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Plant Growth, Fruit Yield, and Tomato Leaf Curl Disease of High Tunnel Organic Tomato Affected by Shade Net and Plastic Mulch Color

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Abstract. **There is an increasing interest in producing organic tomatoes (*Solanum lycopersicum*) in high tunnels (HTs) in the southeast United States. HTs are unheated, passively cooled structures that allow tomato growers to harvest high-quality fruit out of season. However, excessive temperatures inside HTs may negatively impact tomato plant growth and fruit yield. Shade nets have been reported to reduce temperatures inside the HTs. Plastic mulch color has also significantly influenced plant growth and yield under high-temperature conditions. This study aimed to determine the effects of shade net color and plastic mulch color on plant growth, fruit yield, and incidence of tomato yellow leaf curl disease (TYLC) in 'Red Snapper' tomato grown in HTs under elevated temperatures (summer-fall) in southern Georgia, USA. Organic 'Red Snapper' tomato seedlings were transplanted in HTs in 2019 (Season 1) and 2020 (Season 2). The design was a split-plot randomized block where the main plots were externally mounted shade nets (black, silver, and unshaded; 30% shade factor), and the subplots were plastic mulches (black and white). Compared with black mulch, white mulch improved plant height and stem diameter but did not influence fruit yields. Shade nets reduced HT air temperature and root zone temperature (RZT) but did not affect plant height and stem diameter. The diminished photosynthetic photon flux density (PPFD) under the shade nets reduced marketable fruit yield. Thus, shade nets are not recommended once heat challenges do not limit HT tomato production in Georgia (after about mid-October). Shade nets and plastic mulch inconsistently affected TYLC incidence, severity, and area under the disease progress curve (AUDPC). Additional fruit yield reductions occurred due to TYLC because the incidence was 100% 6 weeks after transplanting. Preliminary insect data showed that shade net treatments had similar sweetpotato whitefly (*Bemisia tabaci*) numbers. The high TYLC incidence indicates that 'Red Snapper' may not be suitable for fall HT tomato production in the southeast United States. More research on shading and heat stress management in HT organic tomato production is necessary.**

In the United States, there is an increasing interest in producing organic tomatoes (*Solanum lycopersicum*) in HTs (Frey et al. 2020). HTs allow tomato growers to produce crops out of season and obtain high-quality fruit (Briar et al. 2011; Gude et al. 2022; Warren et al. 2015). HTs modify the environment compared with the open field, which may increase crop yield, quality, and irrigation water use efficiency and reduce damage by pests and diseases (Carey et al. 2009; Reiss et al. 2004). However, the benefits of HTs on crops are not always consistent. For example, in studies conducted in Tennessee, USA, a tomato crop grown in HTs had similar fruit yields as those in the open field (Rogers and Wszelaki 2012); however, the HT tomato fruits were larger, potentially attracting higher prices.

There are few reports on organic HT production in the humid subtropical regions of the United States (Frey et al. 2020). However, there are numerous studies on field-grown tomato production in the southeast United States (Csizinszky 1999; Díaz-Pérez and Batal 2002; Locascio et al. 1997; Ozores-Hampton et al. 2013). In this region, under warm conditions, tomato plant growth and yield may be negatively impacted by high temperatures and viral diseases such as TYLC. TYLC is caused by tomato yellow leaf curl virus (TYLCV) (Riley and Srinivasan 2019) and vectored by the sweetpotato whitefly [*Bemisia tabaci* (Gennadius)].

In tropical and subtropical areas, elevated temperatures inside the HT may negatively impact tomato plant growth and fruit yield during warm seasons. High air temperatures inside HTs negatively influenced bell pepper (*Capsicum annuum*) plant growth and yield because of poor HT ventilation in the Dominican Republic (Díaz-Pérez and Smith 2017). Shading nets are widely used to reduce air temperatures and solar radiation in greenhouses, HTs, and field vegetable production (Aberkani et al. 2010; Díaz-Pérez 2014; El-Gizawy et al. 1992; Gent 2008). In Egypt, shading nets were reported to increase tomato fruit numbers and total yield while reducing the incidence of fruit sunscald (El-Gizawy et al. 1992). In the northeast United States, there was a decrease in the uptake of water, nitrogen (N), and potassium in tomato with increasing shade levels (Gent 2008). In Spain, applying whitening agents to greenhouse coverings and natural ventilation provided efficient greenhouse cooling (Gazquez et al. 2008). The use of shade nets in tomato production has shown variable results. In Kansas, a shade mounted on an HT film cover reduced tomato fruit yield compared with no shade covering (Gude et al. 2022). Covering a greenhouse with 50% shade for more than 6 weeks reduced tomato fruit yield by 30% (Gent 2008).

HTs may mitigate pests and diseases by modifying environmental conditions (Frey et al. 2020; Powell et al. 2014). In Tennessee, USA, HT-grown tomato had a reduced incidence of early blight (*Alternaria solani*) compared with the open field (Rogers and Wszelaki 2012). Field-grown tomatoes in the southeast United States can be severely impacted by the TYLCV transmitted by sweetpotato whitefly [*Bemisia tabaci* (Gennadius)] (Glick et al. 2009; Marchant et al. 2020). However, there is limited information on how HT production may impact the incidence and severity of TYLC in tomatoes grown organically (Maklad et al. 2012). Maklad et al. (2012) reported that virus-transmitting insect vectors such as aphids (*Aphis gossypii* Glover), thrips (*Thrips* spp.), and sweetpotato whiteflies respond differentially to temperature and relative humidity under black and white shade nets in cucumber (*Cucumis sativus*). This study aimed to determine the effects of externally mounted shade net and plastic mulch color on plant growth, fruit yield, and incidence and severity of TYLC in 'Red Snapper' tomato grown in HT under subtropical conditions in the southeast United States.

