

Article

Shade Nets Increase Plant Growth but Not Fruit Yield in Organic Jalapeño Pepper (*Capsicum annuum* L.)

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Abstract

Colored shade nets have gained attention due to their ability to reduce light intensity and alter the light spectrum, thereby influencing vegetable crop quality and yield. However, limited research has examined their effects on jalapeño pepper (*Capsicum annuum* L.) growth and yield. This study evaluated the impact of four nets—black, red, silver, and white (40% shade factor)—compared to an unshaded control. The red net altered light quality by increasing the proportion of red and far-red wavelengths, while the other nets reduced light intensity without spectral modification. Although differences in mean air temperature were minimal between shaded and unshaded conditions, root zone temperatures were consistently lower under shade nets. Shade treatments significantly increased plant height, stem diameter, and leaf chlorophyll content relative to the unshaded control. The highest rates of leaf transpiration and stomatal conductance were recorded under unshaded and white net conditions. Net photosynthesis, electron transport rate, intercellular CO₂ concentration, or photosynthetic water use efficiency were similar among net treatments. Marketable and total yields did not differ significantly among net treatments in either year; however, in 2021, they were positively associated with light intensity. In conclusion, while colored shade nets promoted vegetative growth, they did not enhance fruit yield relative to unshaded conditions in jalapeño pepper.



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1. Introduction

Climate change, characterized by rising temperatures, intensified heatwaves, frequent droughts, heavy rainfall, and hail, poses significant challenges to vegetable production [1–3]. In response to these environmental shifts, the adoption of cost-effective, environmentally friendly, and sustainable technologies becomes imperative for improving vegetable production. Recently, innovative technologies such as shading nets have been utilized to alter the temperature and relative humidity while protecting crops against excessive heat, pests, diseases, hail, and heavy rainfall [4,5]. In addition, photoselective nets can modify the light quality by altering light diffusion, reflectance, transmittance, and absorbance across ultraviolet (UV) [100–400 nm], photosynthetically active radiation (PAR) [400–700 nm], and near-infrared (NIR) [760–1500 nm] wavelength ranges [6,7]. Colored shade nets have a unique effect on the light transmitted to plants compared to commonly used black shade nets [8–10].

Jalapeño pepper (*Capsicum annuum*) is a medium-sized pod-type fruit (5–10 cm long) that can be consumed as either mature green or ripe. Commercial production of jalapeño

pepper in the United States (U.S.) primarily occurs in New Mexico, Texas, and California. Nevertheless, there are also commercial jalapeño pepper growers in Florida and Georgia, albeit on a smaller scale, cultivating them as niche crops [11]. The total hot pepper production in the U.S. was USD 100 million in 4653 ha [12]. Although hot peppers require warm conditions for better growth, excessively high temperatures can reduce flower numbers and fruit set and quality, as well as interfere with normal physiological and biochemical processes, and impact the nutritional quality of field-grown peppers [13,14]. Growers in Mediterranean countries utilize shading technology, as hot summers provide an unfavorable environment for pepper productivity and quality [15].

In recent years in the U.S., the application of shade nets on horticultural crops is becoming popular, especially in protected structures such as high tunnels and greenhouses, and in open field conditions in tree fruits, such as apples, citrus, and grapes, to reduce the fruit loss because of abiotic and biotic stresses, and to improve fruit postharvest shelf life [16,17]. The ideal shading level for most fruits and vegetables is 20–40% of ambient sunlight, as photosynthesis has been found to decrease above a 40% shade level [18]. Further, shade values above 40% may cause flower drop and reduce the fruit set in some crops [19]. Traditional black shading nets were replaced with colored shading nets (red, yellow, or pearl) of similar shading factors, resulting in a 15–40% increase in fruit production in different bell pepper (*Capsicum annuum*) cultivars [20]. One study evaluated the effects of photoselective blue and red shade nets on the productivity of yellow and red sweet peppers compared to open-field conditions [21]. Results indicated that the use of photoselective nets significantly increased both fruit yield and quality relative to unshaded controls.

There is an increased demand for jalapeño pepper production, as the consumption rate has increased compared to other hot peppers in the U.S. [22,23]. Although bell pepper and jalapeño pepper belong to the same species, their growth requirements may differ. There is limited information on the physiology and production of jalapeño peppers [24,25], and no studies have evaluated the effects of colored shading nets on organic jalapeño pepper production. Therefore, this study aims to understand the growth, physiological responses, and yield of organic jalapeño pepper under colored shade nets in the southeast U.S. during the Spring–Summer season.

2. Materials and Methods

2.1. Experimental Site, Design, and Treatments

Two organic jalapeño pepper field trials were conducted in the Spring–Summer of 2019 and 2021 at the Organic Horticulture Farm, University of Georgia, Tifton, GA, USA (lat. 31°5' N, long. 83°5' W). The soil was loamy sand with a pH of 6.5 (a fine loamy, silicious thermic Plinthic Paleudults). In 2019, 'Compadre' jalapeño pepper transplants (Veazey Plant Farm, Tifton, GA, USA) were transplanted on 10 May. In 2021, 'Compadre' seed (untreated; Clifton seed co, Moultrie, GA, USA) was sown in polystyrene 400-cell (2.5 cm × 2.5 cm cell) trays containing a commercial organic potting mixture (Sunshine #1, SunGro Horticulture, Orlando, FL, USA). Seedlings were grown for six weeks in a greenhouse at a mean temperature of 25 °C and transplanted to the organically certified field (29 April 2021). Plants were on raised beds with two rows of plants per bed (45 cm distance between rows) and 30 cm separation between plants within the row [74,074 plants/ha]. Each plot was 6.1 m long and contained 30 plants. Before laying mulch, the soil was fertilized with 358 kg·ha^{−1} N, 125 kg·ha^{−1} P, and 178 kg·ha^{−1} K, using 5:4:3 organic poultry fertilizer (Symphony Organic Fertilizer, ByoSystems LLC, Blacksburg, VA, USA). Drip irrigation tape was placed 5 cm deep in the center of each bed (Ro-Drip; Roberts Irrigation Products, Inc., San Marcos, CA, US). The bed was covered with white-on-black (2019) and black (2021) plastic mulch (RepelGro; ReflecTek Foils, Inc., Lake Zurich, IL, USA).

The change in mulch color was due to updated grower recommendations and material availability in 2021. This substitution had minimal impact on root zone temperature. Plants were irrigated when the cumulative crop evapotranspiration (ET_c) reached about 1.27 cm per week.

The experimental design was a randomized complete block with four replications and five shade net treatments (black, red, silver, and white nets and an unshaded control). According to the manufacturer, the shade factor was 40% for all shade nets (Green-tek, Janesville, WI, USA). Shade nets (2.7 m wide, 2 m high at the peak, and 6.8 m long) [26] were installed one month (11 June 2019 and 29 May 2021) after transplanting into the field using a north–south orientation. Shade nets were suspended above the jalapeño pepper plants using metal fence posts and PVC pipe in tunnel-shaped structures, leaving the ends of the structures uncovered (Figure 1).



Figure 1. Shade nets were installed in the arch-shaped structure for jalapeño pepper plants in Tifton, GA, USA, in 2019 and 2021.

