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Adaptability and Yield Performance of Introduced Tomato Lines under Greenhouse and Open Field Conditions in Honduras

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Abstract. **In Honduras, tomato (*Solanum lycopersicum* L.) is an economically important crop for farmers because of its high domestic consumption, year-round production, and high export potential. However, tomato production faces challenges such as diseases and pests and is confounded by climate change, all of which reduce productivity and quality. Evaluating the adaptation of tomato cultivars is critical to ensuring the long-term sustainability and resilience of the horticulture sector in the region. The objective of this study was to identify tomato lines with adaptability, high yield, pest, and disease resistance under greenhouse and open field production conditions for the Honduran market. Ten tomato lines and two commercial hybrids were evaluated between Feb and Jul 2022 in San Antonio de Oriente, Francisco Morazán, Honduras. Desirable traits related to vegetative growth, productivity, fruit quality, and resistance to insect pests and diseases were measured. Seven lines were highly adapted and had high vegetative growth. The tomato lines were not significantly different in terms of tomato yellow leaf curl disease and late blight disease index; however, the fruit borer susceptibility varied, with AVTO1908 being the most susceptible. The highest performing line was AVTO1903, which had the greatest total marketable yield in both the open field (101.3 t·ha^{-1}) and greenhouse (62.1 t·ha^{-1}). Additionally, AVTO1903 and AVTO1915 had good quality traits (roundness index, total soluble solids, and dry matter), thus demonstrating their potential for sustainable and high-yielding cultivation in Honduras. The growth and productivity of the tomato lines were highly influenced by the environment. This work highlights the advantages of introducing exotic cultivars to combat the effects of climate change and ensure sustained production; however, further research is needed to ensure that local farmer and consumer demands are met.**

Tomato (*Solanum lycopersicum* L.) is an economically important crop worldwide because of its commercial value, high adaptability, and high consumption. Tomato production has grown significantly since 1961, increasing from 28 million tons to 164 million tons within 52 years, and tomato is the most important vegetable crop worldwide (Colvine and Branthôme 2016). This growth has occurred mainly in Asia, with the largest producers of tomatoes including China (with 56 million tons per year), India (with 18 million tons per year), and the United States (with 12.2 million tons per year) (FAOSTAT 2022). In 2021, Honduras ranked 86th among tomato-producing countries, with average production of 81,580 tons annually (FAOSTAT 2022). According to the Fundación Hondureña de Investigación Agrícola (FHIA) (FHIA 2019), tomato production in Honduras is predominantly distributed in the departments of Olancho, Francisco Morazán, El Paraíso, Copán, Comayagua, and Choluteca. In 2020, an area of 1154 ha was cultivated, and an average yield of 70 t·ha^{-1} was obtained (FAOSTAT 2022).

Despite the steady increase in tomato production, farmers face significant limitations, including diseases caused by fungi, viruses, and bacteria. The most important fungal diseases in tropical regions include anthracnose caused by *Colletotrichum coccodes* (Waller) S. Hughes, black spot with causal agent *Alternaria alternata* (Fr.) Keissl, early blight caused by *Alternaria solani* (Cooke) Wint., grey mold originated by *Botrytis cinerea* (Whetzel), and late blight caused by *Phytophthora infestans*. Tomatoes are also affected by bacterial diseases such as bacterial spot (*Xanthomonas* spp.) and bacterial wilt (*Ralstonia solanacearum* species complex) (Gómez et al. 2011; Lewis et al. 2021). The most common viral diseases in this location are tomato chlorosis virus (*Crinivirus*), tomato spotted wilt virus (*Tospovirus*), tomato chocolate spot virus (*Torradovirus*), and tomato yellow leaf curl disease (TYLCD; *Begomovirus*) (Blancard 2017). Additionally, higher temperatures and dry conditions between March and May can create favorable conditions for the growth and development of populations of arthropod pests that attack leaves, flowers, and fruit during the crop cycle (Skendžić et al. 2021). The most common tomato arthropod pests are fruit borer (*Helicoverpa armigera* Hübner.), leafworm (*Spodoptera litura* Fabricio), leafminer (*Liriomyza* spp.), tomato leafminer (*Tuta absoluta* Meyrick), and red spider mites (*Tetranychus urticae* C. L. Koch) (López 2017). Furthermore, abiotic factors such as high temperatures, flooding, and drought stress also cause significant losses to tomato producers.

The vast challenges and limitations faced by tomato producers have resulted in farmers being inclined to opt for less sustainable and environmentally friendly management options (Araújo et al. 2000). To remain profitable, farmers in some regions have become dependent on the excessive use of pesticides and are reluctant to transition to more sustainable production systems; furthermore, these challenges are exacerbated by the effects of climate change (Hedlund et al. 2020). For tomato production to remain profitable in the face of climate change, and to realize its economic potential, strategies to achieve sustainable and resilient horticulture are needed. One important strategy involves using plant genetic resources to identify and develop pest and disease-resistant cultivars that can maintain high levels of production with less dependence on inputs (Atlin et al. 2017). The World Vegetable Center in Taiwan has a global germplasm collection of 6041 tomato accessions, with major research activities including breeding for resistance to late blight, bacterial wilt, TYLCD, and heat tolerance (Ebert and Chou 2015). Additionally, the use of improved production systems, such as low-cost structures, can also be deployed by farmers to mitigate the effects of climate change. The use of improved lines is among the most impactful interventions; in combination with other crop management practices, the use of improved lines can be sustainable and effective for combating the effects of climate change for tomato producers.