Materials and Methods

The study was conducted in three organically certified HTs at the University of Georgia, Horticulture Farm (lat. 31.4803° N, long 83.5211° W), in Tifton, GA, USA, in 2019–20 and 2020–21. HTs (21.9 m long, 9.1 wide, and 4.3 m peak height; Atlas Greenhouse, Alapaha, GA, USA) had a Gothic frame covered by a 152-μm (6-mil) thick transparent polyethylene film. The HT films were installed in 2018; films have a durability of 4 years, according to the HT manufacturer. The HT's side walls were manually opened daily (except when air temperature was <10 C) for passive ventilation to prevent air temperatures inside the HT from reaching values that could damage the tomato plants; the target air temperature range was 18 to 25 °C. The soil is a Tifton Sandy Loam (a fine loamy-siliceous, thermic Plinthic Kandiudults) with an organic matter content of 0.5% and pH of 6.5 (Waters Agricultural Laboratories, Inc., Camilla, GA, USA). Organic fertilizer [8–8–4 (8N–3.49P–3.3K), Nature Safe Fertilizers, Cold Springs, KY, USA] was applied and incorporated into the soil at 190 $kg \cdot ha^{-1}$ N 2 weeks before planting. No additional fertilizer was supplied after transplanting.

The experimental design was a split plot with three replications and three externally mounted shade net treatments (black, silver, and unshaded) as main plots and two plastic mulches (black and white) as subplots. Each of the three HTs had one shade net treatment. Shade nets were placed on the HT's plastic film. Black and silver shade nets (Atlas Greenhouse) had a nominal 30% shade factor (Atlas Greenhouse) and were kept on the HT for the entire season. Black (black-on-black) and white (white-on-black) plastic film mulches were low-density polyethylene films [25 μm thick and 1.52 m wide (Berry Plastics, Atlanta, GA, USA)]. Plastic mulches were laid manually on raised beds (spaced 1.2 m center-to-center).

Tomato 'Red Snapper' (Sakata, Fort Myers, FL, USA) seeds were grown in a controlled growth chamber (model E-41 L1; Percival Scientific, Inc., Perry, IA, USA) [PPFD 600 $\mu mol \cdot m^{-2} \cdot s^{-1}$; night (8 h at 18 °C) and day (16 h at 25 °C)] to ensure virus-free planting materials. Before transplanting, plants inside the growth chamber were acclimated for transplanting by reducing the irrigation 4 d before planting. Seedlings (6 weeks old) were transplanted (14 Aug in both 2019 and 2020) to the HT manually with one row of plants per bed and 30 cm spacing between plants [2.7 plants/m^2 (0.25 plants/ft^2)] (Amundson et al. 2012).

The experimental plot consisted of 10 plants. Plants were irrigated with one drip tape [20.3-cm emitter spacing and an 8.3 $mL \cdot min^{-1}$ emitter flow (John Deere Ro-Drip, Inc., San Marcos, CA, USA)] placed in the center of the bed below the plastic mulch. 'Red Snapper' tomato was chosen for its resistance to a TYLCV-Israeli strain, which is prevalent in the southeast United States. The cultivar is not immune to the virus but exhibits fewer symptoms than susceptible cultivars (Kumar et al. 2023). The TYLC incidence was determined weekly as the percentage of plants showing visual disease symptoms. Leaf tissue samples were collected 6 weeks after transplanting (WAT) to confirm the presence of TYLCV

Table 1. Air and root zone temperatures (RZT) inside a high tunnel as influenced by externally mounted shade net and black mulch color in a 'Red Snapper' tomato crop grown organically. Tifton, GA, USA (Season 1).[i]

Treatment	Air temp (°C)	RZT (°C)	
Shade net			
Black	19.91 c[ii]	20.68	
Silver	20.27 b	20.82	
Unshaded	20.99 a	22.14	
Mulch			
Black		21.51	
White		20.92	
Significance			
Shade net (N)	<0.0001		
Mulch (M)			
N × M		<0.0001	
Interactions			
Shade net		RZT black mulch	RZT white mulch
Black		20.85 cA	20.52 bB
Silver		21.13 bA	20.51 bB
Unshaded		22.56 aA	21.72 aB

[i] Data are averages of daily means from 10 Sep 2019 to 22 May 2020. The outside mean air temperature was 17.35 °C.

[ii] Values within a column (small letters) and a row (capital letter) not followed by the same letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.

Table 2. Air and root zone temperatures (RZT) inside a high tunnel as influenced by externally mounted shade net and black mulch color in a 'Red Snapper' tomato crop grown organically. Tifton, GA, USA (Season 2).[i]

Treatment	Air temp (°C)	RZT (°C)	
Shade net			
Black	24.30 c[ii]	25.36	
Silver	24.47 b	25.52	
Unshaded	25.34 a	27.68	
Mulch			
Black		26.39	
White		25.98	
Significance			
Shade net (N)	<0.0001		
Mulch (M)			
N × M		<0.0001	
Interactions			
Shade net		RZT black mulch	RZT white mulch
Black		25.34 cA	25.37 bA
Silver		25.75 bA	25.30 bB
Unshaded		28.08 aA	27.28 aB

[i] Data are averages of daily means (28 Aug to 18 Nov 2020). The outside mean air temperature was 22.60 °C.

[ii] Values within a column (small letters) and within a row (capital letter) not followed by the same letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.

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using a molecular assay outlined later in this article. No organic insecticides for whitefly control were applied to the crop. Weeds were hand-pulled from the HT regularly.

Air and RZTs. HT air temperature and RZT were measured hourly during season 1 (10 Sep 2019 to 22 May 2020) and season 2 (28 Aug to 20 Nov 2020) with dataloggers (Watchdog 1000 Series; Spectrum Technologies, Inc., Aurora, IL, USA). Dataloggers (2 per HT) were placed on the north and south sides of the HT. The air temperature was measured at canopy height (1 m). The RZT was measured at a depth of 10 cm under the surface of the plastic mulch with soil temperature sensors (A-Series, item 3667A; Spectrum Technologies, Inc., Aurora, IL, USA) connected to the datalogger. Soil sensors [six per HT (three for black and three for white mulch)] were placed midway between two plants in the center of each row.

Photosynthetic photon flux density. Solar radiation was measured as PPFD (400–700 nm), ultraviolet [ultraviolet (380–400 nm)], blue [B (400–500 nm)], green [G (500–600 nm)], red [R (600–700 nm)], and far-red [FR (700–780 nm)] at 12 HR to determine the light quantity and quality inside the HT. Measurements were made at four different spots inside the HT just above the plant canopy using a spectrometer (LI-180; LI-COR, Lincoln, NE, USA) on a clear and sunny day on 15 Jan 2021 at 12 HR (after the last harvest). The spectrophotometer calculated an average of the four measurements.

