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Effect of Soil Addition of Biochar, and Foliar Application of Trehalose and Seaweed on Potato Productivity Under Different Rates of Irrigation

Samar M. A. Doklega[1]; Hemat A. EL-Bauome[1]; Hala A. EL-Sayed[1]; H. M. B. EL-Metwally [2] and O. M. H. Abd El-Rahman[1*]

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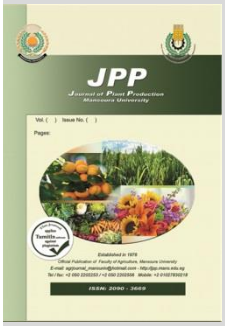
[1] Veg. and Flori. Dept., Fac. of Agric., Mans. Univ., Egypt
[2]Veg. Res. Dept., Hort. Res. Inst., Agric. Res. Center, Giza, Egypt



ABSTRACT

To address water scarcity in arid and semi-arid regions like Egypt and enhance food security, a research trial was conducted to assess the impact of different irrigation rates, soil addition of biochar, and foliar applications of trehalose and seaweed on the enzyme activity, yield and quality of potato. Three irrigation levels: 100% **(I_1),** 80% **(I_2)** and 60% **(I_3)** of the irrigation requirements, with biochar applied at 0.0, 5.0, and 7.0 m^3 fed^{-1}, as well as spraying trehalose and seaweed at a concentration of 1.0 g/L, in addition to the control treatment, were investigated. The **I_3** treatment led to the highest levels of PPO,CAT and MDA, while the **I_1** treatment resulted in the lowest values. Increasing biochar rates reduced enzyme activity, and foliar applications of trehalose and seaweed further decreased these enzyme levels compared to the control. Even under reduced irrigation conditions, trehalose and seaweed application combined with biochar improved plant growth parameters such as plant height, and fresh and dry weights compared to traditional irrigation (I_1 treatment) in the absence of both biochar and foliar applications. The highest tuber yield and quality traits, including total carbohydrates, total sugars, protein percentage and vitamin C content, were achieved under the combined treatment of **I_1** x biochar (7.0 m^3 fed^{-1}) x trehalose. Notably, the **I_2** treatment combined with biochar and either trehalose or seaweed outperformed the **I_1** treatment without additional treatments. This study suggests that integrating biochar with foliar treatments of trehalose and seaweed can significantly enhance potato production under water-limited conditions.

***Keywords**:* PPO, CAT, MDA, Cara, biochar, trehalose, seaweed

INTRODUCTION

Potato (*Solanum tuberosum*) is one of the most important staple crops globally, providing a significant source of nutrition and livelihood for millions of people. Its versatility, high nutritional value, and ability to grow in diverse climates have contributed to its widespread cultivation. However, potato plants are highly susceptible to water deficit, which is a major limiting factor affecting their growth, development and yield. With climate change intensifying water scarcity, it is vital to develop strategies that enhance plant resilience to drought conditions. Water deficit, caused by factors such as drought or inadequate irrigation, adversely affects potato plants at various stages of their life cycle. It leads to reduced photosynthetic activity, stomatal closure, oxidative stress, impaired nutrient uptake, and ultimately results in decreased tuber yield and compromised quality. Recent research has identified biochar as a promising soil amendment, capable of improving water retention and soil fertility. Additionally, seaweed and trehalose have been recognized for their roles in enhancing plant stress tolerance through osmoprotection and nutrient enrichment. Biochar is a carbon-rich material derived from the pyrolysis of organic matter. It has been shown to improve soil water-holding capacity, nutrient availability, and microbial activity, thereby enhancing plant water use efficiency and drought tolerance (Elsherpiny 2023). Seaweed extracts are increasingly recognized for their potential to enhance plant growth and stress tolerance. Rich in bioactive compounds such as polysaccharides, vitamins, minerals, and phytohormones, seaweed extracts provide a natural source of nutrients and growth-promoting substances (Garai *et al.* 2021). When applied to plants, these extracts improve nutrient uptake and enhance physiological processes such as photosynthesis and root development. Seaweed extracts are also known to boost plant resilience to environmental stresses, including drought, by improving water retention and activating defense mechanisms. The presence of alginates and other polysaccharides in seaweed contributes to better soil structure and moisture retention, further supporting plant health. By enhancing both nutrient availability and stress resistance, seaweed extracts offer a sustainable solution for improving crop productivity and quality, making them an attractive option for modern agricultural practices (Zhang *et al.* 2023).Trehalose is a naturally occurring disaccharide sugar that plays a critical role in enhancing plant stress tolerance. It functions as an osmoprotectant, helping plants to stabilize proteins and cellular membranes under adverse environmental conditions, such as drought and extreme temperatures. By accumulating in plant tissues, trehalose helps maintain cell structure and function, allowing plants to continue vital processes like photosynthesis even under stress (Shafiq *et al.* 2015). Additionally, trehalose has been shown to regulate stress-responsive genes, further boosting a plant's ability to cope with environmental challenges. Its ability to protect against oxidative damage and improve water retention makes trehalose a valuable tool in promoting plant health and productivity. As a result, its application in agriculture is being explored as a strategy to enhance crop resilience to drought

*** Corresponding author.**
E-mail address: omarhelmy617@gmail.com
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and other stress factors, thereby contributing to sustainable agricultural practices (Al-Rubaie *et al*. 2023).

The primary objective of this study is to explore the potential impact of biochar application combined with foliar sprays of seaweed or trehalose on enhancing drought stress tolerance in potato plants. The research will evaluate the effects of these treatments on enzyme activity, plant performance, tuber yield and quality characteristics. By clarifying the role of biochar, seaweed and trehalose sprays in alleviating the adverse effects of water deficit, this study aims to offer valuable insights for developing sustainable strategies to improve drought resilience in potato cultivation.

MATERIALS AND METHODS

Experimental site: A field trial A field trial was conducted during two successive seasons of 2021/2022 and 2022/2023 at a privately-owned farm situated in Koffor Elarab village, Talkha district, Dakahlia governorate, Egypt.

Soil sampling: Prior to conducting the experiment, an initial soil sample was collected from a depth of 0-30 cm then it was analyzed following the methods described by Sparks *et al.* (2020) and Dane and Topp (2020), as their characteristics are presented in Table 1.

Table 1. Characteristics of initial soil

Characteristics			Values
Physical properties Particle size distribution (%)	Clay		49.00
	Silt		30.45
	Sand		22.55
	Textural class is clay		
Hydro physical properties	Saturation,%		70.0
	WHC ,%		35.0
Chemical properties	pH (soil suspension, 1: 2.5).		8.100
	EC dSm^{-1}(soil paste extract)		2.870
	Organic matter, %		1.39
	Available nutrients	N, $mgKg^{-1}$	48.5
		P, $mgKg^{-1}$	8.94
		K, $mgKg^{-1}$	210.3

Studied substances: Biochar characterization process followed the methodology outlined by Yang *et al.* (2019). Plant residues consisting of rice, barely, wheat and maize straw were obtained from private farms and transported to agricultural research center (ARC), Egypt, as the pyrolysis of the plant residues was conducted in the absence of oxygen, at temperatures ranging from 400 to 500 °C, for a duration of two hours. The resulting biochar had a nitrogen content (N) of 1.43%, an organic carbon content (OC) of 44.80%, a pH value of 8.9, an electrical conductivity (EC) value of 4.9 dSm^{-1}, and a cation exchange capacity (CEC) value of 66.0 cmol kg^{-1}. The seaweed used in the study was procured from Eco Agro Company, Egypt. The seaweed product had a composition of 20% algae extract, 1.5% alginic acid, and 0.5% mannitol. While trehalose was purchased from Technogene Company located in Dokki, Giza, Egypt.

