi *et al*., 2023).

Although plants treated with the highest concentrations of PBZ (150 ppm) and CCC (3000 ppm) under the lowest irrigation level (50%) did not achieve the best values for most morphological characteristics, WUE and STI, these values were still relatively high compared to plants exposed to the three irrigation levels without foliar application of PBZ and CCC, except for plant height and the fresh weight of 10 flowers. Cycocel at 3000 ppm outperformed PBZ at 150 ppm in this aspect, proving more effective in improving plant growth parameters, enhancing water use efficiency (WUE), and increasing tolerance to reduced water supply levels down to 50%. So, it is recommended to apply foliar spraying with Cycocel at 3000 ppm + irrigation water level at 50% P.C. of *Leucophyllum frutescens* plants cultivated in 30 cm pots, as this treatment demonstrated good performance with a high-stress tolerance index to drought.

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