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Yield performance and nutritional quality of tomato hybrids in response to protected environments during the Amazonian summer

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Abstract: This study evaluated the yield performance of the tomato hybrids 'DS0060', 'Thaise' and 'Trucker' in the open field and environments protected by agricultural film (F) and polycarbonate panels (P) during the Amazonian summer. In the protected environment, the crops produced significantly higher yields than in the open field. 'Thaise' has high thermotolerance and is adaptable to a wide temperature range, making it the best-performing hybrid in environment F. Highest yields were found for 'Thaise' in environment F or P (86.2 and 92.5 t ha^{-1}) together with 'DS0060' and 'Trucker' in environment F (75.3 and 88.2 t ha^{-1}), demonstrating the high yield potential in the interim growing season (January to April). In the open field, the fruit color was paler, fruit flesh firmer and ripening index lower. In environment F, the fruits contained highest levels of soluble solids, lycopene and β-carotene. 'Thaise' contained higher concentrations of these two compounds. Under environment P, the yield of the evaluated tomato hybrids increased considerably, indicating it as a promising possibility for tomato cultivation in tropical regions. 'Thaíse' stood out with high yield and good quality traits, when grown in an F or P environment. These results prove the viability of tomato production as interim crop in tropical regions, under high rainfall and heat, as well as the difference protected environments make for tomato cultivation, in particular the choice of the most suitable cover material for the crop, to ensure high yields coupled with desirable quality properties.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is the fruit vegetable crop for which the market demand is the highest in the world. In 2019, the crop acreage was 5 million hectares, for a production of 181 million tons. Worldwide, Brazil is the 9th largest producer, with an output of 3.6 million tons on 54,500 hectares (FAO, 2021). The high demand for tomato is related to the palatability, culinary versatility and high contents of nutrients, especially those with functional properties such as vitamin C, lycopene and β-carotene (Ali *et al.*, 2021).

In tropical farming, tomato is considered a high-risk crop since the investments of inputs and management required are high. Open-field yield can vary considerably due to pest and pathogen pressure, since up to 75% of the plants may be affected from the very beginning of the season, mainly by bacterial wilts and viruses (Huat *et al.*, 2013). Protected cultivation allows production under adverse conditions, reducing plant exposure to high rainfall and, consequently, to disease incidence (Bazgaou *et al.*, 2018). By minimizing the seasonality effect, year-long production becomes possible, favoring product supply between the main crop seasons.

The cover material for a protected environment must be chosen with a view to reducing the levels of global radiation and incident photosynthetically active radiation (PAR), to ensure an optimized plant performance. Agricultural film can increase plant production by altering the levels of luminosity, humidity and air temperature (Beckmann *et al.*, 2006). In tropical regions however, it can cause a rise in air temperature of 10 to 12°C with flower and fruit dropping, fruit cracking, black spot, and a decline in lycopene synthesis and marketable fruit yield. Nevertheless, under the protective cover, the fruits can accumulate more soluble solids and vitamin C (Florido and Álvarez, 2015; Shimeles *et al.*, 2017; Bazgaou *et al.*, 2018). In this context, polycarbonate can be taken into consideration as an alternative cover for greenhouses, due to the high light transmittance and UV protection, aside from being a very light but durable material (Kwon *et al.*, 2017). Evaluations of the cover material for protected tomato cultivation in tropical regions are insufficient, and little information is available about material that would allow more favorable cultivation conditions in these regions, to achieve higher yields without affecting the tomato quality.

For high tomato yields under high temperatures, thermos tolerant hybrids must be used. These can ensure high yields of high-quality fruit, even under abiotic stress (Scarano *et al*., 2020). The identification of tomato genotypes with high commercial and nutritional quality can help producers chose the most suitable cultivar for each cultivation environment under the agroclimatic conditions of the Amazon region in the summer season. This study analyzed the yield performance of tomato hybrids grown in the open field and in environments covered with agricultural film and polycarbonate in the Amazonian summer, by correlating agronomic performance with fruit quality using principal component analysis.

2. Materials and Methods

Plant material, cultivation environments and experimental design

Three tomato hybrids [‘BSDS0060’ (Blueseeds), ‘Trucker’ (Nunhems) and ‘Thaíse’ (Feltrin)] were grown in three growing environments [open field (O); environment covered with agricultural film (F) and polycarbonate panels (P)]. The study was arranged in a randomized block design (CRD) in a factorial arrangement (3x3) with five replications and seven plants each.

The hybrids for the study had an indeterminate growth habit; fruits suited for salad and were chosen because of their yield and disease resistance. ‘DS0060’ has a late cycle, firm fruits and high fruit cracking resistance; mean fruit weight of 220 to 260g and is tolerant to Tomato spotted wilt virus (TSWV), Tomato mosaic virus (ToMV), Tomato yellow leaf curl virus (TYLCV), *Fusarium oxysporum* f. sp. *lycopersici* (FOL) race 1 and 2 and Verticillium (V) race 1. ‘Trucker’ is a vigorous F_1 hybrid with excellent leaf cover; mean fruit weight of 240 g and tolerance to TYLCV, TSWV, FOL, V and nematodes. ‘Thaise’ is a medium-vigor F_1 hybrid with bright red fruits, excellent market standard due to the flavor, fruit uniformity and long shelf life; mean fruit weight of 230 g and tolerance to TYLCV, ToMV, *Verticillium dahliae* Kleb., *Fusarium oxysporum* f. sp. *lycopersici* (FOL) race 3 and root-knot nematode.