Plant height, stem diameter, and chlorophyll index. In Season 2, plant height (three plants/plot), stem diameter (three plants/plot; 1 cm above soil level), and chlorophyll index (three plants/plot; two leaflets/plant, newest fully expanded leaflet) were measured 24 d after transplanting (DAT) (three plants/plot) to determine the treatment effects on transplant establishment. A chlorophyll meter (SPAD-502; Minolta, Osaka, Japan) measured the chlorophyll index. Plant mortality was determined as the percentage of dead plants 37 DAT.

Harvest. ‘Red snapper’ tomato fruit were harvested (five plants) 13 times (3 Jan to 22 May 2020) in Season 1 and 10 times (17 Nov 2020 to 29 Jan 2021) in Season 2. Harvest duration was reduced in Season 2 because of freezing damage and high plant mortality in January 2021. The fruit were graded as marketable or nonmarketable according to the US Department of Agriculture (USDA) grading standards, counted, and weighed (USDA 1991). Fruit yields are reported per plot (1.5 m long bed) and per plant basis.

Tomato yellow leaf curl. The plants were monitored weekly for TYLC incidence and severity by visual examination for disease symptom expression. Incidence was determined as the percentage of symptomatic plants per 10-plant plot. Severity was measured by using a 1–5 visual scale, where 0 = no symptoms; 1 = slight yellowing (mild symptom); 2 = leaf curling and yellowing (moderate symptom); 3 = yellowing, curling, and cupping (severe symptom); 4 = severe stunting, curling, and cupping; and 5 = plant stops growth and remains dwarf (very severe symptom) (Lapidot and Friedmann 2002). The AUDPC was determined from the severity values (Simko and Piepho 2012).

Total nucleic acid (TNA) was extracted from the symptomatic tissues 6 WAT to confirm the presence of the TYLCV (Adeleke et al. 2022). Briefly, TNA isolation was done using 100 mg of symptomatic leaf tissue with a magnetic bead using 4 M guanidine thiocyanate (GTC) buffer (pH 5.0) with a Bead Mill 24 Homogenizer (Thermo Fisher Scientific, Waltham, MA, USA). Then, TNA was isolated from homogenized samples with a MagMAX 96 viral RNA kit using the KingFisher Flex Purification System (Thermo Fisher Scientific) with the manufacturer’s instructions without DNase treatment. The quantity and purity of isolated TNA were assessed using a NanoDrop Spectrophotometer (Thermo Fisher Scientific). TNA with 230/280 absorbance >1.8 was stored at −80 °C for further laboratory analysis. TNA was subjected to the polymerase chain reaction (PCR) for amplification of TYLCV capsid protein using specific primers (Rojas et al. 2007) following the protocol by Kavalappara et al. (2021). The PCR products were analyzed on 1% agarose gel in 1X Tris base, acetic acid, and EDTA buffer containing Gel Red (Biotium, Fremont, CA, USA).

Insects. Three yellow sticky cards per HT were placed along the row of plants (black mulch only) at ∼1 m from the soil surface (above the plant canopy) on 27 Sep 2021 (Season 2). The sticky cards were collected

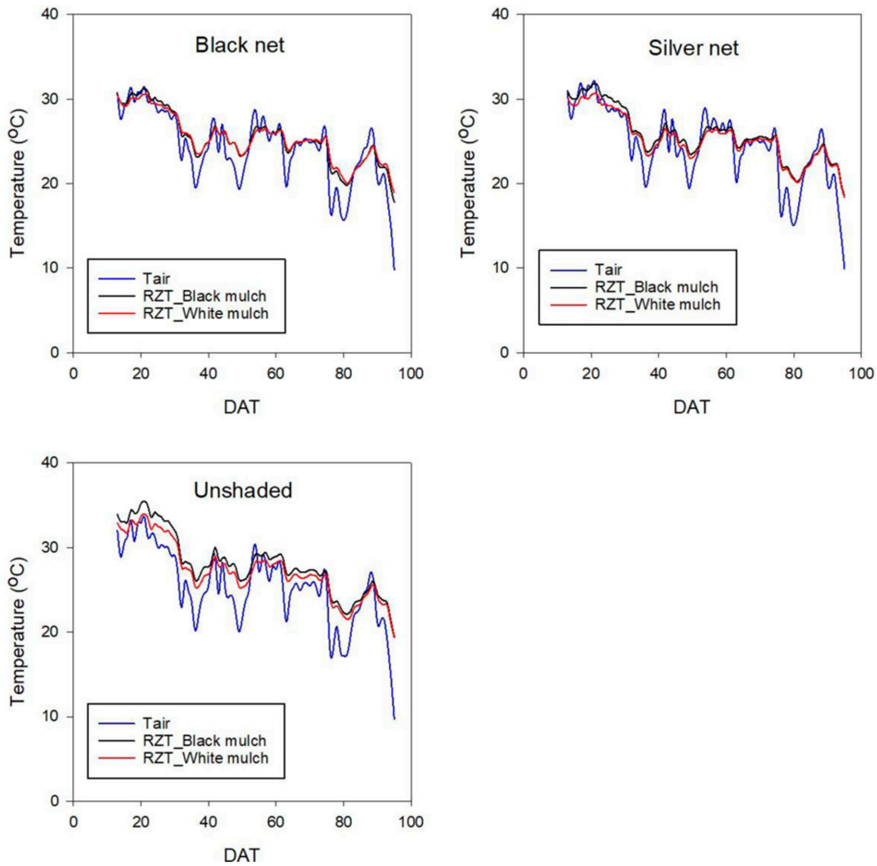

Fig. 1. Mean daily air temperature (Tair) and root zone temperature (RZT) over days after transplanting (DAT) as affected by externally mounted shade net (black net, silver net, and unshaded) and plastic film mulch (black or white) in organic tomato grown in a high tunnel. Planting date was 14 Aug 2020. Tifton, GA, USA (Season 2).

Table 3. Light intensity inside high tunnels influenced by externally mounted shade nets. Tifton, GA, USA (Season 2).[i]

	Light quantity ($\mu mol \cdot m^{-2} \cdot s^{-1}$)					
Shade net treatment	PPFD	Ultraviolet	Blue	Green	Red	Far-Red
Open field	2,088[ii]	53	577	745	779	560
Unshaded	1,336	29	349	479	517	391
Black net	792	16	209	286	303	235
Silver net	825	18	217	297	317	239

[i] Light intensity was measured as photosynthetic photon flux density (PPFD), ultraviolet, blue, green, red, and far-red light in ‘Red Snapper’ tomato crop. Shade nets were placed above the high tunnels.
[ii] Light measurements were made on 15 Jan 2021 at 12 HR.

