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Efficiency of Glycinebetaine in Increasing Potato (*Solanum tuberosum* L.) Plant Tolerance to Drought

Metwaly, E. E.[1] ; W. A. El-Saady[1] ; Z. S. A. El-Shal[2] and Mona A. A. S. Moussa[2]

[1]Vegetable and Ornamental Dept., Agric. Faculty, Mansoura Univ., 35516, Mansoura, Egypt
[2]2Potato and Vegetatively propagated vegetable Research Department, Horticulture Research Institute., Agriculture Research Center, Giza, Egypt

ABSTRACT

Improving plant water use efficiency (WUE) by osmoprotectant represents the main approach to sustainable productivity. Field trials were conducted to elucidate the efficiency of glycinebetaine (GlyBet) concentrations (0, 200, 400, 600 mg/l) for overcoming drought injury (1500, 1200, and 900 m^3/fed) on potato plant productivity. Drought stress significantly decreased potato plant growth (plant height, and leaves number, leaf area, axillary stem number/plant, as well as foliage fresh weight, leaves dry matter), photosynthetic pigment (chlorophyll a, chlorophyll b, and carotenoid), ion% (nitrogen, phosphorous, and potassium), and yield components (tuber weight $plant^{-1}$, tuber number $plant^{-1}$, marketable and non-marketable yield). Alternatively, drought significantly increased antioxidant enzyme activity, non-marketable yield, tuber dry matter, tuber hardness and density, vitamin C, and total soluble solids associated with boosting WUE. The greatest reduction was documented under severe drought (900 m3/fed). . Foliar spraying with GlyBet significantly increased all growth and yield traits except non-marketable yield which is decreased. Additionally, GlyBet spraying increased photosynthetic pigment and proline concentration, ion percentage, and activity of antioxidant enzymes associated with improving relative water content and WUE. The greatest values were recorded with 600 mg/l GlyBet application over other concentrations or nontreated plants. Regarding the interaction effects, the current findings revealed that GlyBet supplementation at all concentrations alongside 1200 and 900 m^3/fed as consumptive water , nullifies the drastic impact on plant growth and productivity as well as some biochemical traits. Accordingly, 600 mg/l GlyBet foliar spraying as an eco-friendly and cost-effective osmoprotectant twice has the potential to mitigate drought injury and increase WUE.

Keywords: Glycine betaine, drought, potato, yield and antioxidant enzymes

INTRODUCTION

Potato (*Solanum tuberosum* L.) ranks as the 1st highest-produced non-cereal food crop and the 4th supreme imperative food crop next to wheat, corn, and rice worldwide (FAOSTAT, 2021). It is grown in 100 countries and their worldwide production boosted from 270 million tonnes in 1961 to 370 million tonnes in 2019, nourishing more than a billion people (Nasir and Toth 2022). Potato is designated a vigorous source of carbohydrates, dietetic fibers, protein, vitamins, and nutrients (Beals, 2019). As a result of its potential to offer a remarkable production per unit input, boosting potato production in developed and developing countries may make a substantial contribution to meeting the nutritional needs of the growing population (Devaux *et al*., 2014). Conversely, because of their thin and shallow roots, utmost potato cultivars are considered drought-sensitive, which is categorized with low yield and quality within drought occurs (Cho *et al*., 2016).

Water scarcity represents the key restricting aspect for sustainable crop productivity worldwide (Alam *et al*., 2022; Metwaly *et al*., 2022 and Farouk *et al*., 2023). Drought usually affects 40-60% of worldwide cultivated lands with 30-44 US$ billion in economic losses (Gupta *et al*., 2020). Drought strongly induces several physio-biochemical and molecular changes, leading to poor plant performance and yield reduction by 10-60% (Metwaly *et al*., 2022; Farouk *et al*., 2023). The magnitude of their losses, however, mostly depends on drought sternness and crop cultivars (Plich *et al*., 2020 and Hill *et al*., 2021). Reduction in vegetative growth is the first visible sign of drought followed by senescence and yield reduction (Metwaly *et al*., 2022 and Farouk *et al*., 2023). Drought may upset potato yield by declining vegetative growth, disturbing metabolic pathways, and decreasing leaf photosynthesis or leaf area duration (Deblonde and Ledent, 2001; Metwaly *et al*., 2022 and Farouk *et al*., 2023). Besides vegetative growth, drought may shorten the growth cycle, reduce the tubers' size and numbers, and reduce tuber quality (Eiasu *et al*., 2007 and Kumar *et al*., 2007) and occasionally the plant death (Saleem *et al*., 2020). Drought-affected plants have developed adaptation strategies for coping with water deficiency, i.e., avoidance, escape, and dehydration tolerance of protoplasts, leading to maintaining water status, ion and redox homeostasis, stabilization of membrane integrity, and hyper-accumulation of osmoprotectants (Saleem *et al*., 2020 and Farouk *et al*., 2023). Egypt's agricultural extension requires an enormous amount of irrigation water, which is scarce to satisfy the predicted demand along with poor irrigation management. These conditions promoted improved water use efficiency (WUE) and increased plant productivity via cost-effective novel approaches including cultivation of drought tolerance cultivars, and effective agricultural performance (Metwaly *et al*., 2022 and Farouk *et al*., 2023), and recently using drought-induced tolerant mediators like

*** Corresponding author.**
E-mail address: elsaady_2003@mans.edu.eg
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phytohormones and osmoprotectants (Metwaly *et al.*, 2022 and Farouk *et al.*, 2023). One of the osmoprotectants used to regulate crop production under normal or stressful conditions is glycinebetaine (GlyBet).

Nowadays, GlyBet is used as an easy method for decreasing the injuries of stress factors on plant productivity and generating drought-stress tolerant crops (Metwaly *et al.*, 2022 and Niu *et al.*, 2023). GlyBet is a low-cost, eco-friendly, and effective osmoprotectant, that is widely distributed in a wide range of biota (Chen and Murata, 2008). The efficiency of GlyBet depends on plant species, and developmental stage at the time of application, in addition, to their concentration used, and the number of applications (Metwaly *et al.*, 2022). GlyBet application improves growth, survival, and crop production in the accumulator and non-accumulator plants in normal or stressful conditions (Yang *et al.*, 2022), *via* regulating several physio-biochemical pathways, enhancing net CO_2 assimilation rates and photosynthetic capacity, maintaining ion homeostasis, and activation reactive oxygen species (ROS) scavenging system (Bai *et al.*, 2022; Niu *et al.*, 2023). In this regard, Shemi *et al.* (2021) mentioned that GlyBet increased vegetative features, and yield as well as organic and non-organic solutes, steadying the secondary structure of both enzymes and proteins.

Some non-accumulator economical crops including potatoes can tolerate drought better when GlyBet is applied. So it has been hypothesized that exogenous application of GlyBet could lessen the destructive effects of drought on potatoes. Hence, the objective of this study was to assess the promising role of GlyBet in improving potato plant drought tolerance, in terms of plant growth, some physio-biochemical attributes, and plant productivity. This finding may suggest a novel water-saving strategy under water scarcity circumstances.

MATERIALS AND METHODS

Experimental layout

Two field experiments were done in clay loamy soil (Table 1) of the experimental station of the Vegetables and Floriculture Dept., Fac. Agric., Mansoura Univ. throughout the 2022 and 2023 seasons, to study the effect of irrigation regimes and GlyBet concentration on potato plant (*Solanum tuberosum*, Cv. Spunta) growth and yield as well as some physio-biochemical attributes under drip irrigation system.

Table 1. Experimental soil characteristics of 2022 and 2023 seasons.