The tomato hybrids were grown in the open field and under the protection of a chapel-shaped greenhouse (6.4 x 20 m), lateral height 3.5 m, central height 4.8 m in the north/south direction and side closure with 30% Aluminet, a thermo-reflective shading screen. As cover material of the structure, a low density transparent agricultural film (F), with UV-A/UV-B protection, 90% transmission, and 25% light diffusion (Nortene 150 µm) was compared with transparent polycarbonate panels (P), with 10 mm thick, a double-layer honeycomb structure and UV-A/UV-B protection (Polisystem).

Area and cultivation conditions of tomato plants

The study was carried out in summer 2019/2020 (November to April) in Sinop, Mato Grosso, Brazil (lat. 11° 52’ 12” S, long. 55° 35’ 54” W; 364 m asl). According to the Köppen classification, the climate is equatorial savanna with dry winters (Aw), with a mean annual temperature of 25.4°C, a maximum of 34°C, annual rainfall of 1801 mm, and a rainy season between October and April.

The tomato seedlings were produced in a climatized greenhouse, planted in the 162 cells of polystyrene trays, containing 31 ml of commercial substrate (Vivato) per cell. The seedlings were planted 29 days after sowing (DAS) in furrows spaced 1.25 m apart and 0.35 m between plants, with a total population of 22,000 plants per hectare. The plants were trellised by the “Florida weave” method, on a structure of 1.3 m high wooden stalks and twine inserted horizontally every 0.4 m to hold up the plants.

The soil at the site was classified as dystrophic red-yellow latosol (LVA). The chemical properties (0-0.2 m layer) are shown in Table 1. Acidity was corrected with 3.0 t ha^{-1} dolomitic lime (90% total neutralizing power), fertilization at planting consisted of 3.4 t ha^{-1} single superphosphate and 30 t ha^{-1} barnyard manure, incorporated to a depth of 0.2 m with a rotary hoe. Topdressing was applied by drip fertigation, distributed in 10 applications throughout the cycle, containing a total of 120 g calcium nitrate (15% N and 19% Ca), 40 g potassium sulfate (48% K_2O and 15% SO_4), 30 g phosphate monophosphate (12% N and 61% P_2O_5), 110 g potassium nitrate (13% N, 44% K_2O and 1.5% S) and 70 g magnesium sulfate (9% Mg and 12% S) per plant.

Irrigation was applied at a mean net depth of 3.5 mm per day, to compensate for the calculated mean daily evapotranspiration (Valeriano *et al.*, 2017). Diseases and pests were controlled as recommended for the crop, by monitoring and applying products (based on pyraclostrobin, fluxapyroxad, trifloxystrobin, prothioconazole, kasugamycin, copper oxychloride, equivalent in metallic copper, mancozeb, carbosulfan, abamectin, haloxyfop-p-methyl, pyriproxyfen, acetamiprid, alpha-cypermethrin, chlorfenapyr, beauveria bassiana) in active principle rotation and at rates recommended by the manufacturer. Weed was controlled by hand weeding between plants and in-between rows.

Table 1 - Soil physicochemical analysis in the experimental area

Physico-chemical characteristics	Data
pH water	5.1
pH $CaCl_2$	4.3
P (mg dm$^{-3)}$	0.9
K (mg dm^{-3})	37
Ca + Mg	1.0
Ca (cmol$_c$ dm^{-3})	0.8
Mg (cmol$_c$ dm^{-3})	0.2
Al (cmol$_c$ dm^{-3})	0.5
H (cmol$_c$ dm^{-3})	3.9
OM (g dm^{-3})	20.0
Sand (g Kg^{-1})	283
Silt (g Kg^{-1})	133
Clay (g Kg^{-1})	584
Sum of bases	1.1
CEC	5.4
V (%)	20.1
Ca/Mg ratio	3.2
Ca/K ratio	8.3
Mg/K ratio	2.6
Ca Sat.	14.7
Mg Sat.	4.6
Al Sat.	30.2
K Sat.	1.8
H Sat.	71.2

Monitoring environmental variables

The microclimatic variables (temperature, relative humidity, global radiation and PAR) of each environment were monitored and recorded at meteorological stations (U30, HOBO) equipped with Sigma sensors installed at the center of each environment, at a mean height of 1.80 m. Readings were taken every 20 min and data compiled in hourly mean per month from 6:00 am to 6:00 pm. Rainfall data were collected at the station installed in the open-field environment from December 12, 2019 to April 17, 2020.

Assessment of agronomic characteristics

Ripe fruits were harvested at ripening stage 6 (intense red color on more than 90% of the fruit surface) (Skolik *et al.*, 2019). Fruits were harvested somewhere between 99 and 137 d.a.s. within a period of about nine days in the protected environments. In the open field, harvest was already carried out 99 d.a.s. due to the poor phytosanitary state of the crop. The total fruit weight (kg plant^{-1}) and total number of fruits were immediately determined and then the commercial standard of the fruits was classified to (i.e., appearance, size and damage level) to determine the commercial fruit weight and number of commercial fruits, underlying the estimation of the overall yield (t ha^{-1}) of 22 thousand plants ha^{-1}.

