Influence of Agrivoltaic Systems on Growth, Yield, and Bioactive Compounds of Arugula (Eruca sativa Mill.)

Nihad Kadhim Karim Mohammed R. Sahib Hadi A. AL-Agele
1E-mail: nihad.kadum@agre.uoqasim.edu.iq
2E-mail: mohammad.radhi@agre.uoqasim.edu.iq
3E-mail: hadi.abdulameer@agre.uoqasim.edu.iq
3-1Department of Horticulture, College of Agriculture, University of Al-Qasim Green, Iraq.

Abstract

This experiment was conducted during the 2025–2026 fall season in a field belonging to Al-Mustaqbal University, Babil Governorate, Iraq (44.4° E longitude, 32.3° N latitude). The study aimed to evaluate the effects of cultivation under shading compared with cultivation in open, unshaded areas, of two irrigation levels (50% and 100%), and of biofertilizer and organic fertilizer application on the growth and yield of arugula (Eruca sativa) plants and on the content of bioactive compounds in its leaves. The experiment was arranged in a split-split-plot layout (3 × 2 × 3) within a randomized complete block design (RCBD), with three replicates. The study included three factors: first, the fertilization factor (F), comprising three levels — F0 (control, no fertilizer applied), F1 (biofertilizer, Bio Health, applied at 200 mL per plant), and F2 (organic fertilizer, vermicompost, applied at 5 g per plant); second, the irrigation factor (I), comprising full irrigation (100%) and deficit irrigation (50%); and third, the shading factor (L), comprising full light/open exposure (L1), full shade beneath photovoltaic solar panels (L2), and partial shade beneath solar panels (L3). The results showed that the full-light treatment (L1) had a significant effect on net photosynthetic rate, which reached 0.869 $g \cdot m^{-2} \cdot day^{-1}$, and on flavonoid content, which reached 0.148 $mg \cdot kg^{-1}$. In contrast, the full-shade treatment (L2) was superior in experimental-unit leaf yield at the second cutting, reaching 884 g / 1.2 m^2, and in leaf nitrate content, reaching 32.73 $mg \cdot kg^{-1}$ dry weight. Irrigation level had a significant effect on phosphorus content only, with the full-irrigation treatment (100%) producing the highest value, 0.397%. The fertilization factor had a significant effect on experimental-unit leaf yield at the second cutting, as well as on nitrogen and potassium percentages and leaf phenolic content, reaching 1041 g /1.2 m^2, 3.010%, 0.343%, and 30.92 $mg \cdot g^{-1}$ dry weight, respectively. The results of the triple interaction among the three factors showed significant superiority in all studied traits.

Keywords: Agrivoltaics, Arugula, Shading, Vegetative growth, Yield, Nutrients, Bioactive compounds

Introduction

The climate crisis has created a growing need to shift from reliance on fossil fuels toward clean and renewable energy sources. At the same time, population growth and soil degradation have increased the demand for new agricultural land, and the rising demand for food and clean energy has led to competition between agricultural land and solar power stations for land use (8). To reduce this competition, agrivoltaic systems

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have emerged as an integrative solution that combines electricity generation with agricultural production, achieving dual land use, increasing productivity per unit area, improving land-use efficiency, mitigating the effects of climate change, conserving water resources, and producing clean energy (30).

Studies have shown that the shading produced by solar panels in agrivoltaic systems reduces evaporation rates, which helps conserve soil moisture and enhances water-use efficiency by limiting evaporative water loss. In addition, agrivoltaic (APV) systems help ease pressure on water resources, particularly in arid and semi-arid regions (2). Integrating this system with sensor-based smart irrigation technologies has also contributed significantly to applying irrigation only when the plant actually needs it, thereby reducing water waste and improving water-resource use. This system further enables autonomous operation in areas with limited infrastructure or those far from urban centers, while allowing real-time management and monitoring through Internet of Things (IoT) technologies, making it an advanced solution for irrigation systems in the modern agricultural sector (1).

On the other hand, there is growing interest in using biofertilizers as an alternative or supplement to chemical fertilizers, given their major role in increasing crop productivity and long-term soil fertility, making them essential for meeting the growing global demand for food. These microorganisms can coexist with plants and supply them with the nitrogen, phosphorus, zinc, and other essential nutrients needed for growth; they are also environmentally friendly and more affordable compared with chemical fertilizers, which are environmentally harmful and costly (23). The integration of agrivoltaics, smart irrigation, and biofertilizers represents a promising approach for enhancing agricultural production efficiency while reducing environmental impact.

Arugula (*Eruca sativa* Mill.) is an ideal model for studying these strategies, being a fast-growing leafy crop rich in biologically active compounds such as glucosinolates and phenolics, and possessing high nutritional value (26,3). Studies have shown that the accumulation of these compounds varies with cultivation systems and growing conditions, such as partial shading, irrigation management, and fertilization type (18,7). Arugula is also sensitive to water and heat stress, which makes it suitable for evaluating the effect of these factors on its growth and productivity within a sustainable agriculture framework.