Seasons	Silt %	Clay %	Sand %	Texture soil	F.C %	W.P %	AW %	PH	E.C (dSm^{-1})	O.M %	$CaCO_3$ %	N ppm	P ppm	K ppm
2022	41.9	36.4	21.7	Clay loamy	36.1	19.0	17.1	8.02	1.48	1.6	3.11	50.9	6.1	291
2023	42.6	35.9	21.5	Clay loamy	35.5	18.8	16.7	8.03	1.51	1.8	3.32	52.0	6.4	296

F.C : Field Capacity; W.P.: Welting point; AW: Available water; OM: Organic matter

A strip plot on a randomized complete block design was utilized for the existing experiments. The vertical plots were assigned to irrigation regimes: well watering (1500 m^3/fed), moderate drought (1200 m^3/fed), and severe drought (900 m^3/fed). Otherwise, the horizontal -plots were assigned to GlyBet application (0.0, 200, 400, and 600 mg/L GlyBet). The twelve treatments were replicated thrice making 36 experimental units (10.5 m^2 with 1.5 m extensive bounded districts).

Crop husbandry

The experimental site was intensely ploughed and formerly added 20 m^3/fed farmyard manure. On the 27th and 29th of December in the first and second years, correspondingly, individual tuber seeds (20-25g) were manually planted at a depth of 12-15 cm and 25 cm apart in each plot. Each plot involves 5 dripper lines with a 3 m length for each and 0.7 m space among two dripper lines. Two lines were utilized for the assessment of the morpho-physiological attributes and the other three lines were utilized for yield and quality assessment. Furthermore, a protective zone was omitted from each of the two experimental units to prevent irrigation water infiltration from overlapping

The experimental units took an equivalent volume of irrigation water throughout the emergence stage via furrow irrigation (using a water counter) for identical plant establishment. The rest volumes of the irrigation water (m^3/fed.) were supplemented by using a water counter at 1.5 bar, water flowed through the drippers (4 liter/h.), depending on the growth stage at two days' intervals beginning on the 5th and 8th February, and finished 10 and 15 April in the 1st and 2nd seasons, correspondingly. The GlyBet concentrations with 0.01% (v/v) Tween-20 were sprayed twice (40 and 55 days from planting), to an overflow in the early morning using a back-sprayer at the rate of 300 and 400 l/fed in the 1st and 2nd spraying respectively.

After two weeks from planting, 120, 125, and 100 kg fed^{-1} of potassium sulfate (50% K_2O), phosphoric acid (50% P_2O_5), and ammonium nitrate (33.5% N) were added throughout the fertigation system at 2-day intervals, Following the Ministry of Agriculture and Land Reclamation, Egypt's approval

Data recording

At 85 days from planting, five erratically selected plants $plot^{-1}$ were harvested and designated for assessing growth and physiological attributes in the shoot system.

1. Vegetative growth features

Plant height (cm), number of leaves and axillary stem as well as leaves area (cm^2) /plant, besides foliage fresh weight (g/plant) and leaves dry matter were determind.

2. Photosynthetic pigment concentration

Chlorophyll a, chlorophyll b, and carotenoids were extracted from the 4th upper leaves using Lichtenthaler (1987) procedure with ice-cold methanol for 48 h. The absorbance of methanolic extract using a spectrophotometer at 470, 652, and 665 nm was recorded, and formerly its concentration was designed.

3. Shoot ion%

Ion % was appraised constantly with AOAC (1990). Ground dried shoots were wet digested with $HClO_3/H_2SO_4$ till clearness, and then brought to 100 ml with deionized water and retained for estimations. Nitrogen was measured by micro-kjldahl, in the meantime P was measured spectrophotometrically (Spekol 11, UK) via ammonium molybdate with ascorbic acid. K was assessed Flame photometrically.

4. Leaf relative water content (RWC) and proline concentration

The RWC (fresh mass – dry mass)/ (turgid mass – dry mass) × 100 according to Farouk *et al.* (2020). Meanwhile, proline (µmol g^{-1} 'FW') was measured spectrophotometrically at 520 nm by the improved ninhydrin protocol of Magne and Larher (1992).

5. Antioxidant enzymes:

Catalase (CAT) activity was assessed spectrophotometrically at lab. conditions by checking the reduction in absorbance at 240 nm following the protocol of Aebi (1983). The peroxidase (POD) activity was evaluated via 4-methyl catechol as substrate (Onsa *et al*., 2004). Superoxide dismutase (SOD) activity was decided by quantifying the reticence in the photoreduction of nitroblue tetrazolium by the SOD enzyme (Kumar *et al*., 2012).

6. Yield and its components

At 110 days after planting, tubers weight (g) and tubers number/ plant were designated by taking the mean of 5 hills, dry matter %, hardness (kg cm^{-2}), density (tubers weight (g) per plant/tubers volume (cm^3) per plant), marketable tubers yield (ton/fed.) as healthy tuber with a weight above or equal to 50 g without (growth cracks, irregularly curved shape, rotten, bottleneck shape, diseased, insect attacked, misshapen tuber, those having a weight less than 50 g and two or more knobs) and total tubers yield (ton/fed.) was (total fresh weight of tubers per plot/plot area) x 4200.

7. Tuber quality

Quality traits of tuber, i.e., ascorbic acid (vitamin C), total soluble solids (TSS), and total carbohydrates were considered (AOAC، 1990). TSS (◦Brix) was estimated using a digital refractometer (Model HI96801, Hanna Instruments). Alternatively, ascorbic acid (mg/100 g tuber fresh weight) was appraised via 2,6-dichlorophenol indophenol reagent. Specific gravity was designed in line with Abdel-Aal (1971) protocol, specific gravity (g/cm^3) = Tuber mass (g)/ tuber volume (cm^3)

The oven-dried tuber was extracted by sulphuric acid (1N) in a boiling water bath for 5 h., and then filtrated using Whatman number 42 filter papers. The total carbohydrates were estimated using phenol-sulphuric acid (Sadasivam and Manickam, 1996).

8. Water use efficiency (WUE)

The WUE was deliberated by Howell (1994) equation as follow,

$$\mathbf{WUE} = \frac{\text{Total tuber yield } \left(\frac{\text{ton/}}{\text{fed}}\right)}{\text{Crop water consumption } \left(\frac{\frac{\text{m3}}{\text{fed}}}{\text{season}}\right)}$$

Statistical Analysis

Exploiting Costat software, a two-way ANOVA was done for statistical analysis (CoHortSoftware, 2006). The means were separated at $p \leq 0.05$ using the LSD pair-wise comparison test.

RESULTS AND DISCUSSION

1. Growth parameters

Table (2) indicates that potato plant growth is significantly ($p \leq 0.05$) influenced by irrigation regimes, GlyBet spraying, and their interaction either in the 1st or 2nd years. Compared with well-watered plants, water deficit significantly declined growth trials. Hence, the lowest plant height (57.22 and 58.06 cm), leaves number $plant^{-1}$ (86.58, and 86.82), leaves area $plant^{-1}$ (1304 and 1318 cm^2), number of axillary stems $plant^{-1}$ (7.32, and 7.56), foliage fresh weight (367.0 and 372.8 g), and leaf dry matter percentage (12.81, and 12.98%) were noted within severe drought in both seasons respectively over well-watered plants.

Table 2. Response of potato plant growth attributes by glycinebetaine and irrigation regimes in both experimental years.

