



Research article

Influence of shading on growth, physiological responses and yield of field-grown Habanero chili (*Capsicum chinense* Jacq.)

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Abstract

Importance of the work: Research on habanero (*Capsicum chinense* Jacq.) chili production and physiology remain limited, despite their economic and culinary relevance.

Objectives: To assess the effects of shade levels on the plant growth, fruit yield, and chemical composition of habanero.

Materials and Methods: A two-season field experiment was conducted using five shade levels [0% (unshaded), 30%, 47%, 63%, 80%] and two cultivars ('Kukulkan' and 'Kabal'). The experiment was conducted using a randomized complete block design with 4 replications and 10 treatments, comprising 5 shade levels and 2 cultivars. Response variables were environmental factors, plant height and stem diameter, leaf pigment content, fruit yield, postharvest water loss and fruit soluble solids, total phenolics, flavonoids, antioxidant capacity, and capsaicin concentration.

Results: Shade-grown plants were taller and had thinner stems relative to unshaded plants. Shading decreased root-zone and canopy temperatures, lowered evaporative demand and reduced plant water use. Total and marketable yields under 30% and 47% shade were comparable to those under unshaded conditions; however, yields declined significantly at 63% and 80% shade levels. While the number of fruits decreased with increasing shade, the individual fruit weight increased. Kukulkan consistently produced higher total and marketable yields than Kabal. Shading reduced fruit soluble solids, total phenols and antioxidant capacity; however, it did not affect capsaicinoid or carotenoid contents, the incidence of fruit sunscald or blossom-end rot or the postharvest rate of fruit water loss.

Main finding: Shading did not increase fruit yields compared to unshaded conditions. However, moderate shading (30% and 47%) did increase individual fruit weight and reduce crop water use. Therefore, moderate shading may be a viable strategy to mitigate environmental challenges without compromising habanero fruit yield or quality.

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Introduction

Capsicum species—commonly known as chilis or peppers—are cultivated worldwide not only as food crops but also as ornamentals, in cosmetics, and as natural pesticides, as well as for making pickles and flavoring products (Bosland and Votava, 2012; Baruah and Lal, 2020). The term “habanero” is derived from La Habana (known in English as Havana), the capital city of Cuba, with the fruit being consumed widely in Mexico, particularly in the Yucatán Peninsula, as well as in Central America, Venezuela and the Caribbean (Macías-Rodríguez et al., 2013). Among the various types of *C. chinense*, the habanero and Scotch bonnet are the most recognized (Lim, 2013).

The heat sensation of chili peppers is produced by alkaloids known as capsaicinoids, compounds present exclusively in the genus *Capsicum* (Pino et al., 2007; Chinn et al., 2011). Among these, capsaicin and dihydrocapsaicin account for about 90% of the total pungency (Lim, 2013; Castro-Concha et al., 2014). Habanero peppers are aromatic and the most pungent among peppers (Lim, 2013). In addition, capsaicin extracted from chili fruit has diverse pharmaceutical applications, including anti-arthritic, anti-obesity, thermoregulatory, anti-cancer, antioxidant, antimicrobial, anti-inflammatory and cardiovascular benefits (Baruah and Lal, 2020).

Habanero pepper is a perennial shrub, 40–150 cm tall, with green-to-pale-green leaves and is self-pollinated (Baruah and Lal, 2020). The fruit is 5 cm long, 2.5 cm wide at the shoulder, lantern-shaped, glossy, and highly pungent [200,000 to 300,000 Scoville heat units (SHU)]; ripe fruits may be orange, red, yellow, or white (Monforte-Gonzalez et al., 2010). Its pungency and distinctive flavor make it a popular chili (Davis et al., 2007; Jarret et al., 2009; Castro-Concha et al., 2014; Baruah and Lal, 2020).

In the USA, both pungent and non-pungent pepper production is concentrated in New Mexico, California, Arizona, Texas, Florida and Georgia. Demand for fresh and dried pungent peppers, including habanero, continues to grow; however, there are no specific statistics on habanero production in the USA, as for statistical purposes, habaneros are included under the general category of “chili peppers” (Wechsler, 2023). Typically, habanero is grown in open, unshaded fields (López-Gómez et al., 2020), with yields in the range of 10–40 t/ha in Mexico (Macías-Rodríguez et al., 2013). Compared to bell pepper, which has been studied thoroughly, there are relatively few published reports on the physiology and production of habanero peppers.

Shade nets are widely used in tropical and subtropical regions for growing a variety of vegetables and fruits. Typically, with bell peppers, shading enhances plant growth, fruit size and yield and may alter the fruit composition (del Amor et al., 2008; Diaz-Perez, 2013; Díaz-Pérez, 2014; Ayala-Tafoya et al., 2015; Ambrozy et al., 2016; Ilic et al., 2017). By lowering radiant heat and evaporative demand, shade nets reduce plant water stress and increase irrigation efficiency in bell pepper (Kittas et al., 2012; Kabir et al., 2020). These benefits are primarily due to reduced solar radiation, air temperature and soil temperature, which help mitigate heat-related stress in plants (Castellano et al., 2008; Arthurs et al., 2013). However, few studies have examined the effects of shading on habanero pepper, as most research has focused on bell pepper. Therefore, the current study should contribute valuable information to address that gap.

Shade nets vary in color and shading percentage, with an increasing shading percentage diminishing the adverse effects of intense solar radiation and high temperatures. However, excessive shading can reduce the light available for photosynthesis, potentially lowering crop productivity. Determining the optimal shading level is crucial for balancing light reduction and alleviating heat stress. In bell pepper, the optimal shade level ranges from 30% [midday photosynthetic photon flux density (PPFD) $\approx 1,400 \mu\text{mol}/\text{m}^2/\text{s}$] to 47% (PPFD $\approx 1,060 \mu\text{mol}/\text{m}^2/\text{s}$), where the benefits of reduced heat load outweigh the drawbacks of diminished light intensity (Diaz-Perez, 2013).

Although shading has been investigated extensively in *Capsicum annuum* L., its role has received little attention in the cultivation of *C. chinense*, particularly in habanero chili (Jaimez and Rada, 2006; Jeeatid et al., 2017; Jiménez-Viveros and Valiente-Banuet, 2023; Cruz et al., 2024). The few available studies have reported mixed responses that vary by shading intensity and production environment. For example, work in Venezuela found that unshaded habanero plants and those grown under 40% shade produced similar yields, whereas 60% shading reduced yields (Jaimez and Rada, 2006). Furthermore, limited information exists regarding the optimal environmental conditions for growing habanero chili (Bosland and Votava, 2012), with, for example, the temperature range suitable for *C. chinense* reported to be similar to that of *C. annuum* (7–29°C). However, this generalization likely reflects a lack of specific research on *C. chinense*, especially given the known variation in temperature requirements among *C. annuum* cultivars (Lim, 2013). From the discussion, it is clear that shading can be advantageous for fruit yield

and quality under high-temperature conditions; however, the ideal shading level for habanero production remains unresolved. The present study aimed to address this gap based on the examination of the effect of varying shade levels (percentages) on plant growth, fruit yield and chemical composition of field-grown habanero chilies in southeastern USA.

