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Interactive Effects of Agrivoltaic Shading, Irrigation, and Biofertilizers on the Chemical Composition of Lettuce Leaves (Lactuca sativa L.)

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Abstract. The agrivoltaic system is one of the most efficient approaches to sustainability, optimizing agricultural land for simultaneous food production and electricity generation. This technique decreases water usage by providing shade to soil and vegetation, therefore reducing evaporation and prolonging soil moisture retention relative to open-field farming. This study sought to examine the impact of shaded versus unshaded cultivation, irrigation levels (100% and 50%), and biofertilizer application on the concentration of chemical characteristics in plant leaves. The findings demonstrated that both shaded and unshaded cultivation markedly enhanced leaf concentrations of chlorophyll, and carbohydrates. Biofertilizer, consisting of a mixture of Trichoderma and mycorrhiza, markedly improved chlorophyll and carbohydrates levels in leaves. Nonetheless, irrigation levels exhibited no substantial impact on the leaf concentrations of flavonoids, nitrates, or carbs. The combination of shaded cultivation with biofertilizer led to substantial enhancements in chlorophyll, flavonoids, carbs, and nitrate levels. The combination of shaded cultivation and irrigation markedly increased the levels of chlorophyll, flavonoids, nitrates, and carbohydrates. Furthermore, the interaction between irrigation and biofertilizer demonstrated notable enhancements in chlorophyll and nitrate levels. Ultimately, the triple combination of shade, irrigation, and biofertilizer significantly influenced all examined parameters, resulting in elevated levels of chlorophyll, flavonoids, nitrates, and carbohydrates in leaf tissues.

Highlights:

1. Agrivoltaics optimize land, reducing evaporation and boosting soil moisture retention.
2. Shade and biofertilizer enhance chlorophyll, flavonoids, carbohydrates, and nitrate levels.
3. Combined shade, irrigation, and biofertilizer significantly improve all leaf chemical parameters..

Keywords: Agrivoltaic system, bio-fertilization, drip irrigation, deficit irrigation, chemical traits

Introduction

Lettuce (Lactuca sativa L.) is an extensively cultivated leafy vegetable for its low calorie and fat content. It flourishes in cool seasons, with ideal growth temperatures of

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23°C during the day and 7°C at night. Lettuce, owing to its perishable nature, requires fast cooling post-harvest. It is abundant in vital vitamins and pigments such as chlorophyll, although susceptible to nitrate buildup, which escalates with nitrogen and inversely correlates with carbohydrates (1; 2).

Agriculture constitutes the foundation of several economies, supplying sustenance for expanding people. Climatic conditions, however, substantially affect food production, resulting in imbalances within ecological systems. By 2050, accelerated population increase is anticipated to intensify food shortages, requiring sustainable agricultural methods to save the environment and improve food production (3; 4). Sustainable agricultural systems are resilient to environmental fluctuations and integrate methods that conserve natural resources, including soil, vegetation, and water. Methods such as drip irrigation and biofertilization have demonstrated efficacy in reducing water consumption (5; 6). Biofertilization diminishes dependence on chemical fertilizers, the overuse of which has negatively impacted soil and plant health. This method promotes plant growth, environmental resilience, and disease resistance while enhancing crop quality.

Biofertilizers enhance root absorption of critical nutrients, including nitrogen, phosphorous, salt, and potassium, crucial for optimal plant growth. Drip irrigation is another sustainable technique that provides water directly to the root zone via emitters positioned on or beneath the soil surface, maintaining optimal soil moisture without causing waterlogging. Agrivoltaic systems, arising in land-limited areas, combine solar panel installations with agricultural practices, facilitating the simultaneous generation of electricity and crops (10). These technologies reduce evaporation and transpiration, thereby chilling plants and preserving water resources (11).

This study presents wooden structures designed to resemble solar panels to assess their impact on lettuce growing and its chemical qualities, considering Iraq's challenges of inadequate electricity and little awareness of agrivoltaic systems.