Treatments	Plant height (cm).		Leaves No / plant		Leaves area (cm^2) / plant		Number of axillary stem/plant		Foliage FW g / plant		leaves DM %	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Water quantity (I, m^3/fed)												
1500 (I_{1500})	67.47	67.84	100.47	100.75	1602	1624	6.18	6.38	444.7	454.7	11.08	11.23
1200 (I_{1200})	59.95	60.27	89.92	90.17	1487	1505	6.91	7.14	403.4	411.0	11.51	11.66
900 (I_{900})	57.72	58.06	86.58	86.82	1304	1318	7.32	7.56	367.0	372.8	12.81	12.98
LSD 5%	5.39	5.41	7.80	7.82	30	29	0.16	0.17	16.9	17.0	1.05	1.07
Glycinebetaine (GlyBet, ppm)												
0 (GlyBet$_0$)	58.76	59.06	88.14	88.34	1368	13.85	5.69	5.87	379.8	387.4	11.41	11.55
200 (GlyBet$_{200}$)	59.82	60.15	89.74	89.97	1461	1479	6.47	6.68	392.9	400.6	11.48	11.63
400 (GlyBet$_{400}$)	63.18	63.54	94.48	94.75	1492	1511	7.20	7.44	413.6	421.5	12.02	12.18
600 (GlyBet$_{600}$)	65.07	65.47	96.93	94.75	1534	1554	7.85	8.12	433.8	441.9	12.28	12.45
LSD 5%	3.98	4.00	6.17	6.18	19	18	0.04	0.05	6.8	6.9	0.73	0.74
Interaction Effects												
I_{1500}+GlyBet$_0$	63.35	63.66	95.03	95.23	1475	1496	5.05	5.21	420.8	430.5	10.62	10.76
I_{1500}+GlyBet$_{200}$	64.97	65.31	97.45	97.71	1590	1611	5.75	5.93	444.1	454.0	10.70	10.85
I_{1500}+GlyBet$_{400}$	69.00	69.39	102.62	102.92	1630	1653	6.68	6.90	444.7	454.7	11.48	11.64
I_{1500}+GlyBet$_{600}$	72.55	72.99	106.78	107.12	1712	1736	7.23	7.48	469.4	479.7	11.51	11.66
I_{1200}+GlyBet$_0$	57.59	57.87	86.40	86.59	1411	1427	5.87	6.06	294.9	402.3	11.06	11.20
I_{1200}+GlyBet$_{200}$	58.73	59.03	88.10	88.33	1503	1521	6.66	6.87	397.6	405.1	11.27	11.42
I_{1200}+GlyBet$_{400}$	60.71	61.05	91.08	91.34	1505	1523	7.26	7.50	404.3	414.0	11.65	11.81
I_{1200}+GlyBet$_{600}$	62.75	63.12	94.13	94.43	1528	1547	7.88	8.12	414.5	422.4	12.04	12.21
I_{900}+GlyBet$_0$	55.34	55.64	83.01	83.20	1219	1233	6.14	6.33	323.7	329.2	12.54	12.70
I_{900}+GlyBet$_{200}$	55.78	56.10	83.67	83.89	1291	1305	7.02	7.24	337.0	242.6	12.47	12.63
I_{900}+GlyBet$_{400}$	59.83	60.19	89.75	90.01	1342	1357	7.67	7.92	389.8	395.8	12.93	13.10
I_{900}+GlyBet$_{600}$	59.92	60.31	89.89	90.18	1363	1378	8.47	8.75	417.5	423.7	13.29	13.47
LSD 5%	8.16	8.18	12.45	12.49	42	41	0.18	0.20	19.7	19.8	1.64	1.67

Foliar spraying of GlyBet in both seasons improved significantly growth attributes (Table 2). The supreme plant height (65.07 and 65.47 cm), leaves number $plant^{-1}$ (96.93, and 94.75), leaves area $plant^{-1}$ (1534 and 1554 cm^2), the number of axillary stems $plant^{-1}$ (7.85, and 8.12), foliage fresh weight (433.8 and 441.9 g), and leaf dry matter percentage (12.28, and 12.45%) in both seasons respectively were documented once 600 mg/l GlyBet treatments over the rest of GlyBet concentrations or nontreated plants.

Foliar application of GlyBet with 1200 or 900 m^3/fed irrigation regimes nullifies drought injuries over nontreated well-watered plants. Spraying of 600 mg/l GlyBet under severe drought boosting plant height by 8.27 and 8.39%; leaves number $plant^{-1}$ by 8.28 and 8.38%; leaves area by 11.81, and 11.75%, number of axillary stems $plant^{-1}$ by 37.94 and 38.23%, foliage fresh weight by 28.97 and 28.70%, and leaves DM% by 5.98 and 6.06% in both seasons over nontreated, severely drought-affected plants (Table, 2).

Drought substantially declined vegetative features, along with the former research (Alam *et al*., 2022; Metwaly *et al*., 2022 and Farouk *et al*., 2023). Water scarcity has been recorded to have a deleterious impact on potato stem length (Chang *et al*., 2018), leaves number $plant^{-1}$ (Aliche *et al*., 2018), stem number $plant^{-1}$ (Chang *et al*., 2018), and leaf area (Kesiime *et al*., 2016). These drastic effects may be owing to accelerating numerous metabolic disorders and molecular modifications (Alam *et al*., 2022), disturbing water and nutrient uptake, and hyperaccumulation of ROS (Farouk *et al*., 2023). Moreover, drought induces phytohormon imbalance that slows down cell turgidity and impairs nutrient balance along with a decline in growth attributes (Saleem *et al*., 2020). Additionally, Hussain *et al*. (2012) indicate that water deficit raises root respiration rate, carbon resource utilization to drop, declined adenosine triple phosphate production as well as over-accumulation of ROS. Moreover, drought diminishes photosynthesis processes via a decline in chlorophyll assimilation or damages its molecules (Saleem *et al*., 2020). Drought also reduces RWC and increases the intercellular ionic concentration, which impedes ATP assimilation and ribulose bisphosphate production capacity (the primary acceptor of CO_2 within photosynthesis), which reduces photoassimilate production needed for plant development (Flexas *et al*., 2006).

Application of GlyBet especially 600 mg/l under normal or drought conditions considerably boosted growth attributes over untreated plants within irrigation regimes (Shemi *et al*., 2021). The enhancement of GlyBet on plant growth under normal or stressful conditions may be resulted from, maintaining water status (Shemi *et al*., 2021 and Metwaly *et al*., 2022), hormonal balance, and boosting either cell division or elongation (Niu *et al*., 2023). Moreover, GlyBet application improved stomatal conductance, and sub-stomatal CO_2 concentration, which in turn enhances CO_2 diffusion along with photosynthesis improvement and plant development (Niu *et al*., 2023). As for the interactions, a few researchers are verifying the existing findings that demonstrate the use of GlyBet reduces the detrimental impacts of drought on plant establishment (Shemi *et al*., 2021).

2. Photosynthetic pigment:

Table 3 shows that the concentration of chlorophyll a, chlorophyll b, and carotenoids in potato leaves expressively decreases under drought conditions. The greatest concentration in both experimental seasons was recorded in 1500 m^3/fed irrigation regimes, which was followed by 1200 m^3/fed and then 900 m^3/fed irrigation regimes.

Table 3 ascertains that spraying GlyBet on potato plants exhibited a positive effect on chlorophylls and carotenoids concentration over nontreated plants. The main effectiveness was 600 mg/L, which increased Chl a (11.30 and 11.43%), Chl b (12.17 and 11.95%), and carotenoids (8.77 and 8.91%) relative to untreated plants.

Table 3. Chlorophyll a, chlorophyll b, and carotenoid concentration of potato leaves as affected by glycinebetaine and irrigation regimes in both experimental years.