Materials and Methods

The experiment was carried out under open-field conditions at the Horticulture Farm of the University of Georgia, Tifton, GA, USA (31.4803° N–83.5211° W; 108 m above sea level), during the spring-summer growing seasons of 2013 (first year) and 2014 (second year). The soil at the site is classified as Tifton Sandy Loam (fine, loamy-siliceous, thermic Plinthic Kandiudults) with an approximate pH of 6.5. Habanero pepper seedlings were produced in a greenhouse using a peat-based growth medium (Pro-Mix; Quakertown, PA, USA) in polystyrene trays with 200 cells (each 2.5 cm × 2.5 cm). At age 6 wk, the seedlings were transplanted by hand on 16 April in the first year and on 14 May in the second year, in double rows per bed, spaced 30 cm between plants and 36 cm between rows.

Habanero peppers were established in raised beds (1.8 m center-to-center spacing; 0.76 m wide) covered with low-density black polyethylene mulch (1.52 m wide, 25 mm

thick; Interagro; Clearwater, FL, USA) and supplied with drip irrigation, according to the production guidelines for bell pepper from the University of Georgia Extension (Kelley et al., 2009), as shown in Fig. 1. A single drip line (30 cm emitter interval, 12.6 mL/min per emitter at 0.55 bar pressure; Aqua Traxx; Toro; Abilene, TX, USA) was installed at a depth of 3 cm along the bed center. Each experimental unit consisted of a single bed, 3 m in length, containing 20 plants. Before transplanting, the soil was amended with N, P and K at rates of 67, 29 and 56 kg/ha, respectively, using a 10–10–10 granular formulation (Rainbow Plant Food; Montgomery, AL, USA), incorporated using rotary tillage. Supplemental N and K fertilization was provided weekly through fertigation beginning 4 wk after transplanting. In total, each plant received 205 kg/ha N, 29 kg/ha P and 240 kg/ha K. Irrigation scheduling supplied water equivalent to 100% of crop evapotranspiration (ET_c), determined as the product of reference evapotranspiration and the crop coefficient for plastic-mulched bell pepper (Simonne et al., 2006). Water applications were triggered when the cumulative ET_c reached 1.2 cm.

The experiment applied a randomized complete block design with 4 replications and 10 treatments, consisting of 5 shade percentages combined with 2 cultivars. Shade treatments consisted of 0% (full sun), 30%, 47%, 63% and 80%, as specified by the shade cloth manufacturer. The actual shade intensity was verified using a photosynthetically active radiation quantum sensor (LI-6400/XT; LI-COR; Lincoln, NE, USA).

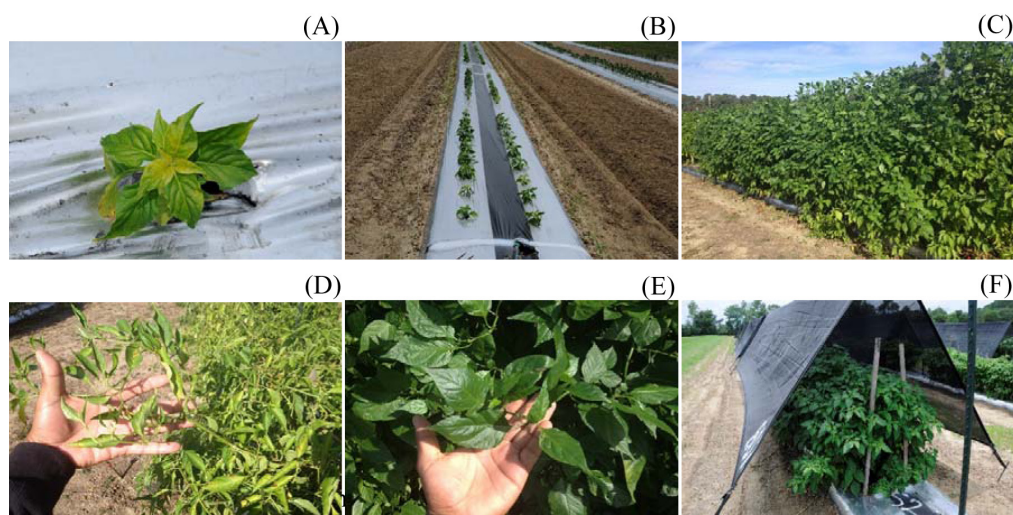


Fig. 1 Photographs taken during the 2013 growing season in Tifton, GA, USA, illustrating habanero plant development: (A) seedlings at early growth stage; (B) young seedlings established in plastic-mulched beds; (C) mature habanero plants; (D) leaves from sun-grown plants; (E) leaves from shade-grown plants; (F) habanero plants cultivated under shade net.

The cultivar treatments consisted of ‘Kabal’ (orange-fruited; Seedway; Lakeland, FL, USA) and ‘Kukulkan’ (red-fruited; Seedway; Lakeland, FL, USA). Shade nets (black polypropylene; Baycor Industrial Fabric; Pendergrass, GA; USA) were installed using metal posts and supporting cables. The structures were pyramidal, reaching a maximum height of 2.0 m at the center of the bed. The base of the structure was about 3 m wide. Shade netting was placed over the crop 4 wk after transplanting (Figs. 2 and 3) on 14 May 2013 and 11 June 2014. The photosynthetic active radiation at 1200 hours and the shading percentage of nets were measured using a ceptometer (SunFleck Ceptometer; Decagon Devices; Pullman, WA, USA).

Microenvironmental factors

Midday canopy temperature was monitored weekly on clear days (three plants per plot) using an infrared thermometer (Spectrum Technologies; Plainfield, IL, USA). The root-zone temperature (RZT) at midday was measured at an 8 cm soil depth using thermocouple probes (Omega Engineering, HPS-HT Series, Stamford, CT, USA) connected to a digital thermometer (Omega Engineering, HH Series) (Model; Maker; Location details). Volumetric soil water content was assessed weekly (three readings per plot) using a portable time-domain reflectometry (TDR) probe (CS-620; Campbell Scientific; Logan, UT, USA),

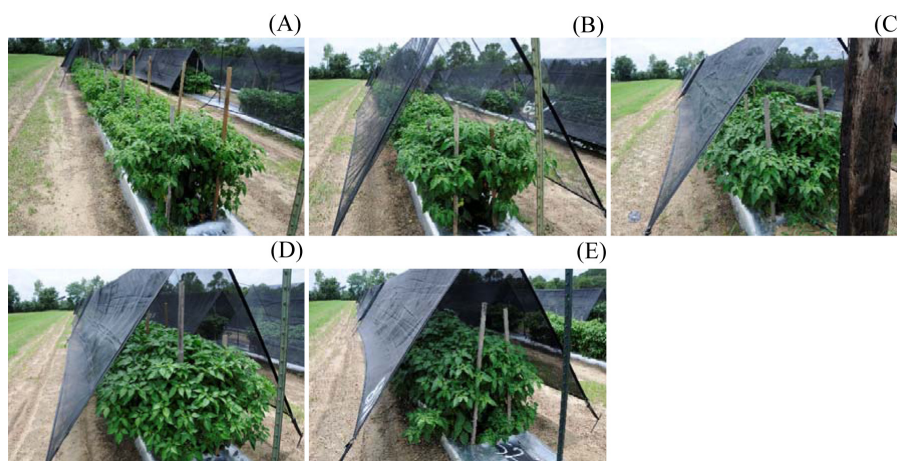


Fig. 2 Habanero plants grown during the 2013 growing season in Tifton, GA, USA, under different shade levels: (A) open field (0% shade); (B) 30% shade; (C) 47% shade; (D) 63% shade; (E) 80% shade.