Evaluation of photosynthetic responses

Photosynthetic parameters were evaluated with a portable infrared photosynthesis analyzer (LCi-SD, ADC). Photosynthetically active radiation (PAR, µmol m^{-2} s^{-1}), net CO_2 assimilation rate (A, µmol CO_2 m^{-2} s^{-1}), leaf transpiration rate (E, mmol H_2O m^{-2} s^{-1}), internal CO_2 concentration in the substomatal chamber (C_i, µmol mol^{-1}), stomatal conductance (g_s, mol m^{-2} s^{-1}). The fourth fully expanded leaf from the plant apex during the harvest period (i.e., fruit filling; between 128 and 136 d.a.s) was used. The measurements were carried out on a sunny and cloudless day between 8 and 10 am. Readings were taken in all treatments except on the open field, due to the high degree of crop damage caused by diseases.

Preparation of tomato samples

Fruits of the nine treatments harvested at 99 DAS were selected according to the market standards and samples of 12 fruits per plot were separated. The material was sanitized by immersion in chlorinated water (100 mg L^{-1} sodium hypochlorite) for 10 min and washed in distilled water. For physicochemical and biochemical analyses, the tomatoes were blended in a food processor (Philips Walita®). All samples were stored in triplicate at -80°C for later analysis.

Physicochemical and biochemical analyses

Fruit flesh firmness, total soluble solids, titratable acidity and ripening index

Flesh firmness of the tomatoes was measured with a penetrometer (TA HD Plus, Stable Micro System) by inserting a 6 mm tip into the skinless fruits to a depth of 9 mm. Soluble solids were determined in a refractometer (PAL-BX/RI, Atago). Titratable acidity (TA) was determined by the procedure described by Zenebon *et al*. (2005), using a benchtop pH meter (Hanna Instruments HI901). Results were expressed in % of citric acid, calculated by the formula:

$$TA = \frac{V \times fc \times 10}{P} \times 100 \tag{1}$$

where V is the volume (in mL) of 0.1 M NaOH used for titration; fc is the correction factor of NaOH and P the sample weight (in g). The fruit ripening index (ratio) was calculated as the ratio between total soluble solids and titratable acidity.

Fruit color

The color coordinates were read with a colorimeter (Color Quest XE, Hunter Lab). Readings were performed in the L*a*b system. The chromaticity (C*) and Hue angle were determined by the formulas:

$$C = (a + b)^{½} \tag{2}$$

$$Hue = tg^{-1}(b/a) \tag{3}$$

Lycopene and β-carotene contents

The lycopene and β-carotene contents were determined as proposed by Nagata and Yamashita (1992). A 1-g sample was homogenized in 10 ml acetone:hexane (4:6 v/v) solution in a turrax blender. The resulting solution was analyzed in a spectrophotometer (Evolution 201, Thermo Scientific) after phase separation. Absorbance was determined at 453, 505, 645 and 663 nm and the results (mg 100^{-1} g) computed by the formulas:

$$Lycopene = -0.0458A_{663} + 0.204A_{645} + 0.372A_{505} - 0.0806A_{453} \tag{4}$$

$$ß\text{ - }carotene = 0.216A_{663} - 1.22A_{645} - 0.304A_{505} + 0.452A_{453} \tag{5}$$

Data analysis

The data were subjected to analysis of variance (ANOVA) and the means compared by the Scott-Knott test ($P<0.05$), using software SISVAR version 5.6 (Ferreira, 2019). Principal component analysis (PCA) was run on software XLSTAT version 2021.3.1.

3. Results and Discussion

Agroclimatic variables

Data on rainfall and daily variations in global radiation, PAR, temperature and relative humidity in the cultivation environments during the experimental period were recorded (Fig. 1A-1E). The conditions of high rainfall and high temperatures restricted the plant cycle to 99 d.a.s. The total rainfall volume was 1841.9 mm, of which 633.1 mm fell between flowering and fruit formation and 531.6 mm during fruit filling and harvesting (Fig. 1A). The air temperature varied from 22 to 29°C (Fig. 1D). For tomato cultivation,