Potato tubers: Potato tubers (Cv Cara) were sourced from ARC (Agricultural Research Center), and these tubers were subsequently divided into pieces, each weighing approximately 40.0 grams on average.

Experimental setup: This experiment was conducted using a split-split plot design to assess the impact of different irrigation rates , soil biochar additions, and foliar applications on the performance of potato plants. The irrigation rates included three levels: I_1 (100%), I_2 (80%), and I_3 (60%) of the crop's irrigation requirements. Biochar was applied to the soil at three rates: 0.0, 5.0, and 7.0 m³ per feddan. Additionally, foliar treatments consisted of trehalose (1.0 g L^{-1}), seaweed extract (1.0 g L^{-1}) and a control treatment (without spraying). In the experimental layout, the irrigation rates were designated as the main plots, while biochar treatments were assigned as the sub-main plots. The foliar treatments were allocated in the sub-sub plots. The total number of treatments was 27 with three replicates (3 irrigation rates treatments x 3 biochar treatments x 3 foliar application x 3 replicates = 81). The experimental unit area was 10.4 m2 (2.8 m × 3.7 m) for each sub-sub plot, which contained 3 ridges (0.85 m width × 3.7 m length), where each one ridge represented one replicate. The planting space was 25 cm. Before the planting process, all plots received the application of calcium superphosphate fertilizer (15% P2O5) rate of 100 kg P2O5 fed-1. Additionally, farmyard manure was applied at a rate of 20 m3 fed-1, and biochar was added at the designated rates. The planting was carried out on the 24th of December in both seasons, using tuber pieces in moist soil conditions. Urea (46.5%N) at a rate 150 kg N fed-1 as well as potassium sulfate (48 % K2O) rate of 50.0 kg fed-1 were added at the recommended times. The foliar applications of trehalose alone and seaweed alone were carried out three times, starting one month after planting and with intervals of 15 days between each application. The volume of foliar spray used for each solution was 800 L fed-1. The tubers were harvested after a period of 135 days from the time of planting.

Measurements:

a.Enzymatic performance at 75 days from planting

To determine enzymatic performance, a sample of five plants was randomly selected for analysis.

- Polyphenol oxidase (PPO, mmol catechol /min/mg) and catalase (CAT, μmol H_2O_2 min^{-1}.$mg^{-1}$$protein^{-1}$) were measured by using spectrophotometric method as described by Alici and Arabaci (2016).
- Malondialdehyde (MDA, μmol.g^{-1}) was spectrophotometrically determined according to Mendes *et al.* (2009).

b. Growth parameters, photosynthetic pigments and leaves chemical content at 75 days from planting

Some growth parameters were measured after 75 days from planting *i.e.*, plant height (cm), fresh and dry weights of foliage (g $plant^{-1}$). NPK content in the dry weight of potato leaves was analyzed using standard methods as outlined by Mertens (2005). The wet digestion process for NPK analysis involved a mixture of perchloric and sulfuric acids in a 1:1 ratio, following the procedure described by Peterburgski, (1968). Nitrogen content was determined using the Kjeldahl method, phosphorus was measured with a spectrophotometer, and potassium was assessed using a flame photometer. While Chlorophyll a, chlorophyll b, and carotene (mg g^{-1}) were determined in fresh samples of leaves at the same period using acetone *via* spectrophotometer, following the method described by Sumanta *et al.* (2014).

c.Yield and quality traits at harvest

For the assessment of yield and quality parameters, a random sample consisting of five plants was selected. Tuber yield and their characteristics *i.e.*, average weight of one tuber (g), No. of tuber $plant^{-1}$ and total tuber yield (Kg $plot^{-1}$and metric ton ha^{-1}). Tubers quality parameters such as total carbohydrates (%), total sugars(%), dry matter (DM,%), total dissolved solids (TDS) and vitamin C (VC, mg $100g^{-1}$) were determined according to AOAC, (2000). As TDS was estimated by a hand refractometer and VC was determined on fresh weight basis using titrimetric estimation with 2,6 dichloro phenol dye solution.

Statistical analysis: The data analysis was conducted using the statistical technique outlined in the methodology presented by Gomez and Gomez (1984). The software used for analysis was CoStat version 6.303, copyrighted between 1998 and 2004. Treatment means were compared using the least significant difference (LSD) test at a significance level of 0.05. To compare the means of various treatments, the Duncan Multiple Range Test was utilized, as described by Duncan (1955).

RESULTS AND DISCUSSION

Enzymatic antioxidants and indicator of oxidation: Table 2 shows the individual and interaction effect of irrigation rates and biochar rates as well as foliar application of either trehalose or seaweed on polyphenol oxidase (PPO) and catalase (CAT) as enzymatic anti-oxidants as well as malondialdehyde (MDA) at a period of 75 days from planting. Under the I_3 treatment [60% of the irrigation requirements], the highest values of PPO, CAT and MDA were observed, while the lowest values were found under the I_1 treatment [100% of the irrigation requirements]. On the other hand, as the rate of biochar increased, the values of these traits decreased, where the highest values of PPO, CAT and MDA were achieved with plants grown on untreated soil with biochar followed by that grown on soil treated with biochar at a rate of 5 and 7 m^3 fed^{-1}, respectively. Furthermore, the addition of both trehalose and seaweed resulted in lower PPO, CAT and MDA levels compared to the control treatment, where the trehalose came in the last order. In this regard, it can be noticed that the combined treatment of I_1 x biochar (7.0 m^3 fed^{-1}) x trehalose recorded the lowest values of PPO, CAT and MDA, whilst the combined treatment (I_3 treatment without soil and foliar applications) caused the highest values of PPO, CAT and MDA. The same trend was achieved for both seasons.

Growth performance and chemical constituents: Table 3 presents the effects of biochar, trehalose and seaweed on the vegetative growth parameters of potato plants under different irrigation rates. The parameters measured include plant height, fresh weight and dry weight at 75 days from planting during the 2021/2022 and 2022/2023 growing seasons.

