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Improving crisphead lettuce productivity grown under water deficit conditions through biochar and zeolite soil amendments, coupled with foliar stimulant applications under a drip irrigation system

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CRISPHEAD lettuce, among other vegetable crops, has attained significant importance in current times owing to its widespread consumption. Consequently, it is imperative to establish specialized cultivation programs tailored to Egyptian conditions, aiming to optimize productivity and meet the growing demand for these essential crops. So, two field experiments were conducted over consecutive seasons (2022 and 2023) to evaluate plant performance with varying irrigation treatments (100% and 80% of irrigation requirements IR) under the drip irrigation system. The main plots focused on irrigation levels, while the sub-main plots examined the impact of soil amendments (control, biochar at 0.5-ton fed^{-1} and zeolite at 0.5-ton fed^{-1}). Additionally, sub-sub plots were designated for the application of stimulants, including control (without), arginine (60 mg L^{-1}), melatonin (100 mmol L^{-1}), and a combined treatment (arginine at 60 mg L^{-1} + melatonin at 50 mmol L^{-1}). This comprehensive approach aims to analyze the combined effects of irrigation, soil amendments, and stimulant application on plant growth parameters and productivity such as fresh and dry weights, leaf area, relative water content, nitrogen, phosphorus, potassium, chlorophyll, carotene, head weight, dry matter, and vitamin C. Also, some enzymatic antioxidants (super oxidase dismutase, peroxidase, and catalyze) and soil properties (available nitrogen, phosphorus, and potassium) were determined. The findings indicated that the application of zeolite and biochar under 80% of irrigation (IR) conditions led to improvements in all studied plant parameters compared to plants cultivated without zeolite and biochar (control) under 100% of IR conditions, with zeolite exhibiting superior effects over biochar. Furthermore, the combined treatment of arginine + melatonin outperformed all other treatments, resulting in maximum values across all studied conditions. Melatonin treatment alone came in second order then arginine treatment alone which ranked higher than the control group (without foliar application). In terms of soil fertility, the post-harvest analysis revealed that zeolite, followed by biochar, contributed to significant improvement. The incorporation of zeolite and biochar into the soil appears to have positively impacted soil fertility parameters, underscoring their potential role in enhancing soil quality and nutrient availability. These findings suggest that both zeolite and biochar can be valuable soil amendments for maintaining or enhancing soil fertility after the cultivation of crisphead lettuce. Also, these results underscore the potential benefits of incorporating zeolite or biochar with soil under reduced irrigation levels and highlight the effectiveness of the combined foliar application of arginine and melatonin in enhancing plant performance.

Keywords: Water deficit, Zeolite, Biochar, Arginine, Melatonin.

1. Introduction

In the face of water scarcity challenges prevalent in arid and semi-arid regions, particularly evident in countries like Egypt, it becomes imperative to reassess water management strategies for vegetable crops (**Abd Ellah, 2020**). The pressing need is to curtail water usage without compromising productivity, acknowledging the vital role water plays in sustaining crops **(Kaniszewski *et al.* 2017).** This is particularly relevant for crisphead lettuce (*Lactuca sativa* var. capitate, family Asteraceae), a vegetable crop with high water requirements. Despite being a limited crop in Egypt previously, crisphead lettuce has gained

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prominence due to its substantial nutritional value, elevating its status to that of an essential commodity in the Egyptian market **(Mostafa *et al.* 2023).**

Addressing this challenge requires a multifaceted approach. Zeolite emerges as a promising solution, playing a dual role in enhancing soil water retention capabilities and improving overall soil fertility **(Moshatati *et al.* 2019; Bahador and Tadayon 2020**). Its water retention properties are crucial in ensuring efficient water utilization in cultivation practices. Simultaneously, the ability of zeolite to contribute to soil fertility can have long-lasting positive effects on crop growth and health **(Cataldo *et al.* 2021; Salehi *et al*. 2021; Ghazi *et al.* 2023).**

Similarly, biochar, recognized for its capacity to enhance soil water retention and improve fertility, presents another avenue for sustainable water management in agriculture (**Abideen *et al.* 2020)**. Its incorporation into the soil structure can foster improved water absorption and nutrient availability, contributing to enhanced crop performance (**Haider *et al.* 2020; Yang *et al.* 2020; Zaheer *et al.* 2020; Elsherpiny, 2023; Elbasiouny *et al.* 2023; Singh *et al.* 2024).**

Beyond soil amendments, there are also roles of specific substances in plant physiology. Arginine, identified as an amino acid, has the potential to improve plant performance and fortify resistance to water stress (**Silveira *et al.* 2021; Hussein *et al.* 2022)**. Additionally, melatonin, known as a plant hormone, is explored for its capacity to enhance plant resilience and performance under conditions of water stress (**Sadak *et al.* 2020; Imran, *et al.* 2021; Elsherpiny and Helmy, 2022).**

In essence, this research aims to integrate these various components - zeolite, biochar, arginine, and melatonin - into a comprehensive strategy for optimizing crisphead lettuce cultivation. By understanding and harnessing the potential of these elements, the study seeks to provide practical insights into sustainable practices that mitigate the impact of water scarcity on vegetable crops, specifically addressing the unique challenges posed by crisphead lettuce cultivation in the Egyptian context.

2. Material and Methods

Experimental layout

Two field experiments were conducted over consecutive seasons (2022 and 2023) in a privet farm located at Meet-Antar, Talkha District, Dakahlia governorate, Egypt to evaluate crisphead lettuce performance with varying irrigation treatments (100% and 80% of irrigation requirements IR) under the drip irrigation system. The main plots focused on irrigation levels, while the sub-main plots examined the impact of soil amendments (control, biochar at a rate of 0.5 ton fed^{-1}, and zeolite at a rate of 0.5 ton fed^{-1}). Additionally, sub-sub plots were designated for the application of stimulants, including control (without), arginine (at rate of 60 mg L^{-1}), melatonin (at rate of 100 mmol L^{-1}), and a combined treatment (arginine at 60 mg L^{-1} + melatonin at 50 mmol L^{-1}). Figure 1 illustrates the schematic diagram showing the studied treatments.

Initial soil properties and studied substances

Table 1 highlights the attributes of the initial soil and delineates the characteristics of the studied zeolite and biochar. Zeolite, arginine and melatonin were purchased from the Egyptian commercial market, while biochar was manufactured according to the standard method described by **Wang and Wang (2019**), involving the combustion of plant residues in a muffle furnace devoid of oxygen, maintained at temperatures ranging from 400 to 500 °C for 30 minutes.

Irrigation

The irrigation water for the experiment was sourced from the Nile River and delivered through a drip irrigation system. The prescribed irrigation requirements for crisphead lettuce under this system were set at 1200 m^{3} fed^{-1} for 100% of the Irrigation Requirement (IR), and accordingly, 80% of IR was equivalent to 960 m^{3} fed^{-1} **(Almeida *et al.* 2015; Kaniszewski *et al*. 2017).** Precise control over the irrigation water quantities was achieved through the utilization of a water discharge gauge positioned on the main pipe of the drip network, in conjunction with control valves and a water control switch.

Transplanting and fertilization

Before the immediate transplanting of seedlings, both zeolite and biochar were incorporated into the soil in accordance with the specified experimental treatments. Also, all plots received calcium superphosphate (6.6%P) before plowing at a rate of 30 units P fed^{-1}. Additionally, foliar spraying was conducted at five intervals: on days 20, 30, 40, 50, and 60 post-transplant.

Crisphead lettuce seedlings "*Lactuca sativa* L. cv Kharga," aged 20 days, were transplanted on the 15th of October in both seasons under investigation. The transplantation was carried out in the center of the ridges, maintaining a plant spacing of 40 cm.

Nitrogen fertilization was administered at two intervals in two equal doses. The first dose was applied two weeks after the transplantation, followed by a subsequent dose two weeks after the initial addition using urea (46% N), and the application rate was 50 units N fed^{-1}. Simultaneously, potassium sulphate, containing 48% K_2O, was applied alongside the nitrogen, with a rate of 25 units of K_2O fed^{-1}. The sub-sub plot area for this investigation was 9.0 m^2 (3.0 m x 3.0 m). All mineral fertilization doses were added as recommended by the Ministry of Agriculture and Soil Reclamation, Egypt.