2.2. Microenvironment

Air temperatures (T_{air}) were measured hourly during the growing seasons (2019 and 2021) (WatchDog 1650, Spectrum Technologies, Inc., Aurora, IL, USA). Root zone temperature (RZT) at a depth of 10 cm, equidistant between plants within a row, was measured using copper–constantan thermocouples (Model 107, Campbell Scientific, Logan, UT, USA) connected to dataloggers (CR10X and CR1000X; Campbell Scientific, Logan, UT, USA). The RZT measurements started on 18 June 2019 and 7 June 2021, and continued until the end of the season.

Light quantity was determined as the amount of light transmitted [photosynthetic photon flux density (PPFD), 400–700 nm; ultraviolet (UV), (380–400 nm); blue (B), (400–500 nm); green (G), (500–600 nm); red (R), (600–700); far-red (FR), (700–780 nm)]. Light readings were taken between 12:00 and 13:00 HR using a spectrometer (LI-180, LI-COR, Lincoln, NE, USA) on sunny and clear days in the mid-section of the bed just above the plant canopy (two measurements per plot) on 9 and 29 June, and 15 July 2021. Regarding light quality

transmittance, spectral ratios of light quantity at different spectra were calculated as B/G, B/R, G/R, R/FR, and PPFD/UV.

2.3. Plant Growth and Leaf Chlorophyll Content

In 2019 and 2021, plant height was measured from the base of the plant to the highest terminal point, and stem diameter was measured 2 cm above the soil level every week (5 plants per plot), starting two weeks after the shading nets were placed. At the last harvest, two randomly selected plants from the middle section of each plot were cut down at the soil level to determine the plant's top dry weight. Leaf area was measured using a leaf area meter (LI-3000C, LI-COR, Lincoln, NE, USA). Specific leaf weight (leaf dry weight-over-leaf area ratio) was used as an indicator of leaf thickness. Leaf chlorophyll index (CI) was measured with a chlorophyll meter (SPAD-502 Plus, Konica Minolta Sensing Americas, Inc., Ramsey, NJ, USA).

Three leaves per plot were collected on 1 July and 20 July 2021 and analyzed individually for chemical composition. Carotenoids (Car), chlorophyll a (Chl *a*), and chlorophyll b (Chl *b*) were determined spectrophotometrically in fresh leaves. Leaf disks (2 cm²) were collected from leaf interveinal areas, placed into tubes, and extracted in 1–1.5 mL ethanol (100% *v/v*) for 24 h. Pigment concentrations were calculated from the absorbance values of the extract at 470, 649, and 664 nm using the following equations [27]:

Chlorophyll a	$\text{Chl } a \text{ (}\mu\text{g/mL)} = 13.36A_{664} - 5.19A_{649}$
Chlorophyll b	$\text{Chl } b \text{ (}\mu\text{g/mL)} = 27.43A_{649} - 8.12A_{664}$
Chlorophyll a + b	$\text{Chl } (a + b) \text{ (}\mu\text{g/mL)} = 5.24A_{664} + 22.24A_{649}$
Carotenoids	$\text{Car (}\mu\text{g/mL)} = (1000A_{470} - 2.13\text{Chl } a - 97.63\text{Chl } b)/209$

2.4. Leaf Mineral Nutrients

In 2019 and 2021, leaf samples (25–30 fully developed leaves from new growth) were collected from five plants in the middle section of the plot. Leaf samples were dried at 70 °C for 2 days to constant weight and analyzed for mineral nutrient concentration at a commercial laboratory (Waters Agricultural Laboratories, Inc., Camilla, GA, USA).

2.5. Leaf Gas Exchange

Leaf gas exchange measurements [net photosynthesis (*A_n*), intercellular CO₂ (*C_i*), stomatal conductance (*g_s*), transpiration (*E*), photosynthetic water use efficiency (WUE) calculated as *A_n/E*, photosynthetically active radiation (PAR), and quantum yield of PSII (PhiPS2)] were conducted with a portable photosynthesis system (LI-COR IRGA-6400XT equipped with an integrated 6400–40 leaf chamber fluorometer; LI-COR, Inc., Lincoln, NE, USA). The airflow rate was 500 μmol·m^{−2}·s^{−1} on the reference side. The CO₂ concentration was set at 400 μmol·mol^{−1} with a CO₂ mixer and a CO₂ tank. The ambient 'light tracking' option from the IRGA was used as a source of light for measurements. Measurements were conducted in developed plants on clear days between 1200 and 1500 h using two fully developed and exposed leaves per plot. Measurements were taken on 26 June and 11 July 2019.

2.6. Fruit Yield

In 2019, jalapeño pepper fruits were harvested and graded as either marketable or unmarketable, although the fruits were not further graded based on fruit length. In 2021, jalapeño pepper fruits were graded based on the fruit length as marketable [large (7–10 cm) and medium (5–7 cm)] and non-marketable. Small fruit (<5 cm long) and fruit with visual symptoms of anthracnose (*Colletotrichum* spp.) or pepper weevil (*Anthonomus eugenii*) were categorized as non-marketable [28]. The number and weight of marketable and

non-marketable fruit per plant were determined. The average individual fruit weight was calculated mathematically from the marketable fruit weight and the number of fruits. There were four harvests in 2019 (4 July to 23 July) and two harvests in 2021 (17 June to 21 July).

2.7. Data Analysis

Data were analyzed using a generalized linear model of one-way analysis of variance (ANOVA) using R Statistical Software, version 4.2.0 [29]. When the ANOVA model revealed significant treatment effects, a within-group separation was performed using Tukey's HSD test at a significance level of 0.05% [30]. Regression analysis and graphs were prepared using the SigmaPlot 14 software (Systat Software, San Jose, CA, USA). Data were analyzed separately by year because the plastic mulch color differed in 2019 and 2021.

3. Results

3.1. Microenvironment

Full-spectrum light, which includes visible wavelengths (blue, green, and red), ultraviolet (UV), and far-red (FR), was highest under unshaded conditions (Table 1). Black shade nets reduced the PPFD by 55%, followed by red (51%), silver (43%), and white (29%), when compared to unshaded conditions. UV, blue, and green light intensities were lowest under black and red shade nets. Red and far-red light intensities followed a similar trend but were comparatively higher under the white and red nets compared to the black and silver shade nets. Black, silver, and unshaded showed a similar blue/green light ratio (B/G) (0.77). The blue/green light ratio (B/G) was the highest in the red (0.79) and the lowest in the white shade net (0.74). The B/R and G/R ratios were the lowest in the red nets (0.4 and 0.5). There was a similar G/R light ratio in black, silver, white, and unshaded treatments. Red/far-red ratios (R/FR) were the highest in unshaded (1.38), followed by black (1.36), silver (1.32), white (1.31), and the lowest under red (1.23) shade nets. A similar PPFD/UV ratio was found in black, red, silver, and unshaded conditions (40.5). Black, silver, and white shade nets exhibited a similar pattern to unshaded nets, with differences primarily in the amount of light transmitted rather than a specific part of the visible spectrum being affected (Figure 2). In contrast, the red shade net significantly reduced the UV, B, and G regions of the spectrum while enriching the R and FR regions.