2 weeks later, enclosed in plastic bags, and mailed to the University of Florida Insect ID Laboratory (University of Florida, Gainesville, FL, USA) for insect identification and quantification.

Statistical analysis. Data were analyzed using the GLIMMIX procedure from SAS® 9.4 (SAS Inst., Inc., Cary, NC, USA). The General Linear Mixed Model (GLMM) was used to analyze temperature, plant parameters, fruit numbers, and yield, where shade net and mulch color were fixed effects, and replication and replication × shade net were random effects. For TYLC, the GLMM with repeated measures was applied to analyze the week and shade net effects on disease incidence, where a compound symmetry covariance structure was used to specify the correlation between the repeated measures. For plant mortality, a GLMM with Beta distribution was used to fit the data, and all fixed effects were statistically insignificant, consistent with the results from using GLMM for split-plot design, although the *P* values were different. Only the results from GLMM for mortality were reported. Residual normality was checked visually through residual plots and Q-Q plots. The Tukey-Kramer test separated treatment means at a 0.05 significance level. The procedure CORR calculated Pearson's correlation coefficient.

Results

HT air and RZTs

In Season 1, the seasonal mean air temperature was highest in the unshaded HT and lowest in HT with the black shade net (Table 1). The mean air temperature was 2.56 °C (black shade net), 2.92 °C (silver shade net), and 3.65 °C (unshaded) higher inside the HT compared with the outside mean air temperature. As in Season 1, in Season 2, the seasonal mean air temperature was highest in the unshaded HT and lowest in the HT with the black net (Table 2). The mean air temperature was 1.70 °C (black net), 1.87 °C (silver net), and 2.74 °C (unshaded) higher inside the HT compared with the outside mean air temperature.

Shade net and plastic mulch color interacted to affect RZT. The unshaded HT had the highest RZT on black than white mulch in the shade net treatments. In contrast, with silver net and unshaded conditions, the RZT was higher on black than white mulch, whereas with the black shade net, there were no RZT differences between the plastic mulches (Table 2). There was a seasonal decreasing trend in air and RZT (Fig. 1).

PPFD

The PPFD was reduced by shade net. Open-field PPFD was 2088 $\mu mol \cdot m^{-2} \cdot s^{-1}$, which decreased by 36% by the HT film cover (unshaded) (Table 3). In addition to the reduction by the HT film cover, the PPFD inside the HT was decreased by 26.1% under the black net and 24.5% under the silver net. The total PPFD reduction was 62% with the black and 60.5% with the silver net compared

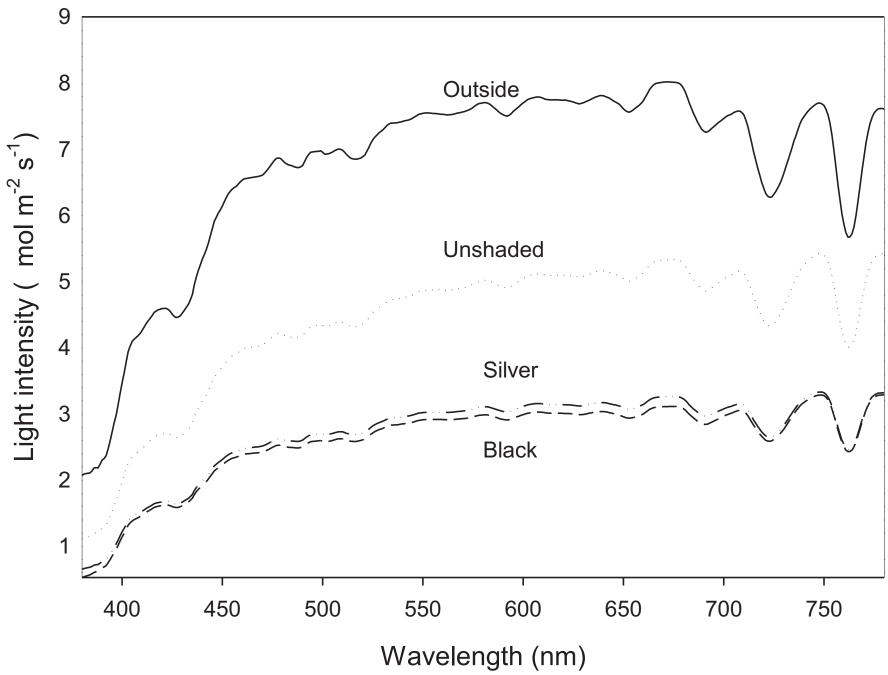

Fig. 2. Light spectrum distribution among externally mounted shade nets (black net, silver net, and unshaded) for wavelengths 380–780 nm. 'Red Snapper' tomato crop was grown organically in a high tunnel. Light measurements were made on 15 Jan 2021 at 1200 HR. Tifton, GA, USA, 2020–21 (Season 2).

Table 4. Plant parameters of tomato 'Red Snapper' grown organically in high tunnels as affected by shade net (externally mounted) and plastic mulch color. Tifton, GA, USA (Season 2).

Treatment	Plant ht[i] (cm)	Stem diam (mm)	Chlorophyll index	Plant mortality (%)
Shade net				
Black	68.7	8.8	30.6	1.7
Silver	75.5	8.8	23.7	1.7
Unshaded	61.7	8.0	30.1	20.0
Mulch				
Black	63.6 b[ii]	7.3 b	25.1 b	11.1
White	73.6 a	9.8 a	31.2 a	4.4
Significance				
Shade net (N)	0.177	0.521	0.141	0.100
Mulch (M)	0.005	0.00	0.018	0.238
N × M	0.273	0.246	0.263	0.670

[i] Plant height, stem diameter, and chlorophyll index were measured 24 d after transplanting [DAT (8 Sep 2020)] and mortality 37 DAT. Shade nets were placed above the high tunnels.
[ii] Values within a column not followed by the same letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.

Table 5. Fruit number and yield (per plot) of organic 'Red Snapper' tomato grown in high tunnel as affected by shade net (externally mounted) and plastic mulch. Tifton, GA, USA.