Treatments	Chl. a mg/100 FW		Chl.b mg/100 FW		Carotenoids mg/100g FW	
	S1	S2	S1	S2	S1	S2
			Water quantity (I, m^3/fed)			
1500 (I_{1500})	33.65	34.08	16.06	16.94	13.23	14.06
1200 (I_{1200})	29.97	30.36	14.91	15.44	12.40	13.18
900 (I_{900})	28.86	29.23	13.08	13.46	10.65	11.31
LSD 5%	2.66	2.70	0.30	0.31	0.38	0.41
			Glycinebetaine ppm			
0 ($GlyBet_0$)	29.38	29.74	13.72	14.30	11.62	12.34
200 ($GlyBet_{200}$)	29.91	30.29	14.66	15.25	12.03	12.78
400 ($GlyBet_{400}$)	31.32	31.72	14.97	15.57	12.08	12.84
600 ($GlyBet_{600}$)	32.70	33.14	15.39	16.01	12.64	13.44
LSD 5%	2.21	2.24	0.19	0.20	0.68	0.73
			Interaction Effects			
I_{1500}+$GlyBet_0$	31.67	32.06	14.79	15.64	12.98	13.78
I_{1500}+$GlyBet_{200}$	32.48	32.90	15.94	16.81	13.03	13.85
I_{1500}+$GlyBet_{400}$	33.68	34.12	16.35	17.24	13.07	13.89
I_{1500}+$GlyBet_{600}$	36.77	37.26	17.18	18.08	13.84	14.72
I_{1200}+$GlyBet_0$	28.79	29.15	14.15	14.66	11.62	12.34
I_{1200}+$GlyBet_{200}$	29.37	29.74	15.08	15.61	12.49	13.27
I_{1200}+$GlyBet_{400}$	30.36	30.75	15.09	15.63	12.53	13.33
I_{1200}+$GlyBet_{600}$	31.37	31.80	15.33	15.87	12.97	13.79
I_{900}+$GlyBet_0$	27.67	28.01	12.23	12.60	10.27	10.91
I_{900}+$GlyBet_{200}$	27.89	28.24	12.96	13.33	10.57	11.23
I_{900}+$GlyBet_{400}$	29.91	30.30	13.46	13.85	10.64	11.31
I_{900}+$GlyBet_{600}$	29.96	30.37	13.67	14.07	11.12	11.82
LSD 5%	4.16	4.21	0.42	0.43	0.87	0.93

The existing investigation established that GlyBet application raised chlorophyll a, chlorophyll b, and carotenoid levels in potato leaves compared to non-treated plants under these irrigation regimes. By enhancing chlorophyll a (8.27 and 8.42%), chlorophyll b (10.86 and 11.66%), and carotenoid (8.27 and 8.34%) content above nontreated severe drought-affected plants, spraying of 600 mg/L GlyBet lessens the destructive effects of drought.

The current finding and earlier research proved that drought induces a substantial deterioration in chlorophylls and carotenoids, that was lessened via GlyBet application (Table 3, Alam *et al*., 2022 and Shemi *et al*., 2021). The drastic impact of drought on chlorophyll and carotenoid concentrations may be attributable to (1) acceleration of the malformation of chloroplast, and plastoglobules over-production (Farouk and Omar 2020); (2) activation of chlorophyllase biosynthesis (Haider *et al*., 2017); (3) devastation of light-harvesting pigment-protein complexes chiral macro-aggregates (Lai *et al*., 2007).

Alternatively, GlyBet supplementation increased phosynthetic pigments under normal or stressful conditions (Shemi *et al*., 2021). These rises might be resulted from, (1) well-organized ROS mitigation capacity via motivation of antioxidant enzymes and osmolyte buildup (Shemi *et al*., 2021); (2) recitals of a vital occupation i.e., cytokinin in enhancing chlorophyll assimilation, and raising chloroplast number cell^{-1} (Hasanuzzaman *et al*., 2019); (3) inducing the accumulation of carotene that protect chloroplasts and chlorophyll against ROS; (4) preventing photoinhibition capacity along with increasing photosynthetic capacity (Niu *et al*., 2023).

3. ion percentage:

Drought stress expressively decreased the percentages of N, P, and K, and the supreme drops of N (13.62 and 13.63%), P (18.53 and 18.59%), and K (34.17 and 33.80%) noted within severe drought over controls in the 1st and 2nd years, correspondingly (Table 4).

Table 4 designates that GlyBet application expressively elevates the shoot's N, P, and K% relative to nontreated plants, and 600 mg/L GlyBet generated the highest ion %.

Table 4. Ion percentage of potato shoots as affected by glycinebetaine under irrigation regimes in both experimental years.

Treatments	N %		P %		K %	
	S1	**S2**	**S1**	**S1**	**S2**	S2
Water quantity (I, m^3/fed)						
1500 (I_{1500})	3.685	3.959	0.464	0.484	4.77	4.91
1200 (I_{1200})	3.306	3.551	0.410	0.428	3.76	3.89
900 (I_{900})	3.183	3.419	0.378	0.394	3.14	3.25
LSD 5%	0.300	0.322	0.035	0.037	0.13	0.13
Glycinebetaine (GlyBet, ppm)						
0 (GlyBet$_0$)	3.240	3.479	0.399	0.416	3.39	3.44
200(GlyBet$_{200}$)	3.299	3.542	0.407	0.424	3.88	3.93
400(GlyBet$_{400}$)	3.454	3.711	0.426	0.445	3.96	4.14
600(GlyBet$_{600}$)	3.572	3.839	0.438	0.457	4.32	4.56
LSD 5%	0.215	0.23	0.026	0.028	0.25	0.23
Interaction Effects						
I_{1500}+GlyBet$_0$	3.493	3.750	0.441	0.460	4.25	4.31
I_{1500}+GlyBet$_{200}$	3.582	3.847	0.452	0.472	4.75	3.81
I_{1500}+GlyBet$_{400}$	3.715	3.991	0.469	0.489	4.86	5.29
I_{1500}+GlyBet$_{600}$	3.951	4.247	0.492	0.513	5.22	5.23
I_{1200}+GlyBet$_0$	3.176	3.410	0.395	0.412	3.01	3.05
I_{1200}+GlyBet$_{200}$	3.238	3.478	0.402	0.419	3.36	3.41
I_{1200}+GlyBet$_{400}$	3.348	3.597	0.416	0.434	4.08	4.13
I_{1200}+GlyBet$_{600}$	3.460	3.719	0.430	0.448	4.60	4.97
I_{900}+GlyBet$_0$	3.051	3.276	0.363	0.378	2.92	2.95
I_{900}+GlyBet$_{200}$	3.076	3.303	0.365	0.381	3.54	3.59
I_{900}+GlyBet$_{400}$	3.299	3.544	0.392	0.409	2.95	2.99
I_{900}+GlyBet$_{600}$	3.304	3.551	0.393	0.410	3.14	3.49
LSD 5%	0.468	0.503	0.058	0.061	0.36	0.38

GlyBet supplementation specifically 600 mg/L with 1200 or 900 m^3/fed irrigation water invalidated the declined injury of water deficit over untreated plants within each irrigation regime.

Earlier studies have formerly confirmed the current outcomes that exhibit a drop in nutrient percentage once drought occurs (Metwaly *et al*., 2022). The defeat in N % under drought can result from an inhibition in nitrate reductase activity (Farahani *et al*., 2009). The deterioration in K % with water deficit may be elucidated by interrupting water status in stomata and plant cells (Sarani *et al*., 2014). Alternatively, the decline in nutrient percentage within drought conditions was mitigated by GlyBet supplementation. The role of GlyBet in boosting nutients% is not implicit and some similar investigators have confirmed current findings (Khoshkharam *et al*., 2021). This promotion may be resulted from a better development of root system, and stabilizing membrane permeability (Hasanuzzaman *et al*., 2019).

4. Relative water content (RWC), and proline concentration

Significant differences were established amongst water regimes for RWC, and proline content (Table 5). Gradually drought stress expressively reduced leaf RWC accompanied by proline over-accumulation relative to control plants. Moderate drought expressively improved proline (28.83% in the 1st year and 27.42% in the 2nd year) over control plants.

Table 5. Relative water content, and proline concentration of potato shoots as affected by glycinebetaine under irrigation regimes in both experimental years.