Table 1. Mid-day photosynthetic photon flux density (PPFD), ultra-violet (UV), blue, green, red, and far-red light intensity and spectral ratios of transmitted light under black, red, silver, and white shade nets and unshaded conditions in organic jalapeño pepper. Spring–Summer 2021, Tifton, GA, USA.

Shade Nets	Light Intensity ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)						Light Quality (Ratios)					
	PPFD	UV	Blue (B)	Green (G)	Red (R)	Far-Red (FR)	Reduced PPFD (%)	B/G	B/R	G/R	R/FR	PPFD/UV
Black	962 d ^z	24 c	263 d	341 d	358 d	263 d	55	0.77 b	0.73 a	0.95 a	1.36 ab	40.5 b
Red	1053 d	26 c	221 e	281 e	551 b	444 b	51	0.79 a	0.4 c	0.50 b	1.23 d	40.6 b
Silver	1217 c	29 b	329 c	433 c	455 c	343 c	43	0.77 b	0.72 a	0.95 a	1.32 bc	41.3 b
White	1534 b	31 b	402 b	544 b	588 b	448 b	29	0.74 c	0.68 b	0.93 a	1.31 c	48.9 a
Unshaded	2151 a	53 a	587 a	764 a	800 a	577 a	--	0.76 b	0.73 a	0.95 a	1.38 a	40.4 b
<i>p</i> -Value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

In 2019, the mean and maximum air temperatures (T_{air}) were highest in the white shade net (30.4 °C and 41.5 °C) and lowest under unshaded conditions (28.4 °C and 33.9 °C) (Table 2). The minimum RZT was highest in the unshaded (28.0 °C) and lowest in black (26.7 °C) and red (26.6 °C) shade nets. Mean RZT was highest in unshaded conditions (39.5 °C) and lowest in black (28.5 °C) and silver (28.6 °C) shade nets. Maximum RZT was highest in unshaded, white, and red shade nets and lowest in black and silver shade

nets. In 2021, the mean air temperature was highest under the red net (27.9 °C) and lowest under the silver net (26.6 °C), while the maximum air temperature was highest under the white net (43.9 °C) and lowest under the silver net (33.6 °C) (Table 3). The minimum, mean, and maximum RZT values were highest in unshaded conditions and lowest in black and silver nets. Mean RZT increased linearly with increasing mid-day PPFD in both 2019 ($R^2 = 0.724$) and 2021 ($R^2 = 0.956$), while air temperature was unrelated to mid-day PPFD. Total cumulative rainfall was higher in 2021 (45.2 cm) than in 2019 (22.2 cm) (Figure 3).

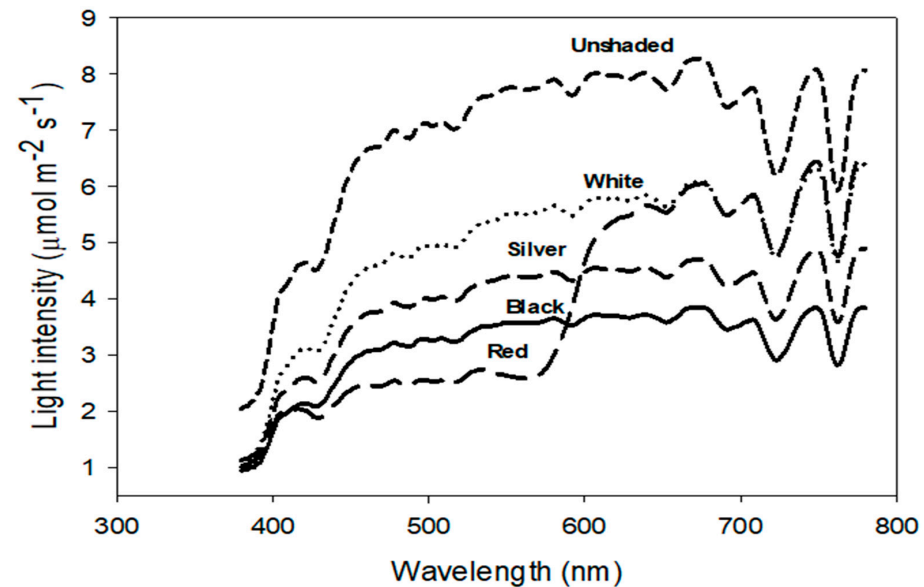


Figure 2. Light spectrum distribution under colored shade nets at 380–780 nm wavelengths in organic jalapeño pepper in Spring–Summer 2021, Tifton, GA, USA.

Table 2. Average seasonal air temperature (T_{air}) and root zone temperature (RZT) under colored shading nets in organic jalapeño pepper. Spring–Summer 2019, Tifton, GA.

Shade Nets	T_{air} (°C)			RZT (°C)		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Black	23.2	29.0 c ^z	36.6 c	26.7 d	28.5 d	30.6 b
Red	22.9	29.9 b	39.4 b	26.6 d	29.5 c	33.1 a
Silver	23	29.8 b	40.2 b	26.9 c	28.6 d	30.6 b
White	22.9	30.4 a	41.5 a	27.3 b	29.9 b	33.2 a
Unshaded	22.9	28.4 d	33.9 d	28.0 a	30.5 a	33.4 a
<i>p</i> -Value	0.529	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

Table 3. Average seasonal air temperature (T_{air}) and root zone temperature (RZT) under colored shading nets in organic jalapeño pepper. Spring–Summer 2021, Tifton, GA, USA.

Shade Nets	T_{air} (°C)			RZT (°C)		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Black	22.8	27.3 ab ^z	34.3 cd	25.1 e	26.7 d	29.2 c
Red	22.9	27.9 a	39.3 b	25.7 c	27.3 c	29.2 c
Silver	22.9	26.6 b	33.6 d	25.5 d	26.8 d	28.7 d
White	23	27.2 ab	43.9 a	25.8 b	27.6 b	29.9 b
Unshaded	22.9	27.5 ab	35.7 c	26.7 a	28.9 a	31.5 a
<i>p</i> -Value	0.843	0.021	<0.001	<0.001	<0.001	<0.001

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

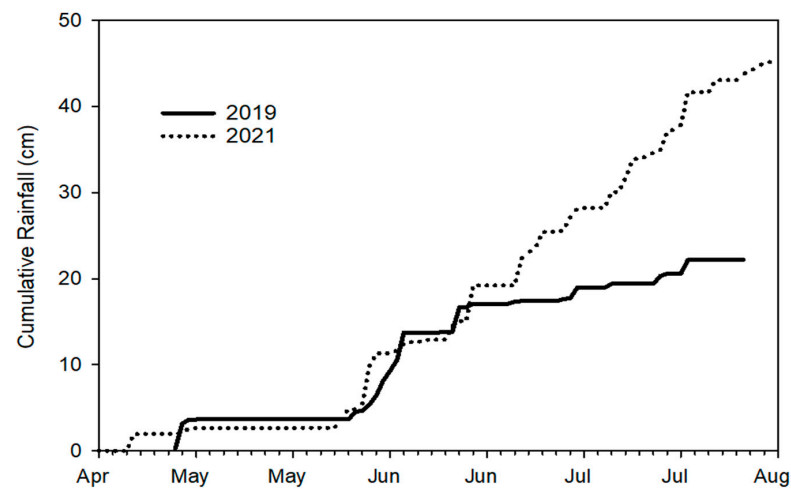


Figure 3. Total cumulative rainfall (cm) derived from nearby weather stations during the crop seasons of jalapeño pepper in Spring–Summer 2019 and 2021, Tifton, GA, USA.