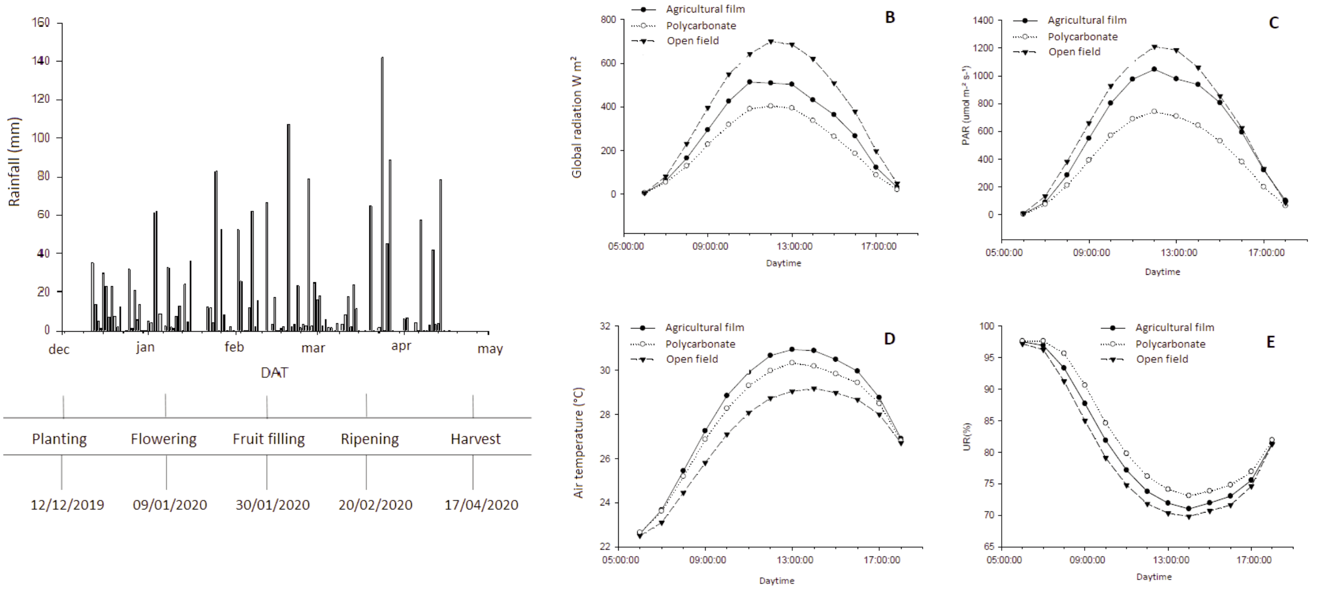

Fig. 1 - Rainfall during the experimental period (A) and daily variation of global radiation (B), PAR (C) air temperature (D) and relative humidity (E) in different growing environments.

the optimal air temperature range is 20 to 24°C during the day and 18°C at night (Shimeles *et al.*, 2017). Above 29°C, yields decrease due to reduced fruit set (Harel *et al.*, 2014). Thus, the high rainfall volume and high temperatures limited open-field tomato cultivation by favoring high disease severity, which impaired the photosynthetic analysis in this plant group. Protected cultivation provided an efficient barrier against excessive rainfall, but raised the maximum temperatures by 6.3% in environment F and by 4.4% in P, compared to the open field. The relative air humidity was quite similar in the evaluated cultivation environments.

Regarding luminosity, global radiation and PAR were lower in environments P and F than in the open field (Figs. 1B and 1C). In environment P, global radiation reached 403.3 W and PAR 742.6 µmol m^{-2} s^{-1} at noon, i.e., about 40% less than in the open field and 25% lower than in environment F. Under low light incidence, tomato has optimized efficiency of PAR use (Radin *et al.*, 2003). This information was confirmed in our study by the higher tomato yield of plants grown in environment P (Table 2). The analysis of the photosynthetic responses (Table 3), net CO_2 assimilation rate (*A*), leaf transpiration rate (E), internal CO_2 concentration (*Ci*) and stomatal conductance (*Gs*) detected no differences between the protected environments. In environment P, the *A* value of hybrid 'Trucker' was 118% higher than in F, with a yield increase of 52% (Table 2). This variation can be attributed to the genetic characteristics of the hybrids and their responses to agroclimatic conditions (i.e., global radiation, PAR, air temperature). In a study of Kwon *et al*. (2017), the *A* of hybrid 'Superdoterang' grown in environments under polycarbonate and glass, respectively, did not differ (24.8 and 21.8 µmol m^{-2} s^{-1}). In this study, the better response of cultivars to the conditions in environment P may be related to a better light capture (of diffuse radiation) at a more efficient wavelength for photosynthesis, ass similarly observed elsewhere (Radin *et al.*, 2003; Kwon *et al.*, 2017).

Yield of tomato hybrids in different growing environments

The protected environments provided significantly higher fruit yields. The marketable fruit weight of the hybrids increased 7-fold in environment P and 4.5-fold in F, compared to the open field (Table 2). These results were better than those of Yeshiwas *et al.* (2016), who reported a 54% increase in tomato yield in a protected environment compared to an open field. 'Thaise' performed well under both cover types (3.90 and 3.27 kg $plant^{-1}$), while 'DS0060' and 'Trucker' had higher yields in environment P (3.23 and 3.57 kg $plant^{-1}$, respectively). The thermotolerance of 'Thaise' was better, making the hybrid adaptable to a wide temperature range, which resulted in

Table 2 - Total fruit weight per plant, weight of marketable fruits, total number of fruits, number of marketable fruits and total yield of tomato hybrids grown in the open field (O) and protected environments covered with agricultural film (F) and polycarbonate (P)