	Marketable[i]		Cull		Total		Fruit wt
Treatment	#/plot	kg/plot	#/plot	kg/plot	#/plot	kg/plot	g
Shade net							
Black	63.9	9.3	53.4	4.4	117.3	13.7	144.7 ab[ii]
Silver	74.0	10.2	68.9	5.4	142.9	15.5	139.6 b
Unshaded	108.7	16.8	113.0	8.9	221.6	25.7	157.2 a
Mulch							
Black	76.2	10.9	72.1	5.8	148.3	16.7	145.1
White	88.2	13.2	84.7	6.7	172.9	19.9	149.2
Season							
1	97.1	14.3	151.1	11.7	248.2	26.0	147.9
2	67.3	9.8	5.7	0.8	73.1	10.6	146.5
Significance							
Shade net (N)	0.018	0.005	0.014	0.018	0.014	0.006	0.025
Mulch (M)	0.159	0.037	0.266	0.325	0.189	0.096	0.377
Season (S)[iii]	0.022	0.013	<0.0001	<0.0001	<0.0001	<0.0001	0.755
N × M	0.211	0.175	0.404	0.338	0.279	0.211	0.376
N × S	0.026	0.025	0.015	0.022	0.023	0.024	0.133
M × S	0.551	0.174	0.217	0.205	0.306	0.164	0.040

[i] Fruit number and yield are expressed per plot (1.5-m long bed).
[ii] Values within a column followed by a different letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.
[iii] The tomato crop was planted on 14 Aug 2019 (Season 1) and 2020 (Season 2).

with the open field. Similarly, ultraviolet, B, G, R, and FR light intensities were reduced following the same trend: open field > unshaded tunnel > silver shaded tunnel > black shaded tunnel. Spectral analysis showed that black and silver nets were wavelength-neutral and reduced the sunlight by a similar amount over the entire visible spectrum (Fig. 2). Inside the HT, PPFD was linearly related to mean air temperature ($R^2 = 0.983$) and RZT ($R^2 = 0.998$).

Plant height, stem diameter, chlorophyll index, and plant mortality

Shade net did not significantly affect plant height, stem diameter, or chlorophyll index during the first 4 WAT (Table 4). In the same period, plants on white mulch were taller and had greater stems and chlorophyll index than plants on black mulch. Plant mortality was not influenced by shade net treatment, although it tended to be the highest in unshaded conditions. There was high variability in plant mortality among plots. Plastic mulch color did not affect plant mortality.

Fruit yields

Fruit yield per plot. Marketable, cull, and total fruit numbers and yields showed shade net × season interactions (Table 5). Marketable fruit numbers and yields were similar between seasons under black and silver nets. In unshaded conditions, however, marketable fruit number and yield were higher in Season 1 than in Season 2 (Table 6). In Season 1, marketable, cull, and total fruit number and yield were the highest in unshaded conditions, and there were no differences among shade net treatments in Season 2. Fruit weight was highest in unshaded conditions and lowest under silver net (Table 5). Plastic mulch treatment did not affect marketable, cull, total fruit numbers, yields, or individual fruit weight.

Fruit yield per plant. Among shade nets, marketable fruit yield was highest in unshaded conditions and lowest under silver nets; the marketable yield was similar between silver and black nets (Table 7). Shade nets did not affect fruit numbers (marketable, cull, and total), cull and total yields, and individual fruit weight. Black and white plastic mulches had similar fruit numbers (marketable, cull, and total) and yields. Season 1 had higher marketable, cull, and total fruit numbers and yields (except marketable yield) than Season 2.

Tomato yellow leaf curl

The progression of TYLC incidence was monitored weekly in both seasons. Disease symptoms included leaf downward curling, yellowing of leaf margins, and plant stunting (Fig. 3). Shade net inconsistently affected the development of TYLC symptoms. The first symptoms observed were 1 WAT in plants under the black shade net in Season 1, and 2 WAT under the silver net and in unshaded plants in Season 2 (Fig. 4). In Season 1, plants under the black net reached 100% incidence earlier than under silver net and in unshaded conditions. In contrast, in Season 2, plants under the black net were the last to reach 100% incidence. All plants in the HT (100%) were severely symptomatic by 5 WAT

Table 6. Effect of shade net (externally mounted) and season interactions on fruit numbers and yields (per plot) of organic 'Red Snapper' tomato grown in high tunnel. Tifton, GA, USA.

	Marketable fruit (#/plot)[i]				Marketable yield (kg/plot)			
	Net				Net			
Season	Black	Silver	Unshaded	*P*	Black	Silver	Unshaded	*P*
1	75.3 B[ii]	68.8 B	147.0 aA	0.004	11.2 B	9.5 B	22.2 aA	0.001
2	52.5	79.2	70.3 b	0.394	7.3	10.8	11.3 b	0.287
P	0.257	0.598	0.002		0.159	0.629	0.002	
	Cull fruit (#/plot)				Cull yield (kg/plot)			
	Net				Net			
Season	Black	Silver	Unshaded	*P*	Black	Silver	Unshaded	*P*
1	101.1 aB	132.4 aB	219.8 aA	0.002	8.1 aB	10.1 aB	17.0 aA	0.0002
2	5.7 b	5.3 b	6.2 b	0.999	0.8 b	0.7 b	0.9 b	0.994
P	0.003	0.0003	<0.0001		0.004	0.0006	<0.0001	
	Total fruit (#/plot)				Total yield (kg/plot)			
	Net				Net			
Season	Black	Silver	Unshaded	*P*	Black	Silver	Unshaded	*P*
1	176.5 aB	201.2 aB	366.8 aA	0.002	19.3 aB	19.6B	39.2 aA	0.001
2	58.2 b	84.5 b	76.5 b	0.816	8.0 b	11.5	12.2 b	0.601
P	0.018	0.019	<0.0001		0.026	0.089	<0.0001	

[i] Fruit number and yield are expressed per plot (1.5-m long bed).
[ii] Values within the same column followed by the same lower-case letter, or values within the same row followed by the same capital letter, are not significantly different at $P \leq 0.05$, according to Tukey's honestly significant difference test.

Table 7. Fruit number and yield (per plant) of organic 'Red Snapper' tomato grown in high tunnel as affected by shade net (externally mounted) and plastic mulch color. Tifton, GA, USA.