3.2. Plant Growth and Chlorophyll Content

Plants grown under black, red, and silver shade nets were significantly taller than in white shade nets and unshaded conditions in both growing seasons (Figure 4A,B). In 2019, stem diameter was not significantly different between treatments. However, in 2021, unshaded conditions resulted in the lowest stem diameter compared to under the shade nets (Figure 4C,D). There were no significant differences in top plant dry weight, leaf area, specific leaf weight, and normalized CI in 2019 (Table 4). In 2021, there were no significant differences in top plant dry weight, specific leaf weight, CI, and normalized CI. However, the leaf area was lower in unshaded conditions than under shade nets. In 2021, plant height increased with increasing PPFD ($R^2 = 0.948$; $p = 0.005$) and mean RZT ($R^2 = 0.864$; $p = 0.022$). However, in 2019, plant height was not linearly related to PPFD and mean RZT. Specific leaf weight (SLW) increased with increasing PPFD (Figure 5).

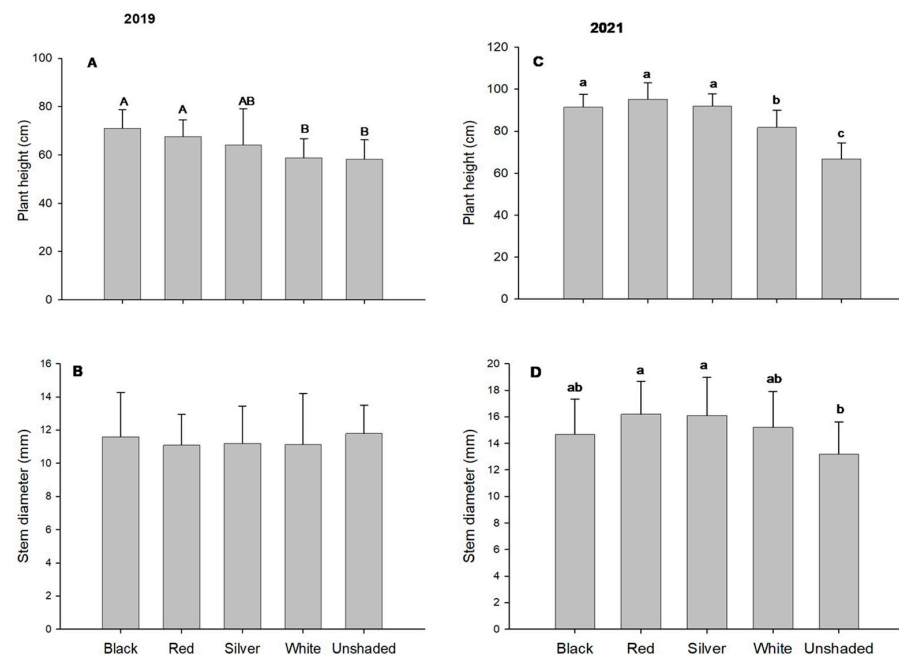


Figure 4. Plant height [2019 (A) and 2021 (B)] and stem diameter [2019 (C) and 2021 (D)] under colored shading nets of organic jalapeño pepper in Spring–Summer, Tifton, GA. Vertical bars indicate standard errors. Different letters above the columns within each figure represent a significant difference between the treatments as indicated by Tukey's HSD test at $p \leq 0.05$.

Table 4. Effect of colored shading nets on above-ground plant dry weight, leaf area, specific leaf weight, chlorophyll index (CI), and normalized CI in organic jalapeño pepper. Spring–Summer of 2019 and 2021, Tifton, GA, USA.

Year	Shade Nets	Above-Ground Dry Weight (g·Plant ^{−1})	Leaf Area (cm ² ·Leaf ^{−1})	Specific Leaf Weight (g·m ^{−2})	CI	Normalized CI
2019	Black	75.2	14.7	40.9	47.2 ab ^z	1.33
	Red	70.3	15.6	50.5	51.2 ab	1.19
	Silver	62.5	16.6	47.1	54.7 a	1.22
	White	80.2	14.2	58.6	54.2 a	0.96
	Unshaded	65.2	13.1	79.8	42.7 b	0.8
	<i>p</i> -Value	0.669	0.398	0.068	0.011	0.197
2021	Black	123.9	24.4 a	46.1	38.5	0.88
	Red	125.6	24.1 a	52	33.8	0.66
	Silver	125.2	24.4 a	49.4	39.1	0.83
	White	102.8	21.8 a	60.4	41.8	0.66
	Unshaded	107.5	16.2 b	62	40.3	0.7
	<i>p</i> -Value	0.295	<0.001	0.115	0.299	0.328

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

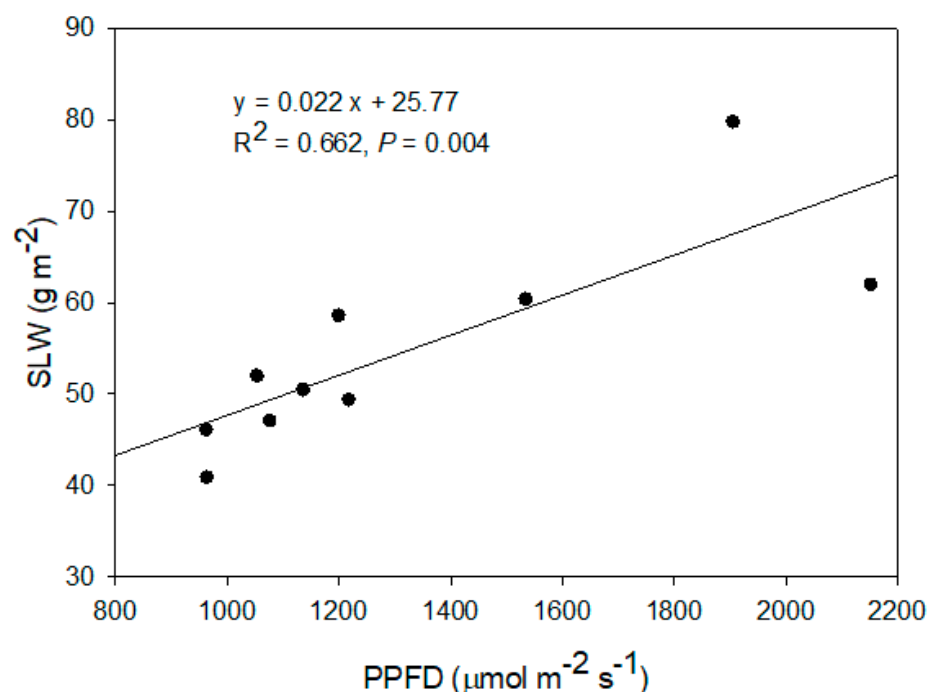


Figure 5. Specific leaf weight as influenced by mid-day PPFD in organic jalapeño pepper under colored shade nets (Tifton, GA, USA, Spring–Summer 2019 and 2021).