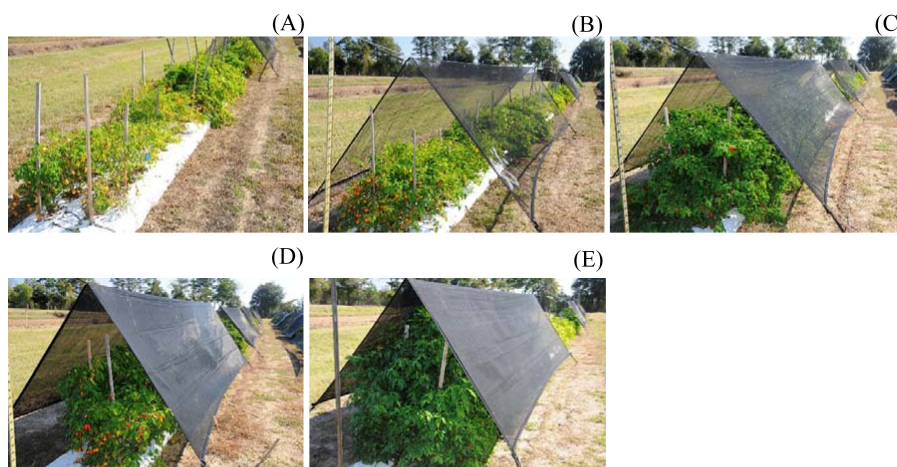


Fig. 3 Photographs showing habanero plants grown during the 2014 growing season in Tifton, GA, USA, under different shade levels: (A) open field (0%); (B) 30%; (C) 47%; (D) 63%; (E) 80% shade.

with 12 cm metallic rods inserted vertically between plants in the row. Measurements of canopy temperature, root-zone temperature and soil water content were collected from 30 May to 6 November in Year 1 and from 10 July to 6 October in Year 2. Daily maximum, mean and minimum air temperatures, as well as rainfall data, were obtained from a University of Georgia weather station located within 300 m of the site.

Stem diameter, plant height and leaf pigments

The plant height and stem diameter of three habanero plants per plot were measured weekly. For pigment analysis, leaf discs (2 cm²; three healthy, fully expanded leaves per plot) were sampled from interveinal regions, placed into test tubes and extracted in about 1.5 mL of absolute ethanol (100% volume per volume) for 24 hr. The chlorophyll *a*, chlorophyll *b* and carotenoid contents were quantified spectrophotometrically, based on concentrations calculated from absorbance readings at 470, 649 and 664 nm following the method of Lichtenthaler and Wellburn (1983). In addition, the leaf chlorophyll index was measured weekly throughout the growing season on three well-exposed, mature and healthy leaves per plot sampled from the upper canopy using a SPAD chlorophyll meter (SPAD-502; Minolta Co., Ltd; Ramsey, NJ, USA).

Harvesting

The habanero chili fruits (full color) were harvested (10 plants per plot) six times in Year 1 (15 and 24 July, 12 and 27 August, 16 September and 2 October) and nine times in Year 2 (29 July, 5 and 14 August, 2 and 16 September, 1 and 23 October and 4 and 14 November). Fruits were graded as marketable (fruit free from damage) and non-marketable [fruit with sunscald or blossom-end rot (BER); damage from insect, disease, or mechanical impact]. Fruit numbers and weights were recorded. The total fruit number and weight were calculated (marketable + non-marketable). Mean fruit weight was determined by dividing the total weight of marketable fruits by the corresponding number of marketable units.

Postharvest fruit water loss

Fruit samples (four per plot) were placed on trays and stored at 20°C under controlled conditions (vapor pressure deficit of 0.702 kPa and air velocity < 0.2 m/s). Fruit water loss was determined by weighing individual fruits daily for 7 d. The fruit water loss rate (WLR) was expressed as the percentage

of weight loss per day (% loss/day), according to Equation 1 developed by Díaz-Pérez et al. (2007):

$$\text{WLR} = (\Delta\text{FW} / \text{FWo}) \times (100 / t) \quad (1)$$

where ΔFW is the change in fresh weight (FW) between measurements, t is the interval in days between successive weighings and FWo is the initial fruit fresh weight at the beginning of the weighing period.

Fruit chemical attributes

Fruit juice samples were obtained by manually pressing a portion of the pericarp, after which the juice was filtered through two layers of cheesecloth. Four fruits per plot (a total of 16 fruits per shade treatment) were analyzed. The soluble solids content (SSC) was determined using a handheld digital refractometer (Brixstix 3810 PAL-1; Atago; Livermore, CA, USA) previously calibrated with distilled water.

For total phenolic compounds, fruits were homogenized and extracted in 95% ethanol for 48 hr at room temperature. Each sample was refrigerated at 4°C until analysis. Total phenols, expressed as gallic acid equivalents, were quantified using the Folin-Ciocalteu assay technique (Singleton et al., 1999). The total flavonoid content was determined from methanolic extracts and expressed as quercetin equivalents (Rawat et al., 2014). The antioxidant capacity was evaluated by both the Trolox equivalent antioxidant capacity (TEAC) and cupric reducing antioxidant capacity (CUPRAC) methods (Barros et al., 2007; Castro-Concha et al., 2014).

Capsaicin and dehydrocapsaicin (DHC) concentrations, along with total Scoville heat units (SHU), were measured by extracting 5 g of fruit tissue with 10 mL of 100% ethanol (Davis et al., 2007). Absorbance of extracts was read at 280 nm using an ultraviolet-visible spectrum spectrophotometer (DU 730 UV/VIS; Beckman Coulter; Brea, CA, USA), according to González-Zamora et al. (2015). The SHU value was calculated using Equation 2:

$$\text{SHU} = (\text{Capsicin} + \text{DHC}) \times 16 \quad (2)$$

where all weights were measured in micrograms per gram.