Research Aims

1.The impacts of shaded versus unshaded cultivation, irrigation rates (100% and 50%) and bio fertilizers on the chemical characteristics of lettuce leaves. This is the first time this type of experiment done in Iraq and in the middle east except Turkey to use the land in the future for both agriculture and producing green energy

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Methods

Site of Experimentation

The experiment was carried out at the agriculture extension farm in Babylon Province, Iraq, during the autumn of 2023. The field was tilled and segmented into experimental plots (2m x 1m) beneath fake solar panels and a control area. The agrivoltaic systems were constructed on the extension farm using wood and were topped with blue plastic, preventing sunlight from reaching the soil. The specifications of the agrivoltaic systems were specified as 12m x 2.5m x 1.5m (length, breadth, and height) with an inclination of 30 degrees.

The composite soil samples were collected from four randomized locations at a depth of 30 cm and tested to ascertain their chemical and physical characteristics. The samples were air-dried, subsequently crushed, and sieved through a 2 mm mesh sieve. The soil samples were examined to ascertain their chemical and physical qualities, as presented in Table 1, while the meteorological data is displayed in Table 2. Bio-fertilizers consisting of a blend of Trichoderma and Mycorrhiza were applied twice throughout the growth season

Table 1. Chemical and Physical Properties of Field Soil.

pH	Ec (ds/m)	N (mg/kg)	P (mg/kg)	K (mg/kg)	Ca (meq/L)	Mg (meq/L)	Na (meq/L)	Hco^{-3} (meq/L)	Co^{3} (meq/L)	Cl (meq/L)
7.81	6.45	152.6	85.6	0.9	31.2	59	31.3	8.8	0	42.8

Organic matter (gm kg^{-1})	Black density (gm/cm^{3})	Soil Texture	Field capacity (%)	Wilting point (%)
0.56	1.3	Silty Clay Loam	40	21

Table 2. The weather data during growing season

Date	Ave. Temp. (C°)	Rainfall (mm)	Wind speed (m/sec)	Relative Humidity (%)
15/10-15/11	32	5.1	72.40	1.79
16/11- 15/12	20	51.1	56.91	1.29

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A drip irrigation system was installed before planting. The plants were planted in two rows within each plot, the distance between the rows is 30 cm, and 20 cm between individual plants within a row. The lettuce grown in the agrivoltaic system and control field (open area) were each broken into treatments, respectively. These treatments combined a fertilizer application level and an irrigation level. The plots are treated with biofertilizers at one of the two levels (0, 100%) and one of two levels of irrigation 100% and 50%. The experimental plots were divided into treatments and replicates and each treatment was replicated six times in both the shaded and control areas for a total of 24 plots in each. The biofertilizer was prepared at the Ministry of Science and Technology, Agricultural Research Department, and was carried on peat moss. The Trichoderma harizianum concentration was 10^9 C.F.U and mixed with Mycorrhiza mosess before being added to the plants using the compost tea drenching method. The biofertilizer was applied two times, the first was added one month after planting, and a second application was added two weeks after the first. The vegetative traits were taken from 10 plants for all the individual measurements

Result and Discussion

Chlorophyll Content in Leaves (mg/100 g Fresh Weight)

Table 3 indicates that the biofertilizer significantly influenced chlorophyll content in the leaves. The maximum reading was 15.65, recorded in samples subjected to the second fertilization level, whereas the minimum reading was 13.79, noted in samples treated with the first fertilization level. The light factor demonstrated a notable impact, with a maximum measurement of 16.39 for plants cultivated in shade, and a minimum measurement of 13.05 for plants produced in light. The irrigation factor significantly influenced chlorophyll content, with a maximum value of 15.57 recorded at 100% irrigation and a minimum of 13.87 at 50% irrigation.

The interaction between biofertilizer and light significantly influenced chlorophyll content. The maximum measurement was 17.93 in samples subjected to the second fertilization level and cultivated in shade, whereas the minimum measurement was 12.73 in samples subjected to the first fertilization level and cultivated in light. The interaction between biofertilizer and irrigation significantly influenced the results, with the maximum value recorded at 16.12 in samples subjected to the second fertilization level at 100%

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irrigation, and the minimum value at 11.52 in samples treated with the first fertilization level at 50% irrigation. The interplay between light and irrigation was notable, with a maximum measurement of 17.65 for shaded plants at 100% irrigation, and a minimum measurement of 12.51 for plants exposed to light at 50% irrigation.