Treatments	Relative water content %		Proline (µmol g^{-1}fw)	
	S1	**S2**	**S1**	**S2**
Water quantity (I, m^3/fed)				
1500 (I_{1500})	75.58	76.59	20.39	21.84
1200 (I_{1200})	71.34	72.29	26.27	27.83
900 (I_{900})	66.03	66.91	22.90	24.35
LSD 5%	1.78	1.80	3.03	3.03
Glycinebetaine (GlyBet, ppm)				
0 (GlyBet$_0$)	68.92	69.81	21.99	23.24
200 (GlyBet$_{200}$)	70.96	71.89	22.84	24.21
400 (GlyBet$_{400}$)	71.56	72.53	23.37	24.93
600 (GlyBet$_{600}$)	72.48	73.48	24.54	26.31
LSD 5%	2.79	2.83	1.61	1.60
Interaction Effects				
I_{1500}+GlyBet$_0$	74.39	75.34	19.16	20.36
I_{1500}+GlyBet$_{200}$	75.30	76.28	19.83	21.26
I_{1500}+GlyBet$_{400}$	75.53	76.55	20.52	22.02
I_{1500}+GlyBet$_{600}$	77.12	78.18	22.04	23.74
I_{1200}+GlyBet$_0$	67.75	68.62	24.62	25.86
I_{1200}+GlyBet$_{200}$	71.36	72.29	26.05	27.35
I_{1200}+GlyBet$_{400}$	72.75	73.74	26.54	28.24
I_{1200}+GlyBet$_{600}$	73.47	74.49	27.88	29.88
I_{900}+GlyBet$_0$	64.62	65.45	22.20	23.50
I_{900}+GlyBet$_{200}$	66.24	67.09	22.63	24.03
I_{900}+GlyBet$_{400}$	66.40	67.30	23.04	24.54
I_{900}+GlyBet$_{600}$	66.85	67.77	23.72	25.31
LSD 5%	3.61	3.66	4.03	4.04

Application of GlyBet significantly improved RWC, and proline over nontreated plants. The spraying with GlyBet at 600 mg/l enhanced RWC (5.16 and 5.25%), and proline (11.59 and 11.49%) over control in the 1st and 2nd seasons respectively.

Regarding the interaction, GlyBet spraying in moderate and severe drought abolishes the destructive impact of water stress on RWC over nontreated drought-affected plants in both years (Table 5). Furthermore, GlyBet spraying to moderate or severe drought-affected plants significantly induces the over-accumulation of proline corresponding to nontreated control plants (Table 5). Conversely, the maximum proline (27.88 and 29.88 µmol g^{-1}fw) was achieved once 600 mg/l GlyBet spraying with 1200 m^{3}/fed irrigation water.

RWC was familiarized as a decent measure for crop water status within drought conditions. The injuries of drought on RWC % were lessened by GlyBet application, leading to an improvement in RWC %, relative to untreated drought-affected plants (Table 5). Earlier, it was discovered that RWC % declined under drought (Alam *et al*., 2022, Shemi *et al*., 2021 and Metwaly *et al*., 2022). The RWC of GlyBet-treated plants within well-watered or water deficient was retained at greater altitudes to an outstanding level over stressed plants without GlyBet application, a motivation that GlyBet will enhance potato water status under water deficit. Regularly, GlyBet spraying lessened the dropping of potatoes RWC % under drought, as confirmed by Yang *et al*. (2022). Due to its solid hydrophilicity and solubility, GlyBet has been shown to maintain plant water status in arid regions as well as contribute to the osmotic adjustment capability of plant tissues (Genard *et al*., 1991). Alasvandyari *et al*. (2017) verified that GlyBet may increase K^{+} accumulation in drought-affected plants, hence supporting the plants' capability to preserve the leaf's water content. Furthermore, GlyBet treatments invigorated root system establishment and then reinforced the capability of water absorption, and upregulation of aquaporin genes, to enhancement water conservation and boost WUE (Yang *et al*., 2022 and Hasanuzzaman *et al*., 2019). This designates that GlyBet spraying might endure potato leaf membrane stabilities under stressful conditions.

A pervasive phenomenon of stress-affected plants is the buildup of a superior amount of compatible osmolytes, that are a lesser molecular weight tremendously soluble, and usually harmless at a great level without affecting metabolic pathways (Ashraf and Foolad, 2007). Proline represents a signaling molecule that impacts cell multiplication and elicits definite gene expression, which is needed for plant endurance within water scarcity or GlyBet supplementation (Metwaly *et al*., 2022). Proline buildup in plants plays a decisive function in preserving osmotic adjustment, so, plant cells can absorb extra water from the soil (Ullah *et al*., 2012). Additionally, proline has been deliberated as a carbon and nitrogen source for speedy rescue from stressful circumstances and performing as a preservative for membrane and macromolecules, as well as a ROS mitigator (Mousavi *et al*., 2009). This increase may be owing to a decline in proline oxidase and proline catabolizing enzymes (Debnath, 2008). Conversely, proline assimilation once GlyBet is applied under normal or stressful conditions is not entirely recognized and requires extra investigation.

5. Antioxidant Enzyme activities

Table 6 ascertains that drought ominously accelerated antioxidant enzyme activity (SOD, Cat, and POD) over well-watered plants. The supreme activity of each enzyme throughout the experimental time was documented under moderate water stress compared with severe drought or well-watered plants.

Application of GlyBet concentration raised progressively SOD, CAT, and POD activity in potato shoots in either the 1st or 2nd season. The utmost effective concentration in this regard is 600 mg/l GlyBet which accelerates SOD, CAT, and POD activities by 11.68, 14.89, and 41.38% in the first season, and by 7.68, 14.00, and 33.34% in the second season over non-treated plants.

The data in the same table indicated that GlyBet spraying under moderate or severe stress significantly improved antioxidant enzyme activities relative to nontreated plants under such irrigation regimes. The maximum activities were documented once treated plants with 600 mg/l GlyBet under moderate drought compared with other concentrations and water stress levels.

Table 6. Antioxidant enzyme activities of potato shoots as affected by glycinebetaine under irrigation regimes in both experimental years.

Treatments	SOD (Unit mg^{-1} protein)		Catalase (Unit mg^{-1} protein)		Peroxidase (Unit mg^{-1} protein)	
	S1	**S2**	**S1**	**S2**	**S1**	**S2**
Water quantity (m^{3}/fed)						
1500 (I_{1500})	2.253	2.350	4.954	5.053	2.272	2.389
1200 (I_{1200})	2.732	2.767	6.118	6.199	2.609	2.768
900 (I_{900})	2.613	2.647	5.552	5.626	2.371	2.497
LSD 5%	0.124	0.190	0.225	0.325	0.107	0.111
Glycinebetaine ppm						
0 (GlyBet$_{0}$)	2.353	2.473	5.088	5.198	2.032	2.237
200 (GlyBet$_{200}$)	2.547	2.580	5.550	5.622	2.368	2.478
400 (GlyBet$_{400}$)	2.604	2.630	5.682	5.758	2.396	2.507
600 (GlyBet$_{600}$)	2.628	2.663	5.846	5.926	2.873	2.983
LSD 5%	0.064	0.090	0.258	0.304	0.216	0.209
Interaction						
I_{1500}+GlyBet$_{0}$	2.091	2.387	4.455	4.645	1.900	2.101
I_{1500}+GlyBet$_{200}$	2.269	2.298	4.945	5.009	2.243	2.333
I_{1500}+GlyBet$_{400}$	2.358	2.389	5.304	5.375	2.250	2.339
I_{1500}+GlyBet$_{600}$	2.296	2.327	5.112	5.183	2.696	2.785
I_{1200}+GlyBet$_{0}$	2.490	2.520	5.475	5.546	2.150	2.386
I_{1200}+GlyBet$_{200}$	2.729	2.764	6.265	6.346	2.540	2.672
I_{1200}+GlyBet$_{400}$	2.809	2.845	6.119	6.201	2.600	2.732
I_{1200}+GlyBet$_{600}$	2.902	2.940	6.613	6.704	3.146	3.281
I_{900}+GlyBet$_{0}$	2.479	2.510	5.334	5.403	2.046	2.224
I_{900}+GlyBet$_{200}$	2.643	2.676	5.439	5.510	2.323	2.430
I_{900}+GlyBet$_{400}$	2.644	2.679	5.623	5.699	2.340	2.449
I_{900}+GlyBet$_{600}$	2.686	2.722	5.812	5.892	2.776	2.885
LSD 5%	0.115	0.216	0.587	0.822	0.301	0.302