Fruit and seed dry weight (DW) was obtained after oven-drying samples at 70°C. The dry matter (DM) percentage was calculated using Equation 3:

$$\text{DM} = [(\text{DW} / \text{FW}) \times 100] \quad (3)$$

The fruit water content (WC) as a percentage was calculated using Equation 4:

$$WC = [(FW - DW / FW) \times 100] \quad (4)$$

Statistical analysis

Data were analyzed using the GLIMMIX procedure of the SAS® software (version 9.4; SAS Institute; Cary, NC, USA). Shade level, cultivar and shade level $\times$ cultivar interaction were considered fixed effects, whereas year, replication and the year $\times$ replication interaction were treated as random effects. When the shade level $\times$ cultivar interaction was significant, the simple effects were examined by testing the effect of shade level within each cultivar and the effect of cultivar within each shade level. Mean comparisons were performed using the Tukey-Kramer test at the 0.05 significance level. Pearson's correlation coefficients were obtained using the CORR procedure in SAS. Percentage data were arcsine-transformed before analysis, although untransformed means are presented in the tables for clarity.

Results

Temperature and rainfall

Seasonal trends of daily air temperatures and rainfall patterns for both years are shown in Fig. 4. During 2013 (16 April to 2 October), the average minimum and maximum temperatures were 19.4°C and 29.2°C, respectively, with a total rainfall of 890 mm. In 2014 (14 May to 14 November), the corresponding averages were 18.2°C and 29.6°C, respectively, with 557 mm of rainfall. At 1200 hours, the mean photosynthetic photon flux density was approximately 2,000 $\mu\text{mol}/\text{m}^2/\text{s}$.

Stem diameter and plant height

Stem diameter decreased, whereas plant height increased with increasing shade percentage (Table 1). Significant interactions between shade percentage and cultivar were observed for both variables in 2013 and 2014 (Tables 1 and 2). Kabal had thicker stems than Kukulkan at 30%, 47% and 80% shade, whereas there were no significant differences at 0% and 63% shade. At 80% shade, stem diameter decreased by 2.7% in Kabal and by 14.9% in Kukulkan compared to

full sun (0% shade). Kabal plants were taller than Kukulkan across all shade levels except at 30%. At 80% shade, plant height increased by 30.7% in Kabal and 29.0% in Kukulkan relative to 0% shade.

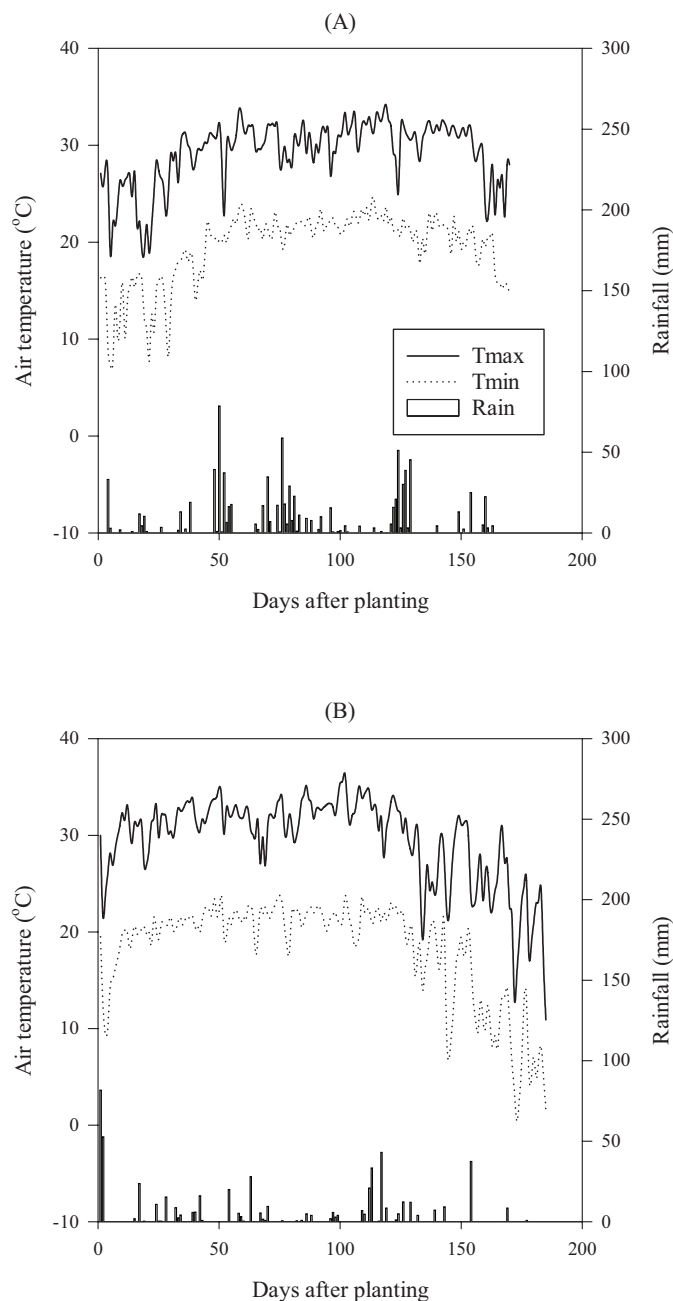


Fig. 4 Seasonal trends of daily maximum (Tmax) and minimum (Tmin) air temperatures and rainfall during growing seasons for habanero pepper plants transplanted on 16 April 2013 and 14 May 2014 in Tifton, Georgia, USA: (A) 2013; (B) 2014.

Table 1 Seasonal mean stem diameter, plant height, root-zone temperature (RZT), canopy temperature and volumetric soil water content (SWC) as affected by shade percentage and cultivar in habanero chili grown in Tifton, GA, USA.

	Stem diameter (mm)	Plant height (cm)	RZT (°C)	Canopy temperature (°C)	SWC (%)
Shade (%)					
0	22.2±5.8	66.0±23.8	28.6±3.3 ^a	27.7±2.4 ^a	3.88±2.05
30	22.3±6.0	70.6±25.9	27.8±3.1 ^b	27.0±2.1 ^b	3.39±1.84
47	22.5±6.2	77.8±30.6	27.0±2.9 ^c	26.8±2.1 ^{bc}	3.77±1.95
63	21.0±5.7	79.2±34.8	26.5±2.7 ^d	26.6±2.1 ^c	3.56±1.85
80	20.3±6.0	86.0±42.4	25.9±2.7 ^e	27.1±2.8 ^b	4.19±1.94
Cultivar					
Kabal	22.2±6.2	80.2±36.4	27.1±3.1	27.0±2.3	3.59±1.91
Kukulkan	21.1±5.8	71.6±28.2	27.2±3.1	27.0±2.3	3.92±1.98
Shade (S)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar (C)	<0.0001	<0.0001	0.051	0.538	<0.0001
S × C	<0.0001	0.008	0.582	0.745	0.030
L	0.001	<0.0001	<0.0001	0.001	0.010
Q	0.0004	<0.0001	<0.0001	<0.0001	<0.0001

L = linear; Q = quadratic response.