Table 2. Effect of biochar, trehalose and seaweed on enzymatic antioxidants and malondialdehyde (MDA) in leaves of potato plants grown under different irrigation rates at period of 75 days from planting during seasons of 2021/2022 and 2022/2023

Treatments			PPO* (mmol catechol /min/mg)		CAT * (µmol H_2O_2.min^{-1}.mg^{-1} protein^{-1})		MDA * (µmol.g^{-1})	
			1st	2nd	1st	2nd	1st	2nd
Irrigation rates								
I_1:100% of the irrigation requirements			0.342c	0.359c	8.02c	8.30c	5.15c	5.36c
I_2:80% of the irrigation requirements			0.462b	0.485b	12.30b	12.69b	7.71b	8.04b
I_3:60% of the irrigation requirements			0.487a	0.512a	12.75a	13.15a	8.26a	8.59a
LSD at 5%			0.002	0.003	0.19	0.08	0.09	0.06
Soil additions								
S_1:Control (without)			0.456a	0.479a	11.47a	11.83a	7.52a	7.84a
S_2:Biochar 5 m^3 fed^{-1}			0.425b	0.447b	10.97b	11.31b	7.01b	7.30b
S_3:Biochar 7 m^3 fed^{-1}			0.411c	0.431c	10.64c	10.99c	6.58c	6.86c
LSD at 5%			0.003	0.003	0.06	0.09	0.08	0.05
Foliar applications								
F_1:Control (without spraying)			0.436a	0.458a	11.09a	11.45a	7.12a	7.42a
F_2:Seaweed (1.0 g L^{-1})			0.430b	0.452b	11.03a	11.37b	7.04b	7.33b
F_3:Trehalose (1.0 g L^{-1})			0.423c	0.443c	10.85b	11.21b	6.90c	7.17c
LSD at 5%			0.003	0.003	0.07	0.08	0.04	0.05
Interaction								
I_1	S_1	F_1	0.364	0.381	8.36	8.66	5.53	5.76
		F_2	0.360	0.380	8.30	8.58	5.50	5.70
		F_3	0.355	0.373	8.26	8.52	5.44	5.65
	S_2	F_1	0.345	0.362	8.20	8.49	5.34	5.56
		F_2	0.341	0.356	8.15	8.42	5.29	5.51
		F_3	0.339	0.356	8.10	8.39	5.24	5.45
	S_3	F_1	0.335	0.352	7.67	7.93	4.73	4.94
		F_2	0.322	0.339	7.59	7.83	4.68	4.88
		F_3	0.320	0.336	7.57	7.84	4.63	4.81
I_2	S_1	F_1	0.500	0.527	13.05	13.43	8.46	8.87
		F_2	0.498	0.523	13.01	13.38	8.44	8.79
		F_3	0.495	0.517	13.00	13.41	8.40	8.75
	S_2	F_1	0.458	0.482	12.07	12.43	7.73	8.07
		F_2	0.450	0.473	12.06	12.47	7.63	7.96
		F_3	0.444	0.466	12.02	12.44	7.49	7.81
	S_3	F_1	0.443	0.464	11.98	12.36	7.22	7.51
		F_2	0.438	0.460	11.96	12.33	7.16	7.49
		F_3	0.435	0.457	11.56	11.98	6.84	7.14
I_3	S_1	F_1	0.516	0.542	13.08	13.51	8.80	9.17
		F_2	0.511	0.535	13.06	13.48	8.58	8.93
		F_3	0.505	0.529	13.07	13.46	8.56	8.91
	S_2	F_1	0.491	0.518	12.95	13.38	8.28	8.59
		F_2	0.482	0.508	12.65	12.95	8.07	8.38
		F_3	0.478	0.501	12.53	12.87	8.04	8.35
	S_3	F_1	0.475	0.497	12.49	12.89	8.02	8.35
		F_2	0.467	0.489	12.48	12.88	7.99	8.29
		F_3	0.462	0.487	12.46	12.90	8.01	8.32
LSD at 5%			0.009	0.010	0.21	0.23	0.12	0.15

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

***PPO: Polyphenol oxidase** ***CAT: Catalase** ***MDA: Malondialdehyde**

Table 3. Effect of biochar, trehalose and seaweed on vegetative growth parameters of potato plants grown under different irrigation rates at period of 75 days from planting during seasons of 2021/2022 and 2022/2023

Treatments			Plant height (cm)		Fresh weight (g plant^{-1})		Dry weight (g plant^{-1})	
			1st	2nd	1st	2nd	1st	2nd
Irrigation rates								
I_1:100% of the irrigation requirements			55.42a	57.85a	318.94a	324.90a	34.65a	36.06a
I_2:80% of the irrigation requirements			52.52b	54.62b	295.78b	299.08b	33.28b	34.66b
I_3:60% of the irrigation requirements			50.32c	52.22c	276.91c	281.63c	31.69c	32.96c
LSD at 5%			0.33	0.43	0.26	1.04	0.26	0.18
Soil additions								
S_1:Control (without)			50.32c	52.26c	277.06c	281.62c	31.57c	32.88c
S_2:Biochar 5 m^3 fed^{-1}			53.34b	55.47b	301.36b	307.22b	33.73b	35.08b
S_3:Biochar 7 m^3 fed^{-1}			54.60a	56.96a	313.21a	318.79a	34.31a	35.72a
LSD at 5%			0.29	0.29	1.26	2.05	0.18	0.21
Foliar applications								
F_1:Control (without spraying)			52.38b	54.43c	294.31b	300.36b	32.97b	34.33b
F_2:Seaweed (1.0 g L^{-1})			52.76ab	54.89b	296.59b	302.27b	33.16b	34.46b
F_3:Trehalose (1.0 g L^{-1})			53.20a	55.48a	301.46a	304.30a	33.54a	34.93a
LSD at 5%			0.39	0.39	2.40	2.31	0.27	0.25
Interaction								
I_1	S_1	F_1	52.26	54.26	294.68	298.90	33.10	34.41
		F_2	52.53	54.75	295.60	299.46	33.23	34.58
		F_3	52.93	54.81	299.47	303.85	33.61	35.14
	S_2	F_1	55.46	58.04	317.91	324.11	34.76	36.12
		F_2	56.27	58.42	320.12	326.96	34.91	36.17
		F_3	56.31	58.92	326.01	329.78	35.33	36.73
	S_3	F_1	57.02	59.60	334.68	344.01	35.38	36.84
		F_2	57.74	60.31	336.89	343.87	35.62	37.05
		F_3	58.29	61.59	345.09	353.15	35.94	37.48
I_2	S_1	F_1	49.56	50.98	270.19	274.49	30.74	32.03
		F_2	49.60	51.69	270.05	275.44	31.16	32.40
		F_3	50.12	52.07	273.38	277.74	31.78	33.09
	S_2	F_1	53.11	54.94	300.54	305.70	33.85	35.31
		F_2	53.28	55.40	303.42	307.43	34.02	35.42
		F_3	53.40	56.08	306.25	311.11	34.23	35.60
	S_3	F_1	54.08	56.54	310.53	315.19	34.51	36.08
		F_2	54.71	56.51	311.25	317.53	34.58	35.95
		F_3	54.78	57.40	316.37	301.33	34.64	36.07
I_3	S_1	F_1	48.13	50.18	259.58	265.37	29.86	31.10
		F_2	48.65	50.60	264.70	269.06	30.07	31.24
		F_3	49.11	50.99	265.91	273.08	30.58	31.89
	S_2	F_1	50.51	52.10	274.60	284.62	31.91	33.21
		F_2	50.58	52.55	280.17	286.51	32.16	33.41
		F_3	51.11	52.82	283.19	288.79	32.43	33.74
	S_3	F_1	51.28	53.19	286.11	290.87	32.63	33.87
		F_2	51.47	53.76	287.12	294.13	32.67	33.93
		F_3	51.99	53.77	290.84	292.04	32.86	34.21
LSD at 5%			1.17	1.18	7.19	6.94	0.72	0.74

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

The I_1 treatment (100% of the irrigation requirements) consistently resulted in the highest plant height, fresh weight and dry weight across both seasons. Specifically, the I_1 treatment led to significant increases in plant height, fresh weight, and dry weight compared to the I_2 treatment (80% of the irrigation requirements) and I_3 treatment (60% of the irrigation requirements. The reduction in irrigation quantity significantly decreased all measured growth parameters, highlighting the importance of adequate water supply for optimal potato growth. The application of biochar significantly improved the vegetative growth parameters compared to the control (no soil addition). Higher levels of biochar (7 m³ fed⁻¹) recorded the maximum values, with significant increases in plant height, fresh weight, and dry weight. This suggests that biochar can effectively enhance soil properties, leading to improved plant growth, especially under varying irrigation rates. Among the foliar applications, trehalose showed the most substantial positive impact on vegetative growth. Trehalose-treated plants exhibited the highest plant height, fresh weight, and dry weight, followed by seaweed treatment, with both significantly outperforming the control. The beneficial effects of trehalose, especially under suboptimal irrigation conditions, underscore its role as an osmoprotectant, helping plants mitigate stress and maintain growth.