Plant sampling

At the 75-day mark from transplanting, three crisphead lettuce plants were sampled from each replicate for the measurement of various growth parameters and yield attributes.

1. Growth parameters

Fresh and dry weights (g plant^{-1}), leaf area (cm^2 plant^{-1}), and relative water content (%) were measured.

2. Chemical traits

To determine nitrogen (N%), phosphorus (P%), and potassium (K%) levels, finely powdered dry crisphead lettuce leaves (0.4 grams) were placed in a digestion flask with 5 mL of H_2SO_4. The mixture underwent heating at 100 °C for 2 hours, followed by the incremental addition of an H_2SO_4/$HClO_3$ mixture **(Peterburgski, 1968).** N, P, and K% were quantified using the Micro-Kjeldahl method, Olsen method, and flame photometer method, respectively, following procedures outlined by **Walinga *et al.* (2013).**

3. Photosynthetic pigments

Chlorophyll content in fresh weight was measured with a SPAD meter (SPAD-502, Minolta Camera, Osaka, Japan), and carotene levels in fresh weight were determined using acetone through a spectro-photometer, as detailed by **Dere, (1998).**

4. Enzymatic antioxidants

Enzymatic antioxidants in fresh leaves of crisphead lettuce, specifically superoxide dismutase, peroxidase, and catalase (unit mg^{-1} protein^{-1}) were determined according to the stander methods as described by **Elavarthi and Martin, B. (2010).**

5. Physical traits of crisphead lettuce heads

Physical traits of crisphead lettuce heads, encompassing head weight (g), head diameter (cm), head height (cm), and the number of outer leaves were measured.

6. Quality traits

Quality traits, including carbohydrates, protein, total sugar, fiber, TDS, dry matter (DM %), and vitamin C (mg 100g^{-1}) were determined following standard methods outlined by **AOAC, (2000).**

7. Soil properties after harvesting

Soil properties at the harvest stage, specifically available nitrogen, phosphorus, and potassium levels (mg kg^{-1}), were determined using the Micro-Kjeldahl method for nitrogen, the Olsen method for phosphorus, and the flame photometer method for potassium. These methods were following **Tandon's (2005)** guidelines.

Statistical Analyses

The statistical analysis of the data employed the methodology outlined by **Gomez and Gomez (1984)** with **CoStat version 6.303 copyright (1998-2004).** Treatment means were compared using the least significant difference (LSD) at a significance level of 0.05 probability.

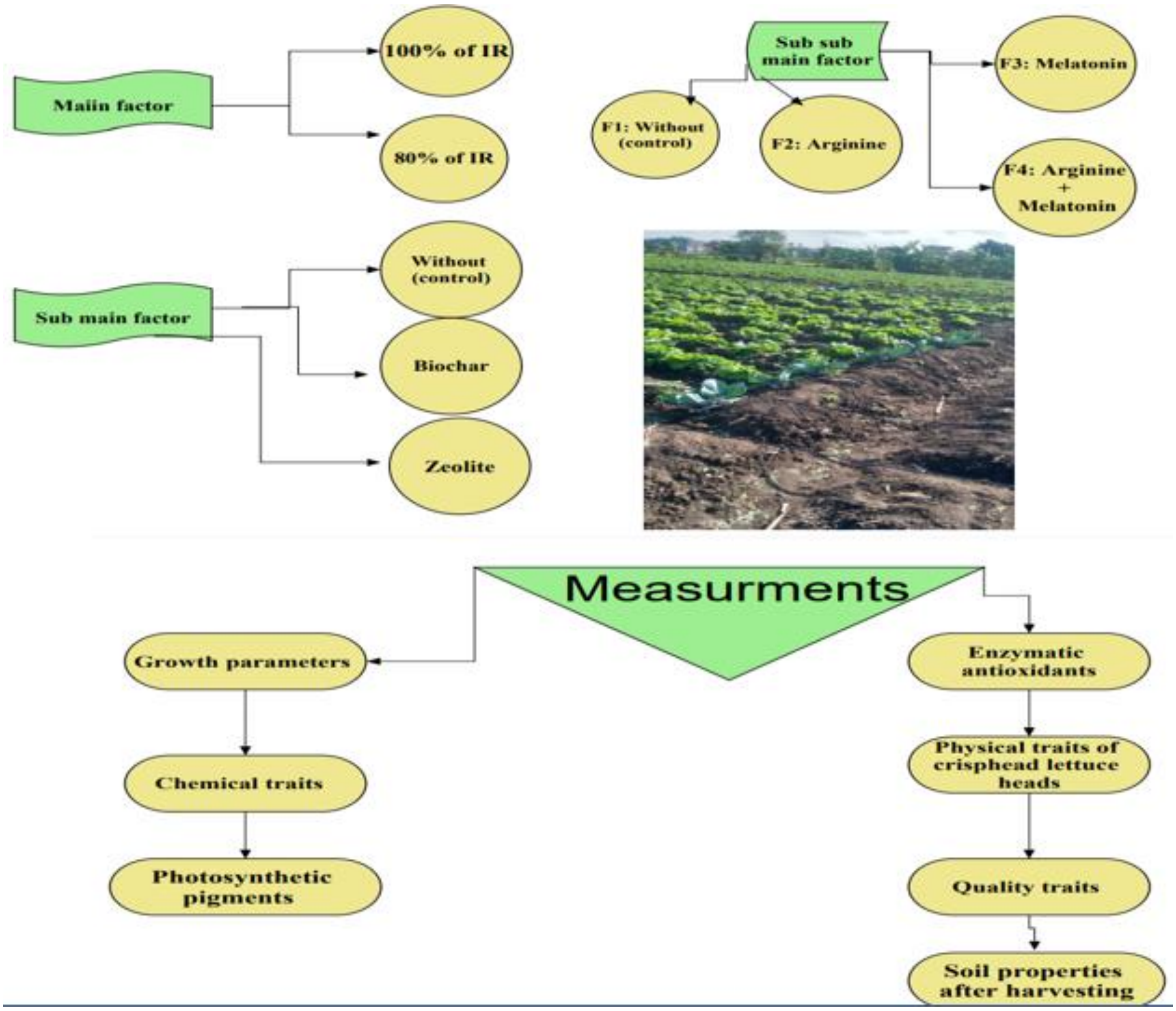

Fig. 1. The flowchart of the studied treatments and measurements.

Table 1. Attributes of initial soil (taken at a depth of 0-30 cm) as well as studied biochar and zeolite properties using the stander methods as described by Tandon, (2005).

Initial soil		Biochar	
Characteristics and unit	**Values**	**Characteristics and unit**	**Values**
Sand	20.00	EC, dSm^{-1}	5.00
Silt	30.45	pH	8.70
Clay	49.55	CEC, cmolc kg^{-1}	70.0
Textural class	Clay	**Zeolite**	
WHC, %	34.95	**Characteristics and unit**	**Values**
Organic matter, %	1.220	CEC, cmolc kg^{-1}	160
EC dSm^{-1}	3.770	P_2O_5, %	1.00
pH	8.000	SiO_2, %	65.0
Available nitrogen, $mgKg^{-1}$	48.02	K_2O	5.00
Available phosphorus, $mgKg^{-1}$	8.000	CaO, %	9.00
Available potassium, $mgKg^{-1}$	231.4	Na_2O, %	1.00

3. Results

Growth criteria and relative water content

Table 2 presents data illustrating the effect of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on the growth criteria of crisphead lettuce subjected to varying irrigation treatments during the 2022 and 2023 seasons, encompassing fresh and dry weights (g plant^{-1}), leaf area (cm^{2} plant^{-1}), and relative water content (%). The results highlight that 100% of irrigation (IR) led to the highest values across all measured traits, while plants irrigated with 80% of IR exhibited the lowest values. In terms of soil amendments, the data underscore the superior impact of zeolite, followed by biochar, over the control group. On the other hand, the combined treatment of arginine + melatonin emerged as the most effective, causing maximum values for all growth parameters. Melatonin treatment alone came in the second order then arginine treatment alone which ranked higher than the control group (without foliar application). Moreover, the application of zeolite and biochar under 80% of IR conditions resulted in improvements in all studied plant parameters; surpassing plants cultivated without these amendments (control) under 100% of IR conditions, with zeolite demonstrating superior effects over biochar. These findings emphasize the positive influence of zeolite, biochar, and the combined application of arginine and melatonin in enhancing the growth performance of crisphead lettuce, particularly under reduced irrigation conditions. The same trend was found for both studying seasons.