The interaction among biofertilizer, light, and irrigation parameters significantly influenced chlorophyll content, with the highest measurement of 18.92 recorded in samples subjected to the second fertilization level, cultivated in shade, and watered at 100%. The minimum measurement of 11.52 was noted for samples subjected to the initial fertilization level, cultivated under light conditions, and irrigated at 50% capacity.

Table (3) The effect of shade cultivation, non-shade cultivation, irrigation factor, biofertilizer factor and their interactions on Chlorophyll (mg/g wet weight)

Treatment		F0	F1	S*I
S1	$I_{0.5}$	11.52	18.92	15.22
	I_1	18.18	16.94	17.65
S2	$I_{0.5}$	13.24	11.52	12.51
	I_1	13.94	11.53	13.59
LSD(0.05)		2.565		1.864
				S
S*F	S1	14.85	17.93	16.39
	S2	12.73	13.37	13.05
LSD(0.05)		1.919		2.225
F		13.79	15.65	
LSD(0.05)		1.519		
				I
F*1	$I_{0.5}$	11.52	16.12	13.87
	I_1	16.06	15.09	15.57
LSD(0.05)		1.85		1.481

Light factor= Shade(S1) ,light (S2)

Irrigation factor = I1 (100%),I2(50%)

Bio fertilizer factor= F0 (Control),F1 (With fertilizer)

Carbohydrate Content in Leaves (mg/g Dry Weight)

Table 4 shows that the biofertilizer factor had a significant effect on carbohydrate content in leaves. The highest value of 1.19 was recorded in samples treated with the

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first fertilization level, while the lowest value of 1.04 was observed in samples treated with the second fertilization level. The light factor also had a significant effect, with the highest reading of 1.32 observed in shaded plants and the lowest reading of 0.87 in light-exposed plants. However, the irrigation factor showed no significant effect on carbohydrate content.

The interaction between biofertilizer and light factors had a significant effect, with the highest value of 1.45 recorded for samples treated with the first fertilization level and grown under shade, while the lowest value of 0.82 was observed for samples treated with the second fertilization level and grown in light. The interaction between biofertilizer and irrigation factors showed no significant effect, whereas the interaction between light and irrigation factors was significant. The highest value of 1.36 was recorded in shaded plants irrigated at 50%, and the lowest value of 0.87 was observed in light-exposed plants irrigated at 50%.

The three-way interaction between biofertilizer, light, and irrigation factors had a significant effect, with the highest value of 1.50 observed in samples treated with the first fertilization level, grown under shade, and irrigated at 50%, while the lowest value of 0.80 was recorded in samples treated with the second fertilization level, grown in light, and irrigated at 50%.

Table (4) The effect of shade cultivation, non-shade cultivation, irrigation factor, biofertilizer factor and their interactions on Carbohydrates (mg.g-1)

Treatment		F0	F1	S*I
S1	$I_{0.5}$	1.50	1.21	1.36
	I_1	1.40	1.32	1.35
S2	$I_{0.5}$	0.94	0.80	0.87
	I_1	0.91	0.84	0.88
LSD(0.05)		0.29		0.35
				S
S*F	S1	1.45	1.26	1.32
	S2	0.92	0.82	0.87
LSD(0.05)		0.31		0.38
F		1.19	1.04	
LSD(0.05)		0.10		
				I
F*I	$I_{0.5}$	1.22	1.00	1.11

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	I_1	1.16	1.08	1.12
LSD(0.05)		N.S		N.S

Light factor= Shade(S1) ,light (S2)

Irrigation factor = I1 (100%),I2(50%)

Bio fertilizer factor= F0 (Control),F1 (With fertilizer)

Nitrate Content in Leaves (mg/kg Dry Weight)

Table 5 indicates that the biofertilizer variable exerted no significant influence on nitrate levels in leaves. Likewise, the irrigation variable did not have a substantial impact. The light factor significantly influenced nitrate content, with a maximum of 31.12 in light-exposed plants and a minimum of 29.98 in shaded plants.