Reactive oxygen species as signaling molecules are produced in plants via photorespiration and oxidative processes in mitochondria; for controlling developmental and metabolic pathways under normal or stressful conditions (Farouk *et al*., 2023). The over-production can reach toxic levels in the plants to counter the harmful impacts of ROS, and plants establish scavenging strategies i.e., to mitigate the ROS level including antioxidant enzymes and molecules (Hossain *et al*., 2013). The degree of ROS injury depends on the equilibrium amongst the assembly and elimination of ROS. Antioxidant enzymes can alleviate the drastic impact of ROS molecules (Mane *et al*., 2008). A current study proved that SOD, CAT, and POD activity was improved by drought, GlyBet, and their interactions, relative to untreated plants under such treatments (Table 6), thus conferring higher drought resistance

The CAT and POD convert H_2O_2 into water and molecular oxygen, and are supposed to limit cellular injury and enhance oxidative stress tolerance (Kusvuran *et al.*, 2013). Superoxide radicals that emerge with metabolic processes are transformed into hydrogen peroxide and molecular oxygen by the SOD enzyme (Kusvuran *et al.*, 2013). The metabolism of hydrogen peroxide is dependent on several functionally interrelated antioxidant enzymes like CAT and POD. As CAT and POD synchronize with SOD and play a prime defensive function in O_2^- and H_2O_2 scavenging process (Hoque *et al.*, 2007). GlyBet spraying significantly increased antioxidant enzyme activity under normal or stressful conditions. Since GlyBet-treated plants can sustain maximum antioxidant enzyme activity at a reasonable level to avert impairment induced by ROS accumulation (Hoque *et al.*, 2007 and Farooq *et al.*, 2010).

6. Yield and its components:

Tables (7,8) outcomes clearly show that drought triggered an extreme drop in yield and components. Relative to control plants, there was a considerable reduction in tuber weight and tuber number plant^{-1}, marketable and non-marketable yield, total yield, tuber dry matter, tuber hardness, and tuber density in both years.

Table 7. Potato yield as affected by glycinebetaine under irrigation regimes in both experimental years.

Treatments	Tubers weight (g) per plant		Tubers No./ plant		Marketable yield (ton/ fed.)		Non Marketable yield (ton/ fed.)		Total yield (ton/ fed.)	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Water quantity (I, m^3/fed)										
1500 (I_{1500})	633.6	662.4	5.50	5.75	19.42	19.68	0.549	0.556	19.97	20.23
1200 (I_{1200})	591.3	618.2	4.99	5.12	16.45	16.67	0.662	0.671	17.12	17.34
900 (I_{900})	543.3	568.0	4.81	4.93	13.24	13.41	0.845	0.856	14.09	14.27
LSD 5%	5.6	5.9	0.44	0.45	0.57	0.59	0.011	0.012	0.58	0.60
Glycinebetaine (GlyBet, ppm)										
0 (GlyBet$_0$)	552.8	577.7	4.89	4.95	14.43	14.61	0.791	0.803	15.22	15.41
200 (GlyBet$_{200}$)	571.4	597.2	4.99	5.08	15.80	16.00	0.724	0.734	16.53	16.74
400 (GlyBet$_{400}$)	602.8	630.4	5.21	5.37	16.91	17.13	0.654	0.662	17.57	17.80
600 (GlyBet$_{600}$)	630.6	659.5	5.45	5.65	18.34	18.58	0.574	0.580	18.91	19.17
LSD 5%	6.6	7.0	0.36	0.38	0.25	0.26	0.006	0.007	0.25	0.26
Interaction Effects										
I_{1500}+GlyBet$_0$	565.4	590.9	5.27	5.33	18.55	18.78	0.625	0.634	19.17	19.41
I_{1500}+GlyBet$_{200}$	588.7	615.3	5.41	5.52	18.86	19.09	0.577	0.585	19.43	19.68
I_{1500}+GlyBet$_{400}$	669.7	700.3	5.62	5.78	19.29	19.51	0.529	0.536	19.79	20.05
I_{1500}+GlyBet$_{600}$	710.6	743.2	6.12	6.35	21.02	21.30	0.467	0.472	21.48	21.78
I_{1200}+GlyBet$_0$	478.9	604.9	4.79	4.84	13.91	14.08	0.773	0.783	14.69	14.87
I_{1200}+GlyBet$_{200}$	582.9	609.2	4.89	4.99	15.94	16.15	0.709	0.718	16.65	16.87
I_{1200}+GlyBet$_{400}$	595.6	622.9	5.05	5.21	17.54	17.77	0.622	0.630	18.16	18.40
I_{1200}+GlyBet$_{600}$	607.7	635.6	5.22	5.42	18.41	18.66	0.546	0.553	18.95	19.21
I_{900}+GlyBet$_0$	514.1	537.2	4.61	4.65	10.83	10.96	0.977	0.990	11.81	11.95
I_{900}+GlyBet$_{200}$	542.5	567.0	4.65	4.74	12.61	12.78	0.885	0.896	13.50	13.67
I_{900}+GlyBet$_{400}$	543.1	567.9	4.98	5.13	13.94	14.12	0.810	0.820	14.75	14.94
I_{900}+GlyBet$_{600}$	573.4	599.8	4.99	5.17	15.58	15.79	0.708	0.717	16.29	16.51
LSD 5%	11.6	12.2	0.69	0.71	0.63	0.64	0.011	0.012	0.64	0.65

Table 8. Potato yield charctaritics as affected by glycinebetaine under irrigation regimes in both experimental years.

Treatments	Tuber dry matter %		Hardness kg cm^{-2}		Density (g/ cm^3)	
	S1	S2	S1	S2	S1	S2
Water quantity (I, m^3/fed)						
1500 (I_{1500})	19.51	19.76	5.211	5.354	0.886	0.896
1200 (I_{1200})	20.62	20.89	5.785	5.944	0.983	0.994
900 (I_{900})	21.50	21.79	6.853	7.041	1.173	1.186
LSD 5%	1.05	1.03	0.205	0.211	0.040	0.041
Glycinebetaine (GlyBet, ppm)						
0 (GlyBet$_0$)	18.46	18.59	5.501	5.648	0.950	0.960
200 (GlyBet$_{200}$)	19.95	20.15	5.779	5.935	0.991	1.001
400 (GlyBet$_{400}$)	21.37	21.69	6.102	6.270	1.038	1.049
600 (GlyBet$_{600}$)	22.38	22.83	6.418	6.597	1.078	1.090
LSD 5%	0.51	0.56	0.557	0.572	0.089	0.091
Interaction Effects						
I_{1500}+GlyBet$_0$	17.74	17.86	4.921	5.053	0.851	0.860
I_{1500}+GlyBet$_{200}$	18.52	18.71	5.061	5.198	0.865	0.874
I_{1500}+GlyBet$_{400}$	20.10	20.40	5.356	5.504	0.911	0.920
I_{1500}+GlyBet$_{600}$	21.65	22.09	5.505	5.661	0.919	0.930
I_{1200}+GlyBet$_0$	18.65	18.78	5.351	5.494	0.922	0.932
I_{1200}+GlyBet$_{200}$	20.42	20.62	5.744	5.899	0.982	0.992
I_{1200}+GlyBet$_{400}$	21.38	21.70	5.864	6.026	0.997	1.008
I_{1200}+GlyBet$_{600}$	22.03	22.47	6.183	6.355	1.032	1.043
I_{900}+GlyBet$_0$	19.01	19.14	6.230	6.397	1.078	1.089
I_{900}+GlyBet$_{200}$	20.91	21.11	6.533	6.710	1.126	1.138
I_{900}+GlyBet$_{400}$	22.62	22.69	7.086	7.281	1.207	1.220
I_{900}+GlyBet$_{600}$	23.47	23.94	7.564	7.775	1.282	1.296
LSD 5%	1.77	1.73	0.524	0.538	0.093	0.095

GlyBet application ominously increased potato yield and their components over untreated treatment. The most effective concentration was 600 mg/L GlyBet, which increased tuber weight and tuber number plant^{-1}, marketable yield, total yield, tuber dry matter, tuber hardness, and tuber density by 14.07, 11.45, 27.09, 24.24, 21.23,16.66, and 13.47% in the first year and 14.15, 14.14, 27.17, 24.52, 22.80, 16.80, 13.54% in the 2nd year respectively, over untreated plants (Tables 7,8).