Leaves chemical constituents and photosynthetic pigments

Table 3 shows the effect of the studied treatments on leaves' chemical constituents *i.e.,* N, P, and K (%), while Table 4 shows the effect of the studied treatments on photosynthetic pigments *i.e.,* chlorophyll content (SPAD, reading) and carotene (mg g^{-1}) during the 2022 and 2023 seasons. The results illustrate that irrigation with 100% IR caused the highest values of all parameters expressed in chemical constituents and photosynthetic pigments, while plants irrigated with 80% IR exhibited the lowest values. Regarding soil amendments, the data show the superior soil amendment to obtain the maximum values was zeolite followed by biochar then the control group. Regarding foliar applications, the combined treatment of arginine + melatonin outperformed all other treatments, resulting in maximum values across all studied conditions. Melatonin treatment alone came in the second order then arginine treatment alone which ranked higher than the control group (without foliar application). Additionally, the application of zeolite and biochar under 80% irrigation (IR) conditions resulted in notable improvements in chemical constituents and photosynthetic pigments, consistently outperforming plants cultivated without these amendments (control) under 100% IR conditions. Zeolite exhibited superior effects over biochar, and this trend remained consistent across both studied seasons. The enhanced performance in chemical constituents and photosynthetic pigments underscores the positive influence of zeolite and biochar in augmenting the physiological and biochemical aspects of crisphead lettuce, particularly when subjected to reduced irrigation levels. These findings further support the potential of zeolite and biochar as effective soil amendments for optimizing plant responses and productivity under water scarcity conditions.

Table 2. Impact of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on growth performance of crisphead lettuce irrigated with varying irrigation treatments during seasons of 2022 and 2023.

Treatments			Fresh weight, g plant^{-1}		Dry weight, g plant^{-1}		Leaf area, cm^2 plant^{-1}		Relative water	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Irrigation requirements IR										
100% of IR			1274.39a	1292.33a	108.14a	109.49a	2369.06a	2426.25a	90.56a	90.94a
80% of IR			1155.72b	1170.72b	89.92b	91.10b	2043.42b	2085.47b	87.21b	87.70b
LSD at 5%			**50.51**	**2.50**	**4.01**	**1.02**	**100.50**	**4.52**	**3.16**	**0.45**
Sub main factor: Soil amendments										
Without (control)			972.08c	984.50c	76.96c	77.98c	1771.21c	1811.13c	85.67c	85.97c
Biochar			1292.17b	1308.92b	104.42b	105.79b	2315.75b	2366.08b	89.28b	89.84b
Zeolite			1380.92a	1401.17a	115.71a	117.12a	2531.75a	2590.38a	91.70a	92.16a
LSD at 5%			**8.03**	**1.98**	**0.67**	**1.43**	**8.091**	**3.63**	**0.09**	**1.93**
Sub-sub main factor: Stimulants										
F_1: Without (control)			1199.50c	1215.50d	94.69d	95.90d	2138.11d	2190.44d	88.29c	88.69a
F_2: Arginine			1207.11bc	1223.00c	97.80c	99.13c	2181.83c	2228.28c	88.65bc	88.98a
F_3: Melatonin			1215.83b	1232.39b	100.67b	101.94b	2228.06b	2278.50b	89.03ab	89.53a
F_4: Arginine+ Melatonin			1237.78a	1255.22a	102.96a	104.22a	2276.94a	2326.22a	89.57a	90.09a
LSD at 5%			**10.17**	**3.60**	**0.85**	**0.73**	**17.42**	**66.62**	**0.70**	***NS**
Interaction										
100% of IR	**Without (control)**	**F_1**	972.33	987.67	78.51	79.30	1765.67	1808.33	85.42	85.48
		F_2	974.00	986.33	80.68	81.58	1823.67	1860.67	86.42	86.64
		F_3	983.67	997.33	83.76	85.08	1875.00	1920.33	86.69	86.93
		F_4	1004.33	1016.00	85.83	87.03	1915.33	1956.00	86.78	87.16
	Biochar	**F_1**	1370.33	1385.33	111.17	112.56	2489.67	2552.67	90.34	91.04
		F_2	1385.00	1401.33	114.24	115.93	2513.00	2563.67	90.68	90.97
		F_3	1395.67	1419.00	117.13	118.73	2567.00	2642.67	91.35	91.70
		F_4	1432.00	1455.67	119.57	120.88	2617.67	2685.67	92.24	92.81
	Zeolite	**F_1**	1438.00	1456.33	122.61	124.05	2666.67	2742.67	92.94	93.32
		F_2	1440.67	1463.33	125.51	127.28	2697.67	2760.67	93.90	94.26
		F_3	1445.00	1464.67	127.99	129.42	2732.33	2786.33	94.50	95.06
		F_4	1451.67	1475.00	130.66	132.06	2765.00	2835.33	95.46	95.94
80% of IR	**Without (control)**	**F_1**	950.00	961.33	67.30	68.25	1670.00	1709.00	84.88	85.22
		F_2	960.33	971.00	70.72	71.85	1692.33	1730.67	84.99	85.25
		F_3	963.67	977.33	73.43	74.25	1708.33	1746.67	85.01	85.34
		F_4	968.33	979.00	75.42	76.47	1719.33	1757.33	85.19	85.72
	Biochar	**F_1**	1164.67	1176.00	88.94	90.04	1970.67	2013.33	87.28	87.73
		F_2	1174.00	1187.33	92.00	93.06	2044.00	2086.00	87.00	87.44
		F_3	1178.00	1192.00	94.80	96.04	2113.33	2145.00	87.53	88.47
		F_4	1237.67	1254.67	97.54	99.04	2210.67	2239.67	87.82	88.54
	Zeolite	**F_1**	1301.67	1326.33	99.59	101.17	2266.00	2316.67	88.90	89.35
		F_2	1308.67	1328.67	103.66	105.05	2320.33	2368.00	88.90	89.32
		F_3	1329.00	1344.00	106.92	108.11	2372.33	2430.00	89.11	89.65
		F_4	1332.67	1351.00	108.76	109.83	2433.67	2483.33	89.92	90.39
LSD at 5%			**24.91**	**8.82**	**2.08**	**1.80**	**42.68**	**16.23**	**1.73**	**3.49**

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

Table 3. Impact of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on chemical constituents in dry leaves of crisphead lettuce irrigated with varying irrigation treatments during seasons of 2022 and 2023.