Study objectives:

1.The effect of cultivation under shading compared with cultivation in the open field

2.The effect of irrigation level (100% and 50%) of water requirement

3.The effect of adding biofertilizers and organic fertilizers

4.The interactive effects among shading, irrigation regimes, and fertilization on vegetative traits, chemical content, and bioactive compounds

2. Materials and Methods

2.1 Site Description and Preparation

The field study was conducted in an agrivoltaic system located in Babil Governorate, Iraq. The land was plowed, leveled, and divided into experimental plots of 6 m² (3 m length × 2 m width),

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distributed beneath the solar panels, between the solar panels, and outside the panels (control), as shown in Figure 1.

The agrivoltaic system at the experimental site was designed using three monocrystalline bifacial solar panels, model M144-(HCBF)-550W. Each panel measured 2277 mm in length × 1133 mm in width × 35 mm in thickness, with a surface area of 2.58 m² per panel. The panels were mounted on metal frames elevated above the soil surface, specifically designed to allow agricultural operations and crop growth beneath the panels without obstruction. The panels were arranged in parallel rows oriented southwest, tilted at an angle of 30° from the horizontal. The total height of the structure from the soil surface to the top of the panel was 3 m, while the height of the lower edge of the panel above the soil surface was 1.5 m. Each panel covered an area of 6 m² (3 m length × 2 m width), with a 3 m spacing left between rows of panels to achieve a balance between the amount of shade and light needed for crop growth, as shown in Figure 1.



Figure 1. Rocket growth in three different locations (shade, partial shade, and open area)

Each experimental unit contained six drip-irrigation lines: three lines for full irrigation and three for deficit irrigation. The spacing between lines was 0.50 m, the spacing between emitters within each line was 0.10 m, and the discharge rate of each emitter was 2.5 L/hour.

Arugula seeds (Egyptian cultivar) were sown on 26 October 2025 at a seeding rate of 9.5 kg/ha^{-1} (11), with 6 rows per experimental unit corresponding to the drip-irrigation lines. The experiment was carried out according to the adopted experimental design with three replicates per treatment, comprising three shading levels beneath the solar panels, between the solar panels, and the control area (open field) in addition to two irrigation levels and the fertilization treatments.

The shading treatments resulting from the agrivoltaic system were classified into three categories: treatments located beneath the solar panels, which received the highest level of shading and are denoted (S); treatments located between the solar panels, which received partial shading and are denoted (B); and the control treatment located outside the agrivoltaic system, which received full sunlight and is denoted (L).

Two irrigation levels were applied: full irrigation and deficit irrigation, with the irrigation schedule based on the allowable moisture depletion method. In the full-irrigation treatments, irrigation was applied when the volumetric moisture content dropped to 25% of field capacity, whereas in the deficit-irrigation treatments it was applied when the volumetric moisture content dropped to 12.5% of field capacity. For fertilization, the biofertilizer (Biohealth)

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was applied at a rate of 200 mL per plant one month after planting, while the organic fertilizer (Vermicompost) was applied at a rate of 5 g per plant.

2.2 Studied Traits

2.2.1 Yield of the experimental unit from leaves for the two cuts (g/1.2 m²)

Plants were cut at the soil surface for each experimental unit and weighed directly in the field.

2.2.2 Net Assimilation Rate (NAR)

The net assimilation rate (NAR) was calculated according to the equation described by (28):

$$NAR = [(W2 - W1) / (T2 - T1)] \times [(\ln A2 - \ln A1) / (A2 - A1)]$$

Where:

W: dry weight of the plant at the first (T1) and second (T2) times; A1: leaf area at time one (T1); A2: leaf area at time two (T2); ln A: natural logarithm of leaf area.

T2 − T1: the time interval between the two cuts (days).

2.2.3 Nitrogen percentage (%)

Total nitrogen percentage was determined using the Micro-Kjeldahl apparatus according to (25).

2.2.4 Phosphorus percentage (%)

Phosphorus percentage was determined using ammonium molybdate and ammonium vanadate; after the yellow color developed, the color intensity of the solution was measured with a spectrophotometer at a wavelength of 430 nm, following the method of (24).

2.2.5 Potassium percentage (%)

Potassium was determined using a flame photometer, following the method proposed by (13).

2.2.6 Leaf total phenolic content (mg·g⁻¹ dry weight)

Total leaf phenolic content was determined using the method of (17): 0.5 mL of the previously prepared extract for each treatment was placed in a test tube, followed by the addition of 3 mL of Folin–Ciocalteu reagent (0.1 concentration), after which 2.5 mL of 0.2% (w/v) sodium carbonate ($Na_2 CO_3$) was added. The mixture was mixed thoroughly and left for three minutes at room temperature, after which absorbance was read using a spectrophotometer at a wavelength of 750 nm.