The interaction effects reveal that the combination of traditional irrigation (I_1 treatment), biochar (7 m³ fed⁻¹) and trehalose resulted in the highest plant growth metrics across both seasons. Even under reduced irrigation conditions, trehalose application combined with biochar improved plant growth parameters compared to traditional irrigation (I_1 treatment) in the absence of both biochar and foliar applications. Generally, the data demonstrate that trehalose, particularly when used in conjunction with biochar, significantly enhances the vegetative growth of potato plants under water deficit conditions. This suggests that trehalose can be an effective foliar treatment to improve crop resilience and productivity, even under less-than-ideal irrigation conditions.

Table 4 provides detailed data on the same studied treatments on the photosynthetic pigments (chlorophyll a, chlorophyll b and carotene) of potato plants, measured 75 days after planting during the 2021/2022 and 2022/2023 growing seasons. The results show that the I_1 treatment (100% of the irrigation requirements) consistently produced the highest levels of chlorophyll a, chlorophyll b and carotene across both seasons. The levels of these pigments decreased as the irrigation quantity was reduced, with the 60% of the irrigation requirements showing the lowest pigment concentrations. This trend emphasizes the critical role of adequate water availability in maintaining optimal photosynthetic activity and pigment production in potato plants. Biochar application had a significant positive effect on the photosynthetic pigments. The higher rate of biochar (7 m^3 fed^{-1}) led to the highest concentrations of chlorophyll a, chlorophyll b and carotene, surpassing the lower biochar application rate (5 m^3 fed^{-1}) which came in the second order followed by the control group (without biochar).

Table 4. Effect of biochar, trehalose and seaweed on photosynthetic pigments of potato plants grown under different irrigation rates at period of 75 days from planting during seasons of 2021/2022 and 2022/2023

Treatments			Chlorophyll a (mg g^{-1})		Chlorophyll b (mg g^{-1})		Carotene (mg g^{-1})	
			1st	2nd	1st	2nd	1st	2nd
Irrigation rates								
I_1:100% of the irrigation requirements			0.954a	1.002a	0.733a	0.770a	0.408a	0.414a
I_2:80% of the irrigation requirements			0.922b	0.966b	0.695b	0.729b	0.379b	0.385b
I_3:60% of the irrigation requirements			0.888c	0.933c	0.654c	0.687c	0.349c	0.355c
LSD at 5%			0.010	0.004	0.006	0.003	0.003	0.002
Soil additions								
S_1:Control (without)			0.886c	0.930c	0.655c	0.688c	0.350c	0.355c
S_2:Biochar 5 m^3 fed^{-1}			0.930b	0.977b	0.705b	0.741b	0.387b	0.393b
S_3:Biochar 7 m^3 fed^{-1}			0.947a	0.994a	0.722a	0.758a	0.399a	0.405a
LSD at 5%			0.009	0.005	0.007	0.004	0.002	0.002
Foliar applications								
F_1:Control (without spraying)			0.917b	0.962b	0.689c	0.723c	0.375c	0.381c
F_2:Seaweed (1.0 g L^{-1})			0.921b	0.967ab	0.694b	0.729b	0.378b	0.385b
F_3:Trehalose (1.0 g L^{-1})			0.928a	0.973a	0.701a	0.736a	0.384a	0.390a
LSD at 5%			0.004	0.006	0.004	0.004	0.003	0.002
Interaction								
I_1	S_1	F_1	0.923	0.967	0.688	0.723	0.375	0.380
		F_2	0.926	0.971	0.694	0.726	0.377	0.382
		F_3	0.930	0.980	0.697	0.730	0.383	0.387
	S_2	F_1	0.959	1.009	0.740	0.780	0.414	0.421
		F_2	0.963	1.012	0.746	0.787	0.417	0.425
		F_3	0.966	1.014	0.752	0.787	0.422	0.429
	S_3	F_1	0.971	1.017	0.756	0.794	0.424	0.430
		F_2	0.974	1.022	0.761	0.800	0.428	0.435
		F_3	0.977	1.027	0.765	0.802	0.431	0.438
I_2	S_1	F_1	0.867	0.908	0.639	0.674	0.340	0.345
		F_2	0.872	0.912	0.647	0.681	0.343	0.350
		F_3	0.881	0.925	0.653	0.684	0.346	0.353
	S_2	F_1	0.934	0.981	0.704	0.738	0.387	0.393
		F_2	0.937	0.983	0.708	0.745	0.390	0.395
		F_3	0.943	0.983	0.714	0.750	0.394	0.400
	S_3	F_1	0.950	0.997	0.725	0.759	0.399	0.404
		F_2	0.953	1.002	0.729	0.763	0.405	0.411
		F_3	0.957	1.003	0.734	0.771	0.408	0.414
I_3	S_1	F_1	0.852	0.894	0.619	0.648	0.322	0.329
		F_2	0.861	0.907	0.624	0.655	0.329	0.335
		F_3	0.865	0.909	0.634	0.666	0.332	0.339
	S_2	F_1	0.886	0.932	0.656	0.686	0.351	0.356
		F_2	0.890	0.938	0.661	0.694	0.353	0.359
		F_3	0.896	0.940	0.667	0.702	0.357	0.362
	S_3	F_1	0.908	0.955	0.671	0.709	0.363	0.369
		F_2	0.914	0.961	0.678	0.710	0.366	0.371
		F_3	0.918	0.962	0.681	0.716	0.371	0.377
LSD at 5%			0.014	0.019	0.012	0.014	0.008	0.007

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

This suggests that biochar enhances soil conditions, potentially improving nutrient availability and water retention, which in turn supports better pigment synthesis in the leaves. Foliar spraying with trehalose resulted in the highest concentrations of chlorophyll a, chlorophyll b and carotene, followed closely by seaweed treatment and then the control group, which came in the last order. Both treatments significantly outperformed the control group, indicating that these substances may play a role in mitigating stress and supporting pigment production, even under reduced irrigation conditions. The interaction effects reveal that the combination of I_1 treatment (100% of the irrigation requirements), higher biochar application (7 m^3 fed^{-1}) and trehalose spraying caused the highest levels of photosynthetic pigments in both seasons. Even under I_2 and I_3 treatments (80% and 60% of the irrigation requirements, respectively), the addition of biochar and foliar applications, particularly trehalose, led to significant improvements in pigment concentrations compared to the control treatments. In summary, the data indicate that both biochar and trehalose have a substantial impact on enhancing the photosynthetic pigments in potato plants. These treatments can potentially improve the plants' ability to capture and utilize light for photosynthesis, which is crucial for growth and productivity, especially under water-limited conditions.