	Hybrid (H)			Mean	F (ANOVA)			CV%
	DS0060	Trucker	Thaíse		A	H	E x H	
Total fruit weight (kg/plant)								
O	0.384 cA [z]	0.860 bA	1.192 bA	0.812 c				
F	2.214 bB	2.636 aB	3.924 aA	2.924 b	54.0 **	5.91**	0.50 NS	12.7 [y]
P	3.424 aA	4.006 aA	4.208 aA	3.879 a				
Mean	2.007 B	2.500 B	3.108 A					
Weight of marketable fruits (kg/plant)								
O	0.192 cA	0.576 cA	0.572 bA	0.446 c				
F	1.834 bB	2.256 bB	3.276 aA	2.455 b	66.4 **	3.60 *	0.55 NS	13.1 [y]
P	3.236 aA	3.576 aA	3.900 aA	3.570 a				
Mean	1.754 A	2.136 A	2.582 A					
Total number of fruit (fruits/plant)								
O	3.60 bB	8.60 bA	12.4 bA	8.20 b				
F	21.0 aB	27.8 aB	48.2 aA	32.3 a	52.2 **	14.0 **	0.86 NS	17.9 [y]
P	24.8 aA	36.6 aA	39.4 aA	33.6 a				
Mean	16.4 C	24.3 B	33.3 A					
Number of marketable fruits								
O	0.80 bA	4.40 bA	3.20 bA	2.80 b				
F	15.2 aB	20.2 aB	35.0 aA	23.4 a	86.2 **	9.73 **	1.51 NS	19.5 [y]
P	20.2 aB	30.0 aA	33.4 aA	27.8 a				
Mean	12.1 B	18.2 A	23.8 A					
Total yield (t ha^{-1})								
O	8.44 cB	18.9 bA	26.2 bA	17.8 c				
F	48.7 bB	58.0 aB	86.2 aA	64.3 b	64.0 **	7.08 **	0.61 NS	17.7 [y]
P	75.3 aA	88.2 aA	92.5 aA	85.3 a				
Mean	44.1 B	55.1 B	68.3 A					

[z] Means followed by the same uppercase letter in the rows or lowercase letter in the columns do not differ statistically from each other by the Scott-Knott test at 5%.
[y] Data transformed into $\sqrt{y+1}$.
** P<0.01, * P<0.05, NS= Not significant P>0.05.

the best performance in environment F, with a total fruit weight of 3.92 kg plant^{-1} and marketable fruit weight of 3.27 kg plant^{-1}, which can be considered reasonable for tomato cultivation at high temperatures (Scarano *et al.*, 2020). The yield recorded in this study exceeded that of 'Superdoterang' which produced 2.8 kg of fruit plant^{-1} in a protected environment covered with polycarbonate (Kwon *et al.*, 2017) and of 'Bishola', with determinate growth habit, which produced 1.81 kg per plant (Yeshiwas *et al.*, 2016).

The total number of fruits was higher in 'Thaíse' in both environments, F and P, while the results of 'Trucker' were better in P (Table 2). However, a higher percentage of fruit of 'Thaise' had to be discarded in environment F (27%) than in environment P (15%). This was most likely caused by the higher global radiation, PAR and air temperature in environment F (Fig. 1B, 1C and 1D).

Tomato cultivation in the Amazon region in the summer is high risk farming, due to the occurrence of rain causing waterlogging of the soil and leaf wetting, which are rather unfavorable factors, particularly when associated with heat. In tropical regions, depending on the year of cultivation and plant management, severe disease and pest damage can occur at the harvest stage (Subin *et al.*, 2020). In this study, fruit loss in the open field was high, causing a decrease of 78% in the number of fruits in 'DS0060', 49% in 'Trucker' and 75% in 'Thaise'. This resulted from the unfavorable agroclimatic conditions during the growing season. High rainfalls together with heat

Table 3 - CO_2 net assimilation rate (A), leaf transpiration rate (E), internal CO_2 concentration in the substomatal chamber (Ci) and stomatal conductance (Gs) in tomato hybrids grown in open field (O), environments protected covered with agricultural film (F) and polycarbonate (P)

Photosynthetic variable	Hybrid (H)			Mean	F (ANOVA)			CV%
	DS0060	Trucker	Thaíse		E	H	E x H	
A (μmol CO_2 m^{-2} s^{-1})								
O	-	-	-	-				
F	11.0 aA [z]	9.24 bA	12.9 aA	11.1 a	2.09 NS	3.51 NS	5.67 *	14.4 [y]
P	7.67 aB	20.1 aA	14.9 aA	14.2 a				
Mean	9.35 B	14.6 A	13.9 A					
E (mmol H_2O m^{-2} s^{-1})								
O	-	-	-	-				
F	3.68 aA	5.45 aA	4.96 aA	4.70 a	0.10 NS	3.24 NS	0.11 NS	12.9
P	3.07 aA	5.36 aA	4.86 aA	4.43 a				
Mean	3.37 A	5.41 A	4.91 A					
Ci (μmol mol^{-1})								
O	-	-	-	-				
F	349.3 aA	373.7 aA	315.0 aA	346.0 a	3.79 NS	0.28 NS	1.05 NS	6.77
P	306.7 aA	295.0 aA	312.3 aA	304.6 a				
Mean	328.0 A	334.3 A	313.7 A					
Gs (mol m^{-2} s^{-1})								
O	-	-	-	-				
F	0.326 aA	0.336 bA	0.690 aA	0.451 a	1.74 NS	2.46 NS	1.57 NS	11.4
P	0.290 aA	1.001 aA	0.790 aA	0.696 a				
Mean	0.3 A	0.6 A	0.7 A					

[z] Means followed by the same uppercase letter in the rows or lowercase letter in the columns do not differ statistically from each other by the Scott-Knott test at 5%.