	Marketable[i]		Cull		Total		Fruit wt
Treatment	#/plant	kg/plant	#/plant	kg/plant	#/plant	kg/plant	g
Shade net							
Black	20.6	3.19 ab[ii]	21.8	1.77	42.4	4.96	158.6
Silver	17.6	2.75 b	26.5	2.14	44.1	4.89	158.0
Unshaded	25.6	4.22 a	28.5	2.36	54.1	6.59	169.6
Mulch							
Black	21.1	3.28	26.5	2.17	47.6	5.44	159.7
White	21.4	3.50	24.7	2.01	46.1	5.52	164.4
Season							
1	25.3 a	3.73	39.2 a	3.01 a	64.5 a	6.74 a	147.9 b
2	17.2 b	3.05	12.0 b	1.17 b	29.2 b	4.22 b	176.2 a
Significance							
Shade net (N)	0.092	0.028	0.336	0.373	0.274	0.062	0.125
Mulch (M)	0.899	0.485	0.429	0.439	0.547	0.932	0.278
Season (S)[iii]	0.013	0.104	<0.0001	<0.0001	<0.0001	<0.0001	0.0001
N × M	0.665	0.805	0.463	0.359	0.648	0.799	0.249
N × S	0.160	0.094	0.220	0.183	0.255	0.179	0.225
M × S	0.481	0.839	0.347	0.661	0.399	0.786	0.038

[i] Fruit number and yield are expressed per plant.
[ii] Values within a column followed by a different letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.
[iii] Tomato crop planted on 14 Aug 2019 (Season 1) and 2020 (Season 2).

Fig. 3. Symptoms of tomato leaf curl virus disease in 'Red Snapper' tomato plants grown organically in high tunnels. Plants show downward leaf curling (left), leaf chlorosis (center), and stunting (right). Tifton, GA, USA (27 Oct 2020).

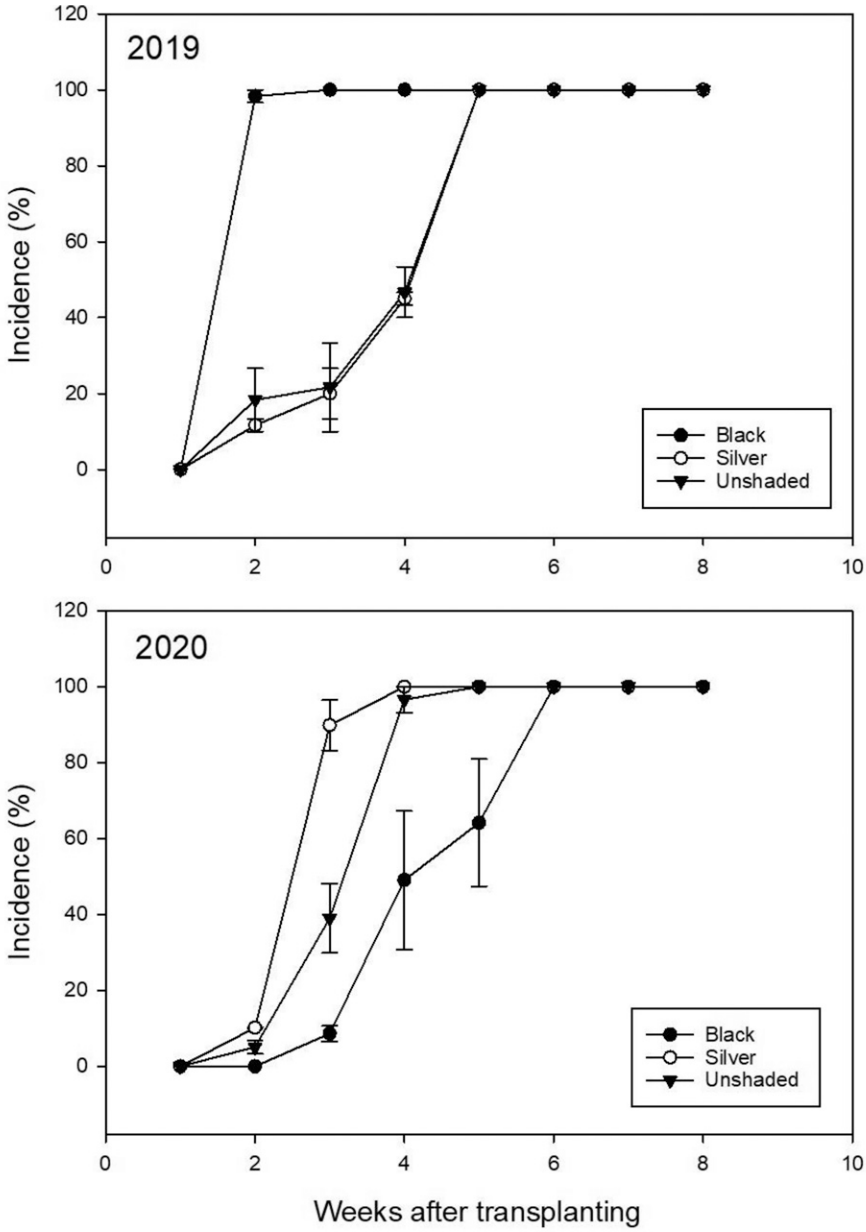

Fig. 4. Weekly progress of the percentage of tomato yellow leaf curl (TYLC) disease incidence on 'Red Snapper' tomato grown organically in a high tunnel. The high tunnels were unshaded or shaded with externally mounted black or silver nets for the entire season. The shading net was placed on top of the high tunnel film. Planting date was 14 Aug in 2019 (Season 1) and 2020 (Season 2). Tifton, GA, USA.

(Season 1) and 6 WAT (Season 2), irrespective of treatment. The presence of TYLCV was confirmed by PCR analysis on symptomatic leaves collected 6 WAT.

In Season 1, TYLC incidence, severity, and AUDPC were the highest under black net. Plastic mulch did not affect TYLC incidence, severity, or AUDPC (Table 8). In Season 2, TYLC severity was the lowest under black net; plastic mulch did not influence severity. There was a shade net by mulch interaction for TYLC incidence and AUDPC. The TYLC incidence and AUDPC were the lowest under black net (Table 9). Plants under the black net had a higher TYLC incidence and AUDPC on white than on black mulch, and mulch had no effect on incidence and AUDPC under the silver net and in unshaded conditions. Plants on black mulch had the lowest incidence and AUDPC under black net.