Leaf chlorophylls (Chl *a*), (Chl *b*), and Chl (*a* + *b*) were highest in the black shade net and lowest in unshaded conditions. However, leaf carotenoids (Car) were not different between shading nets and unshaded conditions (Table 5). There was a positive correlation between Chl *a* ($R^2 = 0.936$; $p = 0.007$), Chl *b* ($R^2 = 0.932$; $p = 0.008$), and Chl *a* + *b* ($R^2 = 0.95$; $p = 0.005$) with red light, while there was no relationship between chlorophyll index, mid-PPFD, and mean RZT with Chl *a*, Chl *b*, and Chl *a* + *b*.

3.3. Leaf Mineral Nutrients

In 2019, shading treatments had no significant influence on leaf mineral concentrations except for iron (Fe), which had an increased concentration in the black net (Table 6). In 2021, foliar nitrogen (N) was highest in the silver net and unshaded conditions but lowest in the white shade net (Table 7). The manganese (Mn) content was highest in the silver net

and lowest in unshaded conditions. The remaining nutrient concentrations did not differ significantly between the treatments.

Table 5. Leaf chlorophyll a (Chl a) and b (Chl b), carotenoids (Car), and total chlorophyll [Chl (a + b)] in organic jalapeño pepper grown under colored shading nets. Spring–Summer of 2021, Tifton, GA, USA.

Shade Nets	Chl a	Chl b	Car	Chl (a + b)
	$\mu\text{g}^{-1}\cdot\text{mL}^{-1}$	$\mu\text{g}^{-1}\cdot\text{mL}^{-1}$	$\mu\text{g}^{-1}\cdot\text{mL}^{-1}$	$\mu\text{g}^{-1}\cdot\text{mL}^{-1}$
Black	7.68 a ^z	3.07 a	1.95	10.75 a
Red	6.79 ab	2.79 ab	1.75	9.58 ab
Silver	7.36 a	2.90 ab	1.9	10.26 ab
White	6.89 ab	2.69 ab	1.83	9.59 ab
Unshaded	6.35 b	2.57 b	1.76	8.92 b
<i>p</i> -Value	0.0017	0.054	0.13	0.003

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

Table 6. Foliar macro- and micronutrient concentrations in organic jalapeño pepper collected at the mid-season fruiting stage, grown under colored shading nets. Spring–Summer 2019, Tifton, GA, USA.

Shade Nets	Macronutrients (%)					Micronutrients ($\text{mg}^{-1}\cdot\text{kg}^{-1}$)					
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Black	4.36	0.36	3.85	1.5	0.45	0.56	38	62	105 a ^z	49	47
Red	4.39	0.36	3.91	1.39	0.42	0.57	34	46	94 b	47	43
Silver	4.41	0.34	3.83	1.46	0.46	0.55	33	44	96 ab	46	40
White	4.15	0.36	3.87	1.48	0.46	0.57	35	45	91 b	45	41
Unshaded	4.09	0.37	3.68	1.43	0.43	0.55	41	56	88 b	50	44
<i>p</i> -Value	0.1101	0.898	0.754	0.822	0.819	0.961	0.584	0.573	0.0029	0.514	0.104

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

Table 7. Foliar macro- and micronutrient concentrations in organic jalapeño pepper collected at the mid-season fruiting stage, grown under colored shading nets. Spring–Summer 2021, Tifton, GA, USA.

Shade Nets	Macronutrients (%)					Micronutrients ($\text{mg}^{-1}\cdot\text{kg}^{-1}$)					
	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
Black	2.78 ab ^z	0.5	2.8	0.87	0.31	0.35	33	12	148	46 ab	66
Red	2.84 ab	0.48	2.76	0.85	0.29	0.35	33	13	127	44 ab	89
Silver	2.88 a	0.48	2.94	0.79	0.31	0.36	31	13	136	47 a	67
White	2.71 b	0.54	2.85	0.85	0.3	0.36	35	13	139	44 ab	70
Unshaded	2.90 a	0.5	2.74	0.77	0.3	0.36	34	13	159	42 b	83
<i>p</i> -Value	0.013	0.497	0.511	0.44	0.744	0.76	0.348	0.881	0.933	0.037	0.833

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

3.4. Leaf Gas Exchange

In 2019, An, Ci, ETR, and WUE were not significantly different between treatments (Table 8). The PPFD ranged from $1881 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in the unshaded treatment to $963.2 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in the black shade net. The quantum yield of photosystem II (PhiPS2) was the lowest in the unshaded treatment, but there were no significant differences between shade nets. Transpiration (E) was highest in the white shade net and unshaded conditions. Stomatal conductance was highest in the white shade net, and the leaf temperature was lowest in the black shade net.

Table 8. Leaf net photosynthesis (An), intercellular CO₂ (Ci), transpiration (E), electron transport rate (ETR), stomatal conductance (g_s), leaf temperature (LeafT), PPFD, PSII efficiency (PhiPS2), and photosynthetic water use efficiency (WUE) in organic jalapeño pepper under colored shade nets. Spring 2019, Tifton, GA, USA.

	An	Ci	E	ETR	g _s	LeafT	PPFD	PhiPS2	WUE
Shade Nets	($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	($\mu\text{mol}\cdot\text{mol}^{-1}$)	($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	($\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	°C	($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)		($\mu\text{mol}\cdot\text{mmol}^{-1}$)
Black	21.9	295.8	9.8 b ^z	137.9	0.48 b	32.5 b	963.2 d	0.34 a	2.4
Red	24.9	295.7	10.4 ab	148.9	0.46 b	33.8 a	1135.6 bc	0.30 a	2.2
Silver	23.7	300.2	9.8 b	135.9	0.46 b	33.5 a	1075.6 c	0.29 a	2.2
White	25.6	304.3	11.6 a	154.2	0.61 a	32.9 ab	1198.8 b	0.30 a	2.2
Unshaded	23.9	302	12.1 a	146.9	0.54 ab	33.8 a	1905 a	0.18 b	2
p-Value	0.226	0.829	0.0003	0.362	0.019	0.003	<0.0001	<0.0001	0.118

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

3.5. Fruit Yield

In 2019, the number and weights of marketable and non-marketable fruits were not different among treatments. However, individual fruit weight was highest in the black shade net and lowest under unshaded conditions (Table 9). In 2021, there were no significant differences in the number and weight of large-sized fruits. However, the number and weight of medium-sized fruits were highest in the unshaded area and lowest in the black and silver shade nets. The total number of marketable fruit and yield per plant were not significantly different among the treatments (Table 10). Small fruit numbers and weights were highest in the unshaded and white shade net, and lowest in the black shade net (Table 11). Fruits infected with anthracnose and pepper weevil, as well as the total non-marketable weight and number of fruits per plant, were not significantly different among treatments. In 2019, total or marketable yields were not affected by shade treatments. The shade net effect on yields was probably masked by the high incidence of bacterial leaf spot (*X. campestris* pv. *vitians*). Plants showed a decreasing total marketable yield with the increasing incidence of bacterial leaf spot (Figure 6). However, in 2021, there was no detectable presence of bacterial leaf spot. The total marketable yield and total yield increased with increasing photosynthetic photon flux density (PPFD) (Figure 7). In 2021, a positive correlation was observed between total yield per plant ($R^2 = 0.882$; $p = 0.018$) and mean RZT.