2.2.7 Leaf total flavonoid content (mg·kg⁻¹ dry weight)

Total leaf flavonoid content was determined according to the method of (17): 0.5 mL of the previously prepared extract was placed in a test tube, 2.5 mL of ethanol was added, and the mixture was thoroughly mixed; 3 mL of 0.01 mol/L aluminum chloride ($AlCl_3$) was then added. The test tubes were left for 10 minutes at room temperature, after which absorbance was read using a spectrophotometer at a wavelength of 400 nm.

2.2.8 Leaf nitrate content (mg·kg⁻¹ dry weight)

Nitrate content was measured according to the method described by (5) using a spectrophotometer at a wavelength of 410 nm.

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2.3 Statistical Analysis

The study was conducted as a factorial experiment using a Randomized Complete Block Design (RCBD), and means were compared using the Least Significant Difference (LSD) test at the 5% probability level.

3. Results and Discussion

3.1 Vegetative Growth and Yield Indicators

3.1.1 Yield of the experimental unit from leaves of the second cut (g/1.2 m²)

The results in Table 1 indicate significant differences among the shading treatments in the yield of the experimental unit from the leaves of the second cut, as the shaded treatment recorded the highest average of 884 g/1.2 m², while the treatment outside the shade recorded the lowest average of 529 g/1.2 m². No significant differences were found between the irrigation periods. The fertilization treatments showed significant superiority, as the biofertilizer treatment (F1) achieved the highest average of 1041 g/1.2 m² compared with the control treatment, which gave the lowest average of 366 g/1.2 m².

The dual interaction between shading treatments and irrigation periods showed significant superiority in the yield of the experimental unit from the leaves of the second cut, as the interaction L2×I1 recorded the highest average of 1074 g/1.2 m², while the interaction L1×I1 gave the lowest average of 489 g/1.2 m². The dual interaction between shading treatments and fertilization treatments also showed significant superiority, as the interaction 1

Table 1. Effect of shading, irrigation periods, fertilization treatments, and their interactions on the yield of the experimental unit from leaves of the second cut (g/1.2 m²)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (Control)	I (Irrigation)	L (Shading)
489	541	686	241	I1 (Full irrigation)	**L1 (Light)**
569	668	769	269	I0.5 (Deficit irrigation)	
1074	880	1887	456	I1 (Full irrigation)	**L2 (Shade)**
695	749	924	411	I0.5 (Deficit irrigation)	
649	662	912	372	I1 (Full irrigation)	**L3 (Half-shade)**
795	868	1070	448	I0.5 (Deficit irrigation)	
207.9	340.6			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
529	604	727	255	**L1**	
884	814	1406	433	**L2**	

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722	765	991	410	**L3**
174.8	241.4			**L.S.D. 0.05**
I Mean	**I×F**			**I**
737	694	1161	356	**I1**
686	762	921	376	**I0.5**
N.S	201.1			**L.S.D. 0.05**
	728	1041	366	**F**
	143.8			**L.S.D. 0.05**

3.1.2 Net assimilation rate ($g \cdot m^{-2} \cdot day^{-1}$)

The results in Table 2 show a significant effect of the shading treatments on the net assimilation rate, as the treatment outside the shade recorded the highest value of 0.869 $g \cdot m^{-2} \cdot day^{-1}$, while the shaded treatment gave the lowest value of 0.495 $g \cdot m^{-2} \cdot day^{-1}$. No significant differences were found between the irrigation periods. The fertilization treatments showed no significant superiority, as F0 achieved the highest value of 0.772 $g \cdot m^{-2} \cdot day^{-1}$ compared with the organic-fertilizer treatment (F2), which recorded 0.663 $g \cdot m^{-2} \cdot day^{-1}$.

The dual interaction between shading treatments and irrigation periods produced significant differences in the net assimilation rate, as the interaction L1×I1 achieved the highest value of 1.085 $g \cdot m^{-2} \cdot day^{-1}$ compared with the interaction L3×I1, which recorded the lowest value of 0.474 $g \cdot m^{-2} \cdot day^{-1}$. The dual interaction between shading treatments and fertilizer type also showed significant superiority, as the interaction L1×F2 achieved the highest value of 0.963 $g \cdot m^{-2} \cdot day^{-1}$ compared with the interaction L2×F1, which recorded the lowest value of 0.328 $g \cdot m^{-2} \cdot day^{-1}$. The dual interaction between irrigation periods and fertilization treatments produced significant differences, as the interaction I0.5×F0 achieved the highest value of 0.842 $g \cdot m^{-2} \cdot day^{-1}$ compared with the interaction I0.5×F1, which recorded the lowest value of 0.423 $g \cdot m^{-2} \cdot day^{-1}$.