The selection of lines included in the trial was based on adherence to market segmentation and the combination of disease resistance genes important for the region. An evaluation of tomato lines from the World Vegetable Center in tropical Honduras provided the opportunity to evaluate the performance and adaptation of introduced lines with the option of further improvement and with the assurance that desirable traits such as yield, fruit quality, and disease resistance can be used by farmers in the future. Therefore, the objective of this study was to evaluate different introduced tomato lines and identify comparatively better adaptability, yield performance, and fruit quality traits of tomato lines under greenhouse and open field conditions in Honduras.

Materials and Methods

Study site conditions. The study was conducted at the Extensive and Intensive Olericulture Unit of the Pan-American Agricultural School, Zamorano, located in the Yegüare Valley, San Antonio de Oriente, Francisco Morazán department, Honduras (lat. 14.0°N, long. 87.1°W, elevation 770 masl), between Feb and Jul 2022. The climatic conditions in this zone include an average temperature of 23.7 °C, with average maximum and minimum temperatures of 39.2 °C and 13.6 °C, respectively, accumulated rainfall of 382.2 mm, and average relative humidity (RH) of 73.3%. The temperature and RH measurements were performed throughout the experimental period to determine the environmental differences between the open field and greenhouse using the iButton Hygrochron DS1923 sensor (iButtonLink, Whitewater, WI, USA). Data were analyzed using the OneWireViewer software (iButtonLink).

Experimental layout. We assessed the performance and adaptability of the tomato entries in two production systems (open field and greenhouse). Independent experiments were performed for both systems; however, the same design was used for both experiments.

Open field. The experiment was arranged in randomized complete blocks with 12 treatments and three replications; each replication included 24 plants in the open field. The field was plowed and leveled with a tractor, and a plot layout was established for the open field experiment. Four raised fields were prepared; each had a height of 0.50 m, length of 100 m, and 1.5 m from center to center. Silver-black plastic mulch (Del Campo Soluciones Agrícolas, Francisco Morazán, Honduras) was used to protect the crop from weeds, improve soil moisture retention, and prevent erosion of the raised field. The seedlings were transplanted 30 d after sowing. Floating row cover (6.4 m × 250 m; Agryl, Francisco Morazán, Honduras) was used as a semi-protected structure from 0 to 40 d after transplanting (DAT).

The fertigation program was calculated based on the soil analysis performed during each trial and aimed to meet the essential nutrient requirements throughout the crop cycle. Recommended production practices were also performed, such as trellising (four to six horizontal trellis wires at 12-cm spacing between wires), pruning of leaves and branches (lower, diseased, and senescent leaves, vegetative branches), and mulching of the soil when necessary (immediately after heavy rains).

Greenhouse. The experiment was arranged in randomized complete blocks with 12 treatments and three replications; each replication included 20 plants. The plants were grown in bags and nonsoil substrate for the greenhouse experiment. The greenhouse had a length of 85 m and width of 10 m. The substrate was prepared using ground corn stover and local compost in 19-L (40.4 cm × 50.5 cm) black grow bags (Grupo Vanguardia, San Pedro Sula, Honduras). The seedlings were transplanted 30 d after sowing.

The fertigation program was calculated based on the soil analysis performed for each trial and aimed to meet the essential nutrient requirements throughout the crop cycle. Recommended production practices were also performed, such as trellising (four to six horizontal trellis wires at 12-cm spacing between wires) and pruning of leaves and branches (lower, diseased, and senescent leaves, vegetative branches). No pollination practices were performed inside the greenhouse.

Plant material. The treatments consisted of 10 tomato lines introduced by the World Vegetable Center and two commercial hybrids (Table 1) that are commonly grown in Honduras. They were evaluated to determine their adaptation, pest and disease resistance, yield and yield components, and fruit quality traits.

Pest and disease quantification. During the experiment involving the open field, the most common and important pests and diseases observed across all the treatments were TYLCD, late blight, and fruit borer. Regarding diseases, during the open field trial, a sample of four plants (as a representative sample) was randomly selected from each replicate per treatment. The disease index for TYLCD and late blight were evaluated at 70 DAT and 100 DAT, respectively. For TYLCD, the disease index (DI) was scored using the scale ranging from 0 to 4 that was described by Lapidot et al. (2006), with modifications (0 = no disease; 1 = very mild symptoms; 2 = mild symptoms; 3 = moderate symptoms; 4 = severe symptoms and considered severe disease). The following formula was used to calculate the percent DI:

$$\mathrm{DI}(\%) = [\Sigma(\mathrm{n\,plant} \times \mathrm{score}) / (\mathrm{total\,plants} \times \mathrm{max\,score})] \times 100 \quad [1]$$

The late blight DI was estimated using a scale ranging from 0 to 5 that was described by Akhtar et al. (2012), with modifications [0 = no visible symptoms (0% DI; immune); 1 = small lesion up to 10% of the total plant area (0.01%–10% DI; highly resistant); 2 = ∼25% of the total plant area is infected (10.01%–25% DI; resistant); 3 = ∼50% of the total plant surface is infected (25.01%–40% DI; tolerant); 4 = approximately more than 75% of the total plant surface is infected (40.01%–60% DI; susceptible); 5 = leaves on the whole plant are blighted and the plant is dead (>60.01% DI; highly susceptible)].

Regarding fruit borer damage (FBD), the amount of fruit damaged by the fruit borer was counted during the first, second, and fourth harvests, and the corresponding percentage was calculated by the following formula (Hanson et al. 2011):

$$\mathrm{FBD}(\%) = (\mathrm{weight\,of\,fruit\,damaged} / \mathrm{weight\,total\,fruit\,yield}) \times 100 \quad [2]$$

Additionally, the scoring system developed by Safna et al. (2018), with modifications, was used to categorize each line according to its percentage of damage as follows: no damage = high resistance; 0% to 10% FBD, resistant; 10.1% to 20% FBD, moderately resistant; 20.1% to 30% FBD, moderately susceptible; 30.1% to 40% FBD, susceptible; and ≥40.1% FBD, highly susceptible.