Table 5 outlines the effects of biochar, trehalose and seaweed treatments on the chemical constituents (nitrogen, phosphorus, and potassium) in the leaves of potato plants grown under different irrigation rates. The data were collected 75 days after planting during the 2021/2022 and 2022/2023 growing seasons. The I_1 treatment (100% of the irrigation requirements) resulted in the highest concentrations of nitrogen (N), phosphorus (P), and potassium (K) in the leaves across both seasons. The nutrient content decreased progressively with reduced irrigation quantity, with the I_3 treatment (60% of the irrigation requirements) showing the lowest values. This suggests that sufficient water availability is crucial for optimal nutrient uptake and assimilation in potato plants. Biochar applications significantly improved the nutrient content in the leaves. The highest rate of biochar (7 m³ fed^{-1}) led to the greatest increases in N, P, and K concentrations, surpassing both the control and the lower biochar rate (5 m³ fed^{-1}). This indicates that biochar enhances soil nutrient availability or retention, contributing to better nutrient absorption by the plants. Trehalose foliar application consistently resulted in the highest concentrations of N, P, and K in the leaves, followed closely by seaweed treatment. Both treatments significantly improved nutrient content compared to the control, indicating that these foliar applications may enhance nutrient assimilation, even under suboptimal irrigation conditions.

Table 5. Effect of biochar, trehalose and seaweed on chemical constitutes in leaves of potato plants grown under different irrigation rates at period of 75 days from planting during seasons of 2021/2022 and 2022/2023

Treatments			N		P		K	
			(%)					
			1st	2nd	1st	2nd	1st	2nd
Irrigation rates								
I_1:100% of the irrigation requirements			3.46a	3.53a	0.400a	0.407a	3.12a	3.18a
I_2:80% of the irrigation requirements			3.11b	3.18b	0.368b	0.375b	2.88b	2.92b
I_3:60% of the irrigation requirements			2.68c	2.74c	0.337c	0.343c	2.60c	2.64c
LSD at 5%			0.08	0.01	0.002	0.002	0.06	0.06
Soil additions								
S_1:Control (without)			2.69c	2.75c	0.335c	0.341c	2.59c	2.63a
S_2:Biochar 5 m^3 fed^{-1}			3.20b	3.27b	0.377b	0.384b	2.95b	3.00b
S_3:Biochar 7 m^3 fed^{-1}			3.35a	3.43a	0.393a	0.400a	3.06a	3.11c
LSD at 5%			0.02	0.02	0.002	0.002	0.04	0.04
Foliar applications								
F_1:Control (without spraying)			3.03c	3.10c	0.364c	0.370c	2.83b	2.88b
F_2:Seaweed (1.0 g L^{-1})			3.09b	3.15b	0.368b	0.374b	2.87ab	2.92ab
F_3:Trehalose (1.0 g L^{-1})			3.14a	3.21a	0.375a	0.382a	2.91a	2.96a
LSD at 5%			0.02	0.02	0.003	0.002	0.04	0.04
Interaction								
I_1	S_1	F_1	3.18	3.24	0.365	0.372	2.87	2.91
		F_2	3.23	3.29	0.370	0.377	2.91	2.95
		F_3	3.25	3.33	0.376	0.384	2.93	2.97
	S_2	F_1	3.51	3.58	0.407	0.415	3.13	3.19
		F_2	3.53	3.60	0.409	0.416	3.20	3.27
		F_3	3.57	3.64	0.412	0.420	3.22	3.26
	S_3	F_1	3.59	3.66	0.415	0.423	3.26	3.33
		F_2	3.61	3.69	0.420	0.424	3.30	3.37
		F_3	3.65	3.74	0.425	0.434	3.32	3.39
I_2	S_1	F_1	2.44	2.49	0.319	0.325	2.44	2.48
		F_2	2.51	2.55	0.323	0.329	2.48	2.53
		F_3	2.54	2.59	0.327	0.330	2.52	2.56
	S_2	F_1	3.38	3.45	0.381	0.389	3.03	3.08
		F_2	3.40	3.47	0.383	0.387	3.06	3.10
		F_3	3.42	3.49	0.391	0.398	3.06	3.11
	S_3	F_1	3.42	3.50	0.393	0.400	3.09	3.14
		F_2	3.43	3.51	0.396	0.405	3.09	3.14
		F_3	3.47	3.54	0.404	0.411	3.12	3.16
I_3	S_1	F_1	2.34	2.39	0.307	0.313	2.35	2.39
		F_2	2.37	2.41	0.313	0.319	2.39	2.43
		F_3	2.41	2.46	0.317	0.322	2.42	2.46
	S_2	F_1	2.61	2.66	0.330	0.333	2.59	2.62
		F_2	2.67	2.73	0.337	0.345	2.62	2.66
		F_3	2.72	2.79	0.346	0.353	2.67	2.71
	S_3	F_1	2.84	2.90	0.358	0.365	2.75	2.79
		F_2	3.07	3.15	0.360	0.367	2.78	2.82
		F_3	3.12	3.18	0.364	0.372	2.83	2.88
LSD at 5%			0.06	0.07	0.008	0.007	0.13	0.13

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

The interaction effects reveal that the combination of the I_1 treatment (100% of the irrigation requirements), higher biochar application (7 m³ fed^{-1}) and trehalose foliar spraying led to the highest concentrations of N, P, and K in the leaves during both seasons. Even under reduced irrigation rates (I_2 and I_3 treatments), the addition of biochar and trehalose foliar spray contributed to significantly higher nutrient levels compared to the control treatments. Nitrogen levels were highest under I_1 treatment (100% of the irrigation requirements) with the addition of 7 m³ fed^{-1} biochar and trehalose foliar spraying.

This combination appears to enhance nitrogen uptake or retention in potato plants, critical for growth and development. Phosphorus content followed a similar trend, with the highest values observed in the I_1 treatment (100% of the irrigation requirements), biochar (7 m³ fed⁻¹), and trehalose-treated plants. Phosphorus is essential for energy transfer and root development, making these findings particularly relevant for improving plant resilience under stress. Potassium content was also highest in the same treatment combinations, underscoring the role of biochar and foliar applications in improving nutrient uptake. Potassium is vital for water regulation and enzyme activation in plants, making its adequate presence crucial for maintaining plant health under varying water conditions. Finally, the data suggest that both biochar and trehalose significantly enhance the nutrient content in potato leaves, especially under water-limited scenarios.