Table 9. Marketable and non-marketable fruit number and yield in organic jalapeño pepper under colored shading nets. Spring–Summer 2019, Tifton, GA, USA.

Shade Nets	N	Marketable		Non-Marketable (Anthracnose and BER) ^y		Total	
		Wt. (g/Plant)	Individual Fruit Wt. (g)	N	Wt. (g/Plant)	N	Wt. (g/Plant)
Black	14.7	371	26.2 a ^z	0.15	3.8	14.9	374.8
Red	14.9	320	21.9 ab	0.28	6.1	15.2	326.1
Silver	16.1	363	22.3 ab	0.11	2.9	16.2	365.9
White	19.1	423	21.8 ab	0.10	1.9	19.2	424.9
Unshaded	17.3	303	17.5 b	0.04	0.9	17.3	303.9
<i>p</i> -Value	0.587	0.426	0.0153	0.328	0.269	0.633	0.448

^y Anthracnose disease in jalapeño pepper is caused by *Colletotrichum* spp. BER (blossom-end rot) is a physiological disorder. ^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

Table 10. Marketable and total fruit number (No.), weight (Wt.), and individual fruit weight in organic jalapeño pepper under colored shading nets. Spring–Summer 2021, Tifton, GA, USA.

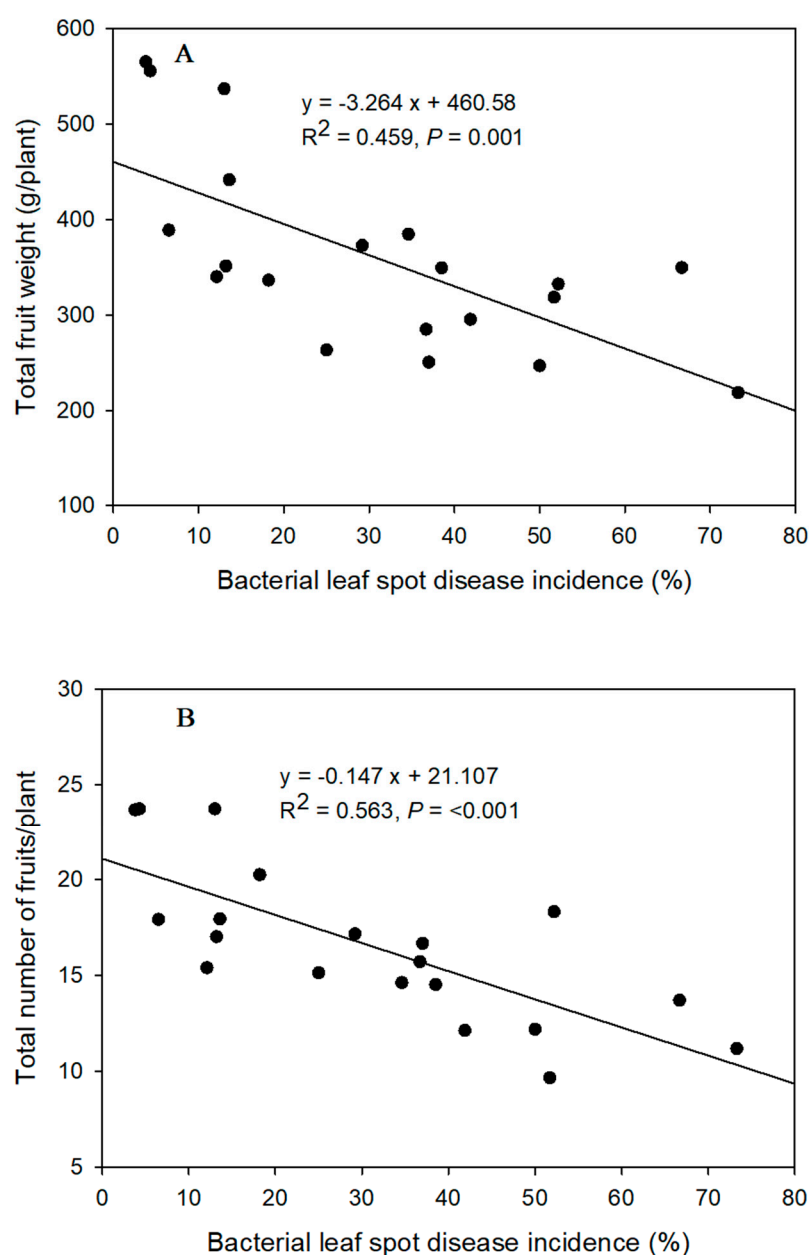
Shade Nets	Large		Medium		Total Marketable		Individual Fruit	Total Yield	
	No. (per Plant)	Wt. (g/Plant)	No. (per Plant)	Wt. (g/Plant)	No. (per Plant)	Wt. (g/Plant)	Wt. (g)	No. (per Plant)	Wt. (g/Plant)
Black	3.5	116.4	6.4 b ^z	151.5 b	10.0	267.9	26.5	19.8	410.0
Red	2.9	98.6	7.4 ab	181.5 ab	10.5	284.0	26.3	21.4	454.3
Silver	3.5	113.3	6.3 b	154.3 b	10.0	270.4	26.9	20.7	445.1
White	3.1	102.5	8.1 ab	198.6 ab	11.2	301.1	26.3	27.7	568.9
Unshaded	3.3	101.4	11.0 a	264.7 a	14.4	366.1	24.3	29.4	635.1
<i>p</i> -Value	0.98	0.985	0.024	0.043	0.303	0.571	0.062	0.073	0.13

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

Table 11. Non-marketable fruit number (No.) and weight (Wt.) in organic jalapeño pepper grown under colored shading nets. Spring–Summer 2021, Tifton, GA, USA.

Shade Nets	Small		Anthracnose		Weevil Infested		Total Non-Marketable Fruit	
	No.	Wt. (g/Plant)	No.	Wt. (g/Plant)	No.	Wt. (g/Plant)	No.	Wt. (g/Plant)
Black	4.4 b ^z	83.7 b	0.33	9.4	5.1	49.0	9.8	142.2
Red	7.0 ab	127.6 ab	0.49	12.4	3.6	34.3	11.1	174.2
Silver	6.8 ab	128.5 ab	0.43	9.9	3.7	38.6	11.0	177.5
White	11.4 a	204.7 a	0.76	17.9	4.3	45.3	16.5	267.8
Unshaded	12.6 a	234.7 a	0.39	7.9	2.0	26.3	15.0	268.9
p-Value	0.007	0.008	0.489	0.667	0.824	0.927	0.832	0.914

^z Means within the same column followed by the same letter are not significantly different based on Tukey's HSD test at $p \leq 0.05$.

**Figure 6.** Total yield per plant (A) and fruit number per plant (B) as affected by bacterial leaf spot incidence [*Xanthomonas campestris* pv. *vesicatoria* (Xcv)] under colored shading nets in organic jalapeño pepper in Spring 2019, Tifton, GA, USA.