Plant growth, yield components, and yield. The numbers of fruits and open flowers of five plants per replicate of each treatment were measured at 53 DAT. The plant height was measured at 82 DAT. The marketable yield, nonmarketable yield, and total yield ($t \cdot ha^{-1}$) were evaluated (Hanson et al. 2011). Harvests were performed at 64, 69, 77, 84, 92, 99, 105, 112, and 119 DAT in the greenhouse, and at 69, 76, 83, 90, and 97 DAT in the field.

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Table 1. Characteristics of tomato lines and hybrids evaluated to determine adaptability, yield performance, and fruit quality traits in the open field and protected environment conditions (greenhouse) in San Antonio de Oriente, Francisco Morazán, Honduras.

		TYLCD		Bacterial wilt	RKN	Late blight			
Entry[i]	Type	*Ty1/Ty3*[ii]	*Ty2*	*Bwr-12*	*Mi*	*Ph-2*	*Ph-3*	Plant habit	Fruit shape
AVTO1903	Introduced line	+[iii]	+	+	+	–	–	D	OB
AVTO1908	Introduced line	–	–	–	–	–	–	SD	SL
AVTO1915	Introduced line	+	+	+	+	–	+	SD	OB
AVTO1954	Introduced line	+	+	+	–	+	+	SD	R
AVTO2101	Introduced line	–	+	+	–	–	–	D	R
AVTO2123	Introduced line	–	+	+	–	–	–	D	OB
AVTO2128	Introduced line	+	–	+	–	–	–	D	Dgl
AVTO2127	Introduced line	+	–	+	–	–	–	D	OB
AVTO2132	Introduced line	*Ty3a*	–	+	–	–	–	D	R
AVTO2138	Introduced line	–	–	+	–	–	–	SD	R
Bianco F1	Commercial hybrid (East–West Seed)	ns	ns	ns	ns	ns	ns	D	OB
Pony Express F1	Commercial hybrid (HM Clause)	ns	ns	ns	IR	ns	ns	D	OB

[i] Entries beginning with AVTO were developed and introduced by the World Vegetable Center in Taiwan.

[ii] *Ty1*/*Ty3* and *Ty2* genes conditioned resistance to tomato yellow leaf curl disease. *Bwr-12* and *Bwr-6* genes conditioned bacterial wilt (*Ralstonia* species complex) resistance. The *Mi* gene conditioned resistance to the root-knot nematode *(Meloidogyne incognita*). The *Ph-2* and *Ph-3* genes conditioned late blight (*Phytophthora infestans*) resistance.

[iii] + = homozygous for resistance allele; – = homozygous susceptible allele; D = determinate; Dgl = deep globe; IR = intermediate resistance; ns = not studied; OB = oblong; R = round; RKN = root-knot nematode; SD = semi-determinate; SL = saladette; TYLCD = tomato yellow leaf curl disease.

Fruit quality trait. To determine the characteristics of fruits, five fruits were randomly selected from each harvest, and measurements of the roundness index (obtained by dividing the polar diameter by the equatorial diameter), total soluble solids (TSS; using the HI 96801® digital refractometer; Hanna Instruments, Woonsocket, RI, USA), and percent dry matter of fruits without seeds oven-dried at 75 °C for 42 h and dry weight were determined. The dry matter of the fruits was calculated using the following formula:

$$\mathrm{dm}(\%) = 100 - \left([(\mathrm{Wi} - \mathrm{Wd}])/\mathrm{Wi})\right] \times 100 \quad [3]$$

where Wi is the initial weight, Wd is the dry weight, and dm is the dry matter.

Data analysis. The data were subjected to an analysis of variance using Statistical Analysis Systems version 9.3 (Statistical Analysis Systems 2011). The randomized complete block design and treatment mean comparisons were performed using the Duncan test ($\alpha \leq 0.05$), and Infostat® (Balzarini et al. 2020) was used for the scatter plot comparison of the performance of the open field and greenhouse. The DI, FBD, and dry matter percent were arcsine-transformed to meet the assumptions of homogeneity of variance. The true means of untransformed data are reported.

Results

Microclimate under greenhouse and open field conditions. The lowest temperatures were recorded during the night. They ranged from 18 to 20 °C in the open field and 19 to 22 °C in the greenhouse. During the day, the highest temperatures were 35 to 41 °C in the greenhouse and 30 to 35 °C in the open field. The average RH in the greenhouse during the night was 90%; however, it was 93% in the open field. During the day, the RH was 59% in the greenhouse; however, it was 79% in the open field (data not shown).

Pests and diseases index. Among the entries, the DI values for both TYLCD (P = 0.7010) and late blight (P = 0.1644) were not significantly different. However, there was some variation in the score ranges among the tomato entries. Regarding TYLCD, the DI ranged from 43% to 60%. The disease incidence rates were 43% (AVTO2138), 47% (Bianco F1), 48% (AVTO2123 and AVTO2132), 51% (AVTO1903 and AVTO2127), 52% (AVTO1908 and AVTO1915), 56% (AVTO2101), and 60% (AVTO2128, AVTO2101, and Pony Express F1) (data not shown).

Regarding late blight, the DI ranged from 30% to 37.5%. Although no statistically significant difference was observed in the mean DI among tomato entries, compared with the introduced inbred lines, the hybrids Pony Express F1 and Bianco F1 had greater DI percentages overall (46.2% and 64.2%) and corresponded to the susceptible classifications (Fig. 1). The pest index attributable to fruit borer was significantly different (P = 0.0016) among the evaluated tomato entries and ranged from 3.6% (AVTO2127) to 24.4% (AVTO1908). Based on the scoring scale, seven lines and one hybrid were classified as resistant to fruit borer, two lines and one hybrid were moderately resistant, and AVTO1908 was moderately susceptible (Fig. 1).