The results of the triple interaction among shading treatments, irrigation periods, and fertilization treatments showed significant differences, as the interaction L1×I1×F1 achieved the highest value of 1.174 $g \cdot m^{-2} \cdot day^{-1}$ compared with the interaction L2×I0.5×F1, which recorded the lowest value of 0.307 $g \cdot m^{-2} \cdot day^{-1}$.

Table 2. Effect of shading, irrigation periods, fertilization treatments, and their interactions on the net assimilation rate ($g \cdot m^{-2} \cdot day^{-1}$)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (Control)	I (Irrigation)	L (Shading)
1.085	1.16	1.174	0.92	I1 (Full irrigation)	**L1 (Light)**
0.654	0.767	0.382	0.813	I0.5 (Deficit irrigation)	
0.5	0.542	0.348	0.611	I1 (Full irrigation)	**L2 (Shade)**

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0.49	0.601	0.307	0.562	I0.5 (Deficit irrigation)	
0.474	0.474	0.372	0.576	I1 (Full irrigation)	**L3 (Half-shade)**
0.723	0.436	0.581	1.152	I0.5 (Deficit irrigation)	
0.223	0.34			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
0.869	0.963	0.778	0.867	**L1**	
0.495	0.572	0.328	0.587	**L2**	
0.599	0.455	0.447	0.864	**L3**	
0.182	0.239			**L.S.D. 0.05**	
I Mean	**I×F**			**I**	
0.686	0.725	0.631	0.702	**I1**	
0.622	0.601	0.423	0.842	**I0.5**	
N.S	0.204			**L.S.D. 0.05**	
	0.663	0.527	0.772	**F**	
	0.138			**L.S.D. 0.05**	

3.2 Chemical Indicators

3.2.1 Leaf nitrogen percentage (%)

The results in Table 3 show no significant effect of the shading treatments or irrigation periods on leaf nitrogen percentage. The fertilization treatments, however, showed significant differences in nitrogen percentage, as the biofertilizer treatment (F1) achieved the highest nitrogen percentage of 3.010%, compared with the control treatment, which recorded the lowest nitrogen percentage of 1.528%.

The dual interaction between shading treatments and irrigation periods showed no significant effect on nitrogen percentage. The dual interaction between shading treatments and fertilization treatments, however, showed significant superiority, as the interaction L1×F1 achieved the highest nitrogen percentage of 3.189% compared with the interaction L2×F0, which gave the lowest nitrogen percentage of 1.272%. The dual interaction between irrigation periods and fertilization treatments also showed significant differences, as the interaction I1×F1 recorded the highest nitrogen percentage of 3.189% compared with the interaction I1×F0, which gave the lowest nitrogen percentage of 1.517%.

The same table shows that the triple interaction among shading treatments, irrigation periods, and fertilization treatments produced significant differences in leaf nitrogen percentage, as the interactions L1×I1×F1 and L1×I0.5×F1 achieved the highest nitrogen percentage of 3.290%, with no significant difference between them, compared with the interaction L2×I1×F0, which recorded the lowest nitrogen percentage of 1.027%.

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Table 3. Effect of shading, irrigation periods, fertilization treatments, and their interactions on leaf nitrogen percentage (%)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (No fertilizer)	I (Irrigation)	L (Shading)
2.489	2.403	3.29	1.773	I1 (Full irrigation)	**L1 (Light)**
2.528	2.777	3.29	1.517	I0.5 (Deficit irrigation)	
2.209	2.427	3.173	1.027	I1 (Full irrigation)	**L2 (Shade)**
2.294	2.567	2.8	1.517	I0.5 (Deficit irrigation)	
2.504	2.66	3.103	1.75	I1 (Full irrigation)	**L3 (Half-shade)**
2.147	2.45	2.403	1.587	I0.5 (Deficit irrigation)	
N.S	0.59			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
2.508	2.59	3.29	1.645	**L1**	
2.252	2.497	2.987	1.272	**L2**	
2.326	2.555	2.753	1.668	**L3**	
N.S	0.446			**L.S.D. 0.05**	
I Mean	**I×F**			**I**	
2.401	2.497	3.189	1.517	**I1**	
2.323	2.598	2.831	1.54	**I0.5**	
N.S	0.343			**L.S.D. 0.05**	
	2.547	3.01	1.528	**F**	
	0.203			**L.S.D. 0.05**	

3.2.2 Phosphorus percentage (%)

The results in Table 4 show no significant differences among the shading treatments (L) in phosphorus percentage. Irrigation periods, however, produced significant differences in the same trait, as the full-irrigation treatment (I1) achieved the highest phosphorus percentage of 0.397%, compared with the deficit-irrigation treatment, which gave the lowest phosphorus percentage of 0.352%. The fertilization treatments also showed significant superiority, as the control treatment (F0) achieved the highest phosphorus percentage of 0.393%, compared with the organic-fertilizer treatment (F2), which recorded the lowest phosphorus percentage of 0.343%.