[y] Data transformed into $\sqrt{y+1}$.

** P<0.01, * P<0.05, NS= Not significant P>0.05.

are factors that increase the risk of disease incidence in tomato crops (Silva *et al.*, 2013). In tropical regions, high pest and pathogen pressure jeopardize production. In this study, 46% of the plants were decimated, and between flowering and the beginning of harvest, the disease severity index had reached a maximum level in all cultivated areas, minimizing the plant yield.

When estimating the total yield, 'Thaíse' cultivated in environment F or P (86.2 and 92.5 t ha^{-1}, respectively) together with 'DS0060' and 'Trucker' cultivated in environment F (75.3 and 88.2 t ha^{-1}, respectively) were the highest yielding (Table 2). These yields are considered high when compared to the hybrids 'Lampião' (73.0 t ha^{-1}), 'Fascínio' (68.3 t ha^{-1}), 'Candieiro' (66.1 t ha^{-1}) and 'Shanty' (62. 4 t ha^{-1}) produced under similar growing conditions as in this study (i.e., protected environment, tropical climate, high temperatures)(Seabra *et al.*, 2022). These results confirm the high yield potential of the evaluated tomato hybrids in the interim growing season, under protected cultivation and at high temperatures. The high yields recorded must be related to the thermotolerance of the evaluated genetic material, mainly of 'Trucker' and 'Thaise', resulting in higher profits for producers.

Physicochemical and biochemical properties of fruits in response to growing environments

Tomato color is an important quality property. The fruits grown in the open field had higher values of luminosity (L*), hue angle (h°) and higher b* coordinates, indicating lighter, brighter and more yellowish fruits. On the other hand, the fruits produced in environments F and P had higher a* coordinates, with more reddish fruits (Table 4). The fruits of hybrid 'DS0060' had higher chromaticity (C*), L*, h° and b* coordinate values, mainly when grown in the open field, also indicating lighter colored fruits, while the a* coordinates of 'Trucker' and 'Thaise' were higher, i.e., the reddish fruit color was more intense. These results showed that the adaptation of hybrid

Table 4 - Chromaticity (C*), luminosity (L*), hue angle (h°), coordinates (a* and b*) of fruits of tomato hybrids grown in open field (O) and protected environments covered with agricultural film (F) or with polycarbonate (P)

Variable	Hybrid (H)			Mean	F (ANOVA)			CV%
	DS0060	Trucker	Thaíse		A	H	A x H	
*C**								
O	51.1 aA *z*	50.8 aA	51.1 aA	51.0 a				
F	52.0 aA	49.8 aB	49.3 aB	50.3 a	1.81 NS	4.10 *	0.90 NS	7.59
P	51.1 aA	49.6 aA	48.8 aA	49.8 a				
Mean	51.4 A	50.0 B	49.7 B					
*L**								
O	51.9 aA	49.4 aB	45.0 aC	48.8 a				
F	46.0 bA	42.8 bB	42.3 bB	43.7 b	35.9 **	28.8 **	2.06 NS	8.66
P	46.7 bA	43.9 bB	42.7 bB	44.4 b				
Mean	48.2 A	45.4 B	43.3 C					
h°								
O	60.7 aA	53.7 aB	44.7 aC	53.0 a				
F	44.8 bA	40.6 bB	39.7 bB	41.7 b	58.9 **	31.6 **	5.27 **	14.8
P	46.5 bA	43.4 bB	40.8 bB	43.6 b				
Mean	50.7 A	45.9 B	41.8 C					
*a**								
O	24.9 bC	29.9 bB	36.2 aA	30.3 b				
F	36.4 aA	37.4 aA	37.8 aA	37.2 a	40.1 **	18.2 **	7.74 **	14.5
P	34.8 aA	35.7 aA	37.0 aA	35.8 a				
Mean	32.0 C	34.3 B	37.0 A					
*b**								
O	43.8 aA	40.3 aB	35.9 aC	40.0 a				
F	36.4 bA	32.6 bB	31.4 bB	33.5 b	38.5 **	25.9 **	1.00 NS	13.9
P	36.7 bA	34.0 bB	31.9 bB	34.2 b				
Mean	39.0 A	35.7 B	33.1 C					

(z) Means followed by the same uppercase letter in the rows or lowercase letter in the columns do not differ statistically from each other by the Scott-Knott test at 5%.

** P<0.01, * P<0.05, NS Not significant P>0.05.

'DS0060' to high solar radiation and heat was poor, and it should be evaluated in growing seasons with milder temperatures.

In this study, the fruits were harvested when more than 90% of the fruit surface had become deeply red (stage 6). The fruit flesh of the tomatoes from the open field was firmer (Table 5). Of the hybrids, 'Trucker' had the firmest fruit flesh. This characteristic is relevant with regard to transport resistance, and is influenced by the ripening stage of the fruit, and possibly by the genetic and environmental characteristics of cultivation.