Plant growth, yield components, and yield. Significant differences in plant height ($P \leq 0.01$), number of flowers per plant ($P \leq 0.01$), number of fruits per plant ($P \leq 0.01$), total marketable yield ($P \leq 0.01$), total unmarketable yield ($P \leq 0.01$), and total yield (P = 0.0001) in the open field were identified. The tallest lines were AVTO1954 (131.0 cm), AVTO1915 (133.4 cm), and Bianco F1 (139.6 cm); however, the shortest line was AVTO2123 (100.8 cm) (Table 2). AVTO1915 had the greatest number of flowers (92.0), and the other entries had between

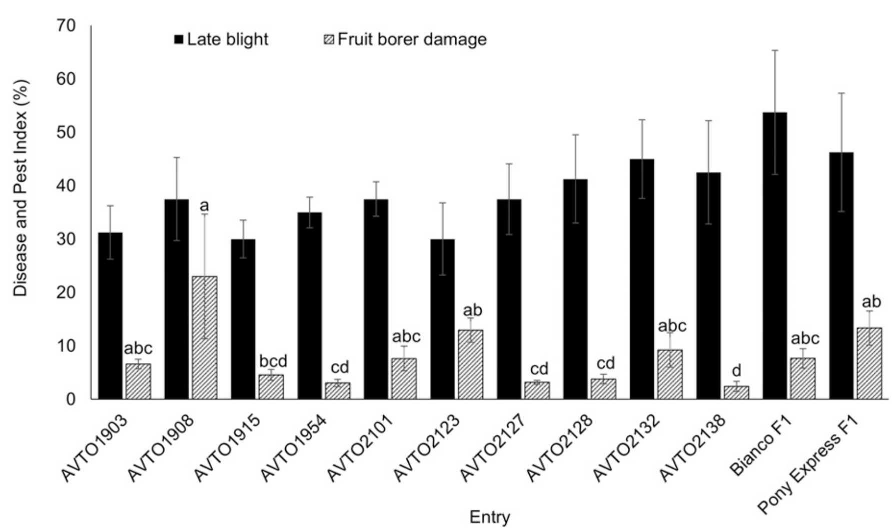

Fig. 1. Disease and pest index of 10 lines and two F1 hybrids of tomato in open field conditions in San Antonio de Oriente, Francisco Morazán, Honduras. Bars with the same letters are not significantly different at $P \leq 0.5$.

Table 2. Growth and yield performance of 10 tomato lines and two F1 hybrids in open field conditions in San Antonio de Oriente, Francisco Morazán, Honduras.

Entry	Plant ht (cm)	Flowers/plant (no.)	Fruits/plant (no.)	Unmarketable yield ($t{\cdot}ha^{-1}$)	Total yield ($t{\cdot}ha^{-1}$)
AVTO1903	124.8 b	72.0 b	48.4 bc	25.8 b	127.1 a
AVTO1908	106.9 de	23.0 de	22.4 d	11.8 de	44.9 f
AVTO1915	133.4 ab	92.0 a	61.3 a	12.1 de	103.4 abcd
AVTO1954	131.0 ab	63.6 b	54.1 ab	8.8 e	82.6 cde
AVTO2101	100.8 e	33.8 cde	45.8 bc	26.9 b	82.3 cde
AVTO2123	84.8 f	30.3 cde	45.4 bc	23.7 bc	88.9 bcde
AVTO2128	126.4 b	43.3 c	41.1 c	13.6 cde	91.3 bcde
AVTO2127	125.4 b	36.1 cd	38.6 c	6.9 e	66.5 ef
AVTO2132	112.9 dc	19.6 e	26.5 d	37.8 a	83.2 cde
AVTO2138	121.5 bc	43.2 c	39.1 c	12.3 de	72.1 def
Bianco F1	139.6 a	45.2 c	45.4 bc	14.3 cde	110.0 abc
Pony Express F1	127.1 b	38.4 c	50.9 b	22.6 bcd	120.3 ab
F value	14.28	17.65	10.87	6.0	4.26
P value	≤0.01	≤0.01	≤0.01	≤0.01	0.0001

Means within the same column followed by the same letters are not significantly different at $P \leq 0.05$.

19.6 and 72 flowers per plant (Table 2). Similarly, AVTO1915 had the greatest number of fruits (61.3) per plant (Table 2). Lower unmarketable yields were found for AVTO1954 and AVTO2127 (8.8 $t{\cdot}ha^{-1}$ and 6.9 $t{\cdot}ha^{-1}$, respectively), whereas the hybrid checks had unmarketable yields of 14.3 $t{\cdot}ha^{-1}$ (Bianco F1) and 22.6 $t{\cdot}ha^{-1}$ (Pony Express F1) (Table 2). The total yield (marketable + unmarketable) in the open field ranged from 44.9 $t{\cdot}ha^{-1}$ (AVTO1908) to 127.1 $t{\cdot}ha^{-1}$ (AVTO1903).

Significant differences in all traits measured were also found among the tomato entries grown in the greenhouse (Table 3). When grown in the greenhouse, the plant height ranged from 60.1 cm for AVTO2123 to 115.8 cm for AVTO1915 (Table 3). The number of flowers per plant was greatest for AVTO1954 (35.2), followed by Pony Express F1 (31.5) and AVTO1915 (31.4) (Table 3). AVTO1903 had the greatest number of fruits per plant (27). Among the tomato lines, AVTO1908 had the highest unmarketable yield (26.2 $t{\cdot}ha^{-1}$), whereas the eight other entries produced comparatively lower unmarketable yields. The total yield (marketable + unmarketable) ranged from 42.1 $t{\cdot}ha^{-1}$ (AVTO2127) to 67.9 $t{\cdot}ha^{-1}$ (AVTO1903) under greenhouse conditions (Table 3).