The dual interaction between shading treatments and irrigation periods, as well as between shading treatments and fertilizer types, showed no significant differences in phosphorus percentage. The dual interaction between irrigation periods and fertilization treatments, however, produced significant differences, as the interaction I1×F1 achieved the highest phosphorus percentage of 0.428% compared with the interaction I0.5×F2, which recorded the lowest phosphorus percentage of 0.323%.

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The same table shows that the triple interaction among shading treatments, irrigation periods, and fertilization treatments produced significant superiority in phosphorus percentage, as the interaction L2×I1×F1 achieved the highest phosphorus percentage of 0.477% compared with the interaction L1×I0.5×F1, which recorded the lowest phosphorus percentage of 0.261%.

Table 4. Effect of shading, irrigation periods, fertilization treatments, and their interactions on leaf phosphorus percentage (%)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (Control)	I (Irrigation)	L (Shading)
0.348	0.353	0.355	0.336	I1 (Full irrigation)	**L1 (Light)**
0.296	0.271	0.261	0.355	I0.5 (Deficit irrigation)	
0.421	0.356	0.477	0.431	I1 (Full irrigation)	**L2 (Shade)**
0.42	0.39	0.437	0.434	I0.5 (Deficit irrigation)	
0.421	0.384	0.454	0.426	I1 (Full irrigation)	**L3 (Half-shade)**
0.339	0.306	0.334	0.378	I0.5 (Deficit irrigation)	
N.S	0.174			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
0.322	0.312	0.308	0.345	**L1**	
0.421	0.373	0.457	0.432	**L2**	
0.38	0.345	0.394	0.402	**L3**	
N.S	N.S			**L.S.D. 0.05**	
I Mean	**I×F**			**I**	
0.397	0.364	0.428	0.398	**I1**	
0.352	0.323	0.344	0.389	**I0.5**	
0.043	0.077			**L.S.D. 0.05**	
	0.343	0.386	0.393	**F**	
	0.059			**L.S.D. 0.05**	

3.2.3 Potassium percentage (%)

The results in Table 5 show no significant effect of the shading treatments or the irrigation periods on leaf potassium percentage. The fertilization treatments, however, showed significant differences in leaf potassium percentage, as the organic-fertilizer treatment (F2) achieved the highest potassium percentage of 0.343%, compared with the control treatment, which recorded the lowest potassium percentage of 0.291%.

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The dual interaction between shading treatments and irrigation periods (L×I), as well as the interaction between shading treatments and fertilizer type (L×F), showed no significant effect on leaf potassium percentage. The dual interaction between irrigation periods and fertilization treatments (I×F), however, produced significant differences, as the interaction I1×F2 achieved the highest potassium percentage of 0.347% compared with the interaction I0.5×F0, which recorded the lowest potassium percentage of 0.264%.

The same table shows that the triple interaction among shading treatments, irrigation periods, and fertilization treatments produced significant superiority in potassium percentage, as the interaction L2×I1×F2 achieved the highest potassium percentage of 0.426% compared with the interaction L3×I0.5×F1, which recorded the lowest potassium percentage of 0.233%.

Table 5. Effect of shading, irrigation periods, fertilization treatments, and their interactions on leaf potassium percentage (%)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (Control)	I (Irrigation)	L (Shading)
0.348	0.353	0.355	0.336	I1 (Full irrigation)	**L1 (Light)**
0.296	0.271	0.261	0.355	I0.5 (Deficit irrigation)	
0.421	0.356	0.477	0.431	I1 (Full irrigation)	**L2 (Shade)**
0.42	0.39	0.437	0.434	I0.5 (Deficit irrigation)	
0.421	0.384	0.454	0.426	I1 (Full irrigation)	**L3 (Half-shade)**
0.339	0.306	0.334	0.378	I0.5 (Deficit irrigation)	
N.S	0.174			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
0.322	0.312	0.308	0.345	**L1**	
0.421	0.373	0.457	0.432	**L2**	
0.38	0.345	0.394	0.402	**L3**	
N.S	N.S			**L.S.D. 0.05**	
I Mean	**I×F**			**I**	
0.397	0.364	0.428	0.398	**I1**	
0.352	0.323	0.344	0.389	**I0.5**	
0.043	0.077			**L.S.D. 0.05**	
	0.343	0.386	0.393	**F**	
	0.059			**L.S.D. 0.05**	

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3.3 Leaf Content of Some Bioactive Compounds

3.3.1 Leaf total phenolic content (mg·g⁻ ¹ dry weight)

The results in Table 6 show no significant effect of the shading treatments or the irrigation periods on leaf total phenolic content. The fertilization treatments, however, showed a significant effect on leaf total phenolic content, as the organic fertilizer (F2) was superior, giving the highest value of 30.92 mg·g⁻ ¹ dry weight, compared with the control treatment, which gave the lowest value of 28.67 mg·g⁻ ¹ dry weight.