Treatments			N %		P %		K %	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Irrigation requirements IR								
100% of IR			3.36a	3.42a	0.354a	0.369a	3.00a	3.15a
80% of IR			3.11b	3.17b	0.324b	0.337b	2.75b	2.89b
LSD at 5%			**0.03**	**0.04**	**0.002**	**0.003**	**0.10**	**0.03**
Submain factor: Soil amendments								
Without (control)			2.90c	2.96c	0.302c	0.315c	2.58c	2.70c
Biochar			3.31b	3.38b	0.348b	0.363b	2.95b	3.10b
Zeolite			3.49a	3.56a	0.367a	0.381a	3.10a	3.25a
LSD at 5%			**0.02**	**0.04**	**0.004**	**0.004**	**0.01**	**0.02**
Sub-sub main factor: Stimulants								
F_1: Without (control)			3.16d	3.22d	0.332d	0.346d	2.82d	2.96d
F_2: Arginine			3.21c	3.28c	0.337c	0.351c	2.86c	3.00c
F_3: Melatonin			3.26b	3.33b	0.341b	0.355b	2.89b	3.03b
F_4: Arginine+ Melatonin			3.30a	3.37a	0.345a	0.359a	2.93a	3.08a
LSD at 5%			**0.03**	**0.02**	**0.003**	**0.003**	**0.02**	**0.03**
Interaction								
100% of IR	**Without (control)**	**F_1**	2.92	2.98	0.304	0.316	2.60	2.74
		F_2	2.95	3.01	0.307	0.321	2.64	2.77
		F_3	3.02	3.07	0.314	0.328	2.68	2.81
		F_4	3.05	3.11	0.318	0.331	2.72	2.85
	Biochar	**F_1**	3.43	3.50	0.361	0.375	3.03	3.18
		F_2	3.44	3.51	0.365	0.382	3.07	3.23
		F_3	3.51	3.58	0.368	0.383	3.11	3.27
		F_4	3.53	3.61	0.372	0.387	3.17	3.34
	Zeolite	**F_1**	3.57	3.66	0.378	0.393	3.19	3.37
		F_2	3.59	3.66	0.384	0.399	3.24	3.40
		F_3	3.61	3.68	0.388	0.403	3.25	3.41
		F_4	3.66	3.74	0.391	0.407	3.29	3.46
80% of IR	**Without (control)**	**F_1**	2.71	2.77	0.285	0.296	2.43	2.55
		F_2	2.79	2.85	0.292	0.304	2.48	2.59
		F_3	2.87	2.93	0.296	0.309	2.51	2.63
		F_4	2.90	2.96	0.299	0.312	2.57	2.70
	Biochar	**F_1**	3.07	3.13	0.323	0.337	2.74	2.89
		F_2	3.12	3.18	0.329	0.342	2.78	2.92
		F_3	3.18	3.24	0.331	0.346	2.82	2.97
		F_4	3.23	3.29	0.335	0.349	2.86	3.00
	Zeolite	**F_1**	3.27	3.32	0.343	0.357	2.91	3.06
		F_2	3.38	3.45	0.346	0.359	2.94	3.09
		F_3	3.40	3.47	0.351	0.364	2.96	3.11
		F_4	3.42	3.50	0.355	0.369	3.00	3.15
LSD at 5%			**0.07**	**0.06**	**0.006**	**0.006**	**0.06**	**0.07**

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

Table 4. Impact of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on photosynthetic pigment contents in fresh leaves of crisphead lettuce irrigated with varying irrigation treatments during seasons of 2022 and 2023.

Treatments			Chlorophyll, SPAD reading		Carotene, mg g^{-1}	
			1st season	2nd season	1st season	2nd season
Main factor: Irrigation requirements IR						
100% of IR			46.04a	46.62a	0.363a	0.378a
80% of IR			43.33b	43.85b	0.307b	0.319b
LSD at 5%			**0.49**	**1.45**	**0.002**	**0.002**
Submain factor: Soil amendments						
Without (control)			41.22c	41.71c	0.277c	0.287c
Biochar			45.60b	46.17b	0.347b	0.362b
Zeolite			47.40a	47.81a	0.381a	0.397a
LSD at 5%			**0.34**	**0.30**	**0.004**	**0.004**
Sub-sub main factor: Stimulants						
F_1: Without (control)			44.19c	44.72b	0.324d	0.337d
F_2: Arginine			44.49bc	45.02ab	0.331c	0.344c
F_3: Melatonin			44.82b	45.34ab	0.339b	0.353b
F_4: Arginine+ Melatonin			45.34a	45.85a	0.346a	0.361a
LSD at 5%			**0.39**	**0.91**	**0.002**	**0.003**
Interaction						
100% of IR	**Without (control)**	**F_1**	41.33	41.97	0.280	0.291
		F_2	41.52	41.99	0.284	0.295
		F_3	41.70	42.19	0.291	0.302
		F_4	42.06	42.59	0.299	0.311
	Biochar	**F_1**	47.03	47.60	0.370	0.385
		F_2	47.26	47.74	0.377	0.392
		F_3	47.89	48.59	0.389	0.406
		F_4	48.13	48.67	0.400	0.417
	Zeolite	**F_1**	48.54	49.07	0.408	0.425
		F_2	48.71	49.43	0.413	0.430
		F_3	48.69	49.38	0.419	0.438
		F_4	49.65	50.18	0.422	0.440
80% of IR	**Without (control)**	**F_1**	40.38	40.84	0.253	0.263
		F_2	40.73	41.22	0.261	0.271
		F_3	40.83	41.28	0.267	0.277
		F_4	41.20	41.64	0.278	0.289
	Biochar	**F_1**	42.92	43.48	0.303	0.315
		F_2	43.27	43.95	0.309	0.321
		F_3	43.67	44.14	0.314	0.327
		F_4	44.62	45.17	0.318	0.331
	Zeolite	**F_1**	44.96	45.36	0.330	0.343
		F_2	45.47	45.79	0.341	0.354
		F_3	46.15	46.45	0.354	0.368
		F_4	46.88	46.87	0.361	0.376
LSD at 5%			**0.95**	**2.23**	**0.006**	**0.006**

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

Enzymatic antioxidants

The findings presented in Table 5 shed light on the influence of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on enzymatic antioxidants in fresh leaves of crisphead lettuce, specifically superoxide dismutase, peroxidase, and catalase (unit mg^{-1} $protein^{-1}$). These analyses were conducted for plants grown under varying irrigation treatments during the 2022 and 2023 seasons. The findings reveal that 100% of irrigation (IR) led to the highest values across all measured enzymatic antioxidants, whereas plants irrigated with 80% of IR exhibited the lowest values, indicating a clear correlation between irrigation levels and enzymatic antioxidant activity. Concerning soil amendments, zeolite demonstrated a superior impact, followed by biochar, when compared to the control group. Additionally, the combined treatment of arginine + melatonin emerged as the most effective, causing maximum values for all studied enzymatic antioxidants followed by melatonin treatment alone and then arginine treatment alone which ranked higher than the control group without foliar application. Furthermore, the application of zeolite and biochar under 80% of IR conditions resulted in improvements in all studied enzymatic antioxidants, surpassing plants cultivated without these amendments (control) under 100% of IR conditions, with zeolite demonstrating superior effects over biochar. This consistent trend across both studied seasons underscores the potential of zeolite and biochar in enhancing the antioxidant defense system of crisphead lettuce, particularly under conditions of reduced irrigation, while emphasizing the effectiveness of arginine and melatonin in further augmenting enzymatic antioxidant activity.

Head traits (physical traits and quality)

Table 6 indicates the impact of the studied treatments on the physical traits of crisphead lettuce heads, encompassing head weight (g), head diameter (cm), head height (cm), and the number of outer leaves. Simultaneously, Table 7 delves into the effects of these treatments on quality traits, including carbohydrates, protein, total sugar, fiber, TDS, dry matter (DM %), and vitamin C (mg $100g^{-1}$) across the 2022 and 2023 seasons. The results consistently indicate that irrigation with 100% irrigation (IR) resulted in the highest values for all parameters related to head traits, both physical and quality aspects. Conversely, plants irrigated with 80% IR exhibited the lowest values, highlighting the strong correlation between irrigation levels and the observed traits. In terms of soil amendments, the data emphasize the superior efficacy of zeolite, followed by biochar, over the control group in achieving maximum values for the studied head traits. Concerning foliar applications, the combined treatment of arginine + melatonin outperformed all other treatments, consistently yielding maximum values followed by melatonin treatment alone then arginine treatment alone and lately the control group (without foliar application). Also, it can be noticed that the application of zeolite and biochar under 80% of IR conditions led to significant improvements in head traits compared to plants cultivated without these amendments (control) under 100% of IR conditions, with zeolite exhibiting superior effects over biochar. This trend remained consistent in the second season, underscoring the potential of zeolite and biochar in enhancing both the physical and quality traits of crisphead lettuce heads, particularly under conditions of reduced irrigation.