A comparison of the marketable yield of field production and greenhouse production (Fig. 2) indicated that AVTO1903, AVTO1915, and Pony Express F1 in both production systems had the highest yields. Bianco F1, AVTO2128, and AVTO1954 had better performance in the open field than in the greenhouse, whereas AVTO2123, AVTO2138, AVTO2101, and AVTO2132 had better performance in the greenhouse than in the open field (Fig. 2). AVTO2127 and AVTO1908 were consistently the poorest performers regardless of the production system (Fig. 2).

Fruit quality trait. Among the entries, significant differences in the fruit roundness index ($P \leq 0.01$), TSS ($P \leq 0.01$), dry matter ($P \leq 0.01$), and number of locules were observed in the open field trial ($P \leq 0.01$) (Table 4). Regarding the roundness index, 58% of the accessions had a value greater than 1, indicating a more oval or elongated shape. The highest value was found for AVTO1908 (1.87) (Table 4). The remaining 42% had roundness index values between 0.84 and 0.99, indicating a more flattened fruit shape (Table 4). AVTO1915 and F1 hybrid checks had the highest TSS (3.3 °Brix), whereas AVTO2102 and AVTO1908 had the lowest TSS (2.6 °Brix) (Table 4). AVTO1954, AVTO2123, AVTO2128, and AVTO2127 had the highest dry matter percentage, which ranged from 6.3% (AVTO2123) to 6.5% (AVTO2128) (Table 4). Additionally, fruits of Bianco F1, AVTO2132, AVTO2101, and AVTO2138 had a greater number of locules (Table 4 and Fig. 3).

Among entries, significant differences in the roundness index ($P \leq 0.01$), TSS ($P \leq 0.01$), and dry matter ($P \leq 0.01$) were observed during the greenhouse trial (Table 5). Regarding the roundness index, AVTO1908 had the highest value, whereas AVTO2101, AVTO2132, and AVTO2138 had the lowest values (Table 5). AVTO1915 and AVTO2127 had the highest TSS values; however, they were not statistically different from those of AVTO1908, AVTO2101, AVTO2138, and the F1 hybrid checks. The percentage of dry matter in the fruits ranged from 4.7% (AVTO1903) to 6.12% (AVTO2132) in the greenhouse (Table 5).

Table 3. Growth and yield performance of 10 tomato lines and two F1 hybrids in the protected environment condition (greenhouse) in San Antonio de Oriente, Francisco Morazán, Honduras.

Entry	Plant ht (cm)	Flowers/plant (no.)	Fruits/plant (no.)	Unmarketable yield ($t{\cdot}ha^{-1}$)	Total yield ($t{\cdot}ha^{-1}$)
AVTO1903	103.7 abc	24.8 bcd	27.2 a	5.9 e	67.9 a
AVTO1908	100.9 bc	18.9 cde	15.3 de	26.2 a	62.7 ab
AVTO1915	115.8 a	31.4 ab	22.6 abc	5.7 e	61.9 abc
AVTO1954	110.8 ab	35.2 a	13.9 e	8.3 cde	52.0 cd
AVTO2101	81.3 d	18.3 de	21.6 bcd	11.1 bcde	65.9 ab
AVTO2123	60.1e	14.7 e	26.7 ab	7.5 de	55.4 bcd
AVTO2128	106.8 abc	26.7 bc	23.4 abc	9.4 bcde	48.3 de
AVTO2127	93.9 c	16.8 de	18.6 cd	8.9 cde	42.1 e
AVTO2132	77.9 d	11.5 e	19.6 bcd	14.5 bc	67.5 a
AVTO2138	95.3 c	28.9 ab	10.6 e	6.8 de	58.6 abcd
Bianco F1	110.1 ab	29.9 ab	21.1 bcd	15.6 b	57.9 abcd
Pony Express F1	102.6 abc	31.5 ab	24.7 abc	13.4 bcd	66.8 a
F value	12.18	6.62	5.8	11.1	58.9
P value	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01

Means within the same column followed by the same letters are not significantly different at $P \leq 0.05$.

Discussion

We evaluated 10 World Vegetable Center-introduced tomato lines and the two most common hybrids used in Honduras because of their adaptability, plant growth, pest and disease resistance, yield, and fruit quality traits under both greenhouse and open field conditions in Honduras. Overall, the results revealed significant differences in plant growth, pest damage, yield, yield components, and fruit quality traits among the entries, thus indicating their potential suitability for the target environment. We observed a notable variation in plant growth among the 10 World Vegetable Center tomato lines and two hybrids when cultivated in both greenhouse and open field conditions in Honduras. These differences in plant height have significant implications for their adaptability to local growing environments. The environmental conditions within the greenhouse and open field settings played a pivotal role in shaping the observed plant heights.

The prevailing viral disease across all treatments at the experimental site was TYLCD. This finding aligns with those of prior studies in Honduras that have consistently identified TYLCD, Tomato Mosaic Havana Virus (*Begomovirus*), and Tomato Mild Spot Virus (*Begomovirus*) as the most common viral diseases that affect tomatoes in the region. These diseases have been confirmed through molecular characterization of tomato plants in the Comayagua region of Honduras (Barboza et al. 2018; Keatinge et al. 2016). In fact, TYLCD is one of the most devastating and widespread viral diseases of tomato worldwide, especially in tropical and subtropical regions (Ontiveros et al. 2022). Therefore, evaluating introduced lines developed in subtropical Asia with TYLCD resistance for adaptation to Honduras was of interest. However, the DI of TYLCD was not significantly different among the tomato entries. Despite having lines with the presence of one or two *Ty* genes, which