The dual interaction between shading treatments and irrigation periods showed no significant effect on leaf total phenolic content. The dual interaction between shading treatments and fertilization treatments, however, produced significant differences, as the interaction L2×F2 achieved the highest value of 32.91 mg·g⁻ ¹ dry weight compared with the interaction L2×F0, which recorded the lowest value of 27.35 mg·g⁻ ¹ dry weight. The dual interaction between irrigation periods and fertilization treatments also produced significant differences, as the interaction I1×F2 achieved the highest value of 31.78 mg·g⁻ ¹ dry weight, while the interaction I1×F0 recorded the lowest value of 28.54 mg·g⁻ ¹ dry weight.

The same table shows that the triple interaction among shading treatments, irrigation periods, and fertilization treatments produced significant differences in leaf total phenolic content, as the interaction L2×I1×F2 achieved the highest value of 34.68 mg·g⁻ ¹ dry weight, compared with the interaction L2×I1×F0, which recorded the lowest value of 26.21 mg·g⁻ ¹ dry weight.

Table 6. Effect of shading, irrigation periods, fertilization treatments, and their interactions on leaf total phenolic content (mg·g⁻ ¹ dry weight)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (Control)	I (Irrigation)	L (Shading)
30.35	31.83	30.34	28.89	I1 (Full irrigation)	**L1 (Light)**
29.85	29.93	30.47	29.16	I0.5 (Deficit irrigation)	
31.15	34.68	32.55	26.21	I1 (Full irrigation)	**L2 (Shade)**
29.02	31.15	27.44	28.48	I0.5 (Deficit irrigation)	
30.17	28.84	31.15	30.52	I1 (Full irrigation)	**L3 (Half-shade)**
29.39	29.11	30.29	28.75	I0.5 (Deficit irrigation)	
N.S	4.804			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
30.1	30.88	30.4	29.02	**L1**	
30.09	32.91	29.99	27.35	**L2**	

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29.78	28.98	30.72	29.63	**L3**
N.S	3.59			**L.S.D. 0.05**
I Mean	**I×F**			**I**
30.56	31.78	31.35	28.54	**I1**
29.42	30.06	29.4	28.8	**I0.5**
N.S	2.662			**L.S.D. 0.05**
	30.92	30.37	28.67	**F**
	2.11			**L.S.D. 0.05**

3.3.2 Leaf total flavonoid content (mg·kg⁻ ¹ dry weight)

The results in Table 7 show significant differences among the shading treatments in leaf total flavonoid content, as the treatment outside the shade recorded the highest value of 0.148 mg·kg⁻ ¹ dry weight, while the shaded treatment gave the lowest value of 0.089 mg·kg⁻ ¹ dry weight. No significant differences were found between the irrigation periods or among the fertilization treatments in leaf total flavonoid content.

The dual interaction between shading treatments and irrigation periods showed significant differences in leaf total flavonoid content, as the interaction L1×I0.5 achieved the highest value of 0.158 mg·kg⁻ ¹ dry weight compared with the interaction L2×I0.5, which recorded the lowest value of 0.043 mg·kg⁻ ¹ dry weight. The dual interaction between shading treatments and fertilization treatments also produced significant differences in leaf total flavonoid content, as the interaction L1×F0 achieved the highest value of 0.164 mg·kg⁻ ¹ dry weight compared with the interaction L2×F1, which recorded the lowest value of 0.069 mg·kg⁻ ¹ dry weight. The dual interaction between irrigation periods and fertilization treatments showed no significant differences in leaf total flavonoid content.

The same table shows that the triple interaction among shading treatments, irrigation periods, and fertilization treatments produced significant differences in leaf total flavonoid content, as the interaction L3×I0.5×F1 achieved the highest value of 0.240 mg·kg⁻ ¹ dry weight, while the interaction L2×I0.5×F0 gave the lowest value of 0.040 mg·kg⁻ ¹ dry weight.