Yield and quality traits: On the other hand, all studied treatments significantly affected tuber yield and their characteristics *i.e.*, average weight of one tuber, No. of tuber plant^{-1}, total tuber yield (Table 6) as well as tubers quality parameters such as total carbohydrates, total sugars, DM, TDS and VC, (Table 7) at harvest stage during seasons of 2021/2022 and 2022/2023. The data illustrated that the plants grown under I_1 treatment possessed the maximum values of all aforementioned traits followed by that grown under I_2 treatment and lately that grown under I_3 treatment. Concerning biochar treatments, it can be noticed that the soil addition of biochar at rate of 7 m^3 fed^{-1} caused the highest values of average weight of one tuber, No. of tuber plant^{-1}, total tuber yield, total carbohydrates, total sugars, DM, TDS and V.C. While the soil addition of biochar at a rate of 5 m^3 fed^{-1} came in the second order, ahead of the control treatment, which remained in the last order. Regarding foliar applications, the superior treatment for obtaining the maximum values was trehalose then seaweed, whilst the plants grown without foliar application had the lowest values of average weight of one tuber, No. of tuber plant^{-1}, total tuber yield, total carbohydrates, total sugars, DM, TDS and VC. As for the interaction effect, the highest values were achieved under the combined treatment of I_1 x biochar (7.0m^3 fed^{-1}) x trehalose. It worth mentioning that the performance under the combined treatment of I_2 x biochar at both levels x either trehalose or seaweed was superior to that of the I_1 treatment without soil and foliar applications (control).

Table 6. Effect of biochar, trehalose and seaweed on tubers yield of potato plants grown under different irrigation rates at harvest stage during seasons of 2021/2022 and 2022/2023

Treatments			Average tuber weight (g)		No. of tuber plant^{-1}		Yield (Kg plot^{-1})		Yield (metric ton ha^{-1})	
			1st	2nd	1st	2nd	1st	2nd	1st	2nd
Irrigation rates										
I_1:100% of the irrigation requirements			158.75a	156.77a	4.11a	4.59a	39.19a	43.23a	35.53a	39.20a
I_2:80% of the irrigation requirements			157.02b	155.03b	3.37b	3.70b	31.86b	34.54b	28.89b	31.31b
I_3:60% of the irrigation requirements			153.87c	152.22c	2.67c	2.89c	24.64c	26.42c	22.34c	23.96c
LSD $_{at 5\%}$			1.18	0.05	0.67	0.70	4.54	6.61	4.12	5.99
Soil additions										
S_1:Control (without)			154.39b	152.43b	2.67b	3.00b	24.76b	27.47b	22.44b	24.91b
S_2:Biochar 5 m^3 fed^{-1}			157.49a	155.50a	3.56a	3.89a	33.68a	36.41a	30.54a	33.01a
S_3:Biochar 7 m^3 fed^{-1}			157.76a	156.09a	3.93a	4.30a	37.25a	40.31a	33.78a	36.55a
LSD $_{at 5\%}$			0.87	0.69	0.53	0.45	5.10	4.23	4.63	3.84
Foliar applications										
F_1:Control (without spraying)			156.30a	154.47a	3.30a	3.59a	31.02a	33.43a	28.12a	30.31a
F_2:Seaweed (1.0 g L^{-1})			156.48a	154.63a	3.37a	3.70a	31.76a	34.47a	28.79a	31.26a
F_3:Trehalose (1.0 g L^{-1})			157.03a	154.94a	3.57a	3.89a	33.82a	36.32a	30.66a	32.93a
LSD $_{at 5\%}$			*NS	*NS	*NS	*NS	*NS	*NS	*NS	*NS
Interaction										
I_1	S_1	F_1	156.42	154.61	3.33	3.67	31.36	34.01	28.44	30.84
		F_2	156.66	154.93	3.33	3.67	31.29	34.04	28.37	30.87
		F_3	157.55	155.24	3.67	4.00	34.70	37.22	31.46	33.74
	S_2	F_1	159.55	157.44	4.00	4.67	38.19	44.09	34.62	39.97
		F_2	159.31	157.38	4.33	4.67	41.38	44.02	37.51	39.92
		F_3	159.82	157.56	4.33	5.00	41.64	47.36	37.75	42.94
	S_3	F_1	159.75	157.96	4.67	5.00	44.73	47.35	40.55	42.93
		F_2	159.77	157.83	4.67	5.33	44.69	50.55	40.52	45.83
		F_3	159.92	158.01	4.67	5.33	44.70	50.47	40.53	45.76
I_2	S_1	F_1	154.13	152.01	2.00	2.67	18.36	24.28	16.65	22.02
		F_2	153.98	152.16	2.67	2.67	24.64	24.30	22.34	22.03
		F_3	154.08	152.56	2.67	2.67	24.67	24.41	22.37	22.13
	S_2	F_1	158.29	155.82	3.67	4.00	34.78	37.42	31.54	33.92
		F_2	158.38	156.14	3.67	4.00	34.88	37.51	31.63	34.01
		F_3	158.28	156.27	3.67	4.00	34.90	37.60	31.65	34.09
	S_3	F_1	158.45	156.58	4.00	4.33	38.07	40.67	34.51	36.88
		F_2	158.58	156.81	4.00	4.33	38.14	40.69	34.58	36.89
		F_3	158.98	156.92	4.00	4.67	38.28	43.94	34.71	39.83
I_3	S_1	F_1	150.90	149.35	2.33	2.33	21.08	20.87	19.11	18.92
		F_2	152.39	150.10	2.00	2.67	18.32	24.06	16.61	21.81
		F_3	153.38	150.91	2.00	2.67	18.37	24.06	16.65	21.81
	S_2	F_1	154.68	153.00	2.67	2.67	24.75	24.52	22.44	22.23
		F_2	154.70	152.84	2.67	3.00	24.71	27.59	22.41	25.01
		F_3	154.40	153.04	3.00	3.00	27.88	27.59	25.27	25.01
	S_3	F_1	154.55	153.42	3.00	3.00	27.86	27.69	25.26	25.11
		F_2	154.58	153.46	3.00	3.00	27.74	27.50	25.15	24.93
		F_3	155.22	153.83	3.33	3.67	31.08	33.92	28.18	30.76
LSD $_{at 5\%}$			3.36	3.71	1.64	1.72	1.64	16.59	14.24	14.54

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
***NS= non-significant**

Table 7. Effect of biochar, trehalose and seaweed on tubers quality of potato plants grown under different irrigation rates at harvest stage during seasons of 2021/2022 and 2022/2023