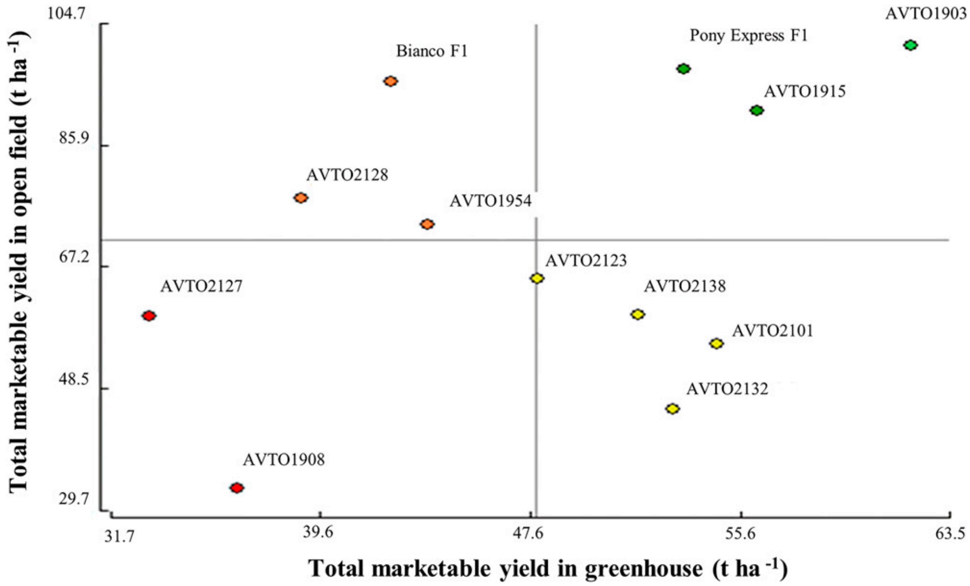

Fig. 2. Comparison of the marketable yield of 10 tomato lines and two F1 hybrids in open field and protected environment (greenhouse) production systems in San Antonio de Oriente, Francisco Morazán, Honduras.

typically confer varying levels of resistance to TYLCD, the incidences of the diseases, which varied from 43% (AVTO2138) to 60% (AVTO2101, AVTO2128, and Pony Express F1), suggested that the present *Ty* genes do not provide complete protection or the disease was misdiagnosed because AVTO2138 does not have any known *Ty* genes but had the lowest TYLCD incidence. It is possible that an additional or different combination of *Ty* genes might be required to confer resistance, as demonstrated by a similar evaluation conducted in Mali (Bihon et al. 2022). This was also observed by Ortiz (2016), who found different scores for accessions evaluated in the field and greenhouse at two different sites in Guatemala and Honduras. Because the *Ty* genes showed varying levels of resistance against TYLCD, further investigations of combined or additional resistance genes could be beneficial. Previous studies have found that combining multiple resistance genes can enhance the efficacy of disease resistance in tomatoes (Bihon et al. 2022). Conducting trials with different combinations of resistance genes could provide insights regarding achieving higher levels of protection against prevalent diseases like TYLCD and late blight. Furthermore, the pathogen that causes the disease should be characterized to ensure an accurate diagnosis.

The late blight DI was not significantly different among entries. However, the range of the DI for World Vegetable Center lines was lower than that of the commercial hybrids, suggesting that the introduced lines might potentially tolerate the disease better than the hybrids. The presence of *Ph* genes, which are associated with late blight resistance, in the World Vegetable Center-developed tomato lines likely contributed to the higher levels of resistance; however, we did not test the commercial hybrids for those genes. Ortiz (2016) found that AVTO1421, developed by World Vegetable Center, had high tolerance to late blight when grown in the open field and protected environments in the highlands of Honduras; however, only this line was tested, and it has not yet been released in the United States. The presence of *P. infestans* in Honduras has persisted since 1982 (CABI 2022). So far, an A1 mating-type clonal lineage is present; however, other strains may be present but have not yet been detected (Blandon 2011; Forbes et al. 2007).

The lack of statistical significance observed during the evaluation of TYLCD and late blight could potentially be explained by the relatively low number of observations per repetition (four plants for each replication per treatment). Future studies should increase the sampling number to improve the accuracy of DIs and reduce variability, especially given the notable range between lines, which varied from 43% to 60% for TYLCD and 30% to 64% for late blight. Additionally, the response of various biotic and abiotic stressors may exhibit cross-protective mechanisms, activating general plant defenses that provide a basic level of protection resulting in different responses (Gorovits and Czosnek 2008). Furthermore, the genetic diversity of the pathogen may affect the individual tomato entry in distinct ways, causing variations in the resistance conferred by genes. This indicates that the resistance is not solely dependent on the presence of genes such as *Ty* or *Ph*, as demonstrated by previous studies (Berdúo-Sandoval et al. 2019; Verlaan et al. 2013). Our results suggest that the average DIs for both TYLCD and late blight are within the category of moderate resistance for the tomato lines evaluated during this study (Akhtar et al. 2012; Lapidot et al. 2006). This finding supports the suitability of introducing these lines to Honduras because of its target environment.

Significant differences in the percentage of FBD among the tomato entries were observed. Our results were similar to those reported by Nasrin et al. (2021), who evaluated introduced tomato lines in Bangladesh and

Table 4. Fruit quality trait of 10 lines and two F1 hybrids in the open field condition in San Antonio de Oriente, Francisco Morazán, Honduras.