Table 5. Impact of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on enzymatic antioxidants in fresh leaves of crisphead lettuce irrigated with varying irrigation treatments during seasons of 2022 and 2023.

Treatments			Super oxidase dismutase		Peroxidase		Catalase	
			(unit mg^{-1} protein^{-1})					
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Irrigation requirements IR								
100% of IR			26.80a	27.14a	0.784a	0.817a	50.67a	51.55a
80% of IR			21.91b	22.15b	0.626b	0.651b	40.61b	41.45b
LSD at 5%			**0.16**	**0.35**	**0.007**	**0.005**	**0.18**	**0.35**
Sub main factor: Soil amendments								
Without (control)			17.59c	17.82c	0.483c	0.502c	35.01c	35.58c
Biochar			26.26b	26.59b	0.765b	0.796b	47.42b	48.44b
Zeolite			29.21a	29.53a	0.866a	0.902a	54.48a	55.47a
LSD at 5%			**0.15**	**0.22**	**0.009**	**0.009**	**0.08**	**0.18**
Sub-sub main factor: Stimulants								
F_1: Without (control)			23.45d	23.71d	0.670d	0.696d	43.71d	44.57d
F_2: Arginine			24.00c	24.31c	0.688c	0.715c	44.97c	45.80c
F_3: Melatonin			24.62b	24.93b	0.717b	0.747b	46.34b	47.17b
F_4: Arginine+ Melatonin			25.35a	25.63a	0.746a	0.777a	47.53a	48.45a
LSD at 5%			**0.23**	**0.20**	**0.005**	**0.005**	**0.13**	**0.23**
Interaction								
100% of IR	**Without (control)**	**F_1**	17.24	17.47	0.487	0.506	35.07	35.48
		F_2	17.96	18.19	0.512	0.531	36.01	36.68
		F_3	18.84	19.10	0.559	0.580	36.49	37.11
		F_4	19.86	20.12	0.561	0.584	37.19	37.83
	Biochar	**F_1**	28.51	28.85	0.852	0.886	52.04	52.98
		F_2	29.37	29.66	0.882	0.919	53.72	54.73
		F_3	29.94	30.43	0.893	0.932	55.54	56.54
		F_4	31.12	31.41	0.900	0.940	56.76	57.86
	Zeolite	**F_1**	31.93	32.29	0.922	0.960	58.94	60.01
		F_2	32.00	32.52	0.934	0.971	60.41	61.38
		F_3	32.36	32.81	0.945	0.989	62.56	63.60
		F_4	32.44	32.86	0.960	1.000	63.27	64.38
80% of IR	**Without (control)**	**F_1**	16.51	16.71	0.405	0.421	33.42	33.98
		F_2	16.61	16.81	0.419	0.435	33.41	33.93
		F_3	16.70	16.90	0.447	0.464	33.81	34.16
		F_4	17.02	17.24	0.479	0.498	34.65	35.51
	Biochar	**F_1**	21.57	21.88	0.592	0.616	37.82	38.85
		F_2	22.34	22.68	0.615	0.640	39.33	40.28
		F_3	23.18	23.47	0.650	0.677	41.10	42.22
		F_4	24.08	24.36	0.733	0.762	43.03	44.08
	Zeolite	**F_1**	24.90	25.08	0.760	0.790	44.95	46.10
		F_2	25.74	26.00	0.763	0.791	46.93	47.83
		F_3	26.72	26.89	0.806	0.837	48.56	49.40
		F_4	27.56	27.79	0.842	0.878	50.25	51.03
LSD at 5%			**0.56**	**0.50**	**0.012**	**0.013**	**0.33**	**0.55**

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

Table 6. Impact of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on head physical traits of crisphead lettuce irrigated with varying irrigation treatments during seasons of 2022 and 2023.

Treatments			Head weight, g plant^{-1}		Head diameter, cm		Head height, cm		No. of outer leaves	
			1st season	2nd season	1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Irrigation requirements IR										
100% of IR			1050.75a	1071.31a	20.57a	20.99a	19.17a	19.94a	9.28a	9.39a
80% of IR			900.72b	919.06b	18.41b	18.78b	16.99b	17.70b	7.33b	7.11b
LSD at 5%			**43.78**	**40.27**	**0.10**	**0.19**	**0.11**	**0.20**	**0.52**	**0.48**
Submain factor: Soil amendments										
Without (control)			761.54c	776.58c	16.53c	16.85c	15.53c	16.18c	6.38c	5.75c
Biochar			1024.67b	1045.54b	20.25b	20.68b	18.71b	19.50b	8.67b	8.79b
Zeolite			1141.00a	1163.42a	21.68a	22.11a	20.01a	20.78a	9.88a	10.21a
LSD at 5%			**3.81**	**6.50**	**0.10**	**0.46**	**0.19**	**0.26**	**0.71**	**0.48**
Sub-sub main factor: Stimulants										
F_1: Without (control)			949.56d	968.72d	19.03d	19.42c	17.62d	18.31b	7.94b	7.89b
F_2: Arginine			960.50c	979.61c	19.33c	19.69bc	17.92c	18.64b	8.11b	8.00b
F_3: Melatonin			977.83b	996.94b	19.64b	20.03b	18.24b	18.99a	8.39ab	8.33ab
F_4: Arginine+ Melatonin			1015.06a	1035.44a	19.96a	20.39a	18.56a	19.33a	8.78a	8.78a
LSD at 5%			**7.81**	**8.57**	**0.17**	**0.34**	**0.14**	**0.35**	**0.62**	**0.57**
Interaction										
100% of IR	**Without (control)**	**F_1**	763.00	779.33	16.50	16.80	15.60	16.17	7.00	6.33
		F_2	767.67	780.33	17.10	17.40	16.10	16.80	7.00	6.33
		F_3	770.33	785.00	17.57	17.90	16.30	17.00	7.00	6.33
		F_4	779.00	795.33	17.70	18.07	16.50	17.20	7.33	6.67
	Biochar	**F_1**	1078.33	1096.67	21.30	21.70	19.50	20.30	9.00	9.33
		F_2	1096.33	1117.67	21.50	21.97	19.87	20.77	9.33	9.67
		F_3	1147.33	1170.00	21.80	22.27	20.40	21.27	9.67	10.33
		F_4	1226.00	1251.00	22.20	22.70	20.60	21.37	10.33	10.67
	Zeolite	**F_1**	1236.33	1259.00	22.50	23.07	20.90	21.70	10.67	11.33
		F_2	1243.67	1268.00	22.70	23.07	21.20	21.97	11.00	11.67
		F_3	1248.00	1271.33	22.90	23.33	21.40	22.17	11.33	11.67
		F_4	1253.00	1282.00	23.10	23.60	21.70	22.57	11.67	12.33
80% of IR	**Without (control)**	**F_1**	743.00	759.00	15.50	15.90	14.50	15.10	5.00	4.67
		F_2	750.67	767.67	15.70	16.00	14.80	15.37	5.33	4.67
		F_3	757.33	772.00	16.00	16.27	15.00	15.70	6.00	5.33
		F_4	761.33	774.00	16.20	16.50	15.40	16.10	6.33	5.67
	Biochar	**F_1**	866.67	889.00	18.17	18.57	16.90	17.60	7.67	7.33
		F_2	878.33	896.33	18.50	18.87	17.07	17.80	7.67	7.33
		F_3	902.33	921.33	18.90	19.30	17.50	18.27	7.67	7.67
		F_4	1002.00	1022.33	19.67	20.10	17.87	18.67	8.00	8.00
	Zeolite	**F_1**	1010.00	1029.33	20.20	20.50	18.30	19.00	8.33	8.33
		F_2	1026.33	1047.67	20.50	20.87	18.47	19.17	8.33	8.33
		F_3	1041.67	1062.00	20.67	21.10	18.87	19.57	8.67	8.67
		F_4	1069.00	1088.00	20.90	21.37	19.27	20.07	9.00	9.33
LSD at 5%			**19.13**	**20.99**	**0.43**	**0.83**	**0.33**	**0.85**	**1.53**	**1.40**

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

Table 7. Impact of soil amendments (zeolite and biochar) and spraying stimulants (arginine and melatonin) on quality traits of crisphead lettuce irrigated with varying irrigation treatments during seasons of 2022 and 2023.