In general, the levels of soluble solids were slightly higher in tomatoes from environment F (Table 5). Among the hybrids, 'DS0060' had the highest soluble solids content. These results are similar to those published by Kwon *et al.* (2017) who found contents between 5.1 and 5.2°Bx, but observed no difference for this variable between cultivation environments. According to the authors, soluble solids may be strongly genetically influenced. 'Lampião' tomatoes, which are sweeter, contained 4.12°Bx and 'Fascínio' 3.48°Bx. According to the above authors, consumers prefer tomatoes with 4.0 to 6.0°Bx (Domiciano *et al.*, 2021). In this study, all hybrids produced fruits with soluble solids contents above 4°Bx. Soluble solids in tomato consist mainly of reducing sugars. Thus, agronomic factors (i.e., seasonal climate variation, management practices) that alter the photosynthetic activity, and consequently sucrose synthesis, can modify glucose and fructose accumulation in fruits, and thus the soluble solids contents (Yeshiwas *et al.,* 2016).

The titratable acidity of the fruits ranged from

Table 5 - Fruit flesh firmness, soluble solids, tritable acidity, ripening index, lycopene and β-carotene contents in fruits of tomato hybrids grown in open field (O) and protected environments covered with agricultural film (F) or with polycarbonate (P)

Variable	Hybrid (H)			Mean	F (ANOVA)			CV%
	DS0060	Trucker	Thaíse		A	H	AXH	
Fruit flesh firmness (N)								
O	9.16 aB (z)	12.4 aA	9.64 aB	10.4 a				
F	7.00 bB	8.32 bA	6.08 bB	7.13 b	30.0 **	12.1 **	1.10 ns	37.9
P	7.00 bA	7.92 bA	5.84 bA	9.62 b				
Mean	7.72 B	9.56 A	7.18 B					
Soluble solids (°Bx)								
O	4.46 bA	4.00 bB	4.06 bB	4.17 c				
F	5.20 aA	4.66 aB	4.60 aB	4.82 a	20.5 **	11.2 **	0.90 ns	10.7
P	4.60 bA	4.46 aA	4.26 bA	4.44 b				
Mean	4.75 A	4.37 B	4.31 B					
Tritable acidity (%)								
O	0.340 aA	0.300 aB	0.280 bB	0.306 a				
F	0.300 bB	0.273 bB	0.333 aA	0.302 a	1.32 ns	4.88 **	8.6 **	12.8
P	0.300 bB	0.306 aB	0.340 aA	0.315 a				
Mean	0.313 A	0.293 B	0.317 A					
Ripening index (SS/TA)								
O	13.1 cA	13.3 bA	14.5 aA	13.6 b				
F	17.3 aA	16.5 aA	12.9 bB	15.6 a	27.4*	12.1*	17.8*	12.3
P	15.3 bA	15.5 aA	13.5 aA	14.8 a				
Mean	15.2 A	15.1 A	13.6 B					
Lycopene (z) (mg 100 g^{-1})								
O	0.395 bB	0.581 cA	0.669 cA	0.548 c				
F	0.861 aC	1.127 aB	1.467 aA	1.150 a	114.7 **	33.9 **	5.36 **	11.3 (y)
P	0.751 aA	0.782 bA	0.833 bA	0.788 b				
Mean	0.669 C	0.828 B	0.989 A					
β-carotene (mg 100 g^{-1})								
O	0.378 bB	0.509 cA	0.574 cA	0.487 c				
F	0.727 aC	0.953 aB	1.231 aA	0.907 a	105.0 **	35.0 **	3.91 **	10.8 (y)
P	0.639 aB	0.681 bB	0.769 bA	0.695 b				
Mean	0.581 C	0.714 B	0.856 A					

(z) Means followed by the same uppercase letter in the rows or lowercase letter in the columns do not differ statistically from each other by the Scott-Knott test at 5%.

(y) Data transformed into $\sqrt{y+1}$.

** $P<0.01$, * $P < 0.05$, NS Not significant $P > 0.05$.

0.27 to 0.34%. There was a significant interaction between environments and hybrids, resulting in the highest acidity in fruits of 'DS0060', grown in the open field, and of 'Thaise' produced in environment F or P (Table 5). These values were lower than the 0.39 to 0.55% reported by Scarano *et al.* (2020), but similar to the range of 0.22 to 0.32% found by Nour *et al*. (2015). Acidity is influenced by the moment of fruit harvest and possibly also by genetic characteristics of the hybrids. The sweetness acidity ratio or relationship between sweetness and acidity, called ripening index, determines the taste, indicating a mild or acid flavor. Fruits with an index equal to or greater than 10 are considered ideal for consumption (Kader and Stevens, 1978). The index in this study exceeded 13, reaching 17.3 in 'DS0060' fruits from environment F (Table 5). For 'DS0060' and 'Trucker', the ripening index in open field cultivation was lower. However, due to the high soluble solids level, all environments and hybrids produced fruits with good market acceptance, i.e., a high ripening index, mainly due to the determined moment of harvest, when more than

90% of the fruit surface had become deeply red, ideal for marketing of the product in the region.