Table 7. Effect of shading, irrigation periods, fertilization treatments, and their interactions on leaf total flavonoid content (mg·kg⁻ ¹ dry weight)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (No fertilizer)	I (Irrigation)	L (Shading)
0.138	0.114	0.142	0.16	I1 (Full irrigation)	**L1 (Light)**
0.158	0.127	0.176	0.169	I0.5 (Deficit irrigation)	
0.135	0.133	0.092	0.18	I1 (Full irrigation)	**L2 (Shade)**
0.043	0.041	0.047	0.04	I0.5 (Deficit irrigation)	
0.094	0.148	0.085	0.049	I1 (Full irrigation)	**L3 (Half-shade)**

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0.155	0.115	0.24	0.11	I0.5 (Deficit irrigation)	
0.071	0.136			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
0.148	0.121	0.159	0.164	**L1**	
0.089	0.087	0.069	0.11	**L2**	
0.125	0.132	0.163	0.08	**L3**	
0.053	0.093			**L.S.D. 0.05**	
I Mean	**I×F**			**I**	
29.42	30.06	29.4	28.8	**I1**	
30.56	31.78	31.35	28.54	**I0.5**	
N.S	N.S			**L.S.D. 0.05**	
	0.113	0.13	0.118	**F**	
	N.S			**L.S.D. 0.05**	

3.3.3 Leaf nitrate content (mg·kg⁻ ¹ dry weight)

The results in Table 8 show significant differences among the shading treatments in leaf nitrate content, as the shaded treatment recorded the highest value of 32.73 mg·kg⁻ ¹ dry weight, while the treatment outside the shade gave the lowest value of 23.90 mg·kg⁻ ¹ dry weight. No significant differences were found between the irrigation periods or among the fertilization treatments in leaf nitrate content.

The dual interaction between shading treatments and irrigation periods showed significant superiority, as the interaction L2×I0.5 achieved the highest value of 34.64 mg·kg⁻ ¹ dry weight compared with the interaction L1×I1, which recorded the lowest value of 23.63 mg·kg⁻ ¹ dry weight. The dual interaction between shading treatments and fertilization treatments also produced significant differences in leaf nitrate content, as the interaction L2×F0 recorded the highest value of 35.00 mg·kg⁻ ¹ dry weight compared with the interaction L1×F2, which recorded the lowest value of 21.98 mg·kg⁻ ¹ dry weight. The dual interaction between irrigation periods and fertilization treatments showed no significant superiority in leaf nitrate content.

The same table shows that the triple interaction among shading treatments, irrigation periods, and fertilization treatments produced significant differences, as the interaction L2×I0.5×F0 achieved the highest value of 36.14 mg·kg⁻ ¹ dry weight compared with the interaction L1×I1×F2, which recorded the lowest value of 19.04 mg·kg⁻ ¹ dry weight.

Table 8. Effect of shading, irrigation periods, fertilization treatments, and their interactions on leaf nitrate content (mg·kg⁻ ¹ dry weight)

L×I	F2 (Organic)	F1 (Biofertilizer)	F0 (Control)	I (Irrigation)	L (Shading)
23.63	19.04	20.11	31.73	I1 (Full irrigation)	**L1 (Light)**
24.17	24.92	24.88	22.7	I0.5 (Deficit irrigation)	

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30.83	32.53	26.09	33.86	I1 (Full irrigation)	**L2 (Shade)**
34.64	32.72	35.06	36.14	I0.5 (Deficit irrigation)	
28.03	25.5	32.11	26.47	I1 (Full irrigation)	**L3 (Half-shade)**
28	27.5	24.44	32.07	I0.5 (Deficit irrigation)	
8.427	10.894			**L.S.D. 0.05**	
L Mean	**L×F**			**L**	
23.9	21.98	22.5	27.22	**L1**	
32.73	32.62	30.57	35	**L2**	
28.01	26.5	28.27	29.27	**L3**	
6.507	7.48			**L.S.D. 0.05**	
I Mean	**I×F**			**I**	
27.49	25.69	26.1	30.69	**I1**	
28.94	28.38	28.12	30.31	**I0.5**	
N.S	N.S			**L.S.D. 0.05**	
	27.03	27.11	30.5	**F**	
	N.S			**L.S.D. 0.05**	

Discussion

The results in Tables 1, 2, 6, and 8, related to yield, net assimilation rate, and leaf content of flavonoids and nitrates, showed a significant increase when the plants were exposed to the shading factor. This can be attributed to the higher yield (Table 1) of plants grown under shade compared with plants grown between the shaded and open areas, since the former were not exposed to water and heat stress, whereas plants grown between the shade and the open field experienced greater environmental stress, which in turn increased the number of branches in those plants. These findings do not agree with those reported by (33,16,34), but are consistent with the findings of (29), who reported that shading had a positive effect on increasing chicory yield, which was 69% heavier than crops grown under direct sunlight. Shading also affected the net assimilation rate (Table 2); the decrease in the assimilation rate under shade is directly attributable to the reduced light and photosynthetically active radiation (PAR) reaching the plants, since light intensity plays a key role in stomatal opening, electron transport, and the activation of enzymes that help the plant fix carbon. This shading therefore reduced the amount of radiation absorbed by the plant, leading to a decline in the leaves' capacity for gas exchange and net photosynthesis, which is consistent with (35,16,6). The higher flavonoid content under high-light conditions can be explained by light acting as a stimulating factor for secondary metabolic pathways in the plant, particularly the phenylpropanoid pathway responsible for forming phenolic compounds; higher light intensity increases the formation of reactive oxygen species (ROS), which drives the plant to enhance the production of antioxidant compounds such as flavonoids to protect cells from oxidative stress. Increased light also stimulates the gene expression of the key enzymes in this