Treatments			Carbohydrates, %		Protein, %		T. Sugar, %		Fiber, %	
			1st season	2nd	1st season	2nd season	1st	2nd	1st season	2nd
Main factor: Irrigation requirements IR										
100% of IR			1.96a	2.05a	2.84a	2.95a	0.96a	1.01a	1.45a	1.51a
80% of IR			1.61b	1.69b	2.36b	2.46b	0.60b	0.63b	1.04b	1.08b
LSD at 5%			**0.01**	**0.02**	**0.04**	**0.01**	**0.05**	**0.01**	**0.08**	**0.01**
Submain factor: Soil amendments										
Without (control)			1.34c	1.40c	2.05c	2.13c	0.32c	0.34c	0.72c	0.75c
Biochar			1.89b	1.99b	2.73b	2.85b	0.89b	0.94b	1.37b	1.43b
Zeolite			2.12a	2.23a	3.02a	3.13a	1.13a	1.19a	1.64a	1.70a
LSD at 5%			**0.02**	**0.02**	**0.03**	**0.03**	**0.02**	**0.02**	**0.04**	**0.01**
Sub-sub main factor: Stimulants										
F_1: Without (control)			1.71d	1.80d	2.51c	2.60d	0.71d	0.75d	1.16d	1.20d
F_2: Arginine			1.76c	1.84c	2.56bc	2.66c	0.75c	0.79c	1.22c	1.26c
F_3: Melatonin			1.81b	1.89b	2.63ab	2.73b	0.80b	0.84b	1.26b	1.32b
F_4: Arginine+ Melatonin			1.87a	1.96a	2.70a	2.80a	0.86a	0.91a	1.33a	1.38a
LSD at 5%			**0.01**	**0.04**	**0.10**	**0.05**	**0.03**	**0.03**	**0.04**	**0.05**
Interaction										
100% of IR	**Without (control)**	**F_1**	1.33	1.40	2.05	2.12	0.31	0.33	0.70	0.73
		F_2	1.40	1.47	2.13	2.22	0.37	0.40	0.77	0.80
		F_3	1.46	1.53	2.19	2.28	0.43	0.45	0.83	0.87
		F_4	1.51	1.58	2.27	2.34	0.48	0.51	0.89	0.94
	Biochar	**F_1**	2.07	2.18	2.94	3.05	1.08	1.14	1.59	1.66
		F_2	2.12	2.23	2.98	3.12	1.10	1.16	1.65	1.71
		F_3	2.16	2.26	3.07	3.20	1.14	1.22	1.69	1.77
		F_4	2.21	2.32	3.15	3.28	1.22	1.29	1.75	1.82
	Zeolite	**F_1**	2.27	2.39	3.25	3.38	1.29	1.36	1.82	1.89
		F_2	2.28	2.39	3.27	3.39	1.31	1.38	1.86	1.93
		F_3	2.32	2.43	3.34	3.47	1.38	1.44	1.88	1.95
		F_4	2.37	2.49	3.39	3.52	1.41	1.47	1.94	2.02
80% of IR	**Without (control)**	**F_1**	1.20	1.26	1.85	1.93	0.21	0.22	0.57	0.59
		F_2	1.24	1.30	1.92	2.00	0.24	0.25	0.62	0.65
		F_3	1.28	1.34	1.96	2.04	0.27	0.28	0.66	0.69
		F_4	1.29	1.36	2.00	2.09	0.29	0.30	0.69	0.72
	Biochar	**F_1**	1.55	1.63	2.33	2.43	0.52	0.55	0.97	1.01
		F_2	1.60	1.68	2.39	2.48	0.61	0.64	1.04	1.09
		F_3	1.66	1.74	2.47	2.57	0.65	0.68	1.09	1.14
		F_4	1.79	1.88	2.52	2.64	0.78	0.82	1.20	1.25
	Zeolite	**F_1**	1.84	1.93	2.62	2.72	0.84	0.89	1.29	1.34
		F_2	1.90	2.00	2.68	2.77	0.89	0.94	1.37	1.41
		F_3	1.96	2.06	2.74	2.84	0.94	0.99	1.42	1.48
		F_4	2.03	2.13	2.84	2.96	0.99	1.04	1.51	1.57
LSD at 5%			**0.03**	**0.09**	**0.23**	**0.12**	**0.07**	**0.06**	**0.11**	**0.13**

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

Cont. Table 7

Treatments			*TDS, %		Vitamin C, %		Dry matter, %	
			1st season	2nd season	1st season	2nd season	1st season	2nd season
Main factor: Irrigation requirements IR								
100% of IR			5.55a	5.78a	6.32a	6.41a	3.38a	3.45a
80% of IR			4.63b	4.82b	5.36b	5.42b	2.69b	2.75b
LSD at 5%			**0.04**	**0.01**	**0.08**	**0.01**	**0.05**	**0.02**
Submain factor: Soil amendments								
Without (control)			3.66c	3.81c	4.63c	4.69c	2.18c	2.22c
Biochar			5.48b	5.71b	6.15b	6.23b	3.25b	3.31b
Zeolite			6.12a	6.36a	6.74a	6.81a	3.69a	3.76a
LSD at 5%			**0.05**	**0.04**	**0.05**	**0.05**	**0.01**	**0.01**
Sub-sub main factor: Stimulants								
F_1: Without (control)			4.90d	5.10d	5.65d	5.72d	2.90d	2.96d
F_2: Arginine			5.00c	5.21c	5.78c	5.85c	3.00c	3.06c
F_3: Melatonin			5.14b	5.35b	5.90b	5.97b	3.07b	3.14b
F_4: Arginine+ Melatonin			5.32a	5.53a	6.04a	6.11a	3.18a	3.24a
LSD at 5%			**0.04**	**0.04**	**0.05**	**0.05**	**0.03**	**0.03**
Interaction								
100% of IR	**Without (control)**	**F_1**	3.62	3.77	4.53	4.61	2.12	2.16
		F_2	3.71	3.87	4.73	4.79	2.26	2.30
		F_3	3.98	4.15	4.89	4.95	2.35	2.40
		F_4	4.23	4.41	5.06	5.13	2.46	2.51
	Biochar	**F_1**	5.95	6.19	6.63	6.72	3.58	3.64
		F_2	6.05	6.33	6.80	6.88	3.70	3.77
		F_3	6.20	6.46	6.95	7.05	3.80	3.88
		F_4	6.36	6.61	7.07	7.15	3.92	4.00
	Zeolite	**F_1**	6.57	6.83	7.23	7.32	4.07	4.14
		F_2	6.61	6.87	7.27	7.38	4.09	4.17
		F_3	6.64	6.90	7.32	7.43	4.11	4.19
		F_4	6.68	6.95	7.37	7.46	4.15	4.24
80% of IR	**Without (control)**	**F_1**	3.34	3.47	4.39	4.45	2.01	2.05
		F_2	3.41	3.55	4.46	4.51	2.05	2.09
		F_3	3.47	3.62	4.48	4.52	2.08	2.12
		F_4	3.53	3.68	4.52	4.57	2.09	2.13
	Biochar	**F_1**	4.46	4.66	5.18	5.26	2.55	2.61
		F_2	4.65	4.85	5.31	5.39	2.68	2.74
		F_3	4.89	5.10	5.48	5.55	2.77	2.83
		F_4	5.28	5.51	5.76	5.83	2.99	3.05
	Zeolite	**F_1**	5.45	5.67	5.91	5.97	3.08	3.14
		F_2	5.56	5.78	6.09	6.13	3.21	3.27
		F_3	5.66	5.88	6.27	6.30	3.35	3.40
		F_4	5.81	6.04	6.44	6.49	3.46	3.54
		LSD at 5%	**0.10**	**0.11**	**0.12**	**0.12**	**0.06**	**0.07**