Insects

Preliminary data (Season 2) showed that the number of parasitoid wasps was the lowest (105/card) under unshaded conditions compared with the silver net (498/card) and black net (466/card). The number of thrips [*Frankliniella occidentalis* (Pergande)] (mean 19.7/card), whiteflies (mean 374/card), aphids (*Aphis gossypii* Glover) (mean 44/card), leafhoppers (*Empoasca fabae* Harris) (mean 10.9/card), and predatory flies (1.6/card) were similar among shade net treatments. Thrips numbers decreased with increasing HT air temperature ($y = -12.90x + 282.6$; $R^2 = 0.999$; $P = 0.017$), whereas the rest of the insect populations were unrelated to HT air temperature.

Discussion

Plastic film coverings retain heat from solar radiation, increasing air and soil temperatures inside HTs (Gude et al. 2022; Knewtson et al. 2010; Kong et al. 2017). In both seasons, air temperatures were higher inside the HTs than outside. The magnitude of the temperature difference was the greatest in the unshaded HTs, probably because the shade nets reduced the amount of light (PPFD and infrared) penetration to the interior of the HT. The mean air temperature was higher in HTs with the silver net than the black net, probably because of enhanced light levels under the silver net. The net manufacturers do not provide sufficient information about the net optical properties. The net shade factor provided by the manufacturer is based on the photosynthetically active radiation (PAR) transmissivity rather than the solar transmissivity. The transmissivity of externally mounted nets changes depending on whether the net is dry or wet; with the same shade factor, dry nets provide less cooling than wet nets (Willits 2001). The net fabric characteristics may also influence light incidence angle, resulting in differences in solar transmissivity in nets with the same shade factor.

'Red Snapper' tomato plants had reduced plant height and stem diameter on black compared with white plastic mulch, probably because of the increased RZT conditions with the black mulch during the plant establishment period the first 4 WAT. Supraoptimal RZT under various colored plastic mulches have been found to reduce plant growth and yield in tomato (Amare and Desta 2021; Díaz-Pérez and Batal 2002). Despite the reduced growth on black mulch during plant establishment, plant yields were unaffected by mulch color. The lack of mulch treatment effect on fruit yields was probably because the effect of mulch color on RZT is drastically reduced once plants reach full canopy cover, as found in tomatillo (*Physallis ixocarpa* Brot. ex Hornem) (Díaz-Pérez et al. 2005).

Shade net treatments did not affect 'Red Snapper' tomato plant height, stem diameter, chlorophyll index, and plant mortality. The lack of effect of shade nets is surprising, considering that shade nets reduced PPFD, air temperature, and RZT. As the seasons progressed from the summer to the fall, air and RZT probably decreased to values that were more favorable to 'Red Snapper' tomato plants, particularly for flowering and fruiting, which may have led to the lack of impact on tomato growth characteristics measured 24 DAT. In tomato grown in HT in Egypt, air and leaf temperatures were lower under shaded than unshaded conditions during the day, while the opposite occurred at night (Abdel-Mawgoud et al. 1996).

Shade nets reduced 'Red Snapper' tomato fruit marketable yields. This reduction in

Table 8. Tomato yellow leaf curl incidence, severity, and AUDPC in 'Red Snapper' tomato grown organically in high tunnel as affected by shade net (externally mounted) and plastic mulch color. Tifton, GA, USA.[i]

	Season 1			Season 2		
	Incidence[ii] (%)	Severity[iii]	AUDPC[iv]	Incidence (%)	Severity	AUDPC
Shade net						
Black	87.2 a[v]	2.32 a	116.2 a	51.8	1.35 b	65.8
Silver	59.6 b	1.92 b	94.4 b	75.0	2.54 a	128.6
Unshaded	60.8 b	2.09 ab	103.2 ab	67.6	2.28 a	113.9
Mulch						
Black	70.7	2.16	107.1	63.4	2.03	100.7
White	67.8	2.05	102.1	65.4	2.09	104.9
Significance						
Shade net (N)	0.0002	0.013	0.013	0.008	0.0008	0.001
Mulch (M)	0.108	0.066	0.079	0.294	0.261	0.163
Week (W)	<0.0001	<0.0001		<0.0001	<0.0001	
N × M	0.248	0.057	0.0502	0.034	0.085	0.038
W × N	<0.0001	<0.0001		<0.0001	<0.0001	
W × M	0.035	0.001		<0.0001	<0.0001	
W × N × M	0.493	<0.0001		<0.0001	<0.0001	

[i] Values are the seasonal mean value per plot (10 plants). Shade nets were placed above the high tunnels.

[ii] Incidence was determined as the percentage of symptomatic plants.

[iii] Severity was measured by using a 1–5 visual scale, where 0 = no symptoms; 1 = slight yellowing (mild symptom); 2 = leaf curling and yellowing (moderate symptom); 3 = yellowing, curling, and cupping (severe symptom); 4 = severe stunting, curling, and cupping; and 5 = plant stops growth and remains dwarf (very severe symptom) (Lapidot and Friedmann 2002).

[iv] AUDPC (area under the disease progress curve) was measured from the severity values (Simko and Piepho 2012).

[v] Values within a column followed by a different letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.

tomato marketable yield under shaded conditions is consistent with other studies (Gent 2008; Gude et al. 2022). In Hungary, external colored shade nets reduced bell pepper fruit yields (Ombódi et al. 2015). Insufficient light inside the HT resulting in diminished leaf net photosynthesis may explain the decreased fruit yields and reduced individual fruit weight. In bell pepper (Díaz-Pérez 2014; Ilic et al. 2017) and tomato (El-Gizawy et al. 1992; Kittas et al. 2012), shade nets have reduced the incidence of physiological disorders such as sunscald and blossom-end rot. However, in the present study, fruit disorder incidences were low, probably because tomato fruits developed in late fall and winter when air temperatures and irradiation were not detrimental to plants. The use of shade nets during the winter probably has more detrimental effects on tomato plants than during other seasons when there is increased daylength and irradiation.

In the present study, the midday PPFD under the black net (792 $\mu mol \cdot m^{-2} \cdot s^{-1}$), silver net (825 $\mu mol \cdot m^{-2} \cdot s^{-1}$), and unshaded conditions (1136 $\mu mol \cdot m^{-2} \cdot s^{-1}$) were lower than the optimal PPFD for leaf net photosynthesis saturation in tomato. Tomato plants in HTs need to receive sufficient PPFD to maximize fruit yields. However, the PPFD of leaf net photosynthesis saturation in tomatoes may be influenced by air temperature and CO_2 (Hu et al. 2019). Tomato seedlings at 20 to 22 °C reached the saturation point at PPFD 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, whereas leaves at 24 to 36 °C did not reach the saturation point even under ambient sunlight of 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Gao et al. 2022).