Treatments			**Carbohydrates**		**Total sugars**		**Dry matter**		**Vitamin C, mg $100g^{-1}$**		***TDS**	
			(%)								**(%)**	
			1^{st}	**2^{nd}**	**1^{st}**	**2^{nd}**	**1^{st}**	**2^{nd}**	**1^{st}**	**2^{nd}**	**1^{st}**	**2^{nd}**
Irrigation rates												
I_1:100% of the irrigation requirements			28.02a	28.50a	5.54a	5.77a	21.54a	22.26a	22.79a	23.00a	7.55a	7.94a
I_2:80% of the irrigation requirements			26.95b	27.39b	5.32b	5.53b	20.64b	21.31b	21.87b	22.15b	7.08b	7.44b
I_3:60% of the irrigation requirements			25.93c	26.35c	5.11c	5.31c	19.73c	20.34c	21.00c	21.27c	6.35c	6.66c
LSD $_{at\ 5\%}$			0.20	0.17	0.04	0.08	0.06	0.23	0.35	0.08	0.08	0.21
Soil additions												
S_1:Control (without)			25.98c	26.39c	5.09c	5.31c	19.70c	20.32c	21.01c	21.27c	6.44c	6.76c
S_2:Biochar 5 m^3 fed^{-1}			27.25b	27.67b	5.39b	5.61b	20.89b	21.57b	22.14b	22.39b	7.17b	7.52b
S_3:Biochar 7 m^3 fed^{-1}			27.69a	28.18a	5.48a	5.70a	21.32a	22.03a	22.52a	22.77a	7.37a	7.75a
LSD $_{at\ 5\%}$			0.17	0.26	0.04	0.03	0.02	0.11	0.13	0.23	0.07	0.04
Foliar applications												
F_1:Control (without spraying)			26.77b	27.23b	5.28b	5.50b	20.51c	21.16b	21.73c	21.99b	6.92c	7.28c
F_2:Seaweed (1.0 g L^{-1})			26.99a	27.43a	5.33a	5.54a	20.64b	21.30b	21.89b	22.15a	7.00b	7.35b
F_3:Trehalose (1.0 g L^{-1})			27.20a	27.64a	5.37a	5.58a	20.81a	21.49a	22.08a	22.31a	7.09a	7.43a
LSD $_{at\ 5\%}$			0.20	0.19	0.04	0.04	0.05	0.14	0.12	0.15	0.05	0.04
Interaction												
I_1	S_1	F_1	26.84	27.24	5.31	5.53	20.54	21.13	21.72	21.97	7.00	7.37
		F_2	26.87	27.18	5.31	5.54	20.63	21.30	21.85	22.11	7.18	7.54
		F_3	27.08	27.43	5.38	5.61	20.77	21.51	22.09	22.31	7.33	7.68
	S_2	F_1	27.90	28.49	5.56	5.77	21.55	22.29	22.80	23.00	7.68	8.06
		F_2	28.36	28.93	5.60	5.82	21.74	22.44	23.00	23.20	7.72	8.07
		F_3	28.44	28.76	5.62	5.83	21.89	22.69	23.28	23.43	7.75	8.10
	S_3	F_1	28.52	29.11	5.66	5.90	22.01	22.75	23.25	23.47	7.68	8.19
		F_2	29.02	29.54	5.69	5.91	22.22	22.95	23.44	23.60	7.79	8.20
		F_3	29.16	29.80	5.75	5.98	22.50	23.27	23.69	23.90	7.83	8.21
I_2	S_1	F_1	25.65	26.06	4.98	5.20	19.27	19.85	20.56	20.83	6.10	6.41
		F_2	25.68	26.17	5.07	5.28	19.56	20.11	20.80	21.07	6.13	6.46
		F_3	25.95	26.49	5.07	5.27	19.56	20.18	20.94	21.17	6.16	6.46
	S_2	F_1	27.22	27.66	5.39	5.61	21.01	21.65	22.20	22.49	7.45	7.82
		F_2	27.27	27.66	5.40	5.65	20.99	21.66	22.23	22.56	7.50	7.87
		F_3	27.52	27.93	5.45	5.68	21.14	21.91	22.31	22.68	7.53	7.92
	S_3	F_1	27.70	28.07	5.45	5.66	21.25	22.01	22.47	22.76	7.60	7.95
		F_2	27.75	28.20	5.52	5.73	21.47	22.21	22.57	22.82	7.61	8.01
		F_3	27.85	28.25	5.51	5.73	21.54	22.24	22.76	22.94	7.62	8.02
I_3	S_1	F_1	24.96	25.34	4.85	5.05	18.87	19.47	20.14	20.45	5.99	6.28
		F_2	25.35	25.78	4.92	5.12	18.97	19.57	20.39	20.65	6.05	6.32
		F_3	25.43	25.83	4.95	5.15	19.16	19.74	20.56	20.82	6.05	6.34
	S_2	F_1	26.10	26.44	5.13	5.32	19.81	20.42	20.99	21.21	6.21	6.54
		F_2	26.12	26.49	5.17	5.36	19.88	20.44	21.22	21.46	6.29	6.61
		F_3	26.28	26.68	5.22	5.41	20.03	20.60	21.25	21.45	6.36	6.67
	S_3	F_1	26.00	26.68	5.23	5.44	20.26	20.87	21.39	21.74	6.61	6.91
		F_2	26.53	26.89	5.27	5.47	20.32	20.97	21.53	21.86	6.73	7.04
		F_3	26.64	27.05	5.27	5.48	20.31	21.01	21.54	21.83	6.89	7.24
LSD $_{at\ 5\%}$			0.60	0.56	0.12	0.11	0.16	0.42	0.45	0.44	0.16	0.12

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
***TDS = Total Dissolved Solid**

Water availability is a critical factor influencing nutrient uptake in plants. Adequate irrigation ensures that nutrients dissolved in the soil solution are readily available for absorption by the plant roots. In the study, the I_1 treatment (100% of the irrigation) resulted in the highest concentrations of nitrogen (N), phosphorus (P), and potassium (K) in the potato leaves, likely due to the enhanced mobility and availability of these nutrients in the soil under optimal moisture conditions. Reduced irrigation, as seen in the I_2 and I_3 treatments (80 and 60% of the irrigation requirements), likely led to reduced soil moisture levels, limiting nutrient solubility and diffusion to the root surface, thereby decreasing nutrient uptake. Furthermore, water stress can reduce root growth and function, further limiting the plant's ability to acquire essential nutrients. The results are in harmony with those of Jalali *et al.* (2018); Nasir *et al.* (2022); Bayatani *et al.* (2023). Biochar is known for its ability to improve soil fertility through multiple mechanisms. Its porous structure enhances soil aeration and water retention, creating a more favorable environment for root growth and nutrient absorption. The high cation exchange capacity (CEC) of biochar also allows it to retain essential nutrients, reducing leaching losses and making them more available to plants (Elsherpiny, 2023). In this study, the application of biochar at 7 m^3 fed^{-1} significantly increased the concentrations of N, P, and K in the leaves, likely due to its role in improving nutrient retention and availability in the soil. Biochar may also enhance microbial activity in the rhizosphere, further contributing to nutrient cycling and availability. Foliar applications of trehalose and seaweed extract were observed to significantly enhance the nutrient content in potato leaves. Trehalose, a disaccharide, acts as an osmoprotectant, helping plants to maintain cellular integrity and function under stress conditions such as drought. By stabilizing cell membranes and proteins, trehalose may improve the efficiency of nutrient assimilation and transport within the plant. Additionally, seaweed extract is rich in bioactive compounds, including hormones, vitamins, and trace elements, which can stimulate plant growth and enhance nutrient uptake. These compounds may activate specific physiological pathways that increase the efficiency of nutrient utilization, even under suboptimal soil moisture conditions. These findings are in accordance with those of Abd El Baky *et al.* (2016); Al-Rubaie *et al.* (2023).The combined application of biochar, trehalose, and optimal irrigation resulted in the highest levels of N, P, and K in the potato leaves, indicating a synergistic effect. Biochar improves soil structure and nutrient retention, while trehalose and seaweed extract enhance the plant's physiological capacity to absorb and assimilate these nutrients. This synergism is particularly evident under I_1 treatment (100% of the irrigation), where the availability of water and nutrients is maximized, allowing the plants to fully benefit from the enhanced soil fertility and foliar treatments. Even under reduced irrigation conditions, the combination of biochar and foliar treatments mitigated the adverse effects of water stress on nutrient uptake, demonstrating their potential to enhance plant resilience.