Values within a column followed by different lower case letters are significantly different ($p < 0.05$), based on Tukey-Kramer test. Superscript letters are shown only for variables without a significant shade × cultivar interaction; variables with significant interaction are presented in Table 2.

Table 2 Interaction effects of shade percentage and cultivar on stem diameter, plant height and volumetric soil water content in habanero chili grown in Tifton, GA, USA.

Shade (%)	Kabal	Kukulkan	<i>p</i> value
Stem diameter (mm)			
0	22.3±6.0 ^{bcA}	22.1±5.7 ^{aA}	0.463
30	22.8±6.4 ^{abA}	21.7±5.6 ^{abB}	0.0001
47	23.3±6.4 ^{aA}	21.8±5.9 ^{abB}	<0.0001
63	20.9±5.7 ^{dA}	21.1±5.7 ^{bA}	0.725
80	21.7±6.2 ^{cdA}	18.8±5.6 ^{cB}	<0.0001
<i>p</i> value	<0.0001	<0.0001	
Plant height (cm)			
0	69.6±25.7 ^{cA}	62.4±21.4 ^{cB}	0.0004
30	72.1±28.8 ^{cA}	69.2±22.9 ^{bA}	0.164
47	82.5±34.4 ^{bA}	73.0±25.8 ^{bB}	<0.0001
63	85.5±40.3 ^{bA}	72.9±27.2 ^{bB}	<0.0001
80	91.5±45.7 ^{aA}	80.5±38.3 ^{aB}	<0.0001
<i>p</i> value	<0.0001	<0.0001	
Soil water content (%)			
0	3.63±1.9 ^{abB}	4.11±2.2 ^{abA}	0.0002
30	3.38±1.9 ^{bA}	3.40±1.8 ^{cA}	0.834
47	3.52±1.9 ^{bB}	4.02±1.9 ^{bA}	<0.0001
63	3.46±1.9 ^{bA}	3.67±1.8 ^{cA}	0.089
80	3.97±1.9 ^{aB}	4.42±2.0 ^{aA}	0.0005
<i>p</i> value	<0.0001	<0.0001	

Values within a column followed by different lowercase letters and within a row followed by different uppercase letters are significantly different ($p < 0.05$), based on Tukey-Kramer test.

Root zone temperature, canopy temperature and soil water content

RZT and canopy temperature values were highest under the 0% shade and declined with increasing shade levels (Table 1). Compared to the unshaded control, the RZT decreased by 0.8, 1.6, 2.1 and 2.7°C at 30%, 47%, 63% and 80% shade, respectively, while canopy temperature was reduced by 0.7,

0.9, 1.1 and 0.6 °C, respectively. The SWC was influenced by a shade percentage × cultivar interaction. The SWC was highest at 80% shade in both cultivars, with Kukulkan having higher values than Kabal at 0%, 47% and 80% shade (Table 2).

Leaf chlorophyll and carotenoids

The leaf Chl *a* and chlorophyll index (SPAD) increased quadratically with shade, peaking at 63% shade level (Table 3). The shade percentage did not significantly affect Chl *b* or carotenoid content. Kukulkan had higher Chl *a*, Chl *b* and SPAD values than Kabal, while the carotenoid levels were similar between the cultivars.

Table 3 Seasonal mean leaf chlorophyll *a* and *b*, carotenoids and chlorophyll index (SPAD) in habanero chili grown in Tifton, GA, USA, as affected by shade percentage and cultivar

	Chl <i>a</i> (µg/mL)	Chl <i>b</i> (µg/mL)	Carotenoids (µg/mL)	SPAD
Shade (%)				
0	3.12±0.55 ^b	1.34±0.17	1.00±0.12	49.6±1.5 ^{ab}
30	3.78±0.46 ^{ab}	1.61±0.20	1.09±0.08	51.2±1.8 ^a
47	3.81±0.20 ^{ab}	1.56±0.06	1.07±0.04	50.0±1.3 ^{ab}
63	4.16±0.16 ^a	1.59±0.18	1.15±0.02	51.2±2.1 ^a
80	3.53±0.66 ^{ab}	1.40±0.24	0.94±0.12	47.8±2.3 ^b
Cultivar				
Kabal	3.39±0.52 ^b	1.38±0.14 ^b	1.00±0.12	48.6±1.9 ^b
Kukulkan	3.97±0.28 ^a	1.62±0.12 ^a	1.10±0.05	51.3±1.8 ^a
Shade (S)	0.023	0.183	0.082	0.002
Cultivar (C)	0.005	0.008	0.067	<0.0001
S × C	0.700	0.896	0.660	0.076
L	0.087	0.545	0.868	0.192
Q	0.017	0.073	0.083	0.003

Values within a column followed by different lowercase letters are significantly different ($p < 0.05$), based on Tukey-Kramer test.

Fruit yield

In general, fruit number decreased as shading increased (Table 4). Marketable and total yields remained relatively stable from 0% to 47% shade; however, fruit number decreased at 63% and 80% shade levels (Fig. 5). The yield of non-marketable fruit decreased and individual fruit size increased with an increasing shade percentage. Shading had no significant effect on the incidence of sunscald, blossom-end rot (BER), or insect damage. Kabal was more susceptible to sunscald and BER than Kukulkan, although both disorders occurred at low incidences (< 2.5%). Based on a planting density of 36,880 plants/ha, the fruit number per plant ranged from 111 (0% shade) to 18 (80% shade).

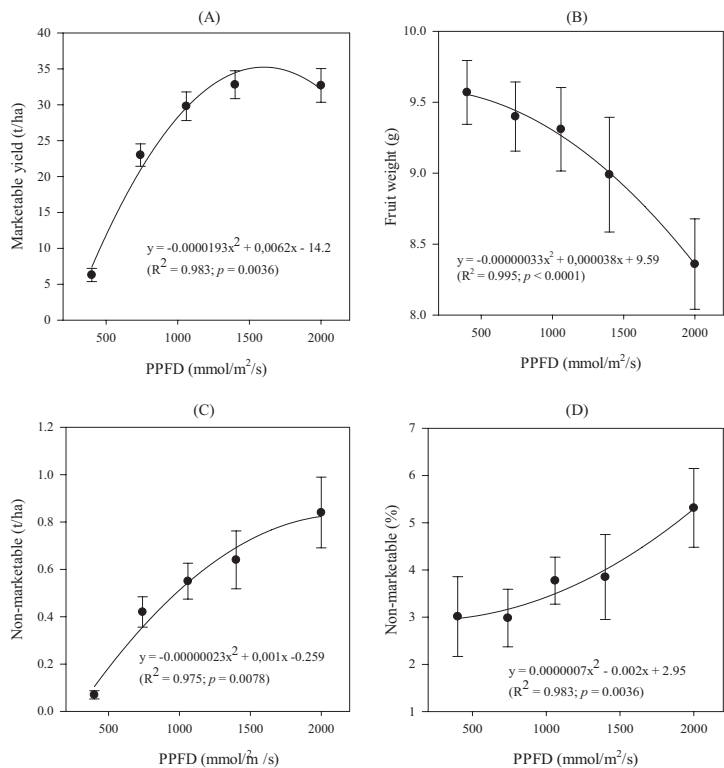


Fig. 5 (A) Habanero fruit marketable yield; (B) individual fruit weight; (C) non-marketable yield; (D) percentage of non-marketable relative to total yield of habanero fruit as a function of photosynthetic photon flux density (PPFD). Each point represents the pooled mean ± SE across cultivars for the cumulative yields of two seasons (Years 1 and 2). R² = coefficient of determination.