Potato yield components are less deleteriously impacted by drought when GlyBet is sprayed. With untreated drought-affected plants, yield components in both experimental years have declined as the addition of 600 mg/L GlyBet under severe drought

As indicated previously and in the current investigation, drought markedly reduced crop yield and its quantity, meanwhile GlyBet application nullifies the injury of drought and boosted yield attributes with normal conditions (Khoshkharam *et al.*, 2021; Shemi *et al.*, 2021 and Metwaly *et al.*, 2022). Potato yield impressively depends on its canopy structure as well as on yield contributing trials like tuber number plant^{-1}, average tuber size, tuber fresh and dry mass, and tuber yield plant^{-1}. All these trials were declined by drought which eventually dropped marketable yield (Aliche *et al.*, 2018). The decline in yield and its quality under drought may result from reduced canopy growth (branches and either leaf number and leaf area per plant) associated with dropping in photosynthesis rate and Calvin cycle enzyme activity (Shemi *et al*., 2021). Additionally, drought stress upset assimilates production and portioning into developed tuber (Shemi *et al*., 2021 and Alam, *et al*., 2022), as well as reducing the number of stolons per plant (Schafleitner *et al*., 2007). Lastly, drought accelerates energy imbalance in chloroplasts that evokes ROS production along with crop senescence and yield reduction (Farouk *et al*., 2023).

GlyBet motivates several physio-biochemical pathways and morpho-anatomical alterations that may be the reason for the rise in crop yield (Shemi *et al*., 2021 and Metwaly *et al*., 2022). These outcomes were approved with the values provided previously (Shemi *et al*., 2021 and Khoshkharam *et al*., 2021). GlyBet attributed the yield improvement to both the defense of a higher net photosynthetic rate and an enhancement in the source-sink relationship (Shemi *et al*., 2021 and Hasanuzzaman *et al*., 2019). GlyBet motivates growth and yield attributes due to its osmoprotective function and regulates ion homeostasis (Niu *et al*., 2023) accompanied by improving drought-affected plant CO_2 assimilation (Shemi *et al*., 2021 and Niu *et al*., 2023), and owing to its role in biosynthesis and transport of hormones such as cytokinins that could have a role in photoassimilates transportation (Taiz and Zeiger, 2006).

7. Tubers chemical quality:

Table 9 shows that drought improved vitamin C and TSS but reduced total sugar and protein over control plants. The supreme vitamin C was eminent during moderate drought. Alternatively, the highest concentration of TSS was gained under severe drought, meanwhile, the maximum total sugars and protein were noted within well-watered conditions either in 1st or 2nd years.

Table 9 shows that GlyBet spraying substantially affected tuber chemical quality attributes. The maximum values were acquired through 600 mg/L GlyBet spraying in 1st or 2nd year, over former concentrations or nontreated plants.

Results in Table 9 display that spraying of GlyBet concentration within irrigation regimes expressively improved vitamin C, TSS, total sugars, and protein as related to nontreated plants in each irrigation regime. The maximum concentration of vitamin C was attained under moderate drought with 600 mg/L GlyBet, but the uppermost TSS was noted under severe drought and spraying 600 mg/l GlyBet. Otherwise, the highest concentration of total sugars and protein was documented under normal conditions and sprayed with 600 mg/L GlyBet.

There are scant reports on the effect of GlyBet and/or drought on tuber quality. Accordingly, Khoshkharam *et al.* (2021); Shemi *et al.* (2021) and Metwaly *et al.* (2022) establish that TSS and vitamin C declined with water deficit, but increased with GlyBet spraying. Moreover, it is recorded that drought stress significantly declines protein and carbohydrate percentage in potato tuber, which might be triggered by the decline of CO_2 fixation, and a drop of assimilates translocation, as well as a deterioration in the starch and protein assimilates gene expression (Younis *et al*., 2000). On the other hand, the raising in carbohydrate% of GlyBet pretreatment might be attributed to the rise of photosynthetic pigments (Table 3), leading to the upgrading of carbohydrate assimilation and build-up.

Table 9. Potato tuber quality as affected by glycinebetaine under irrigation regimes in both experimental years.

Treatments	Vit. C		TSS,%	Total sugars,%			Protein,%	
	S1	S2	S1	S1	S2	S2	S1	S2
Water quantity (I, m^3/fed)								
1500 (I_{1500})	13.28	13.46	4.03	4.25	5.18	4.40	13.32	13.49
1200 (I_{1200})	15.82	16.03	4.56	4.81	4.65	4.85	12.41	12.56
900 (I_{900})	14.94	15.13	4.86	5.13	4.14	4.32	10.82	10.97
LSD 5%	1.06	1.07	0.37	0.39	0.09	0.10	0.14	0.15
Glycinebetaine (GlyBet, ppm)								
0 (GlyBet$_0$)	12.29	12.44	4.19	4.36	4.38	4.56	11.40	11.54
200 (GlyBet$_{200}$)	13.99	14.17	4.48	4.70	4.53	4.72	12.18	12.33
400 (GlyBet$_{400}$)	15.48	15.68	4.54	4.82	4.74	4.95	12.42	12.58
600 (GlyBet$_{600}$)	16.97	17.20	4.72	5.06	4.98	5.19	12.73	12.90
LSD 5%	1.15	1.16	0.35	0.37	0.10	0.11	0.09	0.10
Interaction Effects								
I_{1500}+GlyBet$_0$	10.91	11.05	3.72	3.87	4.85	5.05	12.31	12.46
I_{1500}+GlyBet$_{200}$	12.42	12.58	3.95	4.14	5.12	5.34	13.26	13.43
I_{1500}+GlyBet$_{400}$	14.17	14.35	4.10	4.34	5.13	5.35	13.57	13.74
I_{1500}+GlyBet$_{600}$	15.64	15.85	4.35	4.56	5.64	5.85	14.13	14.32
I_{1200}+GlyBet$_0$	13.26	13.43	4.33	4.50	4.56	4.75	11.77	11.92
I_{1200}+GlyBet$_{200}$	15.16	15.36	4.61	4.84	4.58	4.78	12.55	12.70
I_{1200}+GlyBet$_{400}$	16.57	16.79	4.62	4.89	4.68	4.88	12.56	12.72
I_{1200}+GlyBet$_{600}$	18.30	18.54	4.69	5.02	4.78	4.99	12.75	12.92
I_{900}+GlyBet$_0$	12.69	12.84	4.53	4.71	3.73	3.89	10.12	10.25
I_{900}+GlyBet$_{200}$	14.39	14.57	4.88	5.12	3.88	4.05	10.72	10.86
I_{900}+GlyBet$_{400}$	15.69	15.90	4.92	5.21	4.42	4.61	11.14	11.28
I_{900}+GlyBet$_{600}$	16.99	17.22	5.14	5.50	4.54	4.74	11.32	11.47
LSD 5%	2.01	2.04	0.70	0.75	0.17	0.19	0.21	0.22

Within drought conditions, photosynthesis is principally controlled by stomatal and mesophyll restrictions, i.e., in how far CO_2 remains accessible for chloroplasts when stomatal and mesophyll conductance is retained small to evade extreme transpiration. Only at high-stress levels non-stomatal metabolic limitations, such as reduced ribulose bisphosphate carboxylase regeneration and ATP assimilation inflict carbon assimilation under drought. Conversely, at high irradiances, RuBP exists in excess, and CO_2 should endure the restrictive aspect for photosynthesis (Parry *et al*., 2007). Little CO_2 accessibility for chloroplasts favors the oxygenase reaction of ribulose bisphosphate carboxylase and photorespiration, resulting in up to 50% decline in carbon gain over well-watered plants.