The interaction between biofertilizer and light conditions was significant, with the maximum nitrate content of 31.14 recorded in samples subjected to the initial fertilization level and cultivated in light, whereas the minimum value of 29.68 was noted in samples treated with the same fertilization level and grown in shade. The interaction between biofertilizer and irrigation factors was significant, with a maximum value of 30.77 for samples subjected to the second fertilization level and irrigated at 100%, and a minimum value of 30.25 for samples treated with the first fertilization level and irrigated at 100%.

The interaction between light and irrigation variables significantly influenced nitrate levels, with a peak concentration of 31.18 detected in light-exposed plants irrigated at 50%, and a minimum of 29.97 noted in shaded plants irrigated at 100%. The tri interaction among biofertilizer, light, and irrigation variables exhibited a notable effect, with the maximum nitrate concentration of 31.23 observed in samples subjected to the initial fertilization level, cultivated in light, and irrigated at 50%. Conversely, the minimum value of 29.47 was noted in samples treated with the initial fertilization level, grown in shade, and irrigated at 100%.

Table (5) The effect of shade cultivation, non-shade cultivation, irrigation factor, biofertilizer factor and their interactions on nitrates (mg.kg-1)

Treatment		F0	F1	S*I
S1	$I_{0.5}$	29.90	30.10	30.00
	I_1	29.47	30.47	29.97
S2	$I_{0.5}$	31.23	31.12	31.18

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	I_1	31.04	31.08	31.06
LSD(0.05)		0.55		0.35
				S
S*F	S1	29.68	30.29	29.98
	S2	31.14	31.10	31.12
LSD(0.05)		0.37		0.33
F		30.41	30.69	
LSD(0.05)		N.S		
				I
F*I	$I_{0.5}$	30.57	30.61	30.59
	I_1	30.25	30.77	30.51
LSD(0.05)		0.41		N.S

Light factor= Shade(S1) ,light (S2)

Irrigation factor = I1 (100%),I2(50%)

Bio fertilizer factor= F0 (Control),F1 (With fertilizer)

Phenolic content of leaves (mg.kg-1 dry weight)

Here, no statistically significant impacts of biofertilizer, irrigation level, or shading were detected. Nor were any significant interactions among the treatments observed.

Table (6) The effect of shade cultivation, non-shade cultivation, irrigation factor, biofertilizer factor and their interactions on Phenolic (mg.kg-1 dry weight)

Treatment		F_0	F_1	S*I
S	$I_{0.5}$	1.58	1.75	1.67
	I_1	1.58	1.64	1.61
L	$I_{0.5}$	1.75	1.76	1.76
	I_1	1.72	1.75	1.74
L.S.D (0.05)		N.S		N.S
				S
S*F	S	1.58	1.69	1.64
	L	1.74	1.76	1.75
L.S.D (0.05)		N.S		N.S
F		1.66	1.73	
L.S.D (0.05)		N.S		
				I
F*I	$I_{0.5}$	1.67	1.76	1.71

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	I_1	1.65	1.70	1.67
L.S.D (0.05)			N.S	N.S

Light factor= Shade(S1) ,light (S2)

Irrigation factor = I1 (100%),I2(50%)

Bio fertilizer factor= F0 (Control),F1 (With fertilizer)

Flavonoid Content in Leaves (mg/kg Dry Weight)

Table 7 demonstrates that the biofertilizer did not have a significant effect on flavonoid content in leaves. Similarly, the irrigation and the light factor also showed no significant effect on flavonoid content. However, the interaction between biofertilizer and light factors had a significant impact, with the highest reading of 71.65 observed in samples treated with the second fertilization level and grown under shade, while the lowest reading of 70.43 was recorded in samples treated with the first fertilization level and grown under shade.

The interaction between biofertilizer and irrigation factors showed no significant effect. In contrast, the interaction between light and irrigation factors was significant, with the highest reading of 71.17 recorded for plants grown in light and irrigated at 100%, while the lowest reading of 70.33 was observed in plants grown in light and irrigated at 50%.