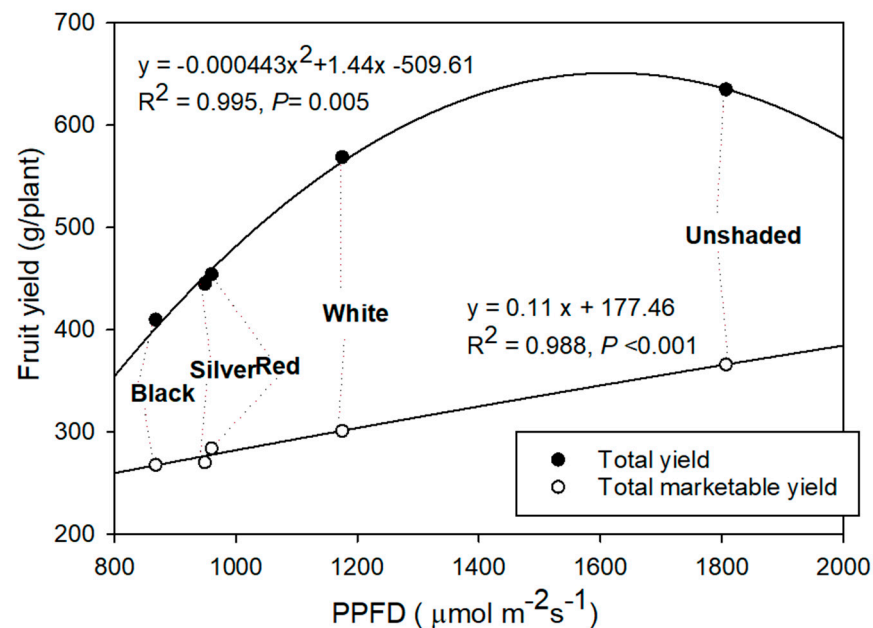


Figure 7. Marketable and total yield per plant as affected by PPFD under colored shading nets in organic jalapeño pepper in Spring–Summer 2021, Tifton, GA, USA.

4. Discussion

4.1. Microenvironment

Colored shade nets significantly alter the quality and quantity of light. Irrespective of net color, shade nets reduce the incidence of solar radiation reaching the plant canopy beneath them [31]. Colored shade nets exhibit transmission, diffusion, and reflection properties based on the net's color and thread density. In our study, only transmitted light was measured. Among the treatments, the red shade net was photosensitive, while the black, silver, and white were neutral shade nets. Photosensitive shade nets can modify the spectral composition of light by shifting the proportion of photosynthetically active radiation (PAR) transmitted toward the specific wavelength corresponding to the net color [32].

The PAR results observed in this study are consistent with those of Arthurs et al. [32], who found that, even with the same nominal shading factor (40%, as specified by the manufacturer), the black shade net reduced PAR the most compared to red, pearl, and blue nets. Furthermore, our findings indicate that the shading factor designated by the manufacturer does not necessarily reflect the actual PAR under the shade net. The extent of PAR reduction mainly depends upon the type and color of the net, as well as the mesh size [33], and the architectural configuration of the net installation.

The effects of shade nets on air temperature remain inconclusive, with contradicting findings reported in the literature. Most previous studies have been conducted in arid climatic areas where the mean air temperature under shade nets was found to increase by 0.5–0.8 °C compared to open-field conditions [32,34]. In contrast, one study reported a reduction of 2.1 to 2.2 °C in air temperature under shade nets compared to unshaded conditions in tea plants. Kalcsits et al. [31], however, observed no significant differences in air temperature, while Díaz-Pérez and St. John [8] reported only a minimal reduction (0.1–0.2 °C) under shaded conditions.

Minor differences in mean air temperature among treatments may be attributed to the height of the shade nets above the plant canopy. One study highlighted the role of net height, showing that 2 m high screen houses resulted in higher air and leaf temperatures compared to 4 m structures, despite receiving equivalent levels of solar radiation [26].

However, another study found that increasing the net height from 4 to 6 m did not affect mean air temperature or relative humidity [35].

Although PPFD did not influence air temperature in this study, mean seasonal RZT increased linearly with increasing PPFD. Our findings align with prior research indicating that shade nets reduce root zone temperatures in comparison to unshaded conditions [8,36].

4.2. Plant Growth

Increased growth indices, such as plant height and leaf area under shade nets, represent adaptive plant responses, as plants in shaded environments can activate the phototropic mechanisms to enhance their light-capturing capacity [37,38]. Consistent with the present study, Kumar et al. [39], Kitta et al. [40], and Díaz-Pérez and St. John [8] reported that shaded plants were taller than those grown under full sunlight. Likewise, Illic et al. [10] observed a higher leaf area index in lettuce under shade nets compared to unshaded conditions. Apical dominance leads to increased auxin transport, promoting cell elongation below the apical meristem zone, which ultimately results in taller plants when grown under shade nets [41].

Although increased plant height and reductions in stem diameter and chlorophyll content are often associated with shade avoidance syndrome [42], the growth responses observed in our study more closely reflect vigorous growth rather than stress-induced elongation. Shaded plants exhibited not only greater height but also thicker stems and enhanced chlorophyll content, with no evidence of a decreased chlorophyll *a/b* ratio, suggesting a balanced pigment composition. These findings are more indicative of acclimation to favorable microclimatic conditions than of shade avoidance syndrome expression.

In the present study, both plant height and leaf area were generally greater under shaded conditions in both years. However, the incidence of bacterial leaf spot disease in 2019 may have partially suppressed these growth responses. Similarly, Awad-Allah et al. [43] reported significant reductions in plant height, branch number, and leaf number in sweet pepper plants infected with bacterial leaf spot.

Modified microclimate conditions under shading, including temperature, light quality and quantity, and humidity, affect plant chlorophyll content [44,45]. Shaded leaves typically exhibit increased concentrations of chlorophyll (*a* and *b*), which enhance the light-capturing efficiency for photosynthesis under low light intensity [46,47]. In lettuce, a strong positive correlation has been reported between total leaf chlorophyll content and light deficiency [48]. Similarly, in the present study, shaded leaves showed elevated Chl *a*, *b*, and total chlorophyll (*a* + *b*), which may be associated with improved plant growth.

Chlorophyll pigments primarily absorb light in the blue and red spectral regions. In this study, a corresponding increase in leaf chlorophyll content was detected under the red light spectrum. These findings further demonstrate that red light influences chlorophyll accumulation in pepper leaves.

4.3. Leaf Mineral Content

In the present study, leaf mineral nutrients did not differ between shaded and unshaded conditions, although the shaded leaves had increased chlorophyll content. Colonna et al. [49] reported that, at harvest time, leafy vegetables accumulated more N, potassium (K), calcium (Ca), and magnesium (Mg) under low light intensity. Similarly, Zhao and Oosterhuis [50] showed that field cotton plants accumulated greater concentrations of leaf nutrients [N, phosphorus (P), and sulfur (S)] under 40% shading than in unshaded conditions. In contrast, a study on tropical perennial legume cover crops showed that increasing PPFD decreased the concentrations of N, P, K, and Boron (B), while increasing the concentrations of Mg, Fe, and Mn.