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pathway, PAL and CHS, which is reflected in increased flavonoid accumulation in the leaves as a defensive and adaptive response to light stress; these findings agree with(27,15), who showed that light intensity plays a pivotal role in regulating the biosynthetic pathways responsible for synthesizing secondary metabolites, including flavonoids, through increased enzymatic activity and antioxidant response in the plant. These results are also consistent with (22), who found that total flavonoid content in kale leaves was higher under high light intensity compared with low light intensity. Studies have also indicated that increased light intensity leads to higher flavonoid content in medicinal plants (9,31). The higher nitrate content in arugula plants grown under shading conditions (Table 8) is attributable to the reduced light intensity, since light is one of the most important factors affecting nitrate uptake and reduction within the plant. Light not only provides the energy required for photosynthesis but also stimulates the gene expression of nitrate reductase (NR) and increases its activity. Nitrate reduction also depends on the availability of energy compounds (ATP) and reducing power (NADPH) generated by the light reactions of photosynthesis. When light intensity decreases, photosynthetic efficiency declines and ATP and NADPH production drops, limiting the plant's ability to convert absorbed nitrate into ammonium and subsequently into amino acids and proteins. As a result, nitrates accumulate in plant tissues, which explains the notable increase in nitrate content in plants grown under shading conditions compared with plants exposed to full light (4).

Regarding the irrigation factor (Table 4), the superiority of the full-irrigation treatment in phosphorus percentage can be attributed to the fact that phosphorus moves toward the root mainly through water-dependent mass flow (20). It is notable that the difference between full and deficit irrigation in phosphorus content was relatively limited, which may be partly explained by the finding of (12) that the soil beneath solar panels retains higher moisture levels, thereby mitigating the effect of water stress under deficit irrigation on phosphorus movement in the soil.

It is observed from the results of Tables 1 and 3 that biofertilizer application significantly increased yield and nitrogen percentage. This can be attributed to its content of microorganisms, including nitrogen-fixing bacteria, which fix atmospheric nitrogen and increase its availability, given its importance for growth and for increasing yield quantity and quality. These microorganisms also reduce root infection by rot, since they secrete antibiotics that limit rot infection and stimulate root growth, as microorganisms secrete natural growth stimulants (auxins and cytokinins) that activate root growth and reduce the accumulation of nitrates and nitrites; this is consistent with (21,32). The reason is attributed to the increase in nitrogen resulting from biofertilization, which in turn contributes to chlorophyll formation, since nitrogen is a component of the porphyrin ring that is fundamental to chlorophyll structure and is directly related to the plant's nitrogen content; (14) reported that 75% of leaf nitrogen is located in the mesophyll cells of plant tissue as a result of biofertilization, and to the ability of Bacillus bacteria and Trichoderma fungi to increase the availability of these elements in the soil for uptake by the plant (19).

It is observed from the results of Tables 5 and 6 that organic fertilizer was superior in potassium percentage and phenolic content, as organic fertilizers contributed to

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supplying the plant with a high proportion of potassium. Organic fertilizers are also an important source of macro- and micronutrients essential for plant growth, in addition to their role in supplying the soil with humus, which improves its physical properties by increasing its capacity to absorb and retain water, reducing nutrient loss, and increasing the biological activity of soil microorganisms; this is consistent with the findings of (36). The increase observed in organically fertilized plants may also be attributed to the role of this fertilizer in improving the soil's physical and chemical properties, increasing the soil organic-matter content, and increasing microbial activity, which increases nutrient availability; this is consistent with (10).

Conclusions

The results of this study demonstrated that agrivoltaic shading can contribute to improving water-use efficiency in arugula production by reducing evaporative water losses and helping maintain soil moisture for longer periods. The application of shading, combined with appropriate irrigation management and biofertilization, provided a promising approach for sustaining plant growth and productivity under environmental conditions characterized by high temperature and limited water availability. Although the responses varied among the studied factors and some measured traits were not significantly affected, the integration of agrivoltaic systems with suitable irrigation and fertilization practices represents a potential strategy for reducing competition between agricultural land and solar-energy production. This approach may be particularly valuable in arid and semi-arid regions, where water scarcity, high temperatures, and climate variability increasingly constrain sustainable crop production.

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