Also, the results of this study demonstrated the potential of biochar application in combination with trehalose or seaweed spray for enhancing drought stress tolerance in potato plants. The findings revealed significant improvements in enzyme levels and tuber yield, and quality traits under the combined treatment of biochar, trehalose, and seaweed. Generally, it can be said that the presence of biochar combined with trehalose or seaweed led to a reduction in the potato plants' self-production of enzymatic antioxidants. However, under conditions of water deficit stress, potato plants exhibited an increase in the production of antioxidants such as PPO and CAT. This adaptive response is aimed at mitigating oxidative damage and scavenging free radicals responsible for such damage. Consequently, the values of PPO and CAT in the leaves were higher under water stress treatments (I_2 and I_3) compared to traditional irrigation (I_1). The results obtained are in agreement with the results reported by Ghazi and El-Sherpiny, (2021) and Awwad *et al.* (2022). MDA serves as a widely utilized biomarker to evaluate oxidative stress and lipid peroxidation in biological systems. It is formed as a byproduct of lipid peroxidation, which occurs when free radicals attack polyunsaturated fatty acids in cell membranes (Singh *et al.* 2014). Elevated levels of MDA indicate escalated oxidative damage, and it is commonly employed as an indicator of cellular oxidative stress. In line with this, the levels of MDA in the leaves increased under water stress treatments (I_2 and I_3), further demonstrating the occurrence of oxidative stress in those conditions. One possible scientific reason behind these results is the impact of biochar on soil properties and water availability. Biochar has been shown to improve soil water-holding capacity by enhancing soil structure and increasing the retention of moisture. This enables better water availability to the plant roots during periods of water deficit. The improved water availability, in turn, helps to maintain stomatal conductance and photosynthetic activity, reducing the negative effects of drought stress on potato plants. Furthermore, the addition of biochar enhances nutrient retention and availability in the soil, promoting overall plant growth and development even under water-limited conditions. The findings are in harmony with those of Elsherpiny (2023). The foliar application of trehalose or seaweed extracts also played a significant role in enhancing drought stress tolerance in potato plants. These biostimulants contain a range of bioactive compounds, including phytohormones (such as cytokinins and abscisic acid), antioxidants, and osmoprotectants (such as proline and betaines). These compounds act as signaling molecules and protectants, regulating plant physiology and mitigating the adverse effects of drought stress. They can improve stomatal regulation, enhance antioxidant defense mechanisms, and alleviate oxidative damage caused by reactive oxygen species generated under drought conditions. Additionally, they can enhance root development and nutrient uptake efficiency, further supporting plant resilience to water deficit (Elansary *et al.* 2016). The combined treatment of biochar, trehalose, and seaweed likely synergistically interacted to maximize the benefits on potato plants under drought stress. Biochar improved soil water retention and nutrient availability, providing a favorable growth environment for the plants. Trehalose or seaweed extracts, when applied foliarly, enhanced physiological responses and stress tolerance mechanisms in the plants, optimizing their water use efficiency and mitigating oxidative damage. The combined effect of these treatments led to improved enzyme activity, increased tuber yield, and enhanced quality traits in the potato plants compared to the control treatment. It is worth noting that the specific mechanisms underlying the observed results may vary depending on various factors such as the specific biochar properties, trehalose or seaweed composition, and the physiological responses of the potato cultivars used. Further research is needed to elucidate the molecular and physiological pathways involved in the enhancement of drought stress tolerance by biochar, trehalose, and seaweed, and to optimize the application methods and dosages for different potato varieties and environmental conditions.

CONCLUSION

This research highlights the importance of combining soil amendments with foliar applications to optimize crop performance and resilience, paving the way for more sustainable and productive agricultural practices. Based on the results, it can be concluded that the treatment combinations involving biochar, trehalose, and seaweed had significant effects on the enzymatic antioxidants, growth parameters, and chemical constituents of leaves, as well as on tuber yield and quality traits of potato plants. The application of biochar, particularly at higher rates, improved soil fertility and nutrient availability, leading to enhanced plant growth and productivity. Foliar applications of trehalose and seaweed extract further bolstered the plants' resilience to water stress, contributing to improved nutrient uptake and tuber quality even under reduced irrigation rates . The synergistic effects of these treatments demonstrate their potential as effective strategies for enhancing potato production, especially in environments facing water scarcity.

Conflicts of interest

Authors have declared that no competing interests exist. The authors contributed equally to put the research methodology and implementing it at all stages.

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تأثير إضافة البايوشار إلى التربة، والرش الورقي للتريهالوز ومستخلص الأعشاب البحرية على إنتاجية البطاطس تحت معدلات ري مختلفة

سمر محمد عبد الحميد دقليجة [1]، همت عبد اللطيف البيومي[1]، هالة عبد الغفار السيد [1]، حماده ماهر بدير المتولي[2] و عمر محمد حلمى عبد الرحمن[1]

[1]قسم الخضر والزينة، كلية الزراعة، جامعة المنصورة، مصر

[2]قسم الخضر، معهد بحوث البساتين، مركز البحوث الزراعية، الجيزة، مصر

الملخص

لمواجهة ندرة المياه في المناطق الجافة وشبه الجافة مثل مصر وتعزيز الأمن الغذائي، تم إجراء تجربة بحثية لتقييم تأثير مستويات الري المختلفة وإضافة البيوشار إلى التربة، والرش الورقي بالتريهالوز والأعشاب البحرية على النشاط الإنزيمي وصفات المحصول والجودة لنباتات البطاطس. وتم دراسة 3 مستويات للري وهي (I_1) : 100% من متطلبات الري، (I_2) :80% من متطلبات الري، و (I_3): 60% من متطلبات الري، مع إضافة مستويات مختلفة من البيوشار (0.0، 5.0، 7.0 م³/فدان)، وكذلك الرش الورقي بمحلول التريهالوز و الأعشاب البحرية بتركيز 1.0 جم/لتر، بالإضافة إلى معاملة الكنترول (بدون رش). معاملة I_3 أدت إلى أعلى مستويات أوكسيديز البوليفينول والكاتالاز والمالونديالدهيد، بينما أسفرت معاملة I_1 عن اقل القيم. أدت زيادة البيوشار إلى تقليل النشاط الإنزيمي، كما أدي الرش الورقي بالتريهالوز والأعشاب البحرية إلى تقليل القيم مقارنه بمجموعة الكنترول. تحت مستويات الري المنخفضة، أدى استخدام التريهالوز والأعشاب البحرية مع البيوشار إلى تحسين معايير نمو النبات، مثل ارتفاع النبات ووزنه الطازج والجاف، مقارنةً بالري التقليدي (معاملة I_1) في غياب كل من البيوشار والرش الورقي. كما تحققت أعلى إنتاجية للدرنات وأفضل الصفات النوعية، مثل الكربوهيدرات، و السكريات الكلية، ونسبة البروتين، ومحتوى فيتامين C ، عند المعاملة المشتركة I_1 × البايوشار (7.0 م³ للفدان) × التريهالوز. ومن الجدير بالذكر أن معاملة I_2 المصحوبة بالبايوشار وإما التريهالوز أو مستخلص الأعشاب البحرية تفوقت على معاملة I_1 بدون أي إضافات. تشير هذه الدراسة إلى أن دمج البايوشار مع التطبيقات الورقية للتريهالوز ومستخلص الأعشاب البحرية يمكن أن يعزز إنتاجية البطاطس بشكل كبير تحت ظروف ندرة المياه.