Table 4 Fruit number, yield and incidence of physiological disorders in habanero chili grown in Tifton, GA, USA, as influenced by shade percentage and cultivar

Shade (%)	Marketable		Non-marketable		Total	Fruit wt (g/fruit)	Sunscald (%)	BER (%)	Insect damage (%)
	(1,000 fruit/ha)	(t/ha)	(1,000 fruit/ha)	(t/ha)	(1,000 fruit/ha)	(t/ha)	(%)	(%)	(%)
0	3,976±1,264 ^a	32.7±9.4 ^a	134.7±92.1 ^a	0.84±0.60 ^a	4,111±1,264 ^a	33.5±3.7 ^a	2.36±1.9	0.54±0.57	0.12±0.18
30	3,699±903 ^{ab}	32.8±7.8 ^a	94.1±69.2 ^b	0.64±0.49 ^{ab}	3,793±884 ^{ab}	33.4±7.7 ^a	1.45±1.4	0.40±0.55	0.12±0.20
47	3,211±796 ^b	29.8±8.0 ^a	77.8±41.1 ^b	0.55±0.30 ^{ab}	3,288±794 ^b	30.4±8.1 ^a	1.44±1.1	0.30±0.36	0.11±0.14
63	2,448±603 ^c	23.0±6.2 ^b	57.4±31.2 ^b	0.42±0.26 ^b	2,506±599 ^c	23.4±6.2 ^b	1.73±1.2	0.36±0.33	0.12±0.21
80	659±373 ^d	6.3±3.7 ^c	7.8±7.8 ^c	0.07±0.07 ^c	667±373 ^d	6.4±3.7 ^c	1.38±2.8	0.34±0.85	0.03±0.07
Cultivar									
Kabal	2,508±1,391 ^b	21.7±11.0 ^b	78.6±68.6	0.51±0.44	2,587±1,419 ^b	8.94±0.87	2.12±2.1 ^a	0.52±0.69 ^a	0.13±0.21
Kukulkan	3,089±1,469 ^a	28.1±12.8 ^a	70.1±70.7	0.50±0.48	3,159±1,505 ^a	9.31±1.55	1.23±1.2 ^b	0.26±0.34 ^b	0.07±0.10
p value	<0.0001	<0.001	<0.0001	<0.001	<0.0001	<0.001	0.301	0.588	0.250
Shade (S)	0.0006	<0.001	0.448	0.870	0.001	0.069	0.009	0.013	0.086
Cultivar (C)									
S × C	0.933	0.807	0.623	0.839	0.936	0.562	0.690	0.225	0.342
L	<0.0001	<0.001	<0.0001	<0.001	<0.0001	0.003	0.174	0.274	0.195
Q	<0.0001	<0.001	<0.0001	<0.001	<0.0001	0.009	0.273	0.433	0.235

Values within a column followed by different lowercase letters are significantly different ($p < 0.05$), based on Tukey-Kramer test.

Postharvest fruit water loss

Shade percentage did not significantly influence postharvest fruit water loss (weight loss), which averaged 1.86% per day. After storage for 7 d at 20°C and a vapor pressure deficit of 0.702 kPa, the fruit weight loss averaged 13.0%, and the fruits were noticeably soft. Kabal had greater water loss (1.99% per day) than Kukulkan (1.73% per day). There was no significant interaction between shade and cultivar for fruit water loss (data not shown).

Fruit chemical attributes

The SSC showed a significant shade $\times$ cultivar interaction (Tables 5 and 6). In both cultivars, SSC was highest at 0% and 30% shade. Above 47% shade, the SSC values remained stable in Kabal but decreased to their lowest level at 80% shade in Kukulkan (Table 6). Total phenols, TEAC and CUPRAC decreased with increasing shade. Shade percentage did not affect flavonoids, capsaicin, dihydrocapsaicin (DHC), or Scoville heat units (SHU), as shown in Table 5. The two cultivars had similar SSC, total phenols, TEAC and CUPRAC levels, while Kabal had higher concentrations of flavonoids, capsaicin, DHC and SHU than Kukulkan.

Fruit and seed fresh and dry weights

The fruit fresh weight (FW) and dry weight (DW) followed a quadratic trend with increasing shade, whereas the dry matter (DM) content declined linearly and the water content (WC) increased linearly (Table 7). Seed FW and DW were highest at 47% shade. Shade percentage did not significantly influence seed number or seed weight. Compared to Kabal, Kukulkan produced fruits with higher FW and WC but lower DM, seed FW and seed DW. Both cultivars had similar fruit DW, seed number and seed weight.

Table 6 Interaction effects of shade percentage and cultivar on fruit soluble solids in habanero chili grown in Tifton, GA, USA

Shade (%)	Kabal	Kukulkan	<i>p</i> value
0	5.9 $\pm$ 0.6 ^{aA}	5.1 $\pm$ 0.2 ^{abB}	0.037
30	5.0 $\pm$ 0.3 ^{abB}	5.9 $\pm$ 0.6 ^{aA}	0.016
47	4.1 $\pm$ 1.1 ^{bA}	4.6 $\pm$ 1.4 ^{bA}	0.161
63	4.6 $\pm$ 0.7 ^{bA}	5.0 $\pm$ 0.8 ^{abA}	0.291
80	4.8 $\pm$ 1.3 ^{bA}	3.2 $\pm$ 1.4 ^{cB}	0.0002
<i>p</i> value	0.0002	<0.0001	

Values within a column followed by different lowercase letters and within a row followed by different uppercase letters are significantly different ($p < 0.05$), based on Tukey-Kramer test.