The plastic film covering the HT may reduce PPFD transmittance as films age. Plastic films vary in PPFD transmittance depending on the quality and plastic film composition (Tantau et al. 2012). In this study, the HT covering alone reduced PPFD by 36%, probably because of dust on the film covering. Thus, washing the film covering may be recommended to prevent excessive reduction in light penetration inside the HT. Film degradation over time may also affect the amount of PPFD transmission through HT film.

There are few reports on the influence of light quantity and quality on insect populations in HTs. The present study's preliminary data (Season 2) showed that shade net did not influence the populations of thrips, whiteflies (vector of TYLCV), and aphids. Interestingly, the populations of beneficial parasitoid wasps were the lowest under unshaded conditions. The high light conditions in the unshaded treatment negatively may have impacted the parasitoid wasps. The PPFD data of this study are only preliminary because light measurements were made in January, possibly resulting in reduced PPFD levels because PPFD changes over the year (Espí et al. 2006; Tantau et al. 2012). HT air temperature does not explain the differences in insect numbers because, except for thrips, which decreased with increasing HT air temperature, HT air temperature was unrelated to insect numbers among shade treatments. In cucumber, there was a positive interaction between virus-transmitting insect incidence with temperature and relative humidity as influenced by shade nets (Maklad et al. 2012).

Shade net and plastic mulch did not consistently influence TYLC incidence, severity, AUDPC, or whitefly numbers. Because the sweetpotato whitefly vectors TYLCV, any impact of shade net on insect populations could affect TYLC incidence. Six WAT, there was a 100% TYLC disease incidence due to viruliferous whiteflies, despite the 'Red Snapper' tomato being tolerant to TYLCV. Even though the incidence of plants showing symptoms of TYLC incidence was high, plants produced some marketable fruit; however, yields were low. Given the high numbers of whiteflies present, the impact of environmental factors such as temperature or light on TYLC symptom expression may not have been detectable, as it could have occurred if fewer whiteflies were present.

Few studies have evaluated the impact of climate modification on insect pests as disease vectors. Insect metabolic rate and food consumption increase with temperatures (Deutsch et al. 2018). In Bangladesh, except for sweetpotato whiteflies [*Bemisia tabaci* (Gennadius)], the number of insect vectors [aphids (*Aphis gossypii* Glover), cotton leafhopper [*Amrasca devastans* (Distant)], and thrips (*Thrips* spp.) and beneficial arthropods increased with increasing air temperature in chili (*Capsicum annuum* L.) (Khatun et al. 2023). In Israel, in tomato grown under black or red shade nets, the incidences of necrotic Potato virus Y (42% to 50%) and TYLCV (15% to 50%), that are vectored by aphids and whiteflies, respectively, were more than two times higher than under yellow or pearl shade nets (Ben-Yakir et al. 2012). In open-field tomatoes grown in warm conditions on various colored plastic mulches, high RZT

Table 9. Tomato yellow leaf curl incidence and AUDPC interactions with plastic mulch color. Tifton, GA, USA (Season 2).

	Incidence[i] (%)				AUDPC[ii]			
	Net				Net			
Mulch	Black	Silver	Unshaded	*P*	Black	Silver	Unshaded	*P*
Black	0.474 bB[iii]	0.759 A	0.688 A	0.001	57.3 bB	128.8 A	115.9 A	<0.0001
White	0.562 aB	0.742 A	0.667 A	0.014	74.3 aC	128.3 A	112.0 B	0.0003
P	0.012	0.502	0.430		0.010	0.923	0.430	

[i] Incidence was determined as the percentage of symptomatic plants.

[ii] AUDPC (area under the disease progress curve) was measured using severity values (Simko and Piepho 2012).

[iii] Values within a column (small letters) and a row (capital letters) not followed by the same letter are significantly different at $P < 0.05$, according to the Tukey-Kramer test.

resulted in decreased plant growth and yield and an earlier expression of symptoms of tomato spotted wilt disease (Díaz-Pérez et al. 2007).

RZT can influence plant growth and function (Cooper 1973). Higher irradiation (PAR and infrared) resulted in augmented air and RZT in the unshaded HT. Thus, the increased air and RZT in the unshaded HT likely enhanced plant mortality and reduced plant growth, particularly in plants grown with black mulch (mean RZT 28.08 °C, Season 2). Plant growth and yield have been reported to decrease in tomato grown on black mulch at mean seasonal RZT above 26.3 °C (Díaz-Pérez and Batal 2002). In the present study, plants on black mulch had reduced plant height and stem diameter during the establishment period (first 4 WAT). This period (August–September) was the warmest, with air temperatures and RZT above the optimum for tomato (Rubatzky and Yamaguchi 1999). As the season progressed into the fall, air temperature and RZT were probably not limiting factors for 'Red Snapper' tomato plant growth.

Although not evaluated in this study, tomato grafted on rootstocks tolerant to heat may allow tomato plants to grow and produce adequate fruit yields under increased air and RZTs (Milenkovic et al. 2020). Grafting may also enhance tomato plant disease tolerance (Smith and Saravanakumar 2022).

In conclusion, externally mounted shade nets (for the entire season) and plastic mulch color were evaluated as heat amelioration TYLC management strategies in HT organic 'Red Snapper' tomatoes planted during warm periods. During the first 4 WAT, plants on white plastic mulch were taller and had thicker stems than those on black mulch. However, the color of the plastic mulch did not influence fruit yield. Shade nets reduced air, RZT, and PPFD. However, despite the amelioration of heat challenges under shade nets, tomato marketable yield decreased probably because the PPFD was below the requirements for tomato leaf photosynthesis. Thus, using externally mounted shade nets is not recommended once high air temperatures are no longer a limiting factor for HT tomato production in Georgia (after about mid-October). Shade nets did not consistently influence TYLC incidence, severity, and whitefly number. Both black and silver shade nets conserved more beneficial parasitoids than unshaded conditions in one study season. HT tomato plants exhibited a high TYLC incidence, suggesting that 'Red Snapper' may not be suited for HT tomato production in Georgia when whitefly populations are high. Thus, more research is necessary on managing heat challenges and TYLC in HT organic tomato production.

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