Entry	Roundness index	Soluble solids (°Brix)	Dry matter (%)	Locule (no.)
AVTO1903	1.19 c	2.8 bc	4.86 b	3.75 bc
AVTO1908	1.87 a	2.6 e	4.14 b	3.50 c
AVTO1915	1.18 c	3.3 a	4.73 b	3.75 bc
AVTO1954	1.00 e	2.9 cde	5.78 a	2.75 c
AVTO2101	0.84 f	2.6 e	4.53 b	5.25 a
AVTO2123	1.08 d	2.7 de	6.28 a	2.75 c
AVTO2128	0.99 e	2.8 cde	6.51 a	2.75 c
AVTO2127	1.03 de	2.9 cd	6.30 a	3.50 c
AVTO2132	0.87 f	2.7 de	4.61 b	5.25 a
AVTO2138	0.84 f	2.7 de	4.43 b	5.75 a
Bianco F1	1.31 b	3.3 a	4.37 b	5.00 ab
Pony Express F1	1.34 b	3.3 a	4.40 b	3.25 c
F value	108.09	7.17	7.56	4.87
P value	≤0.01	≤0.01	≤0.01	≤0.01

Means within the same column followed by the same letters are not significantly different at $P \leq 0.05$.

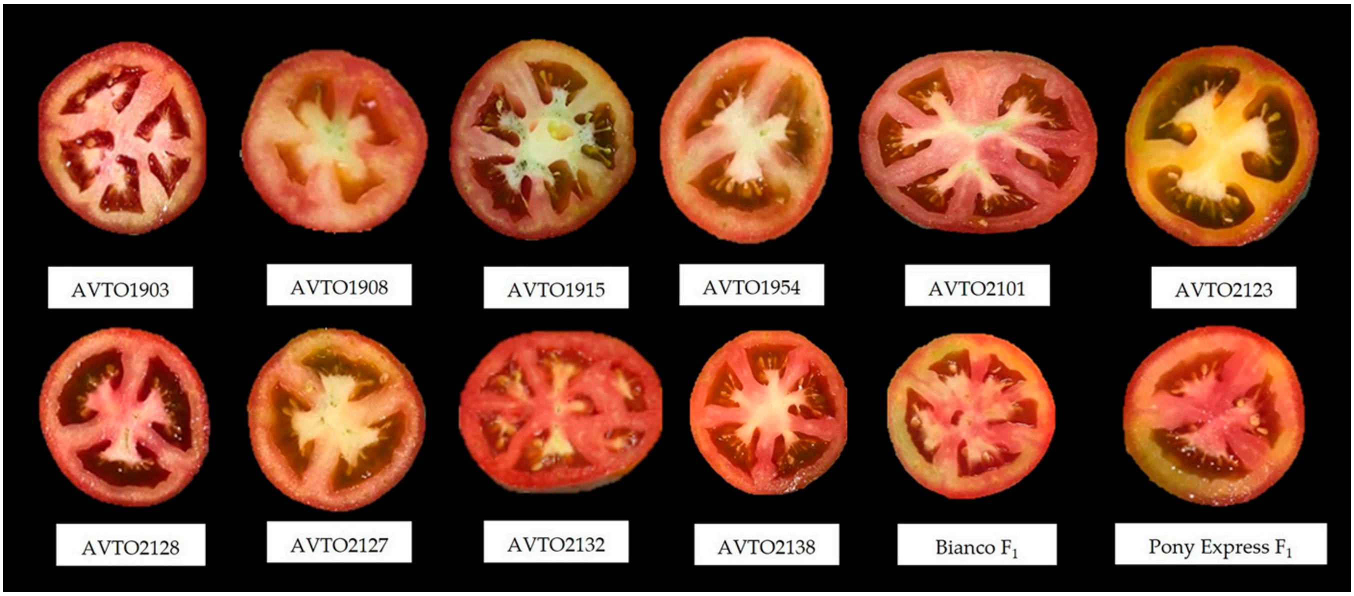

Fig. 3. Vertical cross-section of the fruits of the 10 tomato lines and two F1 hybrids in San Antonio de Oriente, Francisco Morazán, Honduras.

reported damage ranging from 6.6% to 29.7% and found lines that were resistant, moderately resistant, and moderately susceptible. Similarly, Khanam et al. (2003) also found that tomato cultivars had variations in their resistance to fruit borer. The authors determined that the most susceptible cultivar had 33.6% damage, whereas the most tolerant cultivar had 8.7% damage. Variations in the level of tolerance to fruit borer could be attributable to differences in nutritional quality, allelochemical content, or thickness of the fruit pericarp, which can affect the survival and development of the insect (Browne 1975; Sajjad et al. 2011). However, we did not evaluate the fruit nutritional content, pericarp thickness, or other allelochemical compounds during this experiment to develop correlations with host resistance identified among the introduced lines. The antibiotic effects of phenolics and acidity of tomato fruit have also been associated with host plant resistance against fruit borer (Nasrin et al. 2021). However, our results do not support associations with fruit acidity and resistance because AVTO1908 was among the most susceptible to fruit borer and had among the lowest TSS. Overall, some of the introduced lines that we evaluated were adapted to the local climate and are resistant to the predominant pests and diseases.

In both open field and greenhouse conditions, there were significant differences in marketable yield, unmarketable yield, and total yield among the tomato entries. AVTO1915, AVTO1903, Bianco F1, and Pony Express F1 presented the highest field performance values that exceeded the national average in Honduras (70 $t \cdot ha^{-1}$) (FAOSTAT 2022). In terms of marketable yield, our observations were consistent with those of previous studies conducted in Honduras (FHIA 2018, 2019). When evaluating the performance of 39 tomato cultivars in Comayagua, the marketable yield range was 41 to 106 $t \cdot ha^{-1}$ (FHIA 2018), which was in line with our findings. Unmarketable yield was lower for the eight introduced lines, which was consistent with the findings in Honduras, where unmarketable yield ranged from 7.8 to 37.8 $t \cdot ha^{-1}$ (FHIA 2019). Apical necrosis, FBD, fruit cracking, rot, and apical necrosis, which are common issues in Honduran tomato production, were among the primary types of field damage that resulted in fruit rejection (FHIA 2018, 2019).