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

Post-harvest soil analyses

Table 8 outlines the impact of the studied treatments on soil properties, specifically available nitrogen, phosphorus, and potassium (mg kg^{-1}), post-harvest during the seasons of 2022 and 2023. Additionally, Fig 2 represents the individual effects of the studied soil amendments on available nitrogen, phosphorus, and potassium (mg kg^{-1}) during the same seasons. The influence of irrigation treatments on soil properties was unclear, while the effects of both soil and foliar applications were evident and statistically significant. The results in Table 8 and Fig 2 highlight that both zeolite and biochar contributed to an increase in soil nutrient availability compared to untreated soil. Notably, the highest values of available nitrogen and potassium were achieved with zeolite, followed by biochar, and the control group exhibited the lowest values. Conversely, the highest values of available phosphorus were observed with biochar, followed by zeolite, with the control group displaying the lowest values. Concerning foliar applications, the maximum values of available nitrogen, phosphorus, and potassium were realized under the control group compared to all foliar applications. Specifically, the combined treatment of arginine + melatonin exhibited the lowest values of available nitrogen, phosphorus, and potassium, followed by melatonin treatment alone, and arginine treatment alone. These findings underscore the significant impact of soil amendments, particularly zeolite and biochar, in enhancing soil nutrient availability post-harvest.

Table 8. Impact of the studied treatments on soil properties (available nitrogen, phosphorus and potassium) after harvest during seasons of 2022 and 2023.

Treatments			Available-N, $mgkg^{-1}$		Available-P, $mgkg^{-1}$		Available-K, $mgkg^{-1}$	
			1^{st} season	2^{nd} season	1^{st} season	2^{nd} season	1^{st} season	2^{nd} season
Main factor: Irrigation requirements IR								
100% of IR			42.81b	43.53a	10.21b	10.64b	216.11a	219.64b
80% of IR			44.00a	44.90a	10.79a	11.24a	222.27a	225.83a
LSD at 5%			**0.47**	***NS**	**0.15**	**0.13**	***NS**	**0.84**
Submain factor: Soil amendments								
Without (control)			40.94c	41.63c	9.57c	9.97c	206.67c	209.89c
Biochar			43.23b	44.16b	11.58a	12.08a	218.35b	222.00b
Zeolite			46.04a	46.86a	10.36b	10.76b	232.54a	236.32a
LSD at 5%			**0.29**	**0.27**	**0.13**	**0.07**	**1.32**	**0.37**
Sub-sub main factor: Stimulants								
F_1: Without (control)			43.87a	44.74a	10.69a	11.13a	221.40a	224.90a
F_2: Arginine			43.55ab	44.35b	10.57b	11.00b	220.02ab	223.80b
F_3: Melatonin			43.23bc	43.99c	10.44c	10.88c	218.39bc	221.91c
F_4: Arginine+ Melatonin			42.96c	43.78c	10.31d	10.74d	216.93c	220.32d
LSD at 5%			**0.38**	**0.36**	**0.08**	**0.10**	**1.77**	**0.64**
Interaction								
100% of IR	**Without (control)**	**F_1**	40.80	41.36	9.53	9.94	205.42	208.76
		F_2	40.55	41.33	9.41	9.82	204.57	207.92
		F_3	40.33	40.97	9.34	9.72	203.75	206.90
		F_4	40.27	40.90	9.20	9.61	203.02	206.59
	Biochar	**F_1**	43.05	43.82	11.37	11.83	216.64	220.82
		F_2	42.78	43.53	11.25	11.76	215.41	220.26
		F_3	42.39	43.15	10.97	11.43	214.09	217.31
		F_4	42.17	42.92	10.84	11.29	212.93	215.89
	Zeolite	**F_1**	45.98	46.83	10.32	10.71	231.79	235.26
		F_2	45.62	46.35	10.20	10.60	230.04	233.22
		F_3	45.07	45.76	10.10	10.50	228.42	231.80
		F_4	44.67	45.47	10.00	10.41	227.17	230.90
80% of IR	**Without (control)**	**F_1**	41.83	42.62	9.90	10.30	211.60	214.68
		F_2	41.53	42.16	9.81	10.21	209.99	212.73
		F_3	41.21	41.70	9.71	10.14	208.55	211.47
		F_4	40.97	41.96	9.62	10.02	206.48	210.04
	Biochar	**F_1**	44.35	45.48	12.35	12.89	225.31	228.52
		F_2	43.96	45.06	12.10	12.59	223.62	227.36
		F_3	43.75	44.85	12.01	12.57	220.18	223.74
		F_4	43.39	44.43	11.78	12.28	218.58	222.07
	Zeolite	**F_1**	47.19	48.34	10.68	11.12	237.66	241.36
		F_2	46.86	47.69	10.62	11.02	236.51	241.30
		F_3	46.63	47.48	10.50	10.91	235.32	240.24
		F_4	46.30	47.00	10.44	10.84	233.38	236.45
LSD at 5%			**0.94**	**0.87**	**0.20**	**0.24**	**4.33**	**1.56**

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

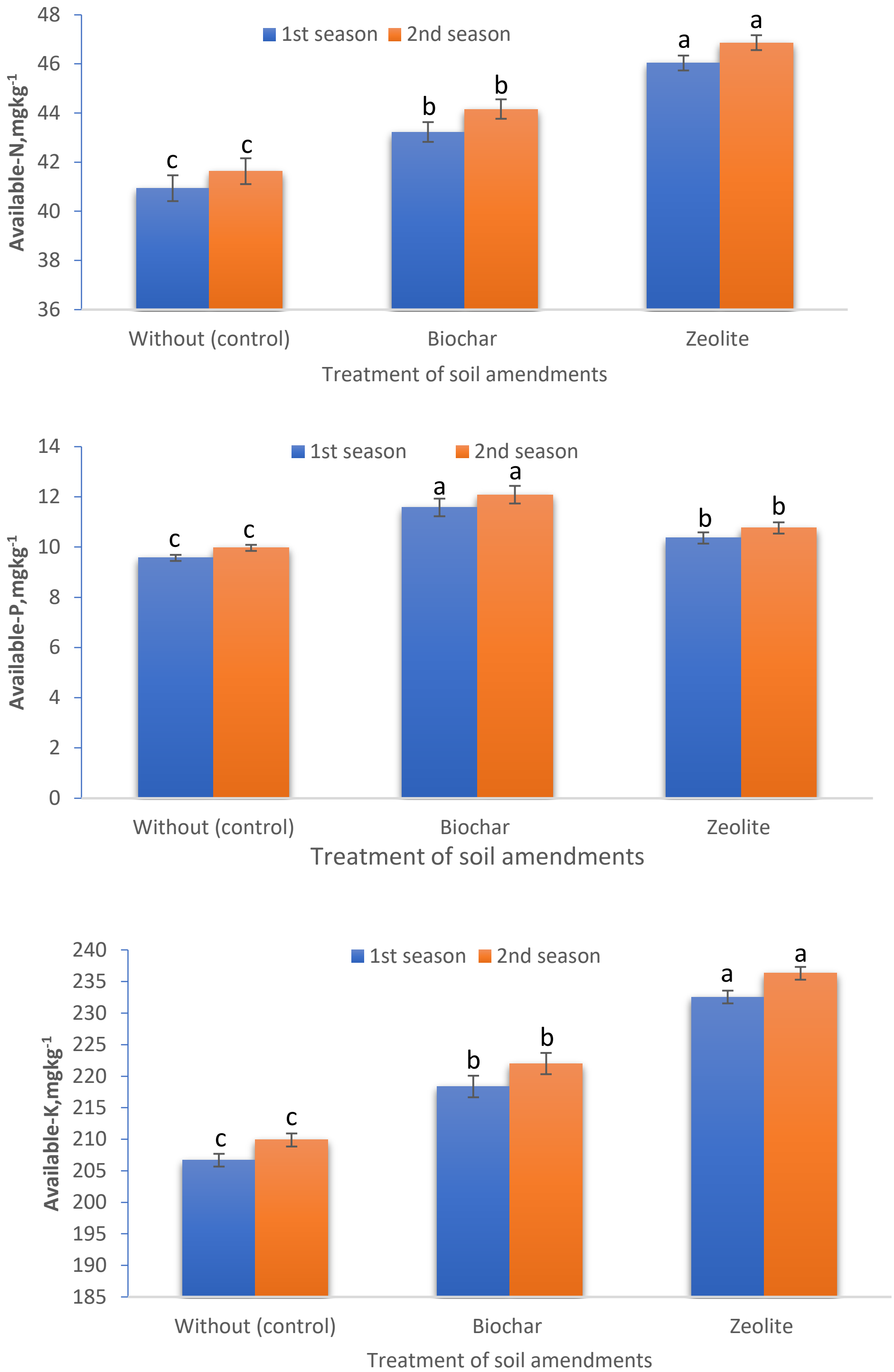

Fig. 2. Individual effect of the studied soil amendments on soil properties (available nitrogen, phosphorus and potassium) after harvest during seasons of 2022and 2023.