Table 5 Chemical components in habanero chili fruits grown in Tifton, GA, USA, as influenced by shade percentage and cultivar

Shade (%)	SSC (%)	Total phenols [gallic acid equivalents (mg/L)]	TEAC (μ M)	CUPRAC (μ M)	Flavonoids [quercetin equivalents (μ g/mL)]	Capsaicin (μ g/g)	DHC (μ g/g)	SHU (μ g/g)
0	5.50 $\pm$ 0.6	486 $\pm$ 87 ^a	2,123 $\pm$ 840 ^a	928 $\pm$ 389 ^a	78.3 $\pm$ 30.3	7,322 $\pm$ 3,297	5,583 $\pm$ 2,512	206,476 $\pm$ 92,863
30	5.44 $\pm$ 0.6	452 $\pm$ 81 ^{ab}	1,814 $\pm$ 563 ^{ab}	770 $\pm$ 317 ^{ab}	76.1 $\pm$ 20.3	8,183 $\pm$ 3,731	6,264 $\pm$ 2,805	231,152 $\pm$ 104,535
47	4.38 $\pm$ 1.1	418 $\pm$ 85 ^{abc}	1,851 $\pm$ 551 ^{ab}	702 $\pm$ 297 ^{ab}	72.2 $\pm$ 14.6	7,093 $\pm$ 1,987	5,411 $\pm$ 1,578	200,065 $\pm$ 56,998
63	4.81 $\pm$ 0.7	404 $\pm$ 79 ^{bc}	1,460 $\pm$ 534 ^b	529 $\pm$ 287 ^b	72.1 $\pm$ 13.6	7,078 $\pm$ 2,006	5,418 $\pm$ 1,608	199,941 $\pm$ 57,742
80	4.15 $\pm$ 1.5	366 $\pm$ 132 ^c	1,372 $\pm$ 359 ^b	489 $\pm$ 454 ^b	66.0 $\pm$ 17.2	6,194 $\pm$ 2,920	4,713 $\pm$ 2,351	174,505 $\pm$ 84,290
Cultivar								
Kabal	4.90 $\pm$ 1.0	431 $\pm$ 98	1,638 $\pm$ 472	696 $\pm$ 373	81.8 $\pm$ 21.3 ^a	7,818 $\pm$ 3,179 ^a	5,977 $\pm$ 2,394 ^a	220,732 $\pm$ 89,112 ^a
Kukulkan	4.87 $\pm$ 1.1	419 $\pm$ 106	1,810 $\pm$ 765	671 $\pm$ 394	64.1 $\pm$ 14.1 ^b	6,529 $\pm$ 2,398 ^b	4,978 $\pm$ 1,947 ^b	184,124 $\pm$ 69,469 ^b
<i>p</i> value								
Shade (S)	<0.0001	0.0015	0.0004	0.0003	0.295	0.359	0.340	0.361
Cultivar (C)	0.472	0.509	0.134	0.697	<0.0001	0.036	0.037	0.037
S $\times$ C	<0.0001	0.810	0.530	0.643	0.348	0.764	0.773	0.769
L	0.0002	0.002	0.0003	0.0009	0.142	0.149	0.138	0.144
Q	0.0008	0.008	0.0012	0.004	0.337	0.125	0.106	0.116

SSC = soluble solids content; TEAC = Trolox equivalent antioxidant capacity; CUPRAC = cupric reducing antioxidant capacity; DHC = dihydrocapsaicin; SHU = Scoville heat units. Values within a column followed by different lowercase letters are significantly different ($p < 0.05$), based on Tukey-Kramer test.

Table 7 Influence of shade percentage and cultivar on fruit and seed fresh and dry weights, fruit dry matter and water content, and seed number in habanero chili fruit grown in Tifton, GA, USA

	Fruit				Seed			
	FW (g)	DW (g)	DM (%)	WC (%)	FW (mg/fruit)	DW (mg/fruit)	Number per fruit	FW (mg/seed)
Shade (%)								
0	7.9±1.8 ^b	0.873±0.19	11.2±1.5 ^a	88.7±1.5 ^b	282±110 ^b	119±90 ^b	39.0±10	7.0±2.1
30	9.5±2.1 ^{ab}	0.989±0.15	10.6±1.2 ^{ab}	89.4±1.2 ^{ab}	298±190 ^b	147±130 ^{ab}	39.3±19	8.0±3.1
47	10.2±2.3 ^a	0.997±0.21	9.9±1.2 ^b	90.1±1.2 ^a	446±250 ^a	219±160 ^a	47.2±18	8.9±2.9
63	10.3±2.9 ^a	1.027±0.26	10.1±1.4 ^b	89.9±1.4 ^a	276±150 ^b	143±130 ^{ab}	36.3±18	9.2±10.3
80	10.0±2.8 ^a	0.953±0.26	9.7±1.3 ^b	90.3±1.3 ^a	279±200 ^b	089±70 ^b	33.8±18	8.6±5.1
Cultivar								
Kabal	9.1±2.3 ^b	0.954±0.23	10.6±1.4 ^a	89.4±1.4 ^b	370±210 ^a	169±140 ^a	40.3±17	9.3±3.6
Kukulkan	10.1±2.7 ^a	0.987±0.21	10.0±1.3 ^b	90.0±1.3 ^a	260±160 ^b	121±110 ^b	37.9±18	7.3±6.9
<i>p</i> value								
Shade (S)	0.003	0.134	0.0004	0.0004	0.003	0.002	0.083	0.683
Cultivar (C)	0.016	0.434	0.009	0.009	0.001	0.018	0.462	0.057
S × C	0.190	0.248	0.178	0.172	0.073	0.0004	0.238	0.133
L	0.002	0.134	<0.0001	<0.0001	0.980	0.505	0.314	0.227
Q	0.0008	0.050	0.0001	0.0001	0.113	0.012	0.119	0.430

Values within a column followed by different lowercase letters are significantly different ($p < 0.05$), based on Tukey-Kramer test.

Discussion

Stem diameter and plant height

Shading is well recognized for promoting vegetative growth in *Capsicum* species (Jaimez and Rada, 2006; Gregoriou et al., 2007; Díaz-Pérez, 2013; Valiente-Banuet and Gutiérrez-Ochoa, 2016; Kabir et al., 2020; De La Cruz-Ricardez et al., 2023). Typically, shade-adapted plants develop larger leaf areas and higher specific leaf areas, with thinner leaves and taller stems than those grown under high light intensity (Larcher, 1995). In the present study, habanero plants exhibited characteristic shade-induced morphological changes, including increased height and larger leaves, accompanied by a progressive reduction in stem diameter with greater shade intensity.

Another study on habanero reported significantly greater height and stem diameter at 30% shade than at 50%, 70%, or 90% (Xu 2015). Comparable responses have been documented in bell pepper, where shading increased height and leaf area but decreased stem diameter, leaf number and leaf thickness with higher shade levels (Díaz-Pérez, 2013; Ayala-Tafuya et al., 2015; Ilic and Fallik, 2017; Kabir et al., 2020).

Root-zone temperature, canopy temperature and soil water content

The RZT is crucial to plant growth because it influences root physiological processes, such as water and mineral

nutrient uptake (Cooper, 1973; Tindall et al., 1990). The RZT may influence plant survival because roots have a lower temperature optimum and are less adapted to extreme RZT fluctuations than shoots (Paulsen, 1994). Root growth increases with increased RZT from a minimum to an optimum level, with further increases in RZT leading to a decline in root and shoot growth (Cooper, 1973; Díaz-Pérez et al., 2008). The optimal range of RZT for bell pepper fruit yield is 25–27.5 °C (Díaz-Pérez, 2010).