We compared the marketable yield of field production and greenhouse production and observed that AVTO1903, AVTO1915, and Pony Express F1 had the highest yields in both production systems. The effect of the growing environment on the yield of tomato and other crops is well-known. Recently, World Vegetable Center-developed tomato lines evaluated in Cambodia generally performed better under open field conditions than in protected greenhouse productions (Ro et al. 2021). The expression of productivity and postharvest quality characteristics should be stable across different environments. Predictable performance over a broad range of conditions benefits farmers and seed producers by expanding the range of adaptation and increasing uniformity and potential sales (Barchenger et al. 2018). We found that AVTO1903 and AVTO1915, as well as the control Pony Express F1, had the highest and most stable yields both in open fields and in macrotunnels following the required local consumption product profile and could be recommended for additional evaluation.

The roundness index, TSS, and dry matter are some of the fruit qualities that were measured during this study, and significant differences were observed among lines in both the open field and greenhouse conditions. The roundness index was an important variable to consider because the elongated or saladette shape is highly preferred over the round shape in Honduras (FHIA 2018). The tomato shape is flattened or spherical when the roundness index is less than 1, and the tomato shape is the saladette type or elongated when the roundness index is more than 1 (Figueroa-Cares et al. 2017). AVTO1908 had the highest

Table 5. Fruit quality traits of 10 introduction lines and two F1 hybrid checks in the protected environment condition (greenhouse) in San Antonio de Oriente, Francisco Morazán, Honduras.

Entry	Roundness index	Soluble solids (°Brix)	Dry matter (%)
AVTO1903	1.14 de	3.7 bcd	4.69 b
AVTO1908	2.16 a	4.1 ab	5.02 ab
AVTO1915	1.19 d	4.3 a	6.08 ab
AVTO1954	1.05 f	3.5 d	5.79 ab
AVTO2101	0.91 g	3.9 abc	5.50 ab
AVTO2123	1.09 ef	3.5 d	5.92 ab
AVTO2128	1.09 ef	4.0 ab	6.04 ab
AVTO2127	1.06 ef	4.4 a	6.00 ab
AVTO2132	0.92 g	3.6 cd	6.12 a
AVTO2138	0.96 g	3.8 bcd	5.00 ab
Bianco F1	1.52 b	4.0 abc	5.20 ab
Pony Express F1	1.33 c	3.9 abc	5.75 ab
F value	138.31	5.8	4.32
P value	≤0.01	≤0.01	0.0003

Means within the same column followed by the same letters are not significantly different at $P \leq 0.05$.

roundness index, with more elongated fruits than the other lines evaluated. Roundness index has been previously reported to be influenced by both genetics and the environment (Figueroa-Cares et al. 2017).

The concentration of TSS found in tomato can vary between 2 °Brix and 5 °Brix, and it increases as the fruit develops and ripens (Beckles 2012). The observed variability in the TSS of the lines depended on their individual genotype and environmental conditions in which they were grown (Bihon et al. 2022). Five lines had TSS values more than 4 °Brix in the open field, and four lines had values more than 3 °Brix in greenhouse. The TSS values reported here are similar to those reported elsewhere (Figueroa-Cares et al. 2017; González et al. 2016). Bihon et al. (2022) assessed the adaptability of World Vegetable Center tomato lines in Mali and South Africa and observed that TSS levels were notably high during the rainy season and even higher during the dry season, thus emphasizing the significant impact of environmental factors on TSS. Negative associations between TSS and yield have been previously reported (Beckles 2012; Bihon et al. 2022), consistent with our findings. However, it is more likely that greenhouse production had negative effects on both yield and TSS in our study because of the high temperatures and lack of pollination. However, it is known that the dry matter content can vary depending on the environmental conditions; however, generally, dry matter in ripe tomatoes can range from 4% to 10% (Ho et al. 1987). The mean dry matter content was 5.1% in open field and 5.6% in the greenhouse, which was similar to those previously reported variations in different seasons (Bihon et al. 2022; Pascual et al. 2013).

Dry matter is also influenced by genotype, source-to-sink ratios, and tillage applied to the crop during fruit development (Casierra-Posada et al. 2007). The accumulation of photo assimilates in the fruit is highly dependent on light for photosynthesis and temperature for the corresponding metabolic activities (Dorais et al. 2000). Considering the rank shifts in the performance of the lines in the two environments, variations in light (not measured during this study) and temperature in the open field and the greenhouse likely contributed to the differences in the mean dry matter content. Overall, this study contributes to future studies and expanding trials across different environmental conditions and regions to assess stability, adaptability, yield performance, and fruit quality traits of tomato cultivars to provide a broader understanding of their performance. Cultivars with consistent performance across diverse environments could be prioritized for commercial use because of their broader adaptation and stability.

Conclusions

We evaluated ten introduced World Veg tomato lines in two distinct production systems in Honduras, focusing on adaptability, yield performance, and fruit quality traits. Our findings underscore the importance of these traits for promoting sustainable agriculture and addressing the diverse challenges faced by farmers in the target environment of a tropical region during the dry season and the beginning of the rainy season. The World Veg tomato lines identified in this study, AVTO1903 and AVTO1915, exhibited desired fruit quality traits that was in alignment with the shaped preference for the Honduran market (saladette shape), high and stable yields, and disease resistance. These findings emphasize the potential of these lines for further validation in on-farm trials and their eventual integration into commercial varieties or breeding programs aimed at enhancing yield, fruit quality, and diseases and pests resistance. Overall, the results can provide insights into sustainable agriculture practices, germplasm improvement, and the potential for enhancing food security in the face of changing environmental conditions for Honduras tomato production systems.

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