Regarding the carotenoid content of the fruits, the lycopene and β-carotene contents were higher in environment F and lower in open-field tomato (Table 5). This result can be explained by the high incidence of solar radiation on the plants (Fig. 1B). The contents were superior to those reported for *saladette* tomato produced in a protected environment at high temperatures, ranging from 0.3 to 0.82 mg 100 g^{-1} for lycopene and 0.06 to 0.09 mg 100 g^{-1} for β-carotene (Domiciano *et al.*, 2021). Among the hybrids, 'Thaise' contained the highest and 'DS0060' lowest levels of these two compounds. The different lycopene contents in the hybrids can be attributed to genetic characteristics, climate, location, cultivation method and fruit ripening stage. According to Nour *et al.* (2015), carotenoid synthesis, mainly of lycopene, is influenced by the genetic characteristics of adaptability to the agroclimatic conditions of the cultivation environment.

Significant positive correlations were observed between the a* coordinate (Table 4) and lycopene (r = 0.743) and β-carotene (r = 0.742) levels. On the other hand, correlations were negative between the content of these carotenoids and L* (r = -0.793, r = -0.810), h° (r = -0.789, r = -0.798) and b* coordinate (r = -0.818, r = -0.837). These results are similar to those reported by Nour *et al.* (2015), who found a negative correlation of the L* value with the lycopene content in tomato. In this study, open-field fruits of 'DS0060' also had mean L* and lower lycopene and β-carotene levels (Tables 4 and 5). For 'Belladona', the chromaticity values were related to the carotenoid contents, except for lycopene (Papaioannou *et al*., 2012). However, this information was not confirmed by the results of this study, where the chromaticity values were weakly correlated with lycopene (r = -0.526) and β-carotene (r = -0.579) contents.

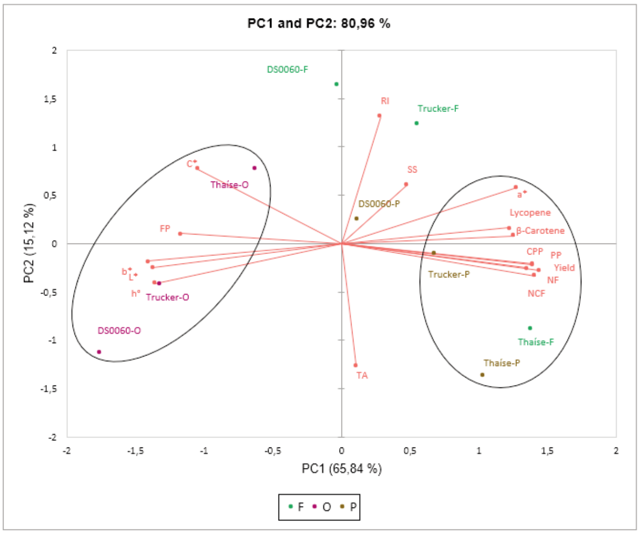

Fig. 2 - Two-dimensional projection and score of productive characteristics (yield; plant production—PP commercial plant production—CPP; number of fruits – NF, number of commercial fruits – NCF, chroma - C*, luminosity - L*, hue angle - h°, coordinates - a* and b*, fruit firmness – FP, soluble solids - SS, titratable acidity – TA, ripening index - RI, lycopene and β-carotene) of tomato cultivars (DS0060, Trucker, and Thaíse) in response to different environments – open field (O), agricultural film (F), and polycarbonate.

Considering all study variables, PCA analysis grouped 'Thaise' grown in environments F and P and 'Trucker' grown in environment P on the PC1+, corresponding to 65.84% of the data, with the best results in terms of yield as well as quality characteristics (Fig. 2). Hybrids 'DS0060', 'Trucker' and 'Thaise' cultivated in the open field (PC1-) produced low yields, fruits with undesirable color and very firm fruit flesh due to the environmental conditions that stressed the plants, causing high yield losses and physiological disorders. The hybrids 'DS0060' and 'Trucker' cultivated in environment F were grouped in PC2+, with low acidity and high fruit ripening indices, probably due to low heat tolerance. These results reinforce the relevance of cultivation in protected environments to warrant high tomato yield during the hot and humid summers of the Amazon region. Equally important is the selection of hybrids adapted to high radiation and high temperatures, which are fairly common under these cultivation conditions.

Protected environments were indispensable to achieve high yields under the unfavorable agroclimatic conditions (i.e., high rainfall, high solar radiation, high temperatures) of the southern Amazon region in the interim crop season (January to April). The protected environment covered with polycarbonate panels considerably increased the fruit yield of the tomato hybrids evaluated, indicating it as a good alternative for tomato cultivation in tropical regions. In protected environments covered with agricultural film or polycarbonate panels, hybrid 'Thaise' produced high yields with good quality characteristics. 'Trucker' stood out with the firmest fruit flesh and lowest acidity. However, 'Thaise' had the highest lycopene and β-carotene levels, a characteristic that appeals to more demanding consumers, since these compounds are strongly related to disease prevention, and their presence in the human diet is essential.

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