4. Discussion

The observed results in the growth criteria and relative water content of crisphead lettuce can be attributed to the intricate interplay of soil amendments, irrigation treatments, and foliar applications. The higher values of fresh and dry weights, leaf area, and relative water content under 100% irrigation (IR) conditions may be linked to the greater availability of water for the plants, fostering optimal growth. Zeolite, with its water retention capabilities, and biochar, known for improving soil structure and water retention, played pivotal roles in enhancing plant parameters **(Moshatati *et al.* 2019).** The superiority of zeolite over biochar in certain contexts can be attributed to their distinct properties and functions as soil amendments (**Bahador and Tadayon 2020**).

Zeolite has excellent water retention and release properties. It can absorb and hold onto water in its porous structure, releasing it gradually to the plant roots. This characteristic helps in maintaining soil moisture levels, especially under conditions of reduced irrigation, and ensures a more consistent water supply for plant uptake **(Cataldo *et al.* 2021).** Zeolite has a high Cation Exchange Capacity, allowing it to effectively exchange essential nutrients with the soil solution and make them available to plant roots. This enhances nutrient availability, promoting better nutrient uptake by plants. Zeolite has selective adsorption properties, meaning it can preferentially adsorb certain ions over others (**Salehi *et al.* 2021).** This selectivity can contribute to improved nutrient availability and reduced competition between nutrients, creating a more favorable environment for plant growth. Zeolite can help regulate soil pH by buffering against drastic changes. This is important for maintaining an optimal pH range for nutrient availability, as certain nutrients are more accessible to plants within specific pH levels. Zeolite can release essential micronutrients gradually, contributing to sustained micronutrient availability for plant uptake. This gradual release can prevent nutrient leaching and enhance nutrient use efficiency (**Ghazi *et al.* 2023).**

The superiority of biochar over the control group can be attributed to its multifaceted impact on soil properties and plant growth (**Haider *et al.* 2020).** Biochar enhances soil structure, water retention, and nutrient availability. Its porous structure provides a conducive environment for microbial activity and nutrient retention, promoting overall soil fertility (**Yang *et al.* 2020; Zaheer *et al.* 2020; Elsherpiny, 2023).** Moreover, the introduction of biochar into the soil contributes to improved water-holding capacity, reducing water stress on plants. The incorporation of biochar in the cultivation of crisphead lettuce under reduced irrigation conditions has likely facilitated better nutrient absorption, water utilization efficiency, and overall growth, resulting in superior plant performance compared to the control group, which lacked these beneficial soil amendments (**Elbasiouny *et al.* 2023; Singh *et al.* 2024).**

The combined application of arginine and melatonin further amplified their effects, highlighting their synergistic influence on plant performance, particularly under reduced irrigation levels. Melatonin and arginine play distinct roles in plant physiology, contributing to various aspects of growth, stress response, and overall health. Melatonin acts as a potent antioxidant in plants, helping to neutralize reactive oxygen species (ROS) and mitigate oxidative stress. It scavenges free radicals, protecting plant cells from damage caused by environmental stressors such as drought (**Sadak *et al.* 2020; Imran, *et al.* 2021; Elsherpiny and Helmy, 2022).** Arginine is a precursor for the synthesis of nitric oxide (NO) in plants. Nitric oxide is a signalling molecule involved in various physiological processes, including responses to abiotic and biotic stresses (**Silveira *et al.* 2021; Hussein *et al.* 2022)**. The consistent trend across both seasons underscores the reliability and efficacy of these interventions in promoting the growth performance of crisphead lettuce.

In the context of leaves' chemical constituents and photosynthetic pigments, the superior effects of 100% IR on nutrient content and pigment concentrations align with the well-established positive correlation between ample water availability and enhanced nutrient uptake. Zeolite and biochar, through their soil amendment effects, notably improved nutrient availability, with zeolite demonstrating superiority. The foliar application of arginine and melatonin, especially in combination, significantly enhanced chemical constituents and pigments, showcasing their positive impact on leaf physiology. The application of zeolite and biochar under reduced irrigation conditions further highlighted their role in mitigating the negative effects of water scarcity on nutrient uptake and pigment synthesis. This consistency across both seasons reinforces the potential of these interventions in sustaining optimal leaf health and function.

Enzymatic antioxidants exhibited variations influenced by soil amendments, foliar applications, and irrigation levels. The higher enzymatic antioxidant activity under 100% IR conditions aligns with the understanding that optimal water availability reduces oxidative stress on plants. Zeolite, with its soil-enhancing properties, particularly its impact on water retention, contributed to heightened enzymatic antioxidant activity. The combined treatment of arginine and melatonin exhibited the most significant impact, emphasizing the role of these foliar applications in bolstering the plant's defense mechanisms against oxidative stress. Under reduced irrigation conditions, the application of zeolite and biochar proved effective in enhancing enzymatic antioxidants, underscoring their potential in mitigating the oxidative stress associated with water scarcity. The consistency of these trends across both seasons reinforces the reliability of these interventions in enhancing the antioxidant defense system of crisphead lettuce.

The physical and quality traits of crisphead lettuce heads were notably influenced by irrigation levels, soil amendments, and foliar applications. Optimal irrigation at 100% IR led to superior head traits, emphasizing the critical role of water availability in head development. Zeolite and biochar played key roles in improving head traits, with zeolite exhibiting greater efficacy. The combined foliar application of arginine and melatonin emerged as the most influential, further enhancing head characteristics. Under reduced irrigation conditions, the application of zeolite and biochar proved effective in overcoming the limitations imposed by water scarcity, leading to significant improvements in head traits. This trend persisted across both seasons, reinforcing the robust impact of these interventions on the physical and quality aspects of crisphead lettuce heads.

The post-harvest soil analyses provide insights into the effects of the zeolite and biochar on soil properties, specifically available nitrogen, phosphorus, and potassium. Both zeolite and biochar positively influenced soil nutrient availability post-harvest. They contributed to higher levels of available nitrogen and potassium. Biochar resulted in the highest values of available phosphorus and this suggests that biochar may have a specific positive influence on phosphorus availability in the soil.

5. Conclusion

Finally, the study emphasizes the critical importance of tailored cultivation practices for crisphead lettuce, acknowledging its increasing significance in response to widespread consumption. The current research work revealed substantial insights into optimizing plant performance. Zeolite and biochar applications under 80% irrigation conditions emerged as key contributors to enhanced plant parameters, surpassing the control under 100% irrigation. Notably, the combined foliar treatment of arginine and melatonin demonstrated superior efficacy, showcasing maximum values across various growth parameters. Post-harvest soil fertility analysis indicated a significant improvement with zeolite followed by biochar. These findings underscore the dual benefits of zeolite and biochar as valuable soil amendments for maintaining or augmenting soil fertility after crisphead lettuce cultivation. In practical terms, incorporating zeolite or biochar under reduced irrigation levels and employing a combined foliar application of arginine and melatonin emerges as a promising strategy for optimizing plant growth and productivity in Egyptian conditions.

Conflicts of interest

The authors have declared that no competing interests exist.

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