The three-way interaction between biofertilizer, light, and irrigation factors had a significant effect on flavonoid content, with the highest reading of 72.32 observed in samples treated with the second fertilization level, grown under shade, and irrigated at 100%, and the lowest reading of 69.84 observed in samples treated with the first fertilization level, grown under shade, and irrigated at 100%.

Table (7) The effect of shade cultivation, non-shade cultivation, irrigation factor, biofertilizer factor and their interactions on Flavonoids (mg.kg-1 dry weight)

Treatment		F0	F1	S*I
	$I_{0.5}$	71.02	70.97	71
S1	I_1	69.84	72.32	71.08
	$I_{0.5}$	70.4	70.27	70.33
S2	I_1	71.17	71.17	71.17

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LSD(0.05)		0.56		0.42
				S
S*F	S1	70.43	71.65	71.04
	S2	70.78	70.72	70.75
LSD(0.05)		1.16		N.S
F		70.61	71.18	
LSD(0.05)		N.S		
				I
F*I	$I_{0.5}$	70.71	70.62	70.66
	I_1	70.5	71.75	71.13
LSD(0.05)		N.S		N.S

Light factor= Shade(S1) ,light (S2)

Irrigation factor = I1 (100%),I2(50%)

Bio fertilizer factor= F0 (Control),F1 (With fertilizer)

Discussion

The use of light as led to a significant increase in chlorophyll content, as shown in Table (3). This finding aligns with the results of (12) and (13), who also reported a significant increase in chlorophyll content in lettuce leaves. However, (14) observed lower chlorophyll content in lettuce leaves. Table (5) shows significant increases, with the highest chlorophyll content recorded under light (31.237) and shade (31.477). These values are considered non-toxic according to European regulations, which state a toxicity threshold of 5000 mg/kg for nitrates. Thus, the nitrate levels in lettuce leaves remain low despite their significance. This contrasts with (15), who reported toxic nitrate levels (5862 mg/kg) in lettuce cultivation (15; 16; 17).

(18) found reduced carbohydrate levels in orchids due to shading stress, which inhibited photosynthesis. However, this study (Table 4) found significant increases in carbohydrate content in leaves grown under shade, exceeding those in light-grown plants. Similarly, (19) observed reduced carbohydrates in shaded cotton plants due to decreased photosynthetic rates.

Chlorophyll and Carbohydrate Observations

Tables (3, 4) indicate significant increases due to the application of biofertilizers comprising a mix of Trichoderma and mycorrhiza fungi. The increase is attributed to mycorrhiza fungi enhancing vegetative growth, thus accumulating carbohydrates.

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Mycorrhiza fungi facilitate the production of enzymes, acids, and nutrients (N, P, K, Ca, Mg, Fe, Zn), improving carbohydrate accumulation (20; 21). Trichoderma fungi contribute by promoting strong vegetative growth through growth regulator production and transforming organic soil materials into simpler forms, enhancing nutrient availability and plant tissue accumulation, ultimately increasing chlorophyll and carbohydrate levels (22; 24; 25).

The chlorophyll data in Table (3) reveal a significant increase with irrigation at two levels (100% and 50%), with a slight advantage at 100%. This advantage is likely because reduced water decreases leaf area, affecting photosynthesis. Additionally, 50% irrigation induces drought stress in leaves, inhibiting new chloroplast formation. Moreover, reduced irrigation impairs root nitrogen uptake, an essential component of porphyrin, the main component of chlorophyll (23; 26).

Non-significant Effects

Tables (3, 4, 5) indicate no significant effects of irrigation at either 100% or 50% levels on other variables, except for chlorophyll, where 50% irrigation had a lesser significant effect than 100%.

Conclusion

the light significantly affected the chemical composition of leaves without reaching toxic levels. Shade-grown plants showed better results for carbohydrates, chlorophyll, and nitrates than light-grown ones. Meanwhile, irrigation at 50% had no significant impact except for chlorophyll, where 100% irrigation proved superior. The use of biofertilizers enhanced carbohydrate content in plant leaves, contributing to higher nutritional value.

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