8. Water use efficiency (WUE)

Figure (1) shows that drought expressively improved WUE associated with control plants. The maximum WUE (17.85, and 17.65%) was gained under severe stress over control plants in both years respectively.

WUE significantly improved by GlyBet spraying over nontreated plants (Figure 1), where the supreme WUE was achieved by supplementation of 600 mg/l GlyBet which raised it by 26.43% (1st year) and by 26.57% in 1st and 2nd year.

Additionally, Figure (1 C,D) indicates that GlyBet spraying under 1200 or 900 m3/fed irrigation regimes enhanced WUE over nontreated well-watered plants. The maximum WUE (41.62% and 41.73% during 1st and 2nd years) was achieved through 600 mg/l GlyBet spraying under severe drought correspondingly.

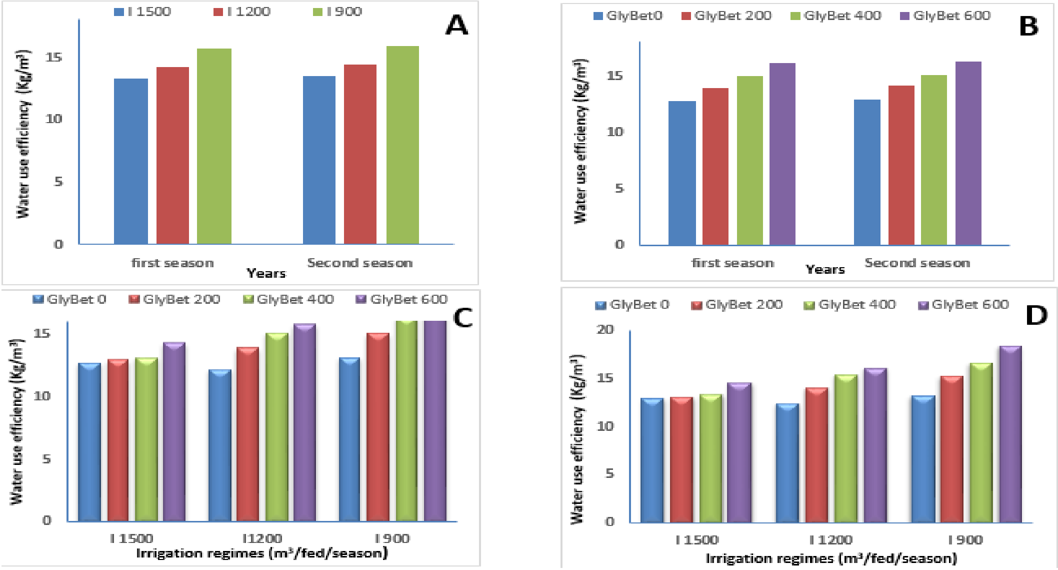

Figure 1. Potato water use efficiency as affected by irrigation regimes (A), glycinebetaine concentration (B), and their interactions (C,D) in both seasons. I 1500, well-watered (1500 m3/fed); I 1200, moderate drought (1200 m3/fed); I 900, severe drought (900 m3/fed); fed., feddan; GlyBet0, non spraying with glycinebetaine; GlyBet 200, spraying with 200 ppm glycinebetaine; GlyBet 400, spraying with 400 ppm glycinebetaine; GlyBet 600, spraying with 600 ppm glycinebetaine.

One of the most imperative physio-biochemical strategies used by drought-affected plants is the enhancement of WUE (Metwaly *et al*., 2022). Current findings revealed that drought and/or GlyBet considerably improved potato plant WUE in both experimental years over non-treated plants. GlyBet application raises potato WUE via manipulating photosynthesis and improving root establishment, leading to restored water absorption (Ahmed *et al*., 2019). The improvement in WUE resulted from lessening transpiration water loss and concurrently preserving leaf water status as well as raising root/shoot ratio along with inducing drought tolerance (Boguszewska-Mankowska *et al*., 2020). The goal is to raise plant WUE in drought-influenced plants. This may be achieved in two ways: by making the crop more capable of producing biomass per unit of water, or by improving the plant's ability to adapt. However, the effect of a drought on a plant's WUE often varies depending on the cultivar of the plant and the intensity of the drought (Gholami Zali *et al*., 2018).

CONCLUSION

Current findings explicitly that the application of GlyBet is an efficacious approach for improving plant performance under drought. Generally, spraying drought-affected potato plants two times at 40 and 55 days from cultivation with 600 mg/L GlyBet might be a prospective manner for dropping the effects of drought and consequently refining WUE and yield components and their quality.

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كفاءة الجليسين بيتين في زيادة تحمل نبات البطاطس للجفاف

السعيد السيد متولى[1]، وليد على السعدي[1] ، زيدان شهاب احمد الشال[2] و منى عبد العزيز عبد الحليم سالم موسى[2]

[1] قسم الخضر والزينة - كلية الزراعة – جامعة المنصورة – 35516 – المنصورة - مصر
[2] قسم بحوث البطاطس والخضر خضرية التكاثر- معهد بحوث البساتين - مركز البحوث الزراعية – الجيزة - مصر

الملخص

تحسين كفاءة استخدام النبات للمياه من خلال المواد المنظمة للاسموزية يمثل النهج الرئيسي لإستدامة الانتاجية. أجريت تجارب حقلية لتقييم كفاءة إستخدام تراكيز مادة الجليسين بيتين (0، 600،400،200 جزء في المليون) في التغلب على التأثير الضار للجفاف (1500، 1200، 900 م3/فدان) على انتاجية البطاطس.أدي الجفاف إلى انخفاض معنوي في نمو البطاطس (ارتفاع النبات، عدد الأوراق لكل نبات، المساحة الورقية /النبات، عدد الافرع /النبات، الوزن الطازج للمجموع الخضري، المادة الجافة)، وتركيز صبغات البناء الضوئي (الكلوروفيل أ، والكلوروفيل ب، والكاروتينويد) والنسبة المئوية للأيونات (النيتروجين، الفوسفور، والبوتاسيوم)، ومكونات المحصول (وزن الدرنات/ نبات، عدد الدرنات/نبات، المحصول القابل والغير قابل للتسويق). ايضا، أدى الجفاف إلى زيادة كبيرة في نشاط الإنزيمات المضادة للأكسدة، ومحصول الدرنات غير القابل للتسويق، والمادة الجافة للدرنات، وصلابة الدرنات وكثافتها، وفيتامين C، والنسبة المئوية للمادة الصلبة، وزيادة كفاءة استخدام المياه. وكانت أكثر الإنخفاضات المسجلة تحت ظروف الجفاف الشديد. أدى الرش الورقي بـالجليسين بيتين إلى زيادة معنوية في جميع صفات النمو والمحصول، باستثناء المحصول غير القابل للتسويق والذي ينخفض عند الرش بـالجليسين بيتين.ايضا، أدى رش الجليسين بيتين إلى زيادة تركيز صبغات البناء الضوئي، ونسبة الأيونات، وتركيز البرولين، ونشاط الإنزيمات المضادة للأكسدة، تحسين المحتوى المائي النسبي وكفاءة استخدام المياه. وكانت أعلى القيم لتلك الصفات تم تسجيلها مع 600 ملجم/لتر من الجليسين بيتين مقارنة بالتراكيز الأخرى أو النباتات غير المعاملة. أوضحت النتائج أن الرش بالجليسين بيتين بجميع تركيزاته يقلل من التأثيرات الضارة للجفاف المعتدل أو الشديد، على نمو النبات وإنتاجيته وكذلك بعض الصفات البيوكيميائية.وبالتالي، فإن استخدام 600 ملجم/لتر من الجليسين بيتين مرتين باعتباره مادة حافظة للأسموزية، وصديقة للبيئة، ومنخفضة التكلفة، لديه القدرة على التخفيف من أضرار الجفاف وزيادة كفاءة إستخدام المياه.

الكلمات الدالة : الجليسين بيتين، الجفاف، البطاطس، المحصول، الإنزيمات المضادة للأكسدة