Shading substantially lowered both RZTs and canopy temperatures, primarily by reducing the transmission of visible and infrared radiation through the nets. Although much research has emphasized the effects of air temperature on plants, RZT is also a critical determinant of plant growth and yield (Cooper, 1973; Abrecht and Bristow, 1996). In bell pepper, shading has been shown to reduce both RZTs and canopy temperatures (Díaz-Pérez and St. John, 2019). Reduced canopy temperatures under shaded conditions can enhance plant growth, leaf gas exchange and decrease water use during periods of high heat (Callejón-Ferre et al., 2009; Kittas et al., 2009; Stamps, 2009; Arthurs et al., 2013; Díaz-Pérez and St. John, 2019). In addition, increased shading has been associated with improved SWC and higher leaf water potential in bell pepper (Kabir et al., 2020). In the present study, shading was effective at lowering temperatures and reducing the light intensity throughout the growing season, consistent with other research (Cruz et al., 2024).

Leaf chlorophyll and carotenoids

Light intensity influences the concentration and composition of plant pigments (Larcher, 1995). Chlorophyll indices (SPAD) are commonly used as indirect indicators of chlorophyll content and leaf nitrogen concentration (Madeira and de Varennes, 2005). In the present study, SPAD and chlorophyll *a* increased with shading up to 63%, after which they declined. This pattern suggested that shading enhanced chlorophyll production in habanero plants, compensating for reduced photosynthetically active radiation. Similar responses have been observed in bell peppers (Ilic et al., 2017).

In the present study, chlorophyll *b* and carotenoid concentrations were not affected by shade level, indicating that shading did not influence these pigments in habanero leaves. *Capsicum* species produce fruits rich in carotenoid pigments that confer their characteristic yellow, orange and red hues; however, beyond fruit coloration, carotenoids primarily function to protect cells and organelles from oxidative damage (Gómez-García and Ochoa-Alejo, 2013). Carotenoids have been reported to increase under shaded conditions. For example, tomato plants grown under shading accumulated more lycopene but less β -carotene than those in open-field conditions (Ilic et al., 2012). Similar light-mediated regulation of carotenoids has been documented in peppers, where these pigments play photoprotective roles in fruit under high-light environments (Yoo et al., 2020).

Fruit yield

In the present study, habanero total yields under full sun were comparable to those obtained at 30% and 47% shade, although individual fruit size increased with increasing shading. The absence of yield differences among these shade levels suggested that habanero plants could maintain adequate photosynthetic activity at the corresponding PPFDs values of 1,400 and 1,060 $\mu\text{mol}/\text{m}^2\text{s}$. Despite reductions in fruit number at 30% and 47% shade, the total yields remained similar to those of the unshaded control, likely due to a compensatory increase in fruit size. The larger fruit size may be attributed to enhanced assimilate partitioning to the fruit and improved plant and fruit water status resulting from reduced canopy temperature and crop evapotranspiration under shaded conditions (Kabir et al., 2022b).

Air temperature and solar radiation can reduce fruit yield by negatively affecting pollination and fruit set (Erickson and Markhart, 2002; Lin et al., 2021). In the present study,

increased shading—and the concomitant reduction in plant canopy temperature—led to a decrease in the number of habanero fruits, suggesting that the cooling effect provided by shading did not enhance the habanero fruit set.

Under tropical conditions, the habanero yield was reported to decrease at 60% shade, while yields remained unaffected at 40% shade or in full sun (Jaimez and Rada, 2006). The yield reduction observed at 63% shade in the present study was likely due to reduced photosynthetic assimilate production. Habanero plants exhibited an increase in leaf chlorophyll *a* concentration in response to shading; however, this enhancement was insufficient to compensate for the reduction in available light. In bell pepper, net photosynthesis has been shown to decline above 47% shade [PPFD of less than 1,060 $\mu\text{mol}/\text{m}^2\text{s}$ (Díaz-Pérez, 2013)].

Variation in fruit size among plants with similar total yields may reflect differences in sink competition and resource allocation, as well as variations in plant water status under varying environmental conditions (Marcelis, 1996). Notably, increased fruit size under shaded conditions, as observed in the present study and elsewhere (Jaimez and Rada, 2006), may confer an advantage in markets that favor larger fruit sizes. In contrast to habanero, often, bell pepper yields are optimized under moderate shading, with maximum marketable yields at 30% shade in Georgia, USA (Díaz-Pérez, 2014; Kabir et al., 2020) and under 35% shade in piquin chili (*C. annum* var. *glabriusculum*) in Mexico (Valiente-Banuet and Gutiérrez-Ochoa, 2016). In the present study, the regression analysis indicated the maximum marketable yield at a PPFD of 1,601 $\mu\text{mol}/\text{m}^2\text{s}$. The non-marketable yield increased with the PPFD but did not reach a plateau, while individual fruit weight decreased as the PPFD increased.

Postharvest fruit water loss

Shade treatments did not affect postharvest water loss in habanero fruit. While shade nets can reduce fruit surface temperature and field transpiration (Ilic and Fallik, 2017), their influence after harvest appeared to be limited. The absence of postharvest differences in the present study suggested that shading did not modify the cuticular transpiration rates in fruit. Similar results have been reported for bell pepper (Díaz-Pérez, 2014; Kabir et al., 2020). Variability among crops and environments suggests that cuticle properties, more than shading *per se*, govern postharvest fruit water loss.

Capsaicinoid content

Generally, in habanero fruit, capsaicin is present at higher concentrations than DHC, though levels vary widely by genotype (Canto-Flick et al., 2008; Antonious et al., 2009; Lim, 2013). Shading effects on capsaicinoids are genotype-dependent, with one study reporting increases under shade, particularly in highly pungent cultivars (Jeeatid et al., 2017). In the present study, shading did not affect the capsaicinoid concentrations in Kukulkan or Kabal.

Fruit and seed fresh and dry weights

Shading influenced seed yield in the present study, with fruits grown under 47% shade producing increased seed fresh and dry weights. Shading may alter assimilate partitioning and nutrient uptake (El-Aidy et al., 1993; Gent, 2005; Diaz-Perez, 2013; Kabir et al., 2022a; De La Cruz-Ricardez et al., 2023). In habanero fruit, seed tissue density is positively correlated with germination performance and negatively correlated with dormancy (de Medeiros et al., 2020), suggesting potential benefits in seed quality from moderate shading.

Conclusions

This study demonstrated that shading induced typical plant morphological changes, including taller plants with larger leaves and reduced stem diameter, effectively lowering both canopy and root-zone temperatures, and improving soil water status compared with unshaded habanero plants. Moderate shading (30%–47%) maintained fruit yields comparable to full sun while increasing individual fruit size, potentially offering a commercial advantage. Fruit chemical attributes, such as soluble solids content, decreased with increased shade, while capsaicinoid concentrations remained unaffected in the cultivars tested. In addition, shading did not affect sunscald or blossom-end rot. Overall, shading did not enhance habanero fruit yields. However, moderate shading could be a helpful management tool when the objective is to increase fruit size.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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