There remains limited information on how colored shade nets affect mineral nutrient uptake and accumulation in vegetable crops. Singh et al. [51] found that lettuce and basil grown under the same colored shade nets displayed different nutrient accumulation patterns. Likewise, Díaz-Pérez [52] reported cultivar-specific differences in foliar nutrient concentrations in bell pepper. In agreement with our findings, Gálvez et al. [53] found no differences in micro- and macronutrient concentrations between shaded (30%) and unshaded treatments in greenhouse-grown bell pepper leaves. Similarly, Díaz-Pérez and St. John [8] also found minimal variation in concentrations of K, Ca, and Mg below 30% shade, or 47% shade for N in bell pepper leaves, supporting the results of the current study.

4.4. Leaf Gas Exchange

According to Ashraf [54], leaf gas exchange is influenced by fluctuations in environmental conditions and the specific crop characteristics. In the present study, leaf gas exchange measurements were utilized to evaluate plant physiological responses under different shade nets. Measurements of net photosynthesis (A_n), intercellular CO_2 (C_i), electron transport rate (ETR), transpiration (E), and water use efficiency (WUE) were conducted under ambient light conditions specific to each shading treatment. Consequently, PPFD levels varied among treatments, ranging from approximately 963 to 1905 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. Although such variation in incident light among treatments limits direct comparisons, the leaf-level measurements reflect instantaneous physiological responses under practical field conditions. To minimize environmental variability and ensure stable measurement conditions, data were collected on clear, cloud-free days during a narrow mid-day window.

Despite differences in PPFD, the A_n , C_i , ETR, and WUE did not vary significantly among treatments. These results are consistent with previous studies in field-grown crops such as tomatoes [55] and bell pepper [56], which showed that maximum net photosynthesis saturates at about 50% (1000 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) to 75% (1500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) of full sunlight. Comparable values of leaf net photosynthesis, intercellular CO_2 , electron transport rate, transpiration, and photosynthetic water use efficiency have been observed under open-field conditions (1942 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) and 30% shade (1258 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) [56]. Similarly, Kitta et al. [57] found that sweet peppers grown under 13% and 34% white shade nets, as well as under 36% green shade nets, maintained similar net photosynthesis as in unshaded conditions, irrespective of shading intensity or net types. These results suggest that physiological acclimatization may mitigate the effects of reduced light availability.

However, it is important to note that leaf-level A_n does not always translate directly into yield outcomes, as whole plant productivity depends on additional factors such as canopy architecture, light interception, source–sink dynamics, and stress response [42]. For example, in bell pepper, although leaf-level photosynthesis declined with increasing shade intensity (0–80%), total yield remained relatively stable across treatments [58]. This response underscores the importance of assessing canopy-level photosynthetic responses to understand light interception dynamics and energy distribution, which ultimately determine yield outcomes in shaded environments.

Our findings are consistent with those of Company et al. [59], who reported that unshaded leaves exhibited higher g_s and E compared to shaded leaves. This disparity may be attributed to stomatal variations, as larger stomata tend to open more slowly than smaller ones [60,61]. However, because stomatal size was not measured in this study, this explanation remains speculative. The observed increase in g_s and E under unshaded conditions is likely attributable to greater stomatal opening in response to higher solar radiation and increased evaporative demand at the leaf surface [62,63].

4.5. Fruit Yield

The emergence of BLS disease in pepper plants during the second week after transplanting in 2019 had notable effects on both vegetative and reproductive growth parameters. The early onset of the disease, occurring shortly after transplanting, suggests that the infection source may have originated at the nursery stage from contaminated seed. This hypothesis is further supported by the fact that the transplants were acquired from a commercial nursery.

Despite the historical association between wet seasons and higher severity of foliar diseases, including BLS [64,65], a recent study has failed to establish a clear link between rainfall amount and prevalence of BLS in pepper plants. Furthermore, there was a decrease in bacterial leaf spot incidence when the mean air temperature exceeded 30 °C. Robinson et al. [66] reported a curvilinear relationship between air temperature and the infectivity of *Xanthomonas campestris* pv. *vitians* on lettuce, observing a reduction in the number of lesions per leaf at temperatures below 15 °C and at 30 °C.

In forecasting BLS disease in mulberry, Maji et al. [67] found a significant positive correlation between disease severity and minimum air temperatures. Pohronezny and Volin [68] documented that early-stage BLS infection in tomato led to reduced marketable fruit weight as a result of defoliation. Jenkins [69] also observed a decrease in bell pepper production with increased BLS infection. Infected bell pepper plants exhibited reduced fruit quality attributes, including decreased fruit length, diameter, number, and weight per plant [43], effects that were also observed in the present study.

In the present study, jalapeño pepper yields under colored shade nets tended to decrease but were not significantly different from those of the unshaded treatment. In contrast, Díaz-Pérez et al. [70] reported increased bell pepper yields under shaded conditions. Similarly, Rylski and Spigelman [19] and Kabir et al. [56] observed enhanced bell pepper production at shading levels of 26% to 30% compared to unshaded conditions. Consistent with the findings of the present study, Gent [71] reported a decrease in tomato yield with increasing shading intensities.

The contrasting responses of jalapeño pepper to shading, compared to bell pepper in previous studies, may be attributed to the increased susceptibility of bell pepper to physiological disorders such as sunscald [10,14] and blossom-end rot [72,73] under unshaded conditions. However, in our study, no such physiological disorders were observed in either shaded or unshaded conditions.

In bell pepper, Kabir et al. [56] found that maximum net photosynthesis, ETR, and WUE occurred at 19% shade, which was associated with increased yield. Likewise, a meta-analysis of fruiting vegetable responses at different shade levels suggested that fruit yield tends to increase at 20% shading [74]. In contrast, the shade nets used in the present study provided 30% to 50% shading, which may not represent ideal conditions for flowering and fruiting in jalapeño pepper, potentially contributing to the observed yield reductions.

To date, no information is available regarding the optimum RZT required for fruit production in jalapeño peppers. In a previous study, Díaz-Pérez and Batal [75] reported that tomato yield decreased when the mean seasonal RZT exceeded 26.3 °C. In contrast, the present study found that total jalapeño pepper yield increased linearly with rising mean RZT. These findings suggest that jalapeño peppers may exhibit greater resilience to heat stress compared to bell peppers and tomatoes.

5. Conclusions

This study showed that the use of colored shade nets did not significantly improve the marketable yield of jalapeño peppers compared to plants grown under full sun in the southeastern USA. Instead, both marketable and total yields tended to increase with

higher light intensity, indicating the crop's tolerance to full sunlight. Although bacterial leaf spot (BLS) likely affected yield outcomes in 2019, results from the disease-free 2021 season confirmed that shading still did not provide a yield advantage under healthier growing conditions.

However, shade nets positively influenced plant growth and microclimatic conditions. All nets reduced light intensity and lowered root zone temperatures, which could prove beneficial under heat stress conditions, conserve water, and potentially extend the growing season. Shaded plants were taller, had thicker stems, a larger leaf area, and higher chlorophyll content compared to unshaded plants.

Overall, while moderate shading (around 40%) did not confer a yield advantage in jalapeño pepper, it did help create a more favorable growing environment for plants. These findings suggest that jalapeño pepper, unlike bell pepper, may be better suited to full sun exposure. Future studies should explore varying levels of shading, alternative net colors, or combinations with heat-sensitive cultivars to refine shading strategies. A deeper understanding of how shading influences plant physiology, disease dynamics, and fruit quality could also aid growers in adapting production systems to the challenges posed